# Interactive comment on "Enhanced sulfate formation through $SO_2+NO_2$ heterogeneous reactions during heavy winter haze in the Yangtze River Delta region, China" by Ling Huang et al.

Response to Reviewer's Comments

Anonymous Referee #1

## General Comments

The paper addresses a popular question under active discussion in the literature, i.e., what is driving the rapid sulfate formation during winter PM2.5 episodes in China. While many previous papers on the subject drew their conclusions primarily from ambient and/or experimental data (e.g., Wang et al., 2016, Cheng et al., 2016), this is one of the few papers (Wang et al., 2014, Zheng et al., 2015, and Shao et al, 2019) that have used a full chemical transport model as the primary tool. The observed data analyzed came from a site in Shanghai, a megacity outside of the North China Plain (NCP), where the majority of papers on the subject so far have studied. The CAMx model is a chemical transport model similar to US EPA's CMAQ model, and has been extensively used and evaluated in research and regulatory modeling in the US and Europe. In this work, the authors demonstrated the adequacy of the model to simulate winter pollution episodes in China, and the improved model performance (sulfate and others) after including heterogeneous oxidation of SO2 by NO2 as an additional source of sulfate and doubled amount of emissions of NH3. The paper is structured and written in a clear, thorough, and objective fashion that gives a reader full details of the model setup, modifications, and performance, allowing one to reproduce the modeling if one wants to. I especially

commend the authors for their thorough model evaluation, covering meteorological parameters, sulfate and its precursors, and PM2.5, at the primary observational site and many other sites in the modeling domain. All these merits of the paper make it a solid modeling study and has allowed a closer examination against the standard of whether or not it helps advance the understanding of the subject. The standard inevitably rises higher as the paper appeared after many recent published papers on the same subject, offering various contradicting explanations and opinions. Among these papers, some proposed a single dominating oxidant, such as NO2 (Wang et al., 2016; Cheng et al., 2016), H2O2 (Ye et al., 2018), O2 catalyzed by transient metals (Guo et al., 2017), or O2 on acid droplets (Hung and Hoffmann, 2015). Some suggested measurement artifacts to be a major (1/3) cause (Song et al., 2019). Interestingly, while this paper was under access review for ACPD, another paper was published in ACP presenting a rather comprehensive modeling study using GEOS-Chem, concluding with a detailed sulfate budget for Beijing that is also constrained by oxygen isotope data.

With all these prior studies being the departure point, and to serve the fast evolving discussion on the subject, the paper, if accepted, would be expected to offer a cohesive opinion with convincing arguments supported by results from the new modeling or observations, answering some open questions raised previously, or raising some neglected factors, or confirming some findings with new evidence. In this regard, however, I do feel that despite the aforementioned favorable attributes of the work, such as a unique locality of the site, a reputable model with careful modification, and a thorough model evaluation, it evidently falls short of offering unique or novel insights about sulfate production in Shanghai and broader regions of China beyond what have already known from the literature. To be specific, the remarks in the abstract about the

uncertainty of NH3 emissions and potential importance of heterogeneous NO2 oxidation have not gone far beyond reiterating the rationale of the study design (i.e., doubling NH3 emissions and adding heterogeneous NO2 oxidation into CAMx). First, the uncertainty of NH3 emissions is already a recognized issue, as stated by the authors too, not only in China but also in the US and elsewhere. NH3 is also just one participant of sulfate chemistry among many others, e.g., SO2, O3, H2O2, Fe3+, Mn2+, so the choice of addressing NH3 only is not a thorough approach. Besides NH3, SO2 (NMB=32%) and O3 (NMB = -33%) are also too low in the model, while none of H2O2, Fe3+ and Mn2+ is mentioned.

Second, the importance of NO2 heterogeneous oxidation appears disconnected from, if not in contradiction with, the reported model results. In the best-performing scenario (Het_2NH3), heterogeneous NO2 oxidation only explained 16% of the observed sulfate, while standard CAMx sulfate chemistry account for as much as 64%, with another 20% unexplained. Such a diminished role of heterogeneous NO2 oxidation due largely to low pH among other factors (e.g., strengths of other oxidants and sources) is nevertheless a much more useful and interesting finding from CAMx modeling, thanks to the authors' effort of accounting for pH effect, than the arguably marginal improvement of model performance (from NMB = -36% to NMB = -20%) per se. For instance, given this result, the authors could, as done by Shao et al. (2019), calculate and report a sulfate budget breaking down all sources considered, followed by thorough discussions on the robustness of each source and its relative importance, considering model assumptions and uncertainties, which should include not only NH3, but also SO2, O3, H2O2, Fe3+, Mn2+, etc.. From such a "local" story developed from CAMx modeling and data in Shanghai, a reader would learn how similar or unique the sulfate chemistry is in

Shanghai, in comparison to elsewhere in China, or how difficult it is to model it because of various uncertainties and/or assumptions in those poorly understood aspects underlying the model. Along these lines, it did occur to me that the authors actually already have all the data needed from their Shanghai site to develop a "local" parameterization, to their aspiration, instead of adopting the gamma value from Wang et al. (2016) (this will be addressed in more detail in my specific comments).

These considerations led me to the recommendation of a major revision, with three general suggestions followed by some specific suggestions.

Response: We sincerely thank the reviewer for such an amazingly detailed and thoughtful review, which no doubtfully help improve our manuscript. We have carefully revised the manuscript with substantial efforts and tried our best to respond to each of the reviewer's comments. Our major revisions to the manuscript are as follows:

(1) We added descriptions of standard sulfate formation mechanism in CAMx.

(2) As suggested by the reviewer, we conducted additional CAMx simulations to enable a closer look at the sulfate formation budget. We dedicated a new section "Sulfate formation budget" in the revised manuscript to discuss the role of each sulfate formation mechanism in details.

(3) We also adjusted the structures of the manuscript by emphasizing more interesting and important results in the main part and moving other relevant results into the supplemental section. Specifically, we moved the discussions of nitrate, ammonium and $PM_{2.5}$ into the supplemental information. The structure of the revised manuscript is as follows (new sections were highlighted):

There are several similar or same comments from the reviewer. We responded to the first of these similar comments in details and the following comments are referred to earlier responses.

Our responses to the reviewer's comment are given below in blue. Revised parts are presented in red. Revised manuscript (with revisions highlighted) and supplemental information is attached after the response.

First, I suggest adding a full description of the standard sulfate mechanism in CAMx, with perhaps a table listing the reactions, equations, parameters, and assumptions (please refer to Table 2 in Shao et al. (2019) as an example), as done for the new source. Currently the readers only are shown how the new source is parameterized, but not what sources are included in the standard CAMx model. The User's manual of CAMx does not provide a dedicated description of sulfate chemistry in the model, but this information is crucial for a paper that dedicated for sulfate chemistry. Also include description of primary emission of sulfate.

**Response:** We have added section 2.1 as well as Table 1 in revised manuscript to show the standard sulfate formation mechanisms in CAMx.

### 2.1 Current sulfate formation pathways in CAMx

In this study, CAMx version 6.40 (Ramboll Environ, 2016) was used as the base model to simulate sulfate formation. Table X lists the sulfate formation pathways that are currently considered implemented in standard CAMx source code. In addition to the traditional $SO_2$ oxidation by OH in the gas phase and $O_3$, $H_2O_2$, and $O_2$ (catalyzed by transitional metal ions, TMI) in cloud droplets, sulfate formation through reactions with methyl hydroperoxide and other organic hydroperoxides (MHP) as well as peracetic and other organic peracids (PAA) in the aqueous phase is also included. For heterogeneous formation pathway, only $SO_2 + NO_2$ reaction is currently considered and implemented

as pseudo gas phase reaction. The rate parameterization is based on results from Zheng et al (2015), where the key parameter (i.e. gamma) is bounded between a lower and upper limit and changes linearly in response to RH. This relatively simple parameterization of $SO_2 + NO_2$ heterogeneous reaction has been included in many previous studies, e.g. Y. Wang et al. (2014), B. Zheng et al. (2015), Cheng et al. (2016), etc.

Description of primary sulfate emissions (monthly totals as well as spatial pattern) has been added to the manuscript in Section 2.3.

Page 32, Line 20: This YRD-specific emission inventory includes emissions from sources of combustion, industry, mobile and residential. Primary sulfate emissions over the 4km domain are estimated to be 994 tons day$^{-1}$ for December 2013 (accounting for 14.8% of primary $PM_{2.5}$) with dense emissions from Shanghai and southern Jiangsu province (see Figure S1 for spatial distribution). At the SAES site, primary sulfate emissions were estimated to 757 kg per month (only accounting for 1.0% of primary PM2.5).

Second, I suggest calculating and reporting a budget of sulfate at the SEAS site, breaking down sources to a level of detail similar to Figure 3 in Shao et al. (2019). I also suggest reporting concentrations of key relevant species for sulfate production (e.g., SO2, O3, H2O2, Fe3+, Mn2+, in addition to NH3, which is already addressed), and discuss their roles toward closing the sulfate budget.

Response: As suggested by the reviewer, we calculated a detailed sulfate budget at the SAES site and added a new section "Sulfate formation budget" to dedicatedly discuss the contribution of each pathway to the sulfate formation in the revised manuscript. Concentrations of key relevant species (e.g. $SO_2$, $O_3$, $H_2O_2$, Fe(III)/Mn(II)) were also reported to the maximum extent available.

Third, the spatial pattern of CAMx-simulated sulfate enhancement by the new pathway and its drivers sounds like an interesting piece (although two figures associated are currently missing) worth highlighting in the main text and abstract. Many of the

descriptive statements associated with PM2.5, nitrate, if not so relevant to sulfate, should be removed.

Response: As suggested by the reviewer, we combined the discussions of spatial pattern of sulfate enhancement by the new pathway for the YRD region and for the outer 36 km domain into one section. Supporting figures were moved from the supplemental information to the main text. The results of spatial pattern were also mentioned in the abstract. Descriptions of $PM_{2.5}$ and nitrate/ammonium and associated figures are moved to the supplemental information.

Specific Comments

Abstract:

- I suggest the authors to rewrite the abstract after the revision. - I would not stress "for the first time" among those substantive achievements by this study.

Response: We have rewritten the abstract after the revision. "for the first time" has been deleted in the revised manuscript.

1. Introduction

- I suggest two additional papers be added into the discussion:

Shao et al.: Heterogeneous sulfate aerosol formation mechanisms during wintertime Chinese haze events: air quality model assessment using observations of sulfate oxygen isotopes in Beijing, Atmos. Chem. Phys., 19, 6107-6123, https://doi.org/10.5194/acp-19-6107-2019, 2019.

Ye et al.: High H2O2 Concentrations Observed during Haze Periods during the Winter in Beijing: Importance of H2O2 Oxidation in Sulfate Formation, Environ. Sci. Technol. Lett. 2018512757-763.

Response: We thank the reviewer for providing these valuable references. We have added these two papers into discussions of the revised manuscript.

Page 29, Line 14: Similar conclusion is also made from a most recent work by Shao et al. (2019), who implemented four heterogeneous sulfate formation mechanisms in GEOS-Chem and assessed model performance using sulfate oxygen isotopes data in Beijing; the author found that $SO_2$ oxidation catalyzed by transition metal ion (TMI) to be dominating over the other three mechanisms. On the contrary, another slightly earlier study by Ye et al. (2018) concluded $SO_2$ oxidation by $H_2O_2$ was the dominant pathway based on observations of atmospheric $H_2O_2$ concentrations in Beijing."

- "Although the RH dependency of the SO2 uptake rate has already been implemented in previous 20 studies (e.g. Zheng et al., 2015; Wang et al., 2014), the effect of aerosol pH has not been explicitly included in any modelling studies yet to our knowledge."

This is not true as Shao et al. (2019) provided a detailed analysis of pH effect with GEOS-Chem.

Response: We were not aware of the Shao et al. (2019) paper when we were writing this manuscript earlier. We have corrected the languages accordingly in the revised manuscript.

2. Methodology

2.1 $SO_2$ + $NO_2$ mechanism in CAMx

- Please add a section preceding the current Sect. 2.1 to describe standard sulfate chemistry in CAMx in detail, showing what sources are considered, how they are

formulated, values of parameters and constants adopted, and references. Refer to Shao et al. (2019) as an example from GEOS-Chem to see the level of detail to be expected.

Response: We have added a new section 2.1 to describe standard sulfate formation mechanisms currently implemented in CAMx. A similar table (Table 1) is compiled to show relevant information. See response to earlier comment above.

- After looking at the reported data and Wang et al. (2016), I think it is actually possible to develop a "local" parameterization, and I strongly encourage the authors to make an attempt to do so, rather than start with the value of from Wang et al. (2016) and back calculate k0. The in Wang et al. (2016) was derived from ambient observational data in their Table S5. Most of those were available from this paper as well. The steps taken can be as follows. First, one can use observed minus modeled sulfate concentration from standard model during selected episodes to obtain the amount of sulfate that is not accounted for by the model, i.e., SO4; calculate d[SO4]/dt using observed length of time for sulfate buildup during selected episodes (EP1 – EP4 for instance); calculate using Eq.(2), by plugging in measured SO2 concentration and aerosol surface area, which can be the value assumed in CAMx, if not measured. In the next step, one can use measured NO2, RH and calculated LWC and pH in Table S1 to get the RH dependence function (Eq.(4)). Such a parameterization is supposed to yield better modeling results. This new parametrization can also be compared to those from Beijing and discuss why they agree/disagree.

Response: We agree with the reviewer that a parameterization based on local data would be more appropriate for this study and we appreciate the reviewer's suggestions of deriving local parameters. The Beijing study was developed by data analysis outside the model, so it is independent of the model. We don't think we have sufficient ambient data for Shanghai to make a similar analysis independently outside the model. More local data is needed to constrain the precursor concentrations and aerosol state (e.g. pH) as well as the sulfate production rate. Our current results indicate this $SO_2 + NO_2$ heterogeneous mechanism is potentially important for Shanghai and there is a need for an independent observation study performed in Shanghai like the one in Beijing to better parameterize the scheme. We include more discussions regarding the uncertainties of the current parameterization in the revised manuscript.

- In Eq. 4., what is the basis for assuming k0 to be constant when RH increases from 56% to even higher values? This assumption would be expected to suppress sulfate production under very high RH, a very favorable condition for heterogeneous sulfate production.

Response: We assumed $k_0$ to be constant when RH increases from 56% up because we were given no information from the study (i.e. Wang et al. 2016) that we constructed our parameterization based on. We agree with the reviewer that higher RH values would provide a very favorable condition for heterogeneous sulfate production. Therefore, our assumption of $k_0$ being constant at high RH values gives a conservative estimation of sulfate formation via $SO_2 + NO_2$ heterogeneous reactions. The RH at SAES site during our modeling period is $52 \pm 18\%$, $57 \pm 19\%$, and $56 \pm 17\%$, for clean, transition and polluted conditions. These values are similar

to that in Beijing under polluted conditions but were higher for clean and transition conditions. As an initial attempt to look the sensitivity of $k_0$ to RH, we performed an additional CAMx simulation by doubling the $k_0$ value when RH increases from 56% to 100% instead of keeping it a constant. Results from the initial sensitivity run show that the sulfate formation with doubled $k_0$ value under high RH values were enhanced by 10% on averaged under polluted conditions. The maximum hourly enhancement of sulfate with the doubled $k_0$ value was around 40%. We realize that our simplification of setting $k_0$ to a constant value at high RH values would lead to underestimation of the contribution from the $SO_2 + NO_2$ heterogeneous reactions. However, without any further observations or supporting data, we feel it would be inappropriate to make any assumptions at the moment. Therefore, we kept the $k_0$ formula as it is right now and mentioned that this is a relatively conservative estimation in the revised manuscript.

Page 31, Line 11: Due to lack of observation data at high RH values, we set a constant $k_0$ value when RH increases from 56% and up. This would lead to a conservative estimation of the sulfate formation due to the $SO_2 + NO_2$ heterogeneous reactions at high RH values, which is a favorable condition for the heterogeneous sulfate production

- Elaborate on what df is in Eq. 5 and how it is calculated in the model.

Response: df is ratio of $SO_2$ concentrations in the aqueous phase to $SO_2$ concentrations in the gaseous phase. It is calculated as:

$$d_f = \frac{[S(IV)(aq)]}{[SO2(g)]} = H_{eff}RTw_L$$

where $H_{eff}$ is the effective Henry's low constant of $SO_2$ (M atm$^{-1}$), R is the universal gas constant (L atm mol$^{-1}$ K$^{-1}$), T is air temperature (K) and $w_L$ is the aerosol water content (μg m$^{-3}$). This description has been added to the revised manuscript in section 2.2.

$$\gamma = 4k_0 d_f [NO_2(g)] \tag{3}$$

where $k_0$ (ppm$^{-1}$) is the RH-dependent parameter; $NO_2(g)$ is the $NO_2$ gas concentration; $d_f$ is the pH-dependent distribution factor of $SO_2$, i.e. the ratio of $SO_2$ concentration in the aqueous-phase to the gaseous-phase and is calculated as Eq. (4) in the model:

$$d_f = \frac{[S(IV)(aq)]}{[SO2(g)]} = H_{eff} RT w_L \tag{4}$$

where $H_{eff}$ is the effective Henry's low constant of $SO_2$ (M atm$^{-1}$), R is the universal gas constant (L atm mol$^{-1}$ K$^{-1}$), T is air temperature (K) and $w_L$ is the aerosol water content (μg m$^{-3}$).

2.2 Model configuration

- Page 5, line 30: "we removed the original heterogeneous sulfate formation reaction which only included a simple parameterization based on RH (Zheng et al. 2015) in the distributed version". Please elaborate on what the reaction is and what oxidant it includes.

Response: This reaction is listed as reaction No.7 in Table 1 that is added in the revised manuscript. Languages have also been modified accordingly in the revised manuscript.

Page 32, Line 31: Note that this CAMx version differs from the distributed CAMx v6.40 in that we removed the original heterogeneous sulfate formation reaction with $NO_2$ which only included a simple parameterization based on RH (ref. reaction No.7 in Table 1) in the distributed version.

- Page 6, line 30: "we used ammonia observations from a similar urban site nearby". When model performance is examined, is the modeled ammonia from the grid cell covering SAES site or from FDU site?

Response: We used modeled ammonia from the grid cell covering SAES site. Modeled ammonia concentrations at SAES site and FDU site show excellent agreement with each

other (R$^2$=0.94); therefore, we used modeled results at SAES to compare with ammonia observations at FDU site. This clarification has been added in the revised manuscript.

Page 34, Line 4: This two-peak diurnal variation is caused by vehicle emissions and evolution of the boundary layer (S. Wang et al. 2015). In summary, observations for gases species (except NH3) and PM species at the SAES site and NH3 at the FDU site were used for model validation at the SAES site in this study.

3. Results and Discussion

3.2 Simulated PM concentrations at SAES site

"Impact of both (noHet vs. Het_2NH3)"

Page 9, line 33 – Page 10, line 3: "This could be related to still biased ammonia emissions, less direct emissions of sulfate and/or SO2, and/or missing of other sulfate formation pathways that needs further investigation. Another explanation is that the SO2 + NO2 heterogeneous reactions implemented in this study were parameterized based on observations in Beijing but the simulation is performed over the YRD region. It would be ideal to use local observations for model parameterization in future studies."

These discussions are too general and speculative, and should be further developed into one of the major sections of the paper, based on additional model diagnostics, calculations, and comparisons against other studies. Below are excerpts of questions to be addressed.

- Ammonia emission was already doubled resulting in 30% overestimate of the observed. How would it further help enhance sulfate production? Direct emission of sulfate in the model needs to be reported. Primary sulfate contributes more than 20% in Beijing according to Shao et al. (2019). What is the contribution to sulfate in Shanghai and YRD?

Regarding the parameterization, how much larger gamma needs to be to reach the observed amount of sulfate? Can the RH dependence function be improved to yield better performance? These questions can be answered by devising a "local" parameterization as outlined above. Standard sulfate chemistry is not mentioned in this discussion, but should definitely be a focus of discussion, because numerous factors can affect its contribution, such as levels of H2O2, Fe3+, Mn2+, assumed aerosol particle properties in the scheme, etc. A most straightforward way of presenting and discussing these results is to have a sulfate budget, and then go over the source one by one, noting their dependencies and robustness of representation by the model. Figure 3 from Shao et al. (2019) gives an example.

Response: Our responses to each of the reviewer's questions are as below:

(1) Ammonia emission was already doubled resulting in 30% overestimate of the observed. How would it further help enhance sulfate production?

We noticed that with double ammonia emissions, gaseous phase ammonia was overestimated by 34%. However, if we looked at total ammonia (gaseous ammonia + ammonium), the MB of total ammonia was reduced from -6.9 $\mu g/m^3$ in the base case scenario to -1.9 $\mu g/m^3$ with doubled ammonia; corresponding NMB reduced from -36% to -10%. As mentioned in Section "Observed and predicted aerosol pH at the SAES site", with doubled ammonia emissions, modeled aerosol pH increased by ~0.7, therefore pushing the simulated aerosol pH closer to observed values. Therefore, with doubled ammonia emissions, the $SO_2$ + $NO_2$ heterogeneous reactions are playing an increasing important role in sulfate production.

(2) Direct emission of sulfate in the model needs to be reported. Primary sulfate contributes more than 20% in Beijing according to Shao et al. (2019). What is the contribution to sulfate in Shanghai and YRD?

We have reported emissions of primary sulfate in the revised manuscript. Contribution of primary sulfate emissions is included in section "Sulfate formation budget" in the revised manuscript.

(3) Regarding the parameterization, how much larger gamma needs to be to reach the observed amount of sulfate? Can the RH dependence function be improved to yield better performance?

As mentioned above, we performed a sensitivity test by doubling $k_0$ values and observed an average of 10% and hourly maximum of 40% of sulfate enhancement. Therefore, adjusting the RH dependence function, especially at high RH values, is expected to improve the model performance. However, without any further observation data available, we were inclined to keep the formula as it is right now. This also emphasizes the need to perform additional observations or experiments at high RH values to improve the parameterizations but is beyond the scope of the current study.

(4) Standard sulfate chemistry is not mentioned in this discussion, but should definitely be a focus of discussion, because numerous factors can affect its contribution, such as levels of H2O2, Fe3+, Mn2+, assumed aerosol particle properties in the scheme, etc. A most straightforward way of presenting and discussing these results is to have a sulfate budget, and then go over the source one by one, noting their dependencies and robustness of representation by the model. Figure 3 from Shao et al. (2019) gives an example.

We conducted additional CAMx simulations by turning off one formation mechanism at a time and constructed a sulfate formation budget. We added a new section "Sulfate formation budget" in the revised manuscript to dedicatedly go over each of the pathways.

*Sulfate formation budget*

To gain a closer look at the sulfate formation via different pathways (e.g. gas phase vs. aqueous phase vs. heterogeneous phase, Table 1), we constructed a sulfate formation budget in a similar manner as Shao et al. (2019). Figure 7 shows the relative contribution of primary sulfate emissions as well as individual sulfate formation pathway to the total sulfate concentrations at the SAES site under different conditions. Overall, primary sulfate emissions and secondary formation accounted for half of the total sulfate concentrations. Of the secondary sulfate, gas-phase reactions always dominated secondary sulfate formation, with relatively consistent contribution around 38~39% under different conditions. As pollution developed, contribution from secondary formation exceeded that of primary emissions, accounting for 60% of total sulfate abundances under polluted conditions. In contrast to the relatively consistent contribution from the gas-phase formation, both aqueous and heterogeneous sulfate formation doubled from clean to polluted periods, with relative contribution increased from 4.1% to 9.4% for the former and from 5.0% to 12.6% for the latter.

If we exclude the contribution of primary sulfate emissions (i.e. smaller pie chart in Figure 7), the absolute sulfate formation via the gas-phase reactions more than doubled from clean (1.59 μg m$^{-3}$) to polluted (3.61 μg m$^{-3}$) periods; however, the relative contribution from gas-phase formation among all formation pathways dropped from 80.9% to 63.3% as pollution developed. Sulfate formation from all aqueous phase reactions increased from 0.17 μg m$^{-3}$ under clean conditions to 0.89 μg m$^{-3}$ under polluted conditions, corresponding to an increase of relative contribution from 8.6% to 15.6%. Under all conditions, aqueous oxidation due to MHP and PAA is negligible, with less than 1% of sulfate contribution. The rest three aqueous pathways in turn dominated aqueous sulfate formation depending on the specific condition. For instance, under clean conditions, oxidation by $O_3$ was the dominant aqueous contributor (accounting for 5.4% of all sulfate formation pathways) but ignorable (<1%) under polluted conditions. While modeled $SO_2$ concentrations increased from 33.2 μg m$^{-3}$ to 53.5 μg m$^{-3}$ as pollution developed, simulated $O_3$ concentrations dropped by almost half from 8.7 ppb (~ 18.7 μg m$^{-3}$)

under clean conditions to 5.2 ppb ($\sim$ 11 $\mu$g m$^{-3}$) under polluted conditions, leading to reduced sulfate formation from aqueous oxidation by $O_3$ under more severe haze. Predicted $O_3$ concentrations in this study are much higher than the values ($\sim$1 ppb) assumed by Cheng et al. (2016) and Wang et al. (2016) but are comparable to values reported by Shao et al (2019; 9 ppb) for a haze episode in Beijing.

Sulfate formation associated with $H_2O_2$ and Fe(III)/Mn(II) showed the opposite trend: the $H_2O_2$ pathway only contributed 1.4% (0.03 $\mu$g m$^{-3}$) of total sulfate formation under clean conditions and increased to 5.6% (0.12 $\mu$g m$^{-3}$) under polluted conditions, representing an increase by a factor of 3. Predicted $H_2O_2$ concentrations at the SAES site was 0.03 ppb on average and maximum value could reach 0.29 ppb. These values are slightly lower than the values observed in Beijing (average around 0.05 ppb and maximum of 0.90 ppb) by Ye et al. (2018) but are comparable in term the magnitude. However, without any $H_2O_2$ observations in Shanghai, it would be in appropriate to conclude whether model is over- or under-predicting $H_2O_2$ levels in Shanghai. Based on our current results, $H_2O_2$ oxidation is not the dominant contributor to sulfate formation during our study period.

Oxidation pathway involving Fe(III)/Mn(II) also contributed more to sulfate formation as polluted developed. Under polluted conditions, Fe(III)/Mn(II) catalyzed sulfate oxidation is the dominant aqueous formation pathway, accounting for 8.4% (0.48 $\mu$g m$^{-3}$) of secondary sulfate formation. CAMx estimates the Fe(III) and Mn(II) concentrations by assuming a constant mass fraction (3.355% for Fe(III) and 1.15% for Mn(II) based on the dust and primary $PM_{2.5}$ concentrations. A value of 10% for Fe (III) and 50% for Mn (II) was set to represent the soluble fraction in the cloud water. 10% of Fe(III) during the day and 90% of Fe(III) during the night and all Mn(II) were assumed to be in the oxidized ionic state. Based on these assumption, modeled soluble concentrations during December 2013 was 1.51 $\pm$ 1.68 $\mu$M for Fe(III) and 0.51 $\pm$ 0.31 $\mu$M for Mn(II), respectively; the range of estimated soluble Fe(III) and Mn(II) was 0.1~10.7 $\mu$M and 0.05~2.47 $\mu$M. These results are somewhat lower than the values reported by Shao et al. (2019) and other studies cited in the paper but the overall magnitudes are well comparable. We realize that assuming constant Fe and Mn mass fraction is a simplification and latest CAMx version has the option to treat Fe and Mn as primary species. However, using this option would put even more burden on the emission inventory to have accurate source speciation profiles for different source sectors. Nevertheless, although this Fe(III)/Mn(II) catalyzed pathways stands out among all aqueous pathways under polluted conditions, the relative contribution (8.4%) is only about one third of that from the $SO_2$ + $NO_2$ heterogeneous reactions (21.1%). As for the $SO_2$ + $NO_2$ heterogeneous reactions, its contribution to sulfate formation doubled from 10.5% (0.21 $\mu$g m$^{-3}$)

under clean conditions to 21.1% (1.2 μg m$^{-3}$) under polluted conditions. Under all conditions, the relative contribution of the $SO_2$ + $NO_2$ heterogeneous reactions exceeds the sum of all aqueous pathways, indicating the importance of heterogeneous oxidation pathways compared to aqueous pathways.

- Once a sulfate budget is available, it would be constructive to compare and discuss it in the context of previous studies, observational and modeling. For instance, Ye et al. (2018) suggested that H2O2 oxidation should be the dominating sulfate formation pathway in Beijing based on their observed amount of H2O2. How much H2O2 does CAMx predict? Without observed values from Shanghai, perhaps one could compare modeled values in Beijing to those observed by Ye et al. (2018). The 10-ppb O3 level at the SEAS site is much higher than the Beijing haze case (1 ppb) assumed by Cheng et al. (2016) and Wang et al. (2016), but similar to what Shao et al. (2019) has in Beijing (9 ppb). O3 is underestimated by 33% by CAMx. Does that partly explain the 19% unaccounted? Guo et al. (2017) speculated catalyzed oxidation with metals (Fe3+, Mn2+) to be important. Does CAMx result agree with their speculation? How much Fe3+ and Mn2+ does CAMx simulate? How do they compare to those in GEOS-Chem by Shao et al. (2019)?

Response: We added a new section "Sulfate formation budget" in the revised manuscript that discussed the contribution from each sulfate formation pathways in details. We also reported the simulated concentrations of each oxidant and compared with Ye et al. (2018) and Shao et al. (2019) results whenever possible. Please refer to the revised manuscript for details.

- Since almost everything is underestimated as shown in Figure S4, a common cause such as meteorology misrepresentation is not ruled out. This is mentioned

briefly but not explored in detail. Could there be a relationship between sulfate bias and biases of meteorological parameters?

Response: We added discussions of biased wind speed to illustrate more on the general underestimation in the revised manuscript. While temperature and relative humidity (especially relative humidity) were generally well simulated by the WRF model, wind speed was overestimated by 0.5 m s$^{-1}$ (Hongqiao) and 1.5 m s$^{-1}$ (Pudong) at the two meteorological stations, respectively. This over-prediction of wind speed could partially explain the general underestimation of all gaseous and PM species simulated by model.

Page 35, Line 4: Nevertheless, model tends to systematically underestimate all gaseous and PM species with NMB values ranging from -5% for $NO_2$ to -68% for $NH_3$. This could be partially explained by the higher simulated wind speeds compared with observed values, especially at Pudong station where the observed average wind speed during the modeling period was 4.5 m s$^{-1}$ while simulated wind speed was 6.0 m s$^{-1}$, representing an over-prediction by 33%.

"Sulfate formation under selected episodes"

I think these episodes should be further analyzed in a quantitative fashion, as done by Wang et al. (2016) and Cheng et al. (2016). By closer examining the variations of sulfate and its depending variables, it might be possible to see similarities or differences in sulfate formation regimes among these episodes, or compared to reported cases from Beijing. For instance, I made an attempt to roughly calculate the ratios of sulfate to SO2 for clean, transition, and polluted conditions, using data from Figures S5 and S6, and found it interesting that they are actually somewhat similar to those reported by Wang et al. (2016) for the three conditions.

Response: As suggested by the reviewer, we added more quantitative discussions with respect to these selected episodes in the revised manuscript.

*- EP3 is evidently an anomaly among the four episodes. Are the modeled wind speeds during this episode too high or direction erroneous? It is hard to tell from Table S3 or Figure S3. Please take a closer look and provide a more satisfactory explanation. SO2 emission change from 2013 to 2014 would not affect only EP3 but also other episodes, so is not a plausible explanation for the anomaly.*

Response: We looked at the model performance of WRF predictions for individual episode. All four episodes had some over-prediction of wind speeds with NMB ranging from 4% of EP2 to as much as 43% of EP3. Clearly, the large over-prediction of wind speeds during EP3 contributed partially to the under-estimated sulfate concentrations by the model. Another potential cause for sulfate underprediction could be failure to capture episodic primary sulfate emissions during EP3. These discussions have been added to the revised manuscript.

3.2.2 Nitrate and ammonium concentrations

3.2.3 PM2.5 concentrations

I think these two sections ought to be moved down after Sections 3.3 and 3.4, as they do not help solve the sulfate problem. The discussions on PM2.5 are somewhat distractive and premature, given the large biases in sulfate and OC. I suggest moving this part to supplement, if the title and focus of the paper is on sulfate.

Response: We followed the reviewer's suggestion by moving "3.2.2 Nitrate and ammonium concentrations" after Sections 3.3 and 3.4 and also moving "3.2.3 PM2.5 concentrations" to the supplemental information in the revised manuscript.

3.3 Predicted aerosol pH at the SAES site

This section is important and should be moved up following section 3.2 in helping explain the sulfate result. Have you looked at temporal variability of pH and see if there is correlation with sulfate production?

Response: In the revised manuscript, we moved this section right after section 3.2 as suggested by the reviewer. We did look at the temporal variability of pH and its correlation with the total sulfate production as well as sulfate production via the $SO_2$ + $NO_2$ heterogeneous reactions only. In both cases, correlation between aerosol pH and sulfate production is weak (with $R^2$ < 0.01). As indicated by Figure 8, aerosol pH becomes more acidic as pollution develops because of higher $SO_2$ concentrations under polluted conditions. At the same time, sulfate formation was enhanced under polluted conditions, leading to negative correlation between aerosol pH and secondary sulfate formation. Similar to Wang et al. (2016), we also plotted aerosol pH against $[SO_4^{2-}]/[SO_2]$ for both observed and modeled data. In both cases, we are seeing negative correlations between aerosol pH and $[SO_4^{2-}]/[SO_2]$.

In the revised manuscript, we strengthened this section by adding more discussions on the comparison between modeled aerosol pH and observation-based aerosol pH, as suggested by the other reviewer.

3.4 Spatial impact of the SO2 + NO2 heterogeneous reactions and ammonia emissions in YRD region

3.5 Simulated sulfate concentrations over China

Too many numbers and descriptive statements appear in these two section as distractions. It appears to be an intriguing finding that despite all the compounding factors, pH value and ammonia stand out to regulate the spatial pattern of sulfate

enhancement from the new pathway, which to me is worth further verifying and discussion, although Figures S7 and S8 are currently missing. I suggest this section be merged into one to as a dedicated section on spatial pattern and its driving factors, with the two figures moved to the main text. The result from this analysis should be mentioned in the abstract.

Response: A similar comment was made by the reviewer above. Please refer to our responses above.

Technical Corrections

Abstract

"In addition, ammonia emissions need to be carefully estimated." and "Substantial efforts are needed to improve the accuracy of ammonia emissions inventory" are duplicated statements.

Response: Modified in the revised manuscript.

Section 2.1

Eq.(6) $k_{net}$ –> $k_{het}$

Response: Corrected in the revised manuscript.

I think you meant to say Table S2 and Table S5, when you say "We used the data in Table S2 and S4 of Wang et al. (2016) to back calculate the RH dependency of $k_0$: : :"

Response: We appreciate the reviewer's detailed review and have corrected this typo in the revised manuscript.

Section 3.1.1

"Bias of predicted wind speed is within 0.31 degree." Please report correct wind speed bias with unit of m/s, and verify bias of wind direction. 0.31 degree is very small.

Response: We have corrected this in the revised manuscript as well as Table S3 in the supplemental information.

### 3.1.1 WRF results simulation

Model performance of WRF results is generally acceptable in this study. Table S3 summarizes the meteorological performance statistics of WRF during December 2013 at Pudong and Hongqiao airport stations in Shanghai (Figure 3). Temperature and relative humidity were well reproduced with NMB and NME within 37% and 41%, respectively; IOA values are above 0.8. Wind speed is slightly overestimated with a MB of 1.5 m s-1 at Pudong and 0.5 m s-1 at Hongqiao station; NMB of predicted wind direction at the two stations is -36% and -27%, respectively. Comparisons of hourly observed and simulated relative humidity, wind speed and temperature at these two stations suggest reasonable model results in terms of temporal variations (Figure S3). Overall, the WRF simulated results are acceptable to be used in subsequent CAMx simulations.

3.2.2

Typo/omission:

"This reduces nitrate underestimation substantially during polluted period from -42 % to -20 % but also leads to even higher nitrate overestimation during clean 25 and transition periods *but*."

Response: Corrected in revised manuscript. And as suggested by the reviewer, this section has been moved to the supplemental information.

Table S3

What is the unit of wind direction?

Response: The unit of wind direction is degree. This has been added to Table S3 in the supplemental information.

Figure S4 and Table S4.

The NMB and IOA appear differently in Table S4 (NMB = -72%, IOA = 0.52) and Figure S4 (NMB = -60%, IOA = 0.55). Please check and correct.

Response: This has been corrected in revised supplemental information.

References cited in this response

Cheng, Y., Zheng, G., Wei, C., Mu, Q., Zheng, B., Wang, Z., Gao, M.,Zhang, Q., He, K.,Carmichael, G., Pöschl1, U., and Su, H.: Reactive nitrogen chemistry in aerosol water as a source of sulfate during haze events in China, Science Advances., 2, e1601530-e1601530, doi:10.1126/sciadv.1601530, 2016.

Guo, H., Weber, R. J., and Nenes, A.: High levels of ammonia do not raise fine particle pH sufficiently to yield nitrogen oxide-dominated sulfate production, Scientific Reports., 7, 12109, doi:10.1038/s41598-017-11704-0, 2017.

Shao et al.: Heterogeneous sulfate aerosol formation mechanisms during wintertime Chinese haze events: air quality model assessment using observations of sulfate oxygen isotopes in Beijing, Atmos. Chem. Phys., 19, 6107-6123, https://doi.org/10.5194/acp-19-6107-2019, 2019.

Wang, Y., Zhang, Q., Jiang, J., Zhou, W., Wang, B., He, K., Duan, F.,Zhang, Q., Philip, S.,and Xie, Y.: Enhanced sulfate formation during China's severe winter haze episode in January 2013 missing from current models, Journal of Geophysical Research: Atmospheres., 119, 10425-10440, doi:10.1002/2013jd021426, 2014.

Ye et al.: High H2O2 Concentrations Observed during Haze Periods during the Winter in Beijing: Importance of H2O2 Oxidation in Sulfate Formation, Environ. Sci. Technol. Lett.2018512757-763.

Zheng, B., Zhang, Q., Zhang, Y., He, K. B., Wang, K., Zheng, G. J., Duan, F, K., Ma, Y, L., and Kimoto, T.: Heterogeneous chemistry: a mechanism missing in current models to explain secondary inorganic aerosol formation during the January 2013 30 haze episode in North China, Atmos. Chem. Phys., 15, 2031-2049, doi:10.5194/acp-15-2031-2015, 2015.

**Anonymous Referee #2**

This study focused on an important and interesting topic of the rapid sulfate formation pathway in hazes. The modelling work in this study is sound and clearly described. In addition, the paper is clearly written and well-organized. However, discussion on the results is relatively weak. In my view, major drawback of this study is that, it spent too much effort discussing the model performance, while too little about the underlying reasons. The following concerns should be addressed before it can be published.

Response: We thank the reviewer for a thoughtful review and recognizing the pros of our study. We have spent tremendous efforts to improve the manuscript by providing analysis and discussions of the underlying reasons. The major revisions we made to the manuscript are listed as follows:

(1) We added descriptions of the standard sulfate formation mechanisms in CAMx so the readers could have a better understanding of what has already been implemented in standard CAMx. This is added as Section "2.1 Current sulfate formation pathways in CAMx" in the revised manuscript.

(2) As suggested by the other reviewer, we conducted additional CAMx simulations and constructed a sulfate formation budget to closely look at the sulfate contribution from each of the pathways, therefore to gain a better understanding of the relative importance of the heterogeneous reactions vs. other traditional pathways to sulfate formation. In the revised manuscript, we dedicated a new section "Sulfate formation budget" to discuss the role of each sulfate formation mechanism in details.

(3) We also added more discussions on the aerosol pH by comparing model predicted aerosol pH vs. observed pH, as suggested by the reviewer. We changed the previous Section "Predicted aerosol pH at the SAES site" to Section "Observed and predicted aerosol pH at the SAES site".

(4) We also adjusted the structures of the manuscript by emphasizing more interesting and important results in the main part while moving other not so relevant results into the supplemental section. Specifically, we moved the discussions of nitrate, ammonium and PM2.5 into the supplemental information since the focus of this study is sulfate. We combined previous Section "Spatial impact of the $SO_2$ + $NO_2$ heterogeneous reactions and ammonia emissions in YRD region" and Section "Simulated sulfate concentrations over China" into one merged Section "Spatial impact of the $SO_2$ + $NO_2$ heterogeneous reactions and ammonia emissions".

(5) We also added discussions in various places of the revised manuscript to address the reviewer's comments, including the difference of hygroscopicity in Shanghai vs. Beijing, justification of doubling ammonia emissions, and citing more references.

Our responses to the reviewer's comment are given below in blue; revised parts are presented in red. Since we have revised the manuscript substantially, we highlighted our revision in yellow in the revised manuscript for reference. Revised manuscript (and supplemental information) is attached after the response.

**Major Comments:**

1. In the abstract and conclusions etc., the authors simply claimed that doubling the ammonia emissions can improve the model performance, without any justification of

doing so. As the predicted NH3 in base scenario is significantly underestimated (Page 9, Line 6), increasing the emissions seems reasonable, but the authors should clarify on this issue.

Response: We have added this clarification of ammonia underestimation in both the abstract and conclusions in the revised manuscript.

In the abstract: Estimation of ammonia emissions is usually associated with large uncertainties and model tends to underestimate ammonia concentrations substantially.

In the conclusion: Ammonia concentrations were significantly underestimated by the model. Doubling ammonia emissions alone exhibited a similar impact (sulfate increase by 5.6 %) with that of the $SO_2 + NO_2$ heterogeneous reactions alone.

2. Although doubling the ammonia emissions will result a higher NH3 in models than observations (NMB of 34%; Page 9, Line 7), the predicted NH4+ is still much lower than observation (NMB of -31%, Page 11, Line 5). As a result, doubling the ammonia emissions may generate a reasonable total ammonia (NH3 + NH4) concentrations? If so, it would further support the model modification of doubling ammonia emissions.

Response: We calculated MB and NMB for total ammonia concentrations before and after doubling ammonia emissions. The MB and NMB of NH3 + NH4 concentrations with the base case scenario were -6.9 µg m$^{-3}$ and -36%, respectively. With doubled ammonia emissions, MB and NMB reduced to -1.9 µg m$^{-3}$ and -10%. We have added this point in the revised manuscript.

P18, Line 16: With doubled ammonia emissions, ammonia concentration was over-predicted by 1.7 ppb with NMB of 34 % but the MB of the total ammonia ($NH_3$ + ammonium) concentrations were reduced from -6.9 μg m$^{-3}$ (NMB of -36%) in the base case scenario to -1.9 μg m$^{-3}$ (NMB of -10%).

3. The causal relationship among aerosol pH and the contribution of SO2+NO2 reactions seems confusing in this study. Prediction of aerosol pH in ISORROPIA model is based on the aerosol compositions. However, the model underestimation of nitrate and ammonium

(section 3.2.2) is more significant than that of sulfate (section 3.2.1). This will surely result in a lower aerosol pH in models than that predicted based on observation results. A comparison of model-based and observation-based aerosol pH should be conducted and discussed. For the aerosol compositions required in ISORROPIA while is not observed here (i.e., Na+, Ca2+, K+, Mg2+), the model predicted concentrations can be used.

Response:  We agree that the more significant underestimation of nitrate and ammonium than sulfate would lead to low bias in simulated pH values. This is also consistent with our results. We have added discussions of comparing model-based and observation-based aerosol pH in the revised manuscript in Section "3.3 Observed and predicted aerosol pH at the SAES site".

4. Adding the SO2 + NO2 heterogeneous reactions alone (noHet vs. Het) cannot obviously improve the sulfate, which may be actually caused by the much lower aerosol pH predicted by the models than the actual (observation-based) pH. Doubling the ammonia emissions may push the predicted pH closer towards the actual pH, which is the actual reason why noHet_2NH3 performs the best. These discussions should be added.

Response: We have added more discussions on predicted aerosol pH under different scenarios in the revised manuscript. However, based on our results, the scenario with best model performance is Het_2NH3, not noHet_2NH3. The overall NMB for the former was only -1% (Table S5) while the latter was -12%. Under polluted conditions, the underestimation of sulfate concentration in Het_2NH3 scenario was -19% as opposed to -32% to noHet_2NH3, suggesting that even with double ammonia emissions but in the absence of the $SO_2$ + $NO_2$ heterogeneous reactions, the model is still substantially underestimating sulfate formation under polluted conditions. We agree with the reviewer that the underlying driving force for enhanced sulfate formation from the $SO_2$ + $NO_2$

heterogeneous reactions were elevated pH values. These discussions were added to Section "*Impact of both (noHet vs. Het_2NH3)*".

5. In the parameterizations of k0, the influence of RH is actually the influence of aerosol water (see discussions in Cheng et al. (2016)), which depends on the average aerosol compositions. The difference of Beijing – Shanghai aerosol hygroscopicity (or growth curves) should be considered.

Response: The hygroscopicity parameter κ in Shanghai was reported to be around 0.25~0.31 (Ye et al., 2011, 2013), which is higher than those reported for Beijing (0.14~0.24; Massling et al., 2009). As pointed out by the reviewer, the differences of hygroscopicity between Shanghai and Beijing would affect the parameterization of $k_0$. We performance an additional sensitivity run by doubling $k_0$ value when RH increase from 56% to 100% instead of keeping it as a constant. Results from the doubled $k_0$ sensitivity run showed that sulfate formation was enhanced by 10% on average with a maximum hourly increase of ~40%. We realize that our parameterization would give a relatively conservative estimation of the sulfate formation due to the $SO_2$ + $NO_2$ heterogeneous reactions. Given the findings that the aerosol hygroscopicity in Shanghai is higher than Beijing, our parameterization of $k_0$ based on observations made in Beijing would again lead to an underestimated contribution from the $SO_2$ + $NO_2$ reactions. We have added these discussions of hygroscopicity in the revised manuscript where the parameterization of $k_0$ is presented.

Page 13, Line 11: Due to lack of observation data at high RH values, we set a constant $k_0$ value when RH increases from 56% and up. This would lead to underestimated sulfate formation due to the $SO_2$ + $NO_2$ heterogeneous reactions at high RH values, which is a favorable condition for the heterogeneous sulfate production. In addition, the differences of aerosol hygroscopicity in Beijing vs. Shanghai could add more uncertainties in the dependency of $k_0$ on RH. Reported values of hygroscopicity parameter κ were 0.25~0.31 for Shanghai (Ye et al., 2011; 2013), which are higher than values reported for Beijing (0.14~0.24; Massling et al., 2009). This could even add more

underestimation of the sulfate formation via this $SO_2 + NO_2$ heterogeneous reactions. Therefore, our results represent a relatively conservative estimation of sulfate formation.

**Minor Comments:**

1. Page 1, Line 20: simulation of specific area "for the first time" is not the major contribution of this study, and should not be highlighted. The same issue applies for description in the Introduction (Page 3, Line 24).

   Response: We have deleted "for the first time" in the revised abstract and revised the descriptions in the introduction accordingly.

2. Page 6, line 19: The classification of clean, transition and polluted conditions following the Beijing scheme is weird. The authors should classify the schemes by local PM2.5 time series to classify the background, small peaks and large peaks (e.g., as described in Zheng et al. (2015b)), or by air quality standard (e.g., Zheng et al. (2016)).

   Response: The main reason that we chose the classification of clean, transition and polluted conditions following the Beijing scheme adopted by Wang et al. (2016) is that we wanted to use the observation data reported by the same study to obtain the parameters of our $SO_2 + NO_2$ heterogeneous reactions. Wang et al. (2016) classified different periods into clean, transition and polluted conditions based on observed sulfate concentrations and provided data necessary to calculate the $SO_2 + NO_2$ heterogeneous reactions. The other reason is that this study focuses on sulfate formation. Therefore, it would make a little bit more sense to directly use sulfate concentrations to classify clean (low sulfate concentrations), transition (medium sulfate concentrations), and polluted (higher sulfate concentrations) conditions. The average $PM_{2.5}$ concentrations based on the current classification were 52.8, 103.1, and 232.3 μg/m³ for clean, transition and polluted periods, which roughly corresponds to the clean (Air Quality Index (AQI) within 0~100), slight-to-medium polluted (AQI with 100~200), and heavy polluted (AQI over 200) periods defined

by China's Technical Regulation on Ambient Air Quality Index (on trial) (http://xxgk.changle.gov.cn/XHBJ/201610/t20161008_350868.htm). With all these considerations, we decided to keep this classification.

3. Page 6, Line 26: The citation should be Cheng et al. (2016). Also the pattern is reported in Zheng et al. (2015b), not Zheng et al. (2015a).

Response: We thank the reviewer for careful reading. We have corrected this in the revised manuscript.

4. Page 11, Line 32: citations to the references are not in the proper format.

Response: Corrected in the revised manuscript.

5. Page 12, Line 4: many observation-based ISORROPIA predictions is against the conclusion that "aerosol pH is always acidic" (e.g., Shi et al., 2017). The authors should be more through citing the references.

Response: More references were added in the manuscript.

P22, Line 25: Our results indicated that the aerosol pH at the SAES site tends to be moderately acidic regardless of the ambient ammonia concentrations. However, the acidity of aerosols in China still remains to be a vigorous debate. For example, Shi et al. (2017) reported a wide range of pH values between 0.33 and 13.6, depending on the source contributions. Xie et al. (2019) found that the predicted particulate pH values increased from moderate acid to near neutral with the increase of nitrate to sulfate molar ratio.

References cited in the response:

Massling, A., Stock, M., Wehner, B., Wu, Z.J., Hu, M., Bruggemann, E., Gnauk, T., Herrmann, H., Wiedensohler, A.: Size segregated water uptake of the urban submicrometer aerosol in Beijing. Atmospheric Environment 43 (8), 1578e1589, 2009.

Shi, G., Xu, J., Peng, X., Xiao, Z., Chen, K., Tian, Y., ... & Russell, A. G.: pH of aerosols in a polluted atmosphere: source contributions to highly acidic aerosol. Environmental Science & Technology, 51(8), 4289-4296, 2017

Wang, G., Zhang, R., Gomez, M. E., Yang, L., Zamora, M. L., Hu, M., Lin, Y.,Peng, J., Guo, S., Meng J and Li, J.: Persistent sulfate formation from London Fog to Chinese haze, Proceedings of the National Academy of Sciences., 113, 13630-13635, doi:10.1073/pnas.1616540113, 2016.

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Ye, X.N., Ma, Z., Hu, D.W., Yang, X., Chen, J.M.: Size-resolved hygroscopicity of submicrometer urban aerosols in Shanghai during wintertime. Atmospheric Research 99 (2), 353e364, 2011.

Ye, X., Tang, C., Yin, Z., Chen, J., Ma, Z., Kong, L., ... & Geng, F.: Hygroscopic growth of urban aerosol particles during the 2009 Mirage-Shanghai Campaign. Atmospheric environment, 64, 263-269, 2013.

# Revised manuscript

# Enhanced sulfate formation through $SO_2+NO_2$ heterogeneous reactions during heavy winter haze in the Yangtze River Delta region, China

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**Abstract.** Rapid sulfate formation is recognized as key characteristics of severe winter haze in China. However, air quality models tend to underestimate sulfate formation during heavy haze periods and heterogeneous formation pathways have been proposed as promising mechanisms to reduce gaps between observation and model simulation. In this study, we implemented a reactive $SO_2$ uptake mechanism through the $SO_2 + NO_2$ heterogeneous reactions in the Comprehensive Air 20 Quality Model with extensions (CAMx) to improve simulation of sulfate formation in the Yangtze River Delta (YRD) region. Parameterization of the $SO_2 + NO_2$ heterogeneous reactions is based on observations in Beijing and considered both impact of relative humidity and aerosol pH on sulfate formation. Ammonia is reported to be critical for the formation of secondary inorganic aerosols. Estimation of ammonia emissions is usually associated with large uncertainties and model tends to underestimate ammonia concentrations substantially. Sensitivity tests were conducted to evaluate the importance of the $SO_2$ 25 $+ NO_2$ heterogeneous reactions as well as ammonia emissions on modelled sulfate concentrations during a period with several heavy haze episodes in the YRD region. Base case model results show large underestimation of sulfate concentrations by 36 % under polluted conditions in the YRD region. Adding the $SO_2 + NO_2$ heterogeneous reactions or doubling ammonia emissions alone leads to slight model improvement (~6 %) on simulated sulfate concentrations in the YRD region. However, model performance significantly improved when both the $SO_2 + NO_2$ heterogeneous reactions and 30 doubled ammonia emissions were included in the simulation: predicted sulfate concentrations during polluted periods increased from 23.1 μg m$^{-3}$ in the base scenario to 29.1 μg m$^{-3}$ (representing an increase of 26 %). Aerosol pH is crucial for the $SO_2 + NO_2$ heterogeneous reactions and our calculated aerosol pH is always acidic and increased by 0.7 with doubled ammonia emissions. Modelling results also show that this reactive $SO_2$ uptake mechanism enhanced sulfate simulations by 1

to 5 $\mu g\ m^{-3}$ for the majority of eastern and central part of China, with more than 20 $\mu g\ m^{-3}$ increase of sulfate concentrations over the north-eastern plain. These findings suggest that the $SO_2$ + $NO_2$ heterogeneous reactions could be important for sulfate formation in the YRD region as well as other parts of China. More studies are needed to improve the parameterization of the $SO_2$ + $NO_2$ heterogeneous reactions based on local data further evaluate this mechanism in other

5 regions. In addition, ammonia emissions were found to be a key driving variable of the spatial patterns of sulfate enhancement due to the new pathway. Substantial efforts are needed to improve the accuracy of ammonia emissions inventory.

## 1 Introduction

Rapid sulfate ($SO_4^{2-}$) formation has been reported to be key characteristics of severe winter haze in China. However, most air

10 quality models tend to underestimate sulfate formation during severe winter haze episodes in China because standard $SO_2$ oxidation pathways, including gas-phase chemistry (i.e. oxidized by hydroxyl radical OH) and aqueous-phase chemistry (i.e. oxidized by ozone ($O_3$), hydrogen peroxide ($H_2O_2$)) are suppressed by weak photochemical activity and low ozone concentrations (Quan et al., 2014)). Meanwhile, analysis of severe haze events in China show enhanced secondary inorganic aerosols, especially sulfate concentrations. For example, Quan et al. (2014) found that observed sulfate accounted for 13 %

15 of $PM_{2.5}$ (particulate matter with dynamic equivalent diameter less than 2.5 $\mu m$) on normal clean days and increased to 25 % on haze days during the infamous 2013 January Beijing haze period. For the same haze episode, Cheng et al. (2016) used concentration ratios of sulfate to sulfur dioxide ($[SO_4^{2-}]/[SO_2]$) to diagnose sulfate production rate; this ratio increased with $PM_{2.5}$ levels and was 6 times higher under the most polluted conditions than normal conditions. Most current air quality models (e.g. CMAQ, GEOS-Chem, WRF-Chem, CAMx), which only include the traditional gaseous- or aqueous-phase

20 mechanisms for sulfate formation, do not show very good model performances of sulfate concentrations against observations during haze periods in China (Wang et al., 2014; Zheng et al., 2015; Gao et al., 2016a, 2016b; Li et al., 2015). The under-prediction of sulfate concentrations could be related to uncertainties of the emissions inventory, bias of simulated meteorological fields, and/or some missing sulfate formation mechanisms that are not included in the current models.

Heterogeneous sulfate production chemistry has been proposed by several studies to explain the high concentrations and

25 rapid formation of sulfate during haze episode in China (e.g. He et al., 2014; Wang et al., 2014; Zheng et al., 2015; Wang et al., 2016; Cheng et al., 2016; Guo et al., 2017). He et al. (2014) suggested a synergistic effect between $NO_2$ and $SO_2$ on the surface of mineral dust (i.e. mineral oxides) as an important source of sulfate in China and emphasized the essential role of $O_2$ involved in this process. More generally, heterogeneous loss of $SO_2$ on aerosol surfaces (not limited to mineral dust) or deliquescent aerosols is discussed by many studies, although the exact underlying mechanism is still unknown (e.g. Wang et

30 al., 2014; Zheng et al., 2015). For this kind of heterogeneous reactions, the sulfate production rate has been parameterized as a pseudo first-order reaction with respect to the gaseous $SO_2$ concentration with the $SO_2$ reactive uptake coefficient ($\gamma$) on aerosol surfaces being the key parameter. This uptake coefficient, representing the probability that a $SO_2$ gas molecule

colliding with an aerosol surface results in sulfate formation, is reported to be heavily dependent on relative humidity (RH) (Zheng et al., 2015; Wang et al., 2016). Parameterized reactive uptake of $SO_2$ has been implemented in several current air quality models, including GEOS-Chem, WRF-Chem, CMAQ and CAMx, and generally improved model performance of sulfate concentrations during haze episodes in China (e.g. Wang et al., 2014; Zheng et al., 2015; Gao et al., 2016b). Two more recent papers, Wang et al. (2016) and Cheng et al. (2016) further suggested that reaction between $NO_2$ and $SO_2$ in aerosol water may contribute substantially to sulfate formation during haze events in China. Both studies emphasized the importance of higher aerosol pH (5.4–6.2 reported by Cheng et al. (2016) and 6.0–7.6 by Wang et al. (2016)) sustained by abundant gas-phase ammonia ($NH_3$) during haze periods being an essential precondition for this mechanism. However, the near-neutralized aerosol pH that facilities $SO_2$ oxidation by $NO_2$ is questioned by Guo et al. (2017) who concluded from a thermodynamic analysis that aerosol pH was always acidic (4.5–5) regardless of the ambient $NH_3$ concentrations and that the $NO_2$-mediated oxidation of $SO_2$ was unlikely to be important in China or any other region of the world. Guo et al. (2017) pointed out that within low pH ranges (up to 4.5), $SO_2$ oxidation catalyzed by transition metal (i.e. Fe(III) and Mn(II)) might become a dominant sulfate formation pathway in aerosol water and suggested it as an alternative to $SO_2 + NO_2$ reactive uptake as being a potential sulfate contributor under haze conditions. Similar conclusion is also made from a most recent work by Shao et al. (2019), who implemented four heterogeneous sulfate formation mechanisms in GEOS-Chem and assessed model performance using sulfate oxygen isotopes data in Beijing, who found that $SO_2$ oxidation catalyzed by transition metal ion (TMI) to be the dominant sulfate formation mechanism. On the contrary, another slightly earlier study by Ye et al. (2018) concluded $SO_2$ oxidation by $H_2O_2$ was the dominant pathway based on observations of atmospheric $H_2O_2$ concentrations in Beijing. Song et al. (2018b) suggested the heterogeneous hydroxymethanesulfonate (HMS) chemistry being a potentially important contributor to heavy haze pollution in northern China. Hung et al. (2018) reported the interfacial $SO_2$ oxidation on the surface of aqueous micro-droplets as a potential pathway to explain fast conversion of $SO_2$ to sulfate.

To investigate whether the $SO_2 + NO_2$ reactions in aerosol water could help better predict the enhanced sulfate formation during haze periods in the Yangtze River Delta (YRD) region, we implemented a parameterized $SO_2 + NO_2$ reactive uptake mechanism in the Comprehensive Air Quality Model with Extensions (CAMx), which is a widely used air quality model in China (e.g. Wang et al., 2009; Huang et al., 2012; Li et al., 2013, 2015; Jia et al., 2017; etc.). Our parameterization specifically incorporated RH and aerosol pH dependencies derived from measurement data during the 2015 Beijing haze event (Wang et al., 2016). Although the RH dependency of the $SO_2$ uptake rate has already been implemented in previous studies (e.g. Zheng et al., 2015; Wang et al., 2014), the effect of aerosol pH has not been explicitly included in most of the previous modelling studies, except for a most recent study by Shao et al (2019), who also considered aerosol pH in their model parameterization.. While most of the previous studies were trying to improve model predictions in the northern part of China, especially the Beijing-Tianjin-Hebei region (e.g. Gao et al., 2016b; Zheng et al., 2015), this work is one of the few studies that focus on the Yangtze River Delta region, which has also suffered from severe haze problems in recent years due to urban expansion and industrialization (e.g. Li et al., 2011; M. Wang et al., 2015; Xu et al., 2016; Ming et al., 2017). In

addition to the $SO_2 + NO_2$ heterogeneous reactions, we also investigated model sensitivities to ammonia emissions, which have been reported to be crucial for the formation of secondary inorganic aerosols and large uncertainties exist with current ammonia emission inventory (Huang et al., 2011; Fu et al., 2013).

## 2 Methodology

### 2.1 Current sulfate formation pathways in CAMx

In this study, CAMx version 6.40 (Ramboll Environ, 2016) was used as the base model to simulate sulfate formation. Table 1 lists the sulfate formation pathways that are currently considered implemented in standard CAMx source code. In addition to the traditional $SO_2$ oxidation by OH in the gas phase and $O_3$, $H_2O_2$, and $O_2$ (catalyzed by Fe(III)/Mn(II)) in cloud droplets, sulfate formation through reactions with methyl hydroperoxide and other organic hydroperoxides (MHP) as well as peracetic and other organic peracids (PAA) in the aqueous phase is also included. For heterogeneous formation pathway, the $SO_2 + NO_2$ reaction is currently considered and implemented as pseudo gas phase reaction with the rate parameterization based on results from Zheng et al (2015), where the key parameter (i.e. gamma) is bounded between a lower and upper limit and changes linearly in response to RH. This relatively simple parameterization of $SO_2 + NO_2$ heterogeneous reaction has been included in many previous studies, e.g. Y. Wang et al. (2014), B. Zheng et al. (2015), etc.

### 2.2 $SO_2 + NO_2$ mechanism in CAMx

In this study, we implemented the $SO_2 + NO_2$ reactive uptake mechanism in CAMx version 6.40 (Ramboll Environ, 2016) as a pseudo gas-phase reaction:

$$SO_2 + NO_2 \xrightarrow{k_{het}} SO_4^{2-} \tag{1}$$

Since the vapor pressure of sulfuric acid is very low, we assumed all sulfuric acid partitions to the aerosol phase. The rate constant $k_{het}$ is related to the reactive uptake coefficient $\gamma$ for $SO_2$ as follows:

$$\frac{d[SO_4^{2-}]}{dt} = k_{het}[NO_2(g)][SO_2(g)] = \frac{1}{4}\gamma\bar{C}S[SO_2(g)] \tag{2}$$

where $\bar{C}$ is the mean molecular speed (m/s), and $S$ is the aerosol surface area concentration ($m^2/m^3$). Based on the observations during the Chinese haze events (Wang et al., 2016), this uptake coefficient $\gamma$ depends on aerosol pH, RH, and $NO_2$ concentration. Therefore, we assumed a functional form of $\gamma$ as the product of each of these dependencies:

$$\gamma = 4k_0 d_f[NO_2(g)] \tag{3}$$

where $k_0$ (ppm$^{-1}$) is the RH-dependent parameter; $NO_2(g)$ is the $NO_2$ gas concentration; $d_f$ is the pH-dependent distribution factor of $SO_2$, i.e. the ratio of $SO_2$ concentration in the aqueous-phase to the gaseous-phase and is calculated as Eq. (4) in the model:

$$d_f = \frac{[S(IV)(aq)]}{[SO2(g)]} = H_{eff}RTw_L \tag{4}$$

where $H_{eff}$ is the effective Henry's low constant of $SO_2$ (M atm$^{-1}$), R is the universal gas constant (L atm mol$^{-1}$ K$^{-1}$), T is air temperature (K) and $w_L$ is the aerosol water content (µg m$^{-3}$). We used the data in Table S2 and S5 of Wang et al. (2016) to back calculate the RH dependency of $k_0$ under clean (observed sulfate concentration less than 10 µg m$^{-3}$), transition (sulfate between 10 and 20 µg m$^{-3}$), and polluted (sulfate more than 20 µg m$^{-3}$) conditions during Beijing 2015 episodes. Aerosol pH was calculated using the ISORROPIA thermodynamic equilibrium model implemented in CAMx assuming a metastable aerosol liquid phase which is an appropriate assumption for most ambient conditions including the Chinese haze events (Guo et al. 2017). Wang et al (2016) only reported NOx (not $NO_2$) concentrations in Beijing during the 2015 haze event. We simply assumed a $NO_2$/NOx ratio of 0.5. Inserting $NO_2$ concentrations, γ values from Wang et al. (2016), and calculated aerosol pH from ISORROPIA into Eq. 3, we obtained the expression of $k_0$ depending upon RH as follows (parameters for $k_0$ calculation is shown in Table S1):

$$k_0 = \begin{cases} \text{RH<21\%:} & 199.25 \\ \text{21\%≤RH<41\%:} & (284.22\text{-}199.25)\times(\text{RH-21\%})/(41\%\text{-}21\%)+199.25 \\ \text{41\%≤RH<56\%:} & (322.16\text{-}284.22)\times(\text{RH-41\%})/(56\%\text{-}41\%)+284.22 \\ \text{RH≥56\%:} & 332.16 \end{cases} \tag{5}$$

Due to lack of observation data at high RH values, we set a constant $k_0$ value when RH increases from 56% and up. This would lead to underestimated sulfate formation due to the $SO_2 + NO_2$ heterogeneous reactions at high RH values, which is a favorable condition for the heterogeneous sulfate production. In addition, the differences of aerosol hygroscopicity in Beijing vs. Shanghai could add more uncertainties in the dependency of $k_0$ on RH. Reported values of hygroscopicity parameter κ were 0.25~0.31 for Shanghai (Ye et al., 2011; 2013), which are higher than values reported for Beijing (0.14~0.24; Massling et al., 2009). Therefore, our results represent a relatively conservative estimation of sulfate formation. The rate constant $k_{het}$ of $SO_2 + NO_2$ is formulated as:

$$k_{het} = k_0 d_f \bar{C} S \tag{6}$$

$SO_2$ lifetime (in hr) associated with the $SO_2 + NO_2$ reactive uptake mechanism is calculated as:

$$SO_2 \; lifetime = \frac{1}{k_{het}[NO_2(g)]} \tag{7}$$

Figure 1 shows the $SO_2$ lifetime as a function of aerosol pH for clean, transition, and polluted conditions, with other variables kept constant. The $SO_2$ lifetime shortens as aerosol pH becomes more neutralized, indicating faster conversion of $SO_2$ to sulfate by $SO_2 + NO_2$ reactive uptake on aerosol. For pH within 2 to 7, one unit increase in aerosol pH shortens $SO_2$ lifetime by about one order of magnitude. The blue, orange, and red symbols in Figure 1 correspond to the clean, transition, and polluted conditions during Beijing 2015 based on data in Table S1. As shown in Figure 1, the aerosol pH values calculated by ISORROPIA are 5.5 (for clean conditions) and 4.1-4.2 (for transition and polluted conditions), all lower than

the values (7.6) reported by Wang et al. (2016). As noted by Guo et al. (2017), it is important to make a consistent assumption for aerosol state (i.e., metastable) in deriving and implementing the parameterization for reactive uptake. A most recent paper by Song et al (2018a) identified coding errors with the ISORROPIA model, which resulted unrealistic pH values of 7.7 using the standard ISORROPIA model with the stable state assumption in previous studies. Nevertheless, our results are not compromised by this coding error because the metastable assumption was chosen in our ISORROPIA calculation.

## 2.3 Model configuration

Two versions of the Comprehensive Air Quality Model with extensions (CAMx) modified based on the original version 6.40 (Ramboll Environ, 2016) were used in this study: one with the $SO_2 + NO_2$ heterogeneous reactions (described in Section 2.1) and one without (forcing $k_{het}$ equals to zero). The modeling domain consists of three nested grids (Figure 2): the outer 36 km domain (D01) covers most of China, Japan, Korea, parts of India, and southeast Asia; the 12 km domain (D02) covers eastern China and the inner 4 km domain (D03) covers Shanghai, Jiangsu province, Zhejiang province, Anhui province, and parts of surrounding provinces, together referred as the Yangtze River Delta (YRD) region. Meteorological fields were based on simulation results from the Weather Research and Forecasting (WRF) model (version 3.7) driven by the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Operational Global Analysis data (http://dss.ucar.edu/datasets/ds083.2/). Details of the WRF configurations can be found in previous studies (Liu et al., 2018). Boundary conditions for D01 were generated from the Model for OZone And Related chemical Tracers (MOZART) global chemistry model (Emmons et al., 2010). The Carbon Bond 6 (CB6) mechanism (Yarwood et al., 2010) was used for the gas phase chemistry and the static two-mode coarse/fine (CF) scheme was used to represent particle size distribution. The Zhang dry deposition (Zhang et al. 2003) and default wet deposition scheme was used to for removal processes. Anthropogenic emissions for areas outside the YRD region were from the Multi-resolution Emission Inventory for China (MEIC, http://www.meicmodel.org/). For emissions within the YRD region, an YRD-specific emission inventory (Huang et al., 2011; Li et al., 2011) was updated to year 2014 and utilized in this study. This YRD-specific emission inventory includes emissions from sources of combustion, industry, mobile and residential. Primary sulfate emissions over the 4km domain are estimated to be 994 tons day$^{-1}$ for December 2013 (accounting for 14.8% of primary $PM_{2.5}$) with dense emissions from Shanghai and southern Jiangsu province (see Figure S1 for spatial distribution). At the SAES site, primary sulfate emissions were estimated to 757 kg per month (only accounting for 1.0% of primary $PM_{2.5}$). Biogenic emissions were simulated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN, version 2.1, Guenther et al. 2012) based on the WRF simulation results. The modeling episode is December 2013, during which several heavy haze events with hourly $PM_{2.5}$ concentration higher than 500 μg m$^{-3}$ were observed in the YRD region.

Four simulations with identical model configuration and input data including meteorology, initial/boundary conditions, and emission inventory (except ammonia emissions) were conducted using the above two different CAMx versions:

- noHet (base case): simulation based on CAMx version without the $SO_2 + NO_2$ heterogeneous reactions (this is also our base case). Note that this CAMx version differs from the distributed CAMx v6.40 in that we removed the original heterogeneous sulfate formation reaction with $NO_2$ which only included a simple parameterization based on RH (ref. reaction No.7 in Table 1) in the distributed version. This is done on purpose to quantify the influence of the newly parameterized $SO_2 + NO_2$ heterogeneous reactions on sulfate formation.

- Het: simulation based on CAMx with the $SO_2 + NO_2$ heterogeneous reactions. Other model configurations were identical to scenario noHet.

- noHet_2NH$_3$: CAMx version and model configurations were same as scenario noHet except ammonia emissions were doubled for the 4 km domain.

- Het_2NH$_3$: CAMx version and model configurations were same as scenario Het but ammonia emissions were doubled for the 4 km domain.

We first ran CAMx for 36 km/12 km domains with two-way nested; for the 4 km domain, we used boundary conditions extracted from the 12 km model outputs and conducted the above four scenarios. Fourteen vertical layers were used extending from the surface to 100 mb. In addition to default CAMx outputs, we modified the source code to generate

15 additional diagnostic variables (e.g. aerosol pH, RH, and $k_{het}$) to evaluate the $SO_2 + NO_2$ heterogeneous reactions.

### 2.4 Observations

Hourly observations of ozone, $SO_2$, $NO_2$, $PM_{2.5}$ and its components including sulfate, nitrate, ammonium, organic carbon (OC), and elemental carbon (EC) are available between 1 December and 29 December 2013 at a monitor site located at the center of the urban area of Shanghai (referred as SAES site, 31.1695$\degree$N, 121.4305$\degree$E, Figure 3). Hourly $PM_{2.5}$ observations

20 are also available at another 23 monitor sites across the YRD region (Figure 3; see locations in Table S2). During this period, YRD region experienced relative clean days as well as several heavy haze episodes with peak $PM_{2.5}$ exceeding 600 μg m$^{-3}$ during a most heavily polluted period of December 5$^{th}$ to 7$^{th}$. At the SAES site, maximum hourly $PM_{2.5}$ concentration reached 540.3 μg m$^{-3}$ on December 6$^{th}$ with a monthly average of 118.7 μg m$^{-3}$. We followed the method in Wang et al (2016) to divide the period into clean (observed sulfate <10 μg m$^{-3}$), transition (10-20 μg m$^{-3}$), and polluted (>20 μg m$^{-3}$) periods

25 based on observed hourly sulfate concentration at the SAES site. Compared with clean period, all PM species increased by more than 3 times (sulfate, nitrate and ammonium (SNA) increase by more than 5 times) during polluted period as indicated by the enhancement ratio (calculated as the ratio of average concentrations during the polluted period divided by those during the clean period). In terms of fraction of $PM_{2.5}$, SNA increased from 44 % during clean period to 69 % during polluted period while carbonaceous aerosols (OC and EC) decreased from 32 % to 24 %. This is consistent with the

30 commonly observed characteristics of winter haze periods in China reported by many previous studies (e.g. Wang et al., 2014; Zheng et al., 2015b; Cheng et al., 2016) that SNA is playing a more important role during the heavy haze periods. Average sulfate concentration of clean, transition and polluted periods was 6.7, 14.2, and 36.1 μg m$^{-3}$, respectively, accounting for 17-23 % of $PM_{2.5}$ (Figure S2).

Observations of ambient ammonia concentrations are also available at the SAES site; however, the quality of measurements is questionable. Therefore, we used ammonia observations from a similar urban site nearby (referred as FDU site, ~15 km north from the SAES site, 31.3005 ̊N, 120.9778 ̊E, Figure 3) for analysis in this study. Observations at the FDU site have been discussed by S. Wang et al. (2015) and demonstrated data reliability. Diurnal $NH_3$ concentrations at the FDU site

5    during our modeling period showed a weak bimodal pattern with an average of 7.3 ppb (ranging 1.6–25 ppb) during this period (Figure S3). This two-peak diurnal variation is caused by vehicle emissions and evolution of the boundary layer (S. Wang et al. 2015). In summary, observations for gases species (except $NH_3$) and PM species at the SAES site and $NH_3$ at the FDU site were used for model validation in this study.

## 2.5 Statistical metrics for model validation

10   For WRF and CAMx model performance valuation, mean bias (MB), normalized mean bias (NMB), and index of agreement (IOA) were used in this study. Calculations of these selected metrics are shown below:

$$MB = \frac{1}{N}\sum(P_j - O_j) \qquad (8)$$

$$NMB = \frac{\sum(P_j - O_j)}{\sum O_j} \times 100 \qquad (9)$$

$$IOA = 1 - \frac{\sum(P_j - O_j)^2}{\sum(|P_j - \bar{O}| + |O_j - \bar{O}|)^2} \qquad (10)$$

where $P_j$ and $O_j$ are predicted and observed hourly concentrations or values, respectively. N is the number of paired model and observation data. $\bar{O}$ is the average concentration/value of observations. IOA ranges from 0 to 1 with 1 indicating perfect agreement between model and observation.

15   **3 Results and discussions**

**3.1 Model evaluation**

**3.1.1 WRF results evaluation**

Model performance of WRF results is generally acceptable in this study. Table S3 summarizes the meteorological performance statistics of WRF during December 2013 at Pudong and Hongqiao airport stations in Shanghai (Figure 3).

20   Temperature and relative humidity were well reproduced with NMB and NME within 37% and 41%, respectively; IOA values are above 0.8. Wind speed is overestimated with a MB of 1.5 m s$^{-1}$ at Pudong and 0.5 m s$^{-1}$ at Hongqiao station; NMB of predicted wind direction at the two stations is -36% and -27%, respectively. Comparisons of hourly observed and simulated relative humidity, wind speed and temperature at these two stations suggest reasonable model results in terms of temporal variations (Figure S4). Overall, the WRF simulated results are acceptable to be used in subsequent CAMx

25   simulations.

### 3.1.2 CAMx base scenario (noHet) evaluation

Figure 4 depicts the time series of simulated and observed concentrations for sulfate and $PM_{2.5}$ during 1 to 29 December 2013 at SAES site (see Figure S5 in Supplemental Information for other species). Overall, the model is successful in capturing the temporal variations of ozone and PM species with IOA values above 0.5 (Table S4). Nevertheless, model tends

5   to systematically underestimate all gaseous and PM species with NMB values ranging from -5% for $NO_2$ to -68% for $NH_3$. This could be partially explained by the higher simulated wind speeds compared with observed values, especially at Pudong station where the observed average wind speed during the modeling period was 4.5 m s$^{-1}$ while simulated wind speed was 6.0 m s$^{-1}$, representing an overprediction by 33%. For sulfate, the model captured the day-to-day sulfate variations reasonably well with an overall MB of -2.8 μg m$^{-3}$ and IOA of 0.80. For clean and transition periods, model showed slight

10   over-prediction with MB of 1.1 and 0.5 μg m$^{-3}$ (Table S5). However, during polluted period when observed sulfate concentrations are higher than 20 μg m$^{-3}$, model significantly underestimated sulfate formation with a MB of -13.0 μg m$^{-3}$ (NMB of -36 %). Observed maximum sulfate concentration reached 93.4 μg m$^{-3}$ but model only predicted 52.2 μg m$^{-3}$. Nitrate and ammonium concentrations were also underestimated by 20 % on average and exacerbated to more than 40 % during polluted periods. For carbonaceous aerosols, elemental carbon (EC) was underestimated by 32 % while organic

15   carbon (OC) exhibited even more underestimation of almost 50 %. Underestimation of OC is usually associated with underestimation of secondary organic aerosols (SOA). Discussion of OC under-prediction is beyond the scope of current work and will be addressed in future studies. Results of the four CAMx simulations in this study showed negligible changes in predicted EC/OC concentrations and thus are excluded in the following discussions.

Figure 5 depicts the averaged $PM_{2.5}$ during the modeling episode over the YRD region with observations at 24 monitoring

20   sites. Observed $PM_{2.5}$ concentrations generally showed a decreasing trend from north to south of the YRD region, which was well captured by the model. For sites located in southern Jiangsu and southern Zhejiang province, the model showed favorable agreement with the observations. Underestimations existed for sites located in the northern part of Jiangsu and Zhejiang province. MB across all 24 monitoring sites ranged from as low as -90.4 μg m$^{-3}$ (site in north Jiangsu province) to slight overestimation of 11.4 μg m$^{-3}$ (site in south Zhejiang province); corresponding NMB ranged from -46 % to 16 %

25   (Table S2).

### 3.2 Simulated sulfate concentrations at SAES site

Four scenarios – noHet, Het, noHet_2NH$_3$ and Het_2NH$_3$ were conducted to evaluate the impact of the $SO_2$ + $NO_2$ heterogeneous reactions and ammonia emissions on sulfate simulation. We first analyzed the modeled sulfate results at the SAES site; then we discussed the spatial patterns over the YRD region. Similar discussions of nitrate, ammonium and $PM_{2.5}$

30   are included in the supplemental information. Table 2 shows the average sulfate concentration for different scenarios by clean, transition, and polluted periods; corresponding scatter plots are shown in Figure 6. A complete summary of statistical metrics for each scenario/period is presented in Table S5.

*Impact of SO₂ + NO₂ heterogeneous reactions (noHet vs. Het)*

As shown in Figure 6, simulated sulfate concentrations compared well with observations under clean and transition conditions in the noHet scenario with over-prediction by 16 % and 4 %, respectively. By contrast, large under-prediction of sulfate concentration existed during polluted periods (MB of -13.0 μg m$^{-3}$, NMB of -36 %). Adding the SO₂ + NO₂ heterogeneous reactions showed small enhancement on sulfate formation, reducing the overall NMB from -16 % to -12 %. If only polluted periods are considered, simulated sulfate concentrations increased from 23.1 to 24.6 μg m$^{-3}$ with the heterogeneous reactions, corresponding to an increase by 6.5 %. Thus even with the SO₂ + NO₂ heterogeneous reactions, model was still under-predicting sulfate concentrations on heavy haze days with a NMB of -32 %. This is because aerosol pH was always acidic (pH < 3; this will be discussed in the following section) and the SO₂ + NO₂ heterogeneous reactions were not being appreciable within this pH range (Figure 1). Model performances for clean and transition periods were slightly compromised with the SO₂ + NO₂ heterogeneous reactions since the base scenario was already overestimating sulfate concentrations.

*Impact of NH₃ emissions (noHet vs. noHet_2NH₃)*

Being the dominant base gas in the atmosphere, ammonia plays an essential role in the formation of secondary inorganic aerosols and estimation of ammonia emissions is usually associated with large uncertainties (e.g. Huang et al., 2011; Fu et al., 2013). With the base case ammonia emissions, NH₃ concentration was under-predicted by 3.0 ppb (NMB of -60 %). With doubled ammonia emissions, ammonia concentration was over-predicted by 1.7 ppb with NMB of 34 % but the MB of the total ammonia (NH₃ + ammonium) concentrations were reduced from -6.9 μg m$^{-3}$ (NMB of -36%) in the base case scenario to -1.9 μg m$^{-3}$ (NMB of -10%). NMB of sulfate concentrations during polluted period is -32 %, which is similar to the enhancement caused by that of the SO₂ + NO₂ heterogeneous reactions. Clearly, doubling ammonia emissions is not enough to close the gap between observed and simulated sulfate concentrations during heavy haze periods. We performed additional sensitivity tests with even higher ammonia emissions and found that 10 times ammonia emissions would be needed to achieve an average sulfate concentration (33.2 μg m$^{-3}$) that is comparable with observation (36.1 μg m$^{-3}$) under polluted conditions (with no heterogeneous reactions). However, in that case, model performance of ammonia is significantly compromised with over-prediction by 32.3 ppb. These results indicate that the uncertainties associated with the ammonia emissions are not enough to fully explain the under-prediction of sulfate formation during heavy haze periods in the YRD region.

*Impact of both (noHet vs. Het_2NH₃)*

A fourth scenario (Het_2NH₃) with the SO₂ + NO₂ heterogeneous reactions as well as doubled ammonia emissions gave the best model performance of sulfate concentrations with an overall MB of -0.2 μg m$^{-3}$ (NMB of -1 %, Figure 6). During polluted periods, average sulfate concentration was predicted to be 29.1 μg m$^{-3}$ (representing an increase of 26% from the base case) and NMB was reduced from -36 % in the base scenario to -19 % in the Het_2NH₃ scenario. Maximum sulfate concentration simulated under scenario Het_2NH₃ was 97.2 μg m$^{-3}$, which compared well with the observed maximum of 93.4 μg m$^{-3}$ at the SAES site. With doubled ammonia emissions, the heterogeneous reactions were playing an increasing

important role in sulfate formation by boosting average sulfate concentrations from 24.5 (noHet_2NH$_3$) to 29.1 µg m$^{-3}$ (Het_2NH$_3$) under polluted conditions, representing an increase by 19 %. This is because with more ammonia available, aerosol pH was elevated by ~0.7 pushing it closer towards the actual pH (as discussed more in section 3.3) and the rate of the heterogeneous reactions is positively correlated with aerosol pH (Figure 1), therefore leading to the best model performances from the Het_2NH$_3$ scenario. These results indicate that the SO$_2$ + NO$_2$ heterogeneous reactions as well as sufficient ammonia emissions are both needed to greatly improve model simulation of sulfate formation under polluted conditions. However, it is to mention that model performance under clean and transition periods got compromised most under scenario Het_2NH$_3$.

Figure S6 shows a Q-Q plot of modeled versus observed sulfate concentrations for the four scenarios. Underestimations of sulfate concentrations become noticeable around 35 µg m$^{-3}$ in all scenarios and between 35 to 55 µg m$^{-3}$, there appears to be a systematical low bias in predicted sulfate concentrations that neither doubled ammonia emissions nor the heterogeneous reactions or both could stimulate notable sulfate formation. Scenario Het_2NH$_3$ gives the best model performance with an overall MB of -0.2 µg m$^{-3}$ but still underpredicts sulfate formation under heavy haze periods by -19 %. This could be related to still biased ammonia emissions, less direct emissions of sulfate and/or SO$_2$, and/or missing of other sulfate formation pathways that needs further investigation. For example, Shao et al. (2019) included heterogeneous sulfate formation via oxidations by O$_3$, H$_2$O$_2$, and Fe(III)/Mn(II), in addition to the aqueous phase reactions and concluded that the metal-catalyzed reactions dominated the heterogeneous sulfate formation. These heterogeneous reactions were not included in the current study and could lead to some underestimated of sulfate formation. As mentioned above, the parameterization of the k$_0$ values is relatively conservative at high RH conditions, which are favorable for sulfate formation. In addition, reported aerosol hygroscopicity Bias in meteorology could also play some roles here as we are seeing systematically underestimation of all gaseous and PM species. Another explanation is that the SO$_2$ + NO$_2$ heterogeneous reactions implemented in this study were parameterized based on observations in Beijing but the simulation is performed over the YRD region. It would be ideal to use local observations for model parameterization in future studies.

### *Sulfate formation budget*

To gain a closer look at the sulfate formation via different pathways (e.g. gas phase vs. aqueous phase vs. heterogeneous phase, Table 1), we constructed a sulfate formation budget in a similar manner as Shao et al. (2019). Figure 7 shows the relative contribution of primary sulfate emissions as well as individual sulfate formation pathway to the total sulfate concentrations at the SAES site under different conditions. Overall, primary sulfate emissions and secondary formation accounted for half of the total sulfate concentrations. Of the secondary sulfate, gas-phase reactions always dominated secondary sulfate formation, with relatively consistent contribution around 38~39% under different conditions. As pollution developed, contribution from secondary formation exceeded that of primary emissions, accounting for 60% of total sulfate abundances under polluted conditions. In contrast to the relatively consistent contribution from the gas-phase formation, both aqueous and heterogeneous sulfate formation doubled from clean to polluted periods, with relative contribution increased from 4.1% to 9.4% for the former and from 5.0% to 12.6% for the latter.

If we exclude the contribution of primary sulfate emissions (i.e. smaller pie chart in Figure 7), the absolute sulfate formation via the gas-phase reactions more than doubled from clean (1.59 µg m$^{-3}$) to polluted (3.61 µg m$^{-3}$) periods; however, the relative contribution from gas-phase formation among all formation pathways dropped from 80.9% to 63.3% as pollution developed. Sulfate formation from all aqueous phase reactions increased from 0.17 µg m$^{-3}$ under clean conditions to 0.89 µg m$^{-3}$ under polluted conditions, corresponding to an increase of relative contribution from 8.6% to 15.6%. Under all conditions, aqueous oxidation due to MHP and PAA is negligible, with less than 1% of sulfate contribution. The rest three aqueous pathways in turn dominated aqueous sulfate formation depending on the specific condition. For instance, under clean conditions, oxidation by $O_3$ was the dominant aqueous contributor (accounting for 5.4% of all sulfate formation pathways) but ignorable (<1%) under polluted conditions. While modeled $SO_2$ concentrations increased from 33.2 µg m$^{-3}$ to 53.5 µg m$^{-3}$ as pollution developed, simulated $O_3$ concentrations dropped by almost half from 8.7 ppb (~ 18.7 µg m$^{-3}$) under clean conditions to 5.2 ppb (~ 11 µg m$^{-3}$) under polluted conditions, leading to reduced sulfate formation from aqueous oxidation by $O_3$ under more severe haze. Predicted $O_3$ concentrations in this study are much higher than the values (~1 ppb) assumed by Cheng et al. (2016) and Wang et al. (2016) but are comparable to values reported by Shao et al (2019; 9 ppb) for a haze episode in Beijing.

Sulfate formation associated with $H_2O_2$ and Fe(III)/Mn(II) showed the opposite trend: the $H_2O_2$ pathway only contributed 1.4% (0.03 µg m$^{-3}$) of total sulfate formation under clean conditions and increased to 5.6% (0.12 µg m$^{-3}$) under polluted conditions, representing an increase by a factor of 3. Predicted $H_2O_2$ concentrations at the SAES site was 0.03 ppb on average and maximum value could reach 0.29 ppb. These values are slightly lower than the values observed in Beijing (average around 0.05 ppb and maximum of 0.90 ppb) by Ye et al. (2018) but are comparable in term of the magnitude. However, without any $H_2O_2$ observations in Shanghai, it would be in appropriate to conclude whether model is over- or under-predicting $H_2O_2$ levels in Shanghai. Based on our current results, $H_2O_2$ oxidation is not the dominant contributor to sulfate formation during our study period.

Oxidation pathway involving Fe(III)/Mn(II) also contributed more to sulfate formation as polluted developed. Under polluted conditions, Fe(III)/Mn(II) catalyzed sulfate oxidation is the dominant aqueous formation pathway, accounting for 8.4% (0.48 µg m$^{-3}$) of secondary sulfate formation. CAMx estimates the Fe(III) and Mn(II) concentrations by assuming a constant mass fraction (3.355% for Fe(III) and 1.15% for Mn(II) based on the dust and primary $PM_{2.5}$ concentrations. A value of 10% for Fe (III) and 50% for Mn (II) was set to represent the soluble fraction in the cloud water. 10% of Fe(III) during the day and 90% of Fe(III) during the night and all Mn(II) were assumed to be in the oxidized ionic state. Based on these assumptions, modeled soluble concentrations during December 2013 was 1.51 $\pm$ 1.68 µM for Fe(III) and 0.51 $\pm$ 0.31 µM for Mn(II), respectively; the range of estimated soluble Fe(III) and Mn(II) was 0.1~10.7 µM and 0.05~2.47 µM. These results are somewhat lower than the values reported by Shao et al. (2019) and other studies cited in the paper but the overall magnitudes are well comparable. We realize that assuming constant Fe and Mn mass fraction is a simplification and latest CAMx version has the option to treat Fe and Mn as primary species. However, using this option would put even more burden on the emission inventory to have accurate source speciation profiles for different source sectors. Nevertheless,

although this Fe(III)/Mn(II) catalyzed pathways stands out among all aqueous pathways under polluted conditions, the relative contribution (8.4%) is only about one third of that from the $SO_2 + NO_2$ heterogeneous reactions (21.1%). As for the $SO_2 + NO_2$ heterogeneous reactions, its contribution to sulfate formation doubled from 10.5% (0.21 μg m$^{-3}$) under clean conditions to 21.1% (1.2 μg m$^{-3}$) under polluted conditions. Under all conditions, the relative contribution of the $SO_2 + NO_2$ heterogeneous reactions exceeds the sum of all aqueous pathways, indicating the importance of heterogeneous oxidation pathways compared to aqueous pathways.

### *Sulfate formation under selected episodes*

We further selected four heavy haze episodes (EP1-EP4) with observed sulfate concentrations continuously exceeding 30 μg/m$^3$ (as highlighted in Figure 4) at the SAES site. These episodes lasted from 9 hours (EP2) to as long as 37 hours (EP1) with episode average sulfate concentrations are all above 50 μg m$^{-3}$ (Figure S7) except for EP3 (36.2 μg m$^{-3}$) (Table S6). Maximum hourly sulfate concentrations ranged from 48.6 μg m$^{-3}$ for EP3 to 93.4 μg m$^{-3}$ for EP2. The averaged molar sulfate and $SO_2$ ratio ($[SO_4^{2-}]/[SO_2]$) for EP1 and EP2 are higher (0.52 and 0.70, respectively) than that for EP3 (0.17) and EP4 (0.19). In the base case scenario, sulfate formation was significantly underestimated for all four episodes with NMB ranging from -39% to -72%. Figure S8 shows the sulfate formation budget for the four episodes of the base case scenario. The gas phase oxidation pathway was the dominant contributor, accounting for 52% (EP2) to 79% (EP3) of total secondary sulfate formation, followed by the $SO_2 + NO_2$ heterogeneous reactions with contributions of 20% ~ 39%. For EP1 and EP2, the Fe/Mn-catalyzed oxidation pathway contributed ~10% of sulfate formation but were negligible for the other two episodes. It is interesting to note that for all selected episodes except EP3, sulfate formation was enhanced in scenario Het_2NH$_3$ by 10.4 to 14.6 μg m$^{-3}$ while EP3 only exhibits minimal increase of modeled sulfate concentrations by only 0.8 μg m$^{-3}$. We performed additional sensitivity tests and found that even with 10 times ammonia emissions, modeled sulfate concentration during EP3 is enhanced by only 2.3 μg m$^{-3}$, which is still much lower compared to the observed values. We suspect that other factors, for example, meteorology might be biased during EP3 and lead to the underpredicted sulfate concentrations. For instance, we looked at the model performance of WRF predictions for individual episode. All four episodes had some over-prediction of wind speeds with NMB ranging from 4% of EP2 to as much as 43% of EP3. Clearly, the large over-prediction of wind speeds during EP3 contributed partially to the underestimated sulfate concentrations by the model. Another potential cause for sulfate underprediction could be failure to capture episodic primary sulfate emissions during EP3. When EP3 is excluded, modeled sulfate concentrations during heavy pollution episodes are greatly enhanced from 33.5 μg m$^{-3}$ in the base scenario to 46.2 μg m$^{-3}$ in scenario Het_2NH$_3$ (increase by 38 %), due to the combined influences of the $SO_2 + NO_2$ heterogeneous reactions and doubled ammonia emissions.

### 3.3 Observed and predicted aerosol pH at the SAES site

Aerosol pH, which is calculated from ISORROPIA either based on observations or within CAMx, is crucial for the heterogeneous $SO_2 + NO_2$ reactions to be effective. Observation-based aerosol pH was calculated using forward metastable mode by ISORROPIA to be consistent with CAMx ISORROPIA configuration. Figure 8 shows the distribution of

observation-based and modeled aerosol pH at the SAES site by scenario/period. As indicated by both observation-based and modeled pH values, aerosols become more acidic as pollution develops. This is consistent with the higher $SO_2$ concentrations observed under polluted conditions (Figure S9). For observation-based values, aerosol pH dropped by 35% from clean to polluted conditions while modeled aerosol pH dropped by 13~17% under different scenarios. As also shown

5   by Figure 8, observation-based aerosol pH values are consistently higher than modeled values for all scenarios. Averaged observed-based pH value during clean, transition, and polluted period is 5.5, 4.7, and 3.6, while corresponding value for base scenario (noHet) is 2.8, 2.6 and 2.3, each representing an underestimation by 48%, 45% and 34%. Maximum aerosol pH reached 5.0, 4.4, and 3.8 under clean, transition and polluted periods in the base scenario in contrast to observation-based values of 7.7, 6.5, and 5.3. Adding the $SO_2 + NO_2$ heterogeneous reactions causes small decrease (0.03~0.07) in predicted

10  aerosol pH. The discrepancies between observation-based and model-based aerosol pH values might be due to significant underprediction of $NH_3$ and ammonium concentrations. Therefore, when $NH_3$ emissions are doubled, modeled aerosol pH increases by ~0.7 to 3.0–3.5 and underestimation of aerosol pH for scenario noHet_2NH3 is reduced to 36% during clean periods and 15% during polluted periods. Maximum aerosol pH during clean, transition and polluted periods is 5.7, 5.1, and 4.2 under scenario noHet_2NH3. Again, adding the $SO_2 + NO_2$ reactions on top of doubled $NH_3$ emissions slightly decreases

15  the aerosol pH by 0.03–0.12, with stronger reduction associated with more enhancement of sulfate formation. Both observation-based and model-based aerosol pH values at the SAES site indicate that aerosol pH is acidic, which is lower than the more neutralized values reported in previous studies for the Beijing-Tianjin-Hebei region (e.g. 5.4 to 6.2 reported by Cheng et al. (2016) and 6.0 to 7.6 by Wang et al. (2016), the latter was later found to be associated with a coding bug in ISORROPIA). This difference might be due to lower ammonia levels in Shanghai compared with Beijing (S. Wang et al.

20  2015). However, even when ammonia emissions are increased by 10 times, maximum modeled aerosol pH value is 4.8 under polluted condition, which is still lower than the values reported for north China. Our results indicated that the aerosol pH at the SAES site tends to be moderately acidic regardless of the ambient ammonia concentrations. However, the acidity of aerosols in China still remains to be a vigorous debate. For example, Shi et al. (2017) reported a wide range of pH values between 0.33 and 13.6, depending on the source contributions. Xie et al. (2019) found that the predicted particulate pH

25  values increased from moderate acid to near neutral with the increase of nitrate to sulfate molar ratio.

### 3.4 Spatial impact of the $SO_2 + NO_2$ heterogeneous reactions and ammonia emissions

Figure 9 shows the spatial distribution of monthly mean sulfate, $SO_2$, ammonia concentrations, and aerosol pH simulated in the base case and the differences between base case and other three sensitivity runs in the YRD region. Similar plots of nitrate, ammonium, and $PM_{2.5}$ are shown in Figure S10. Overall, impacts of the heterogeneous reactions and ammonia

30  emissions over the YRD region are similar to that observed at the SAES site. With the $SO_2 + NO_2$ heterogeneous reactions only, predicted monthly mean sulfate concentrations show ubiquitous increase of 0.1–5 μg m$^{-3}$ across the domain with larger increase observed in the north and northwest directions. Regions with relative higher increase of predicted sulfate concentrations closely track regions with relatively high aerosol pH and high ammonia concentrations. Aerosol pH decreases

slightly because more $SO_2$ is pulled into the aerosol phase. For nitrate concentrations (Figure S10), however, the heterogeneous reactions lead to increase in the northwest region but decrease for the rest of the YRD region and magnitudes of changes in in both directions are within 1 μg m$^{-3}$. Predicted ammonium concentrations show less than 1 μg m$^{-3}$ increase over the majority of the domain. Domain average $PM_{2.5}$ concentrations increased by 1.2 μg m$^{-3}$ with spatial patterns similar
5  to sulfate.

With doubled ammonia emissions, predictions of all three inorganic PM species are enhanced with most profound impacts observed for nitrate (Figure 8 and Figure S10). Uniform increase across the YRD region is observed for predicted sulfate concentrations; for nitrate and ammonium, increase of predicted concentrations is more significant towards the south. Domain averaged sulfate, nitrate, ammonium and $PM_{2.5}$ concentrations increase by 0.5, 6.2, 0.3, and 8.0 μg m$^{-3}$, respectively.
10  Aerosol pH is also elevated (on average by 0.3) with more ammonia available. In south Anhui and south Zhejiang provinces, elevation of aerosol pH exceeds one unit. Areas with larger pH increase are also areas with relatively lower pH values in the base scenario, indicating that aerosol pH responds nonlinearly to changes in ammonia emissions.

When both the heterogeneous reactions and doubled ammonia emissions are considered, simulated sulfate concentrations are enhanced by 2.7 μg m$^{-3}$ across the YRD region. Again, areas with relatively larger enhancement of sulfate concentrations are
15  regions with relatively high aerosol pH values and not necessarily regions with maximum increase of aerosol pH. Minimal changes in nitrate and ammonium concentrations are observed with and without the heterogeneous reactions when ammonia emissions are doubled. For $PM_{2.5}$, domain average concentrations increase by 11.6 μg m$^{-3}$. Simulated $PM_{2.5}$ concentrations show better agreement with observations at the 24 monitoring sites (Figure 5); averaged NMB is reduced from -21 % in the base scenario to -11 % in scenario Het_2NH$_3$.

20  Figure 10 further compares the average simulated sulfate concentrations between the base case and Het scenario for the outer 36 km domain during the modelling period. In the base case simulation, high sulfate concentrations were noticed at scattered cities over the North China Plain, Central China and the central part of the Sichuan Basin, corresponding to regions with elevated $SO_2$ concentrations. Implementing the $SO_2$ + $NO_2$ heterogeneous reactions enhanced simulated sulfate concentrations by at least 1~5 μg m$^{-3}$ for regions to the east of the "Hu Line". In particular, Northeast China Plain shows
25  most significant sulfate enhancement of more than 10 μg m$^{-3}$; simulated average sulfate concentrations in the Northeast China Plain increased from less than 20 μg m$^{-3}$ during the base case scenario to more than exceed 30 μg m$^{-3}$ in the Het scenario. For other regions, including the North China Plan and Sichuan Basin that show relative high sulfate concentrations in the base case scenario, sulfate concentrations were increased by 5-10 μg m$^{-3}$ due to the implementation of the reactive $SO_2$ uptake mechanism. The spatial pattern of sulfate enhancement generally follows that of predicted ammonia concentrations,
30  once again suggesting the important role of ammonia emissions for this mechanism. Future studies and local sulfate observations are needed to evaluate this mechanism for other parts of China, especially for Northeast China Plain.

## 4 Conclusions

In this study, we implemented a new parameterization of the $SO_2 + NO_2$ heterogeneous reactions based on observations in Beijing to improve model simulation of sulfate formation under heavy haze conditions in the YRD region. Unlike previous studies that only considered the influence of relative humidity on sulfate formation, we also included the impact of aerosol pH in our parameterization. Four CAMx sensitivity runs were conducted to evaluate the importance of the $SO_2 + NO_2$ heterogeneous reactions as well as ammonia emissions on simulated sulfate concentrations in the YRD region. Base case simulation showed reasonable model performance of sulfate with an overall MB of -2.7 μg m$^{-3}$ but significantly underpredicted sulfate concentrations by 36 % during polluted conditions. Implementation of the $SO_2 + NO_2$ heterogeneous reactions alone showed slight improvement of sulfate simulation (increase by 6.5 %) under polluted conditions due to acidic aerosol pH. Ammonia concentrations were significantly underestimated by the model. Doubling ammonia emissions alone exhibited a similar impact (sulfate increase by 5.6 %) with that of the $SO_2 + NO_2$ heterogeneous reactions alone. Nevertheless, aerosol pH increased by 0.7 with doubled ammonia emissions, which enabled the $SO_2 + NO_2$ heterogeneous reactions to become effective. Thus, in a fourth scenario where both the $SO_2 + NO_2$ heterogeneous reactions and doubled ammonia emissions were considered, simulated sulfate concentrations during polluted periods increased from 23.1 μg m$^{-3}$ in the base case to 29.1 μg m$^{-3}$, representing an increase by 26 %. Results for sulfate simulations over entire China shows that for some parts of China, especially the Northeast China Plain, implementing the $SO_2 + NO_2$ heterogeneous reactions could lead to as much as 20 μg m$^{-3}$ increase of sulfate concentrations and the spatial pattern of sulfate enhancement follows closely to that of ammonia concentrations. These findings suggest that the $SO_2 + NO_2$ heterogeneous reactions could be important for sulfate formation under heavy haze periods and aerosol pH (in other words, ammonia emissions) is crucial in this process. However, under-prediction of sulfate concentration still exists (by 20 %) in the YRD region under polluted conditions even with the $SO_2 + NO_2$ heterogeneous reactions and doubled ammonia emissions, which urges further efforts to better constrain the parameterization of the $SO_2 + NO_2$ heterogeneous reactions using local data and to improve the accuracy of ammonia emissions inventory.

*Date and code availability.* All data and modified CAMx code is available upon request from the corresponding authors.

*Competing interest.* The authors declare that they have no conflict of interest.

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*Author contribution.* L.H., J.A., L.L., C.H. and G.Y. designed the research; B.K. and L.H. modified the code; R.Y. conducted WRF simulation; J.A. conducted CAMx simulations; L.H. and J.A. analyzed the data; L.L., G.Y., C.H. and Y.W. provided important academic guidance; L.H. and J.A. wrote the paper with contributions from all authors.

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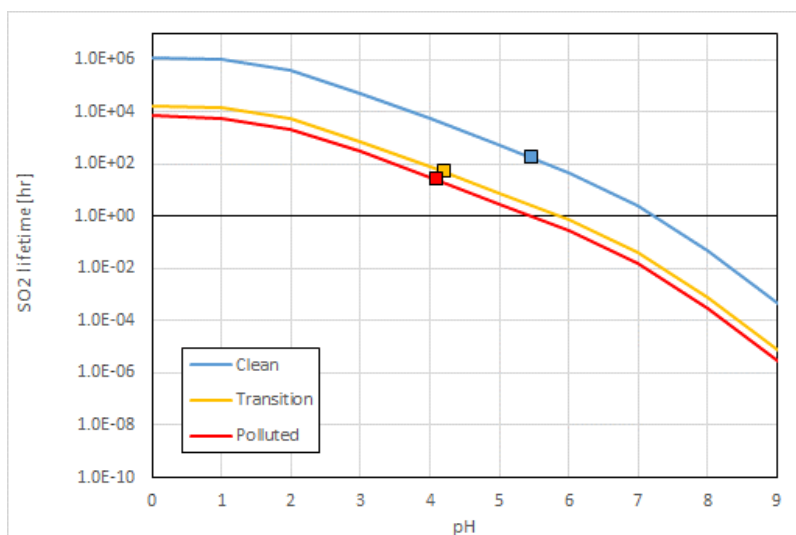
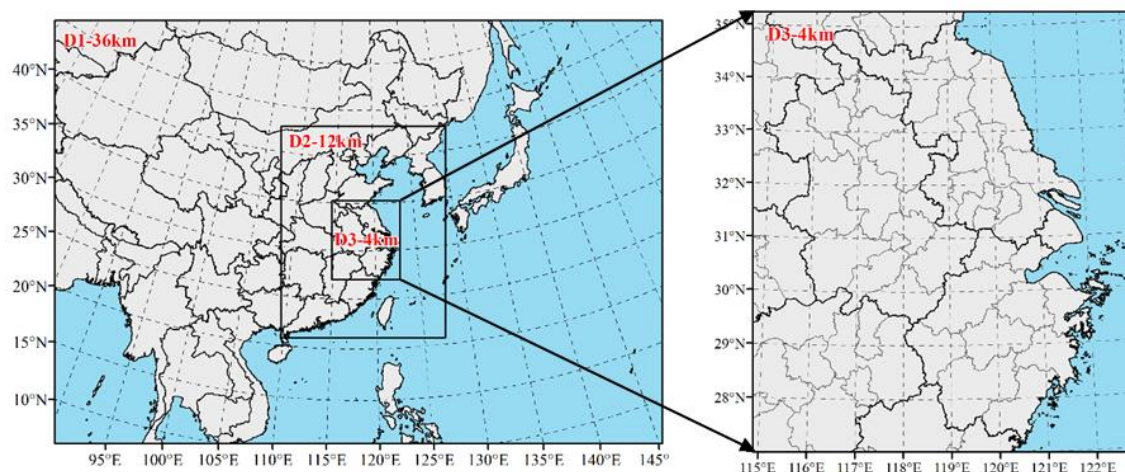


**Figure 1: SO$_2$ lifetime (in hr$^{-1}$) due to SO$_2$ + NO$_2$ reactive uptake mechanism as a function of aerosol pH under clean, transition, and polluted conditions. Values of relative humidity, temperature, and NO$_2$(g) concentrations are based on values in Table S1.**

5    **Figure 2: CAMx model domains**

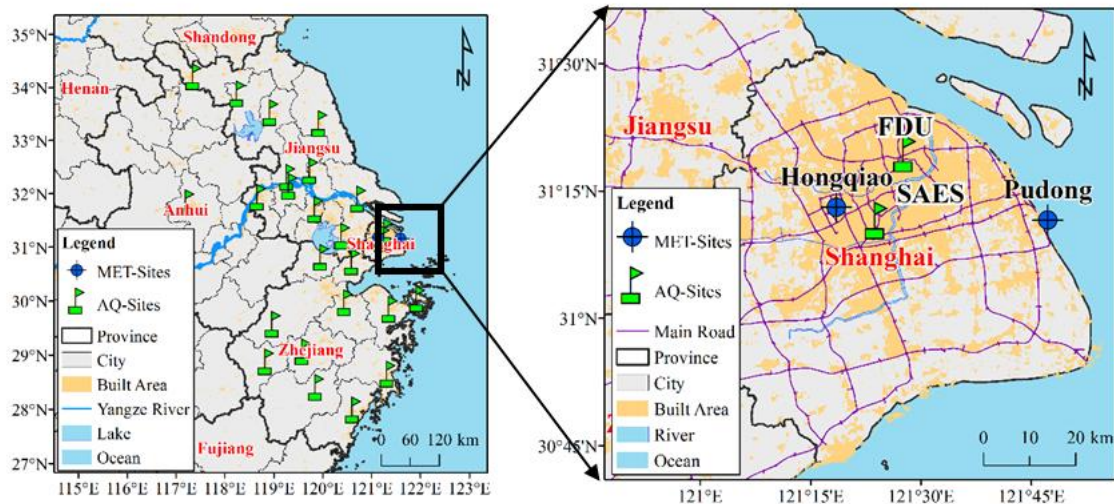



**Figure 3: Locations of observations sites for WRF (two MET-Sites) and CAMx model performance evaluation (SAES site and FDU site within Shanghai; another 23 AQ-sites distributed over Jiangsu, Zhejiang, and Anhui province with locations shown in Table S2).**

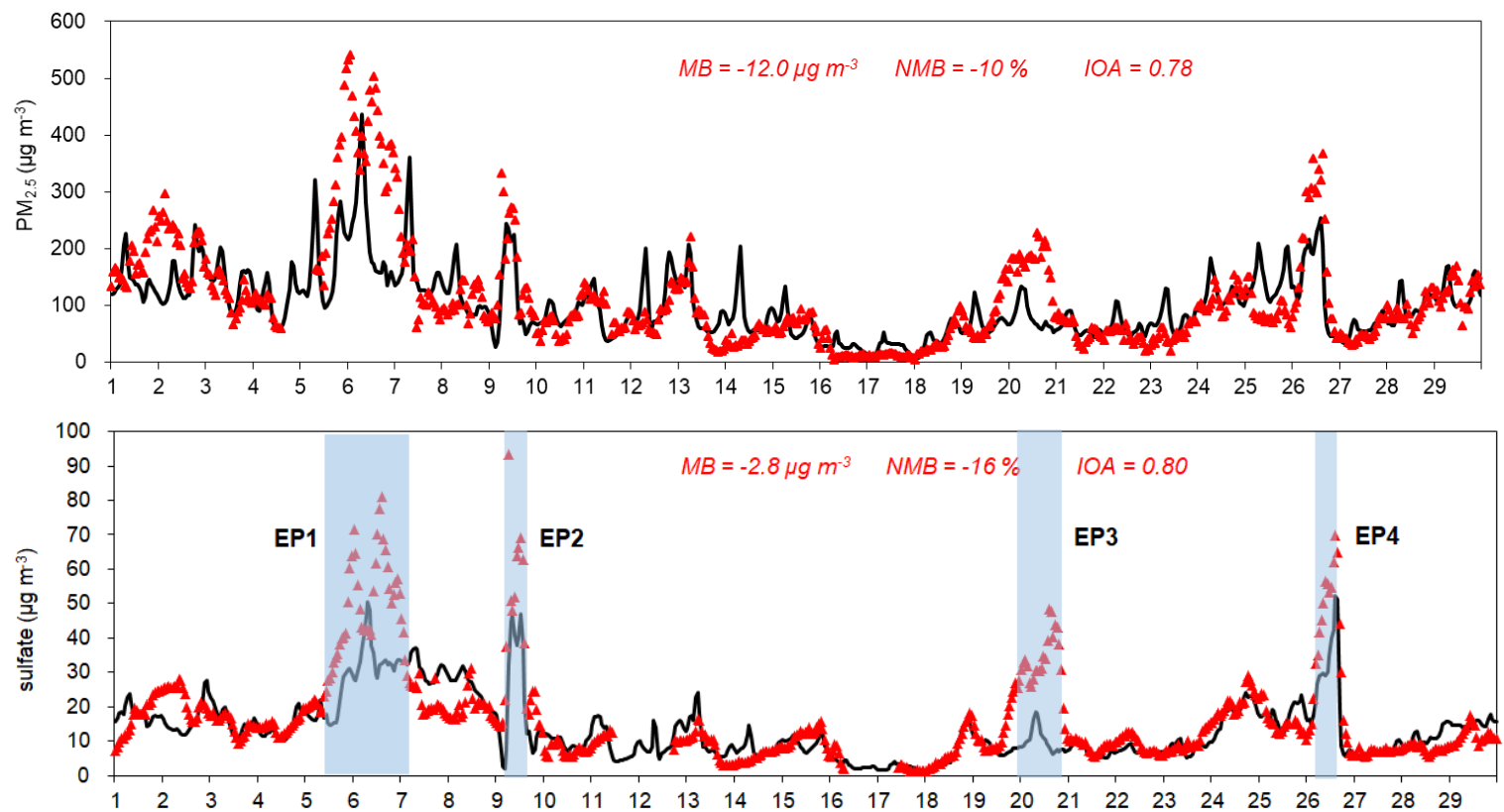



**Figure 4: Simulated and observed PM₂.₅ (upper) and sulfate (bottom) concentrations (in µg m⁻³) at SAES site during 1 to 29 December 2013**

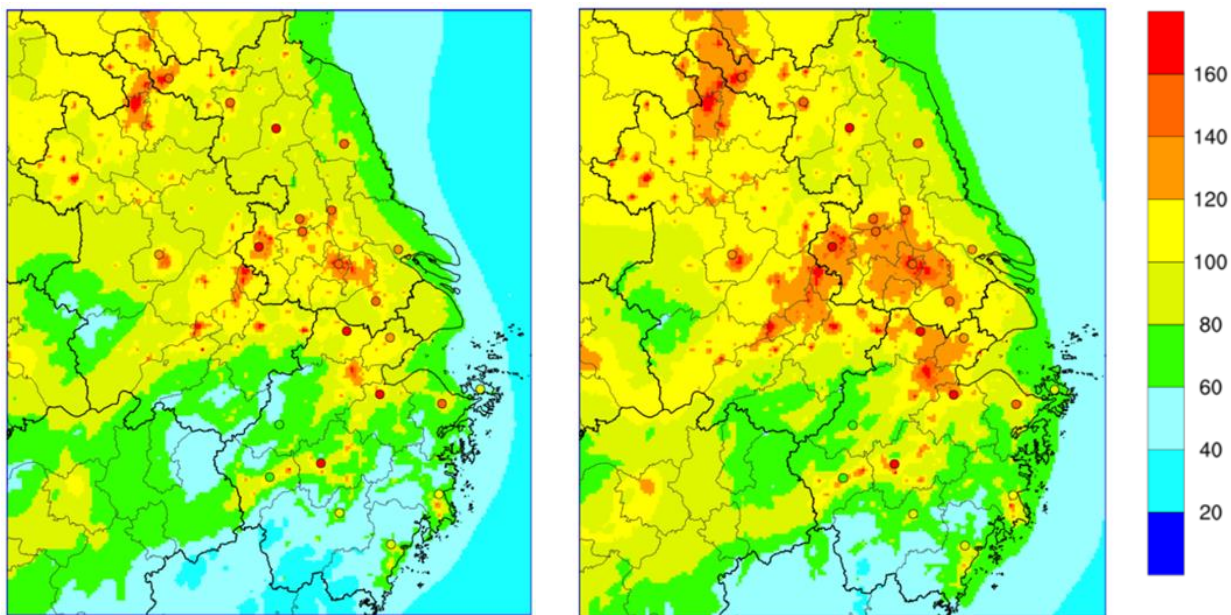



**Figure 5: Spatial distribution of observed and simulated monthly average PM$_{2.5}$ concentrations (in µg m$^{-3}$) over the YRD region for the base case scenario (left) and Het_2NH$_3$ scenario (right). Locations of the monitoring sites are listed in Table S2.**

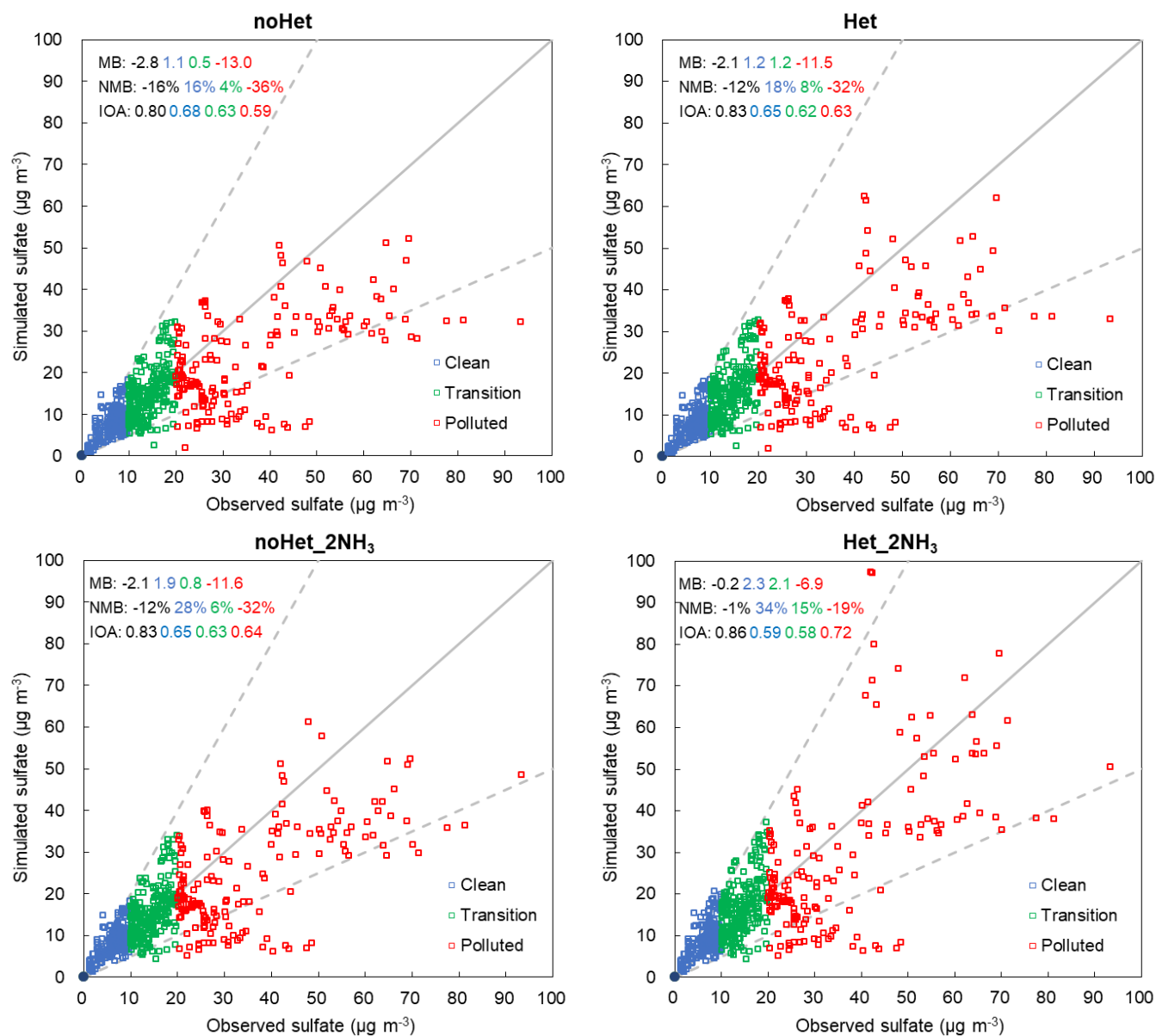



**Figure 6: Scatter plots of hourly sulfate concentrations for different scenarios at SAES site during 1 to 29 December 2013. Solid lines indicate 1:1 lines and dashed lines are 1:2 and 2:1 lines.**

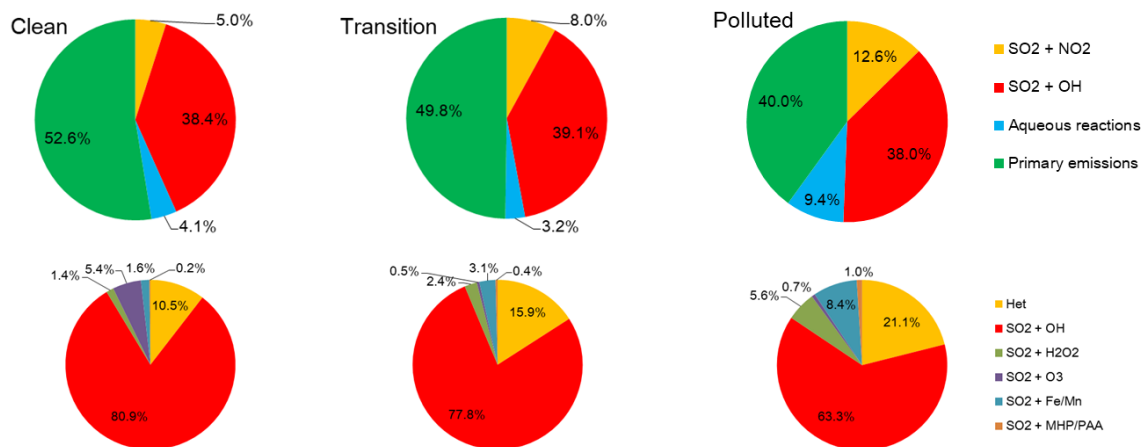



**Figure 7: Relative contribution of different pathways to sulfate concentrations at the SAES site during clean, transition and polluted periods. Primary sulfate emissions were excluded in the bottom row.**

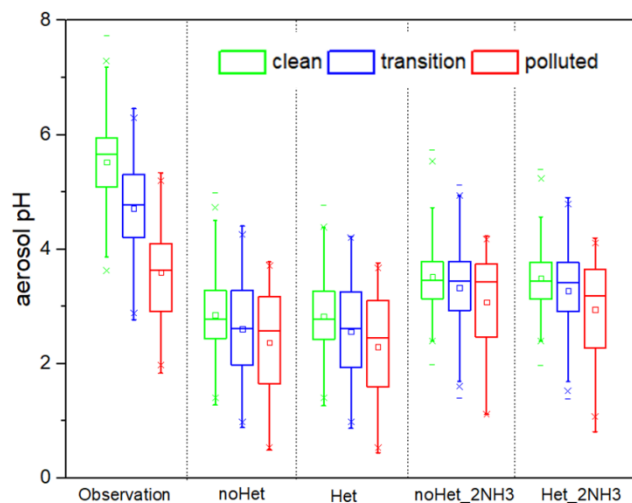



Figure 8: Box and whisker plot of observed and predicted aerosol pH by scenario and period.

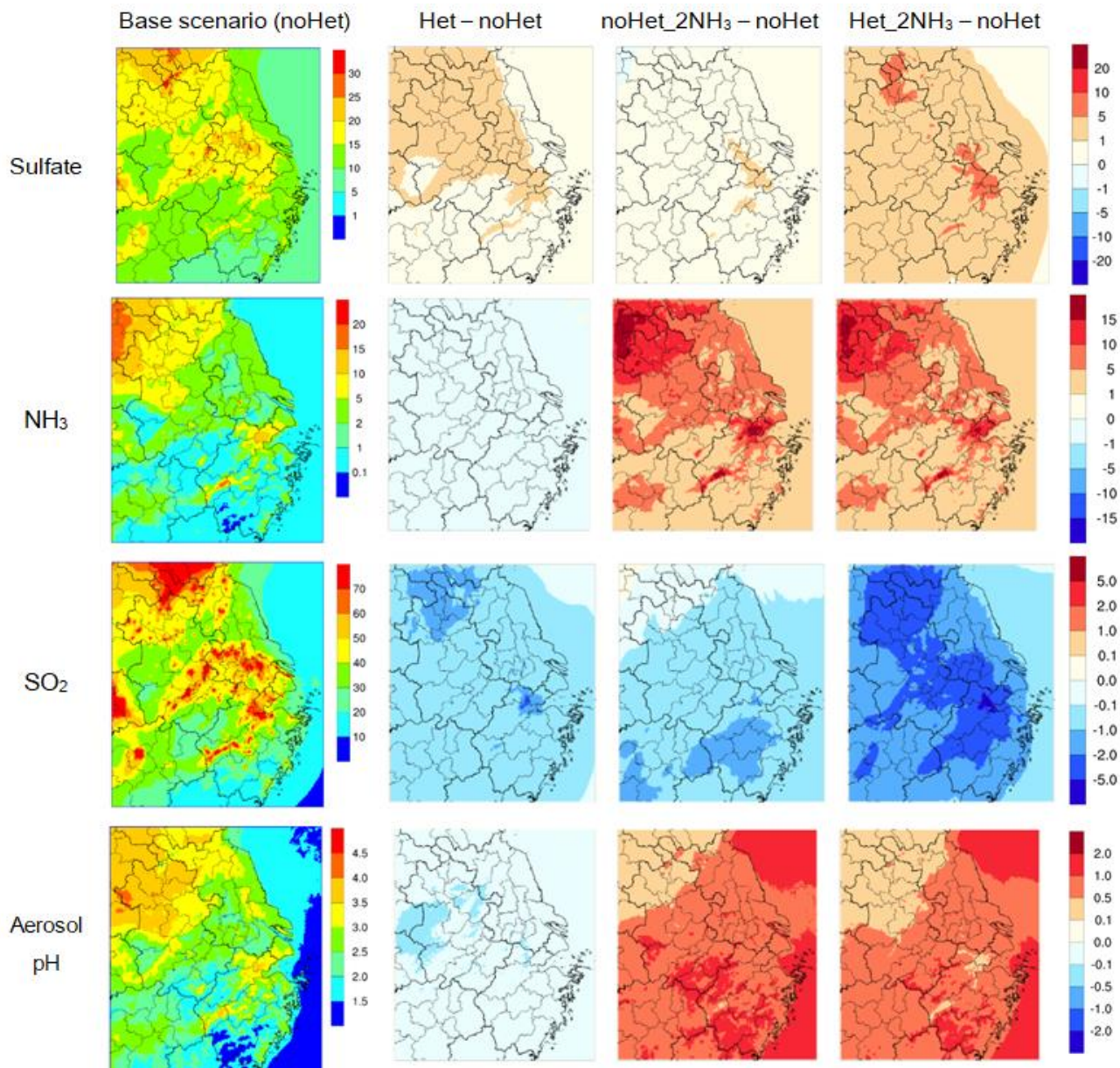



**Figure 9: Spatial distribution of simulated monthly sulfate (top row), NH₃ (second row), and SO₂ (third row) concentrations (µg m⁻³) and aerosol pH (bottom row) over the YRD region for the base case scenario (first column) and the differences (µg m⁻³ for concentrations) between the base case and other three scenarios: Het (second column), noHet_2NH₃ (third column) and Het_2NH₃ (fourth column).**

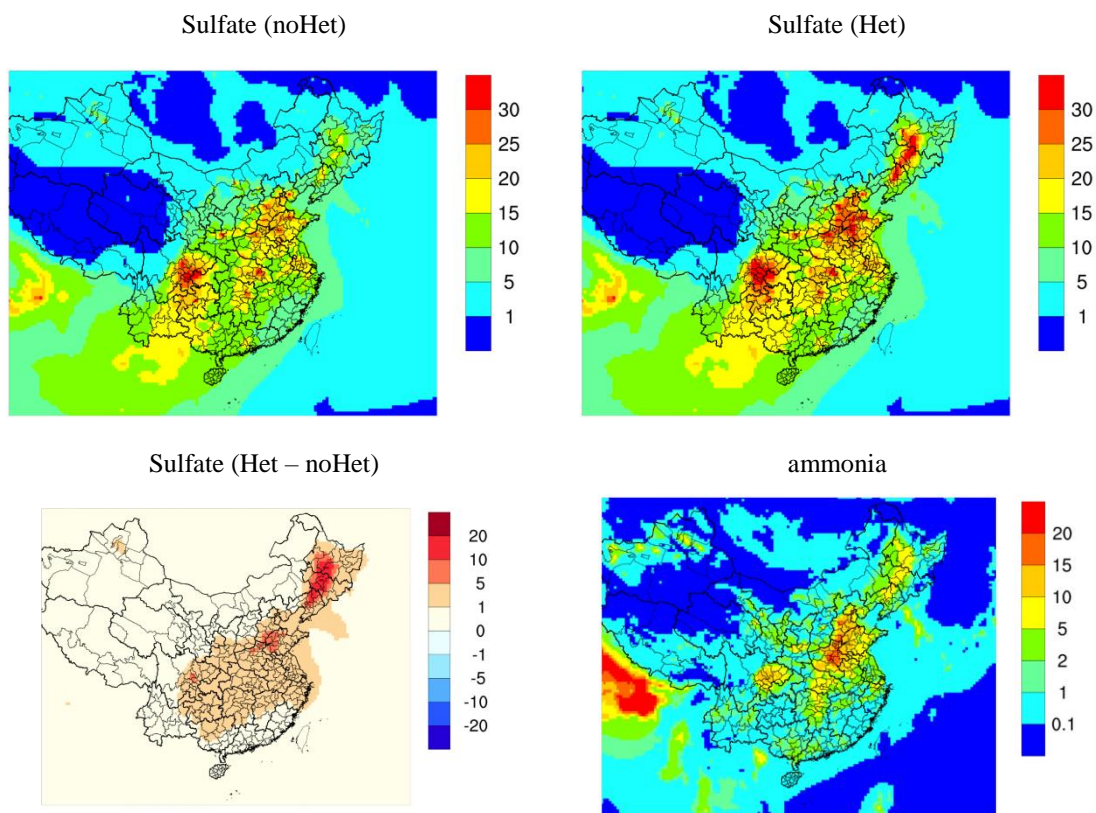



**Figure 10: Spatial distribution of simulated monthly sulfate concentrations (μg m⁻³) over the 36 km domain for the base case scenario (top left), Het (top right) and the differences between the two scenarios (bottom left) and ammonia concentrations (in μg m⁻³; bottom right).**

5    **Table 1. Sulfate formation pathways currently implemented in CAMx version 6.40**

| No. | Oxidants | Rate expression | Reference |
|-----|----------|-----------------|-----------|
| *Gaseous Phase* | | | |
| 1 | OH | $k_1[\text{OH}][\text{SO}_2(\text{g})]$ | Seinfeld and Pandis (2006) |
| | | $k_1 = \left[\dfrac{k_0[M]}{1+\dfrac{k_0[M]}{k_\infty}}\right]0.6^G$ | |
| | | $G = \{1 + [\log\left(\dfrac{k_0[M]}{k_\infty}\right)]^2\}^{-1}$ | |
| | | $k_0 = 4.50 \times 10^{-31}\,(T/300)^{-3.9}$ | |
| | | $k_\infty = 1.30 \times 10^{16}(T/300)^{-0.7}$ | |
| *Aqueous Phase* | | | |

| | | | |
|---|---|---|---|
| 2 | $O_3$ | $(k_2[SO_2 \cdot H_2O] + k_3[HSO_3^-] + k_4[SO_3^{2-}])[O_3(aq)]$ | Jacobson (1997) |
| | | $k_2 = 2.4 \times 10^4 \text{ M}^{-1}\text{s}^{-1}$ | |
| | | $k_3 = 3.7 \times 10^5 \text{ M}^{-1}\text{s}^{-1}$ | |
| | | $k_4 = 1.5 \times 10^9 \text{ M}^{-1}\text{s}^{-1}$ | |
| 3 | $H_2O_2$ | $k_5[H^+][HSO_3^-][H_2O_2(aq)]/(1+13x[H^+])$ | Jacobson (1997) |
| | | $k_5 = 7.45 \times 10^7 \text{ x exp}(-15.96 \text{ x } (298/T - 1)) \text{ M}^{-1}\text{s}^{-1}$ | |
| 4 | Fe(III)/Mn(II) | when aerosol pH <=4.2: | Martin and Good (1991) |
| | | $750[Mn(II)][S(IV)] + 2600[Fe(III)][S(IV)]-k_6[Mn(II)][Fe(III)][S(IV)][H^+]^{0.67}$ | |
| | | when aerosol pH > 4.2: | |
| | | $750[Mn(II)][S(IV)] + 2600[Fe(III)][S(IV)]-k_7[Mn(II)][Fe(III)][S(IV)][H^+]^{-0.74}$ | |
| | | $k_6 = 2.51 \times 10^{13} \text{ M}^{-2}\text{s}^{-1}$ | |
| | | $k_7 = 3.72 \times 10^7 \text{ M}^{-2}\text{s}^{-1}$ | |
| 5 | Methyl hydroperoxide ($CH_3OOH$) and other organic hydroperoxides | $k_8[H^+][HSO_3^-][CH_3OOH(aq)]$ $k_8 = 1.90 \times 10^7 \text{ x exp}(-12.75 \text{ x } (298/T - 1)) \text{ M}^{-2}\text{s}^{-1}$ | Jacobson (1997) |
| 6 | Peracetic acid ($CH_3C(O)OOH$) and other organic peracids | $k_9[H^+][HSO_3^-][CH_3C(O)OOH(aq)]$ $k_9 = 3.60 \times 10^7 \text{ x exp}(-13.42 \text{ x } (298/T - 1)) \text{ M}^{-2}\text{s}^{-1}$ | Jacobson (1997) |
| *Aerosol Aqueous Phase (implemented as pseudo gas phase)* | | | |
| 7 | $NO_2$ | $k_{10}[SO_2(g)]$ | Zheng (2015) |
| | | $k_{10} = \left(\dfrac{d_p}{2D} + \dfrac{4}{v\gamma}\right)^{-1} S_p$ | |
| | | $\gamma_{low} = 2 \times 10^{-5}$ | |
| | | $\gamma_{high} = 5 \times 10^{-5}$ | |

**Table 2 Observed and simulated sulfate concentrations (μg m$^{-3}$) for different scenarios by clean, transition, polluted periods at SAES site during 1 to 29 December 2013**

| Period | Observed | noHet | Het | noHet_2NH$_3$ | Het_2NH$_3$ |
|---|---|---|---|---|---|
| all | 17.2 | 14.4 | 15.1 | 15.2 | 17.0 |
| clean | 6.7 | 7.8 | 8.0 | 8.6 | 9.1 |
| transition | 14.3 | 14.7 | 15.3 | 15.0 | 16.3 |
| polluted | 36.1 | 23.1 | 24.6 | 24.5 | 29.1 |

*Supplement of*

# Enhanced sulfate formation through $SO_2+NO_2$ heterogeneous reactions during heavy winter haze in the Yangtze River Delta region, China

**Ling Huang et al.**

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**Model performances of nitrate and ammonium concentrations**

In addition to sulfate, we also look at modeled nitrate and ammonium concentrations under different scenarios; associated model performance metrics are summarized in Table S7 and S8. For the base case scenario, nitrate and ammonium concentrations were underestimated by 20 %. When only polluted period is considered, underestimation almost doubled to 36 % and 41 % for nitrate and ammonium, respectively. Doubling ammonia emissions results in higher nitrate concentrations simply because more ammonia becomes available to form nitrate. This reduces nitrate underestimation substantially during polluted period from -42 % to -20 % but also leads to even higher nitrate overestimation during clean and transition periods. The impact of the $SO_2 + NO_2$ heterogeneous reactions on nitrate formation, on the other hand, is more complicated. With the base case ammonia emissions, predicted nitrate concentrations show negligible changes with the implementation of the heterogeneous reactions. However, with doubled ammonia emissions, predicted nitrate formation is enhanced by 0.3–1.1 μg m$^{-3}$ (noHet_2NH$_3$ vs. Het_2NH$_3$). Response of simulated nitrate concentrations to the $SO_2 + NO_2$ heterogeneous reactions, in other words, to increased sulfate concentrations, could be affected by two opposing factors. At one hand, nitrate concentrations decrease due to replacement by enhanced formation of sulfate. On the other hand, nitrate formation could be enhanced with more effective hydrolysis of $N_2O_5$ on sulfate aerosols (Hallquist et al., 2003). A most recent study by Vasilakos et al. (2018) discussed the nitrate substitution paradox with less sulfate and concludes that this paradox is attributable to positive bias in model simulated aerosol pH. Nevertheless, compared with doubled ammonia emissions, the heterogeneous reactions only had small impact on modeled nitrate concentration.

For ammonium, doubling ammonia emissions also leads to higher simulated ammonium concentrations but to a less extent compared with nitrate. Under-prediction of ammonium under polluted conditions is reduced from 41 % in the base case to 31 % in the noHet_2NH$_3$ scenario. With the base case ammonia emissions, adding the $SO_2 +$

$NO_2$ heterogeneous reactions leads to slight increase in ammonium concentrations. When ammonia emissions are doubled, the heterogeneous reactions substantially improve modeled ammonium concentrations. Overall MB of ammonium in scenario Het_2NH$_3$ is only -0.4 μg m$^{-3}$ (NMB of -3 %) and under-prediction during polluted period is reduced to 24 % in the Het_2NH$_3$ scenario (from 41 % in the base case scenario). These results suggest that both the heterogeneous reactions as well as sufficient ammonia emissions are needed to improve model simulation of ammonium concentrations.

**Model performance of PM$_{2.5}$ concentrations**

In the base case scenario, PM$_{2.5}$ concentrations are underestimated by 36 % at the SAES site during polluted periods (Table S9). With doubled ammonia emissions, PM$_{2.5}$ under-prediction is reduced to 30 % during polluted periods, resulting an overall NMB of -2 %. PM$_{2.5}$ concentrations do not change much with the heterogeneous reactions when ammonia emissions are at base case level. With doubled ammonia emissions, concentrations of all three inorganic species are enhanced with the heterogeneous reactions; thus under-prediction of PM$_{2.5}$ during polluted periods in scenario Het_2NH$_3$ is further reduced to 26 % and the overall NMB is only 1 %. The maximum of simulated PM$_{2.5}$ concentration increases from 460.6 μg m$^{-3}$ in the base scenario to 531.6 μg m$^{-3}$ in scenario Het_2NH$_3$ (increase by 15 %), which compares well with observed maximum value of 540.3 μg m$^{-3}$.

**References**

Hallquist, M., Stewart, D. J., Stephenson, S. K., and Cox, R. A.: Hydrolysis of N2O5 on sub-micron sulfate aerosols, Physical Chemistry Chemical Physics., 5, 3453-3463. doi:10.1039/B301827J, 2003.

Vasilakos, P., Russell, A., Weber, R., and Nenes, A.: Understanding nitrate formation in a world with less sulfate, Atmospheric Chemistry and Physics, 18, 12765-12775, doi: 10.5194/acp-18-12765-2018, 2018.

**Table S1.** Summary of parameters representing clean, transition, and polluted conditions during Beijing 2015. Temperature (T) and relative humidity (RH) are directly adopted from Table S2 of Wang et al. (2016). $NO_2$ concentrations are assumed to be 50 % of NOx. Liquid water content (LWC) and aerosol pH are calculated by ISORROPIA assuming a metastable aerosol in CAMx.

| Conditions | Temperature [K] | RH [%] | $NO_2$(g) [ppb] | LWC [$\mu g\ m^{-3}$] | Aerosol pH [-] |
|---|---|---|---|---|---|
| Clean | 273.4 | 21 | 32 | 1.24 | 5.5 |
| Transition | 274.4 | 41 | 58 | 12.3 | 4.2 |
| Polluted | 273.9 | 56 | 45.5 | 35.8 | 4.1 |

**Table S2.** Statistical summary of monthly PM$_{2.5}$ simulated from noHet and Het_2NH$_3$ scenarios at 23 monitoring sites in Zhejiang, Jiangsu and Anhui province during 1 to 29 December 2013.

| No. | Province | City | Latitude | Longitude | Observed mean | noHet | | | | Het_2NH$_3$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Modeled mean | MB | NMB | IOA | Modeled mean | MB | NMB | IOA |
| 1 | | Hangzhou | 29.64 | 119.03 | 66.5 | 60.1 | -6.4 | -10% | 0.74 | 74.0 | 7.5 | 11% | 0.75 |
| 2 | | Ningbo | 29.85 | 121.52 | 153.0 | 108.9 | -44.1 | -29% | 0.71 | 122.5 | -30.5 | -20% | 0.78 |
| 3 | | Wenzhou | 28.02 | 120.67 | 86.6 | 56.5 | -30.1 | -35% | 0.71 | 69.3 | -17.3 | -20% | 0.75 |
| 4 | | Jiaxing | 30.76 | 120.76 | 131.9 | 102.5 | -29.5 | -22% | 0.73 | 116.5 | -15.4 | -12% | 0.80 |
| 5 | | Huzhou | 30.86 | 120.09 | 189.3 | 119.8 | -69.6 | -37% | 0.67 | 140.6 | -48.7 | -26% | 0.77 |
| 6 | Zhejiang | Quzhou | 28.94 | 118.87 | 71.4 | 82.8 | 11.4 | 16% | 0.72 | 89.8 | 18.5 | 26% | 0.66 |
| 7 | | Zhoushan | 30.02 | 122.12 | 99.0 | 59.5 | -39.5 | -40% | 0.67 | 72.2 | -26.8 | -27% | 0.75 |
| 8 | | Taizhou | 28.65 | 121.42 | 106.9 | 75.3 | -31.7 | -30% | 0.76 | 88.8 | -18.2 | -17% | 0.82 |
| 9 | | Lishui | 28.45 | 119.91 | 91.0 | 61.5 | -29.5 | -32% | 0.62 | 75.1 | -15.9 | -17% | 0.68 |
| 10 | | Shaoxing | 30.01 | 120.58 | 198.7 | 138.8 | -60.0 | -30% | 0.64 | 166.1 | -32.6 | -16% | 0.72 |
| 11 | | Jinhua | 29.11 | 119.65 | 164.3 | 88.2 | -76.1 | -46% | 0.59 | 105.5 | -58.8 | -36% | 0.68 |
| 12 | | Nanjing | 32.01 | 118.74 | 170.5 | 139.4 | -31.1 | -18% | 0.76 | 152.5 | -18.0 | -11% | 0.80 |
| 14 | | Xuzhou | 34.28 | 117.29 | 142.0 | 139.5 | -2.4 | -2% | 0.70 | 150.0 | 8.0 | 6% | 0.71 |
| 15 | | Changzhou | 31.76 | 120.00 | 144.9 | 127.1 | -17.8 | -12% | 0.83 | 141.8 | -3.1 | -2% | 0.86 |
| 16 | | Suzhou | 31.25 | 120.56 | 154.8 | 119.3 | -35.5 | -23% | 0.74 | 132.7 | -22.1 | -14% | 0.79 |
| 17 | | Nantong | 31.93 | 120.94 | 132.1 | 92.9 | -39.2 | -30% | 0.73 | 104.3 | -27.8 | -21% | 0.78 |
| 18 | Jiangsu | Huai'an | 33.60 | 119.04 | 200.1 | 109.7 | -90.4 | -45% | 0.55 | 120.5 | -79.6 | -40% | 0.57 |
| 19 | | Yancheng | 33.37 | 120.13 | 145.1 | 130.8 | -14.3 | -10% | 0.75 | 140.2 | -4.9 | -3% | 0.76 |
| 20 | | Yangzhou | 32.38 | 119.39 | 144.9 | 137.6 | -7.3 | -5% | 0.75 | 149.7 | 4.8 | 3% | 0.77 |
| 21 | | Zhenjiang | 32.21 | 119.43 | 143.5 | 140.7 | -2.7 | -2% | 0.78 | 154.1 | 10.7 | 7% | 0.79 |
| 22 | | Taizhou | 32.49 | 119.90 | 158.0 | 119.1 | -39.0 | -25% | 0.73 | 126.9 | -31.2 | -20% | 0.77 |
| 23 | | Suqian | 33.95 | 118.29 | 139.9 | 115.9 | -24.0 | -17% | 0.74 | 126.4 | -13.5 | -10% | 0.74 |
| 24 | Anhui | Hefei | 31.91 | 117.16 | 132.2 | 115.0 | -17.1 | -13% | 0.77 | 126.8 | -5.4 | -4% | 0.77 |

**Table S3.** Statistic summary of WRF simulated meteorological parameters during December 2013 at Pudong and Hongqiao airport monitoring site.

| Meteorological parameter | Statistics metric | Pudong | Hongqiao |
|---|---|---|---|
| Temperature [°C] | NMB | 0.37 | 0.01 |
| | NME | 0.41 | 0.16 |
| | IOA | 0.86 | 0.98 |
| Relative humidity [%] | NMB | 0.00 | 0.01 |
| | NME | 0.16 | 0.14 |
| | IOA | 0.85 | 0.92 |
| Wind speed [m s$^{-1}$] | NMB | 0.33 | 0.14 |
| | NME | 0.42 | 0.29 |
| | IOA | 0.79 | 0.89 |
| Wind direction [degree] | NMB | -0.36 | -0.27 |

**Table S4.** Statistical analysis of base case model performance

| Species | Observed mean [μg m$^{-3}$][*] | Modeled mean [μg m$^{-3}$][*] | MB | NMB | IOA |
|---|---|---|---|---|---|
| $O_3$ | 20.1 | 13.5 | -6.6 | -33% | 0.76 |
| $NO_2$ | 71.5 | 67.7 | -3.8 | -5% | 0.79 |
| $SO_2$ | 62.9 | 42.9 | -20.0 | -32% | 0.57 |
| $NH_3$ | 7.4 | 2.4 | -5.0 | -68% | 0.53 |
| $PM_{2.5}$ | 118.7 | 106.7 | -12.0 | -10% | 0.78 |
| sulfate | 17.2 | 14.5 | -2.7 | -16% | 0.80 |
| ammonium | 12.7 | 9.7 | -3.0 | -21% | 0.79 |
| nitrate | 24.4 | 19.6 | -4.8 | -20% | 0.77 |
| EC | 4.3 | 2.9 | -1.4 | -32% | 0.72 |
| OC | 18.7 | 9.6 | -9.1 | -49% | 0.60 |

[*]Units for all species except $NH_3$ are μg m$^{-3}$; unit for $NH_3$ is ppb.

**Table S5.** Statistical metrics of sulfate for different scenarios at SAES site during 1 to 29 December 2013

| Scenario | Period | Mean observed sulfate [$\mu$g m$^{-3}$] | Mean modeled sulfate [$\mu$g m$^{-3}$] | MB [$\mu$g m$^{-3}$] | NMB [-] | IOA [-] |
|---|---|---|---|---|---|---|
| noHet | all | 17.2 | 14.4 | -2.8 | -16% | 0.80 |
| | clean | 6.7 | 7.8 | 1.1 | 16% | 0.68 |
| | transition | 14.2 | 14.7 | 0.5 | 4% | 0.63 |
| | polluted | 36.1 | 23.1 | -13.0 | -36% | 0.59 |
| Het | all | 17.2 | 15.1 | -2.1 | -12% | 0.83 |
| | clean | 6.7 | 8.0 | 1.2 | 18% | 0.65 |
| | transition | 14.2 | 15.3 | 1.2 | 8% | 0.62 |
| | polluted | 36.1 | 24.6 | -11.5 | -32% | 0.63 |
| noHet_2NH$_3$ | all | 17.2 | 15.2 | -2.1 | -12% | 0.83 |
| | clean | 6.7 | 8.6 | 1.9 | 28% | 0.65 |
| | transition | 14.2 | 15.0 | 0.8 | 6% | 0.63 |
| | polluted | 36.1 | 24.5 | -11.6 | -32% | 0.64 |
| Het_2NH$_3$ | all | 17.2 | 17.0 | -0.2 | -1% | 0.86 |
| | clean | 6.7 | 9.1 | 2.3 | 34% | 0.59 |
| | transition | 14.2 | 16.3 | 2.1 | 15% | 0.58 |
| | polluted | 36.1 | 29.1 | -6.9 | -19% | 0.72 |

**Table S6.** Observed sulfate and PM$_{2.5}$ concentrations and statistical metrics of sulfate during selected episodes

| No. | EP1 | EP2 | EP3 | EP4 |
|---|---|---|---|---|
| Episode | 12/5 13:00 - 12/7 2:00 | 12/9 5:00 - 12/9 14:00 | 12/20 0:00 - 12/20 20:00 | 12/26 4:00 - 12/26 16:00 |
| Mean observed sulfate [$\mu$g m$^{-3}$] | 51.2 | 58.2 | 36.2 | 51.3 |
| Mean observed PM$_{2.5}$ [$\mu$g m$^{-3}$] | 379.9 | 242.0 | 186.2 | 287.4 |
| Max observed sulfate [$\mu$g m$^{-3}$] | 81.2 | 93.4 | 48.6 | 69.7 |
| [$SO_4^{2-}$]/[$SO_2$] | 0.52 | 0.70 | 0.17 | 0.19 |
| Mean modeled sulfate [$\mu$g m$^{-3}$] | 31.3 | 35.6 | 10.1 | 33.4 |
| MB [$\mu$g m$^{-3}$] | -19.8 | -22.6 | -26.2 | -21.8 |
| NMB | -39% | -39% | -72% | -46% |
| IOA | 0.46 | 0.53 | 0.25 | 0.54 |

**Table S7.** Statistical metrics of nitrate for different scenarios at SAES site during 1 to 29 December 2013

| Scenario | Period | Mean observed nitrate [µg m$^{-3}$] | Mean modeled nitrate [µg m$^{-3}$] | MB [µg m$^{-3}$] | NMB [-] | IOA [-] |
|---|---|---|---|---|---|---|
| noHet | all | 24.4 | 19.6 | -4.8 | -20% | 0.77 |
| | clean | 9.6 | 12.0 | 2.4 | 25% | 0.74 |
| | transition | 22.0 | 20.8 | -1.2 | -5% | 0.76 |
| | polluted | 48.4 | 28.3 | -20.1 | -42% | 0.62 |
| Het | all | 24.4 | 19.6 | -4.8 | -20% | 0.77 |
| | clean | 9.6 | 12.1 | 2.5 | 26% | 0.73 |
| | transition | 22.0 | 20.9 | -1.1 | -5% | 0.75 |
| | polluted | 48.4 | 28.1 | -20.2 | -42% | 0.62 |
| noHet_2NH$_3$ | all | 24.4 | 26.8 | 2.3 | 10% | 0.82 |
| | clean | 9.6 | 15.9 | 6.3 | 66% | 0.55 |
| | transition | 22.0 | 28.7 | 6.7 | 31% | 0.56 |
| | polluted | 48.4 | 38.9 | -9.5 | -20% | 0.72 |
| Het_2NH$_3$ | all | 24.4 | 27.4 | 2.9 | 12% | 0.83 |
| | clean | 9.6 | 16.2 | 6.6 | 69% | 0.55 |
| | transition | 22.0 | 29.3 | 7.3 | 33% | 0.57 |
| | polluted | 48.4 | 40.0 | -8.4 | -17% | 0.75 |

**Table S8.** Statistical metrics of ammonium for different scenarios at SAES site during 1 to 29 December 2013

| Scenario | Period | Mean observed ammonium [μg m$^{-3}$] | Mean modeled ammonium [μg m$^{-3}$] | MB [μg m$^{-3}$] | NMB [-] | IOA [-] |
|---|---|---|---|---|---|---|
| noHet | all | 12.7 | 10.1 | -2.6 | -21% | 0.79 |
| | clean | 4.9 | 5.8 | 0.9 | 19% | 0.80 |
| | transition | 11.0 | 10.5 | -0.4 | -4% | 0.76 |
| | polluted | 26.2 | 15.4 | -10.8 | -41% | 0.61 |
| Het | all | 12.7 | 10.4 | -2.4 | -19% | 0.80 |
| | clean | 4.9 | 5.9 | 1.0 | 20% | 0.79 |
| | transition | 11.0 | 10.8 | -0.2 | -1% | 0.77 |
| | polluted | 26.2 | 15.9 | -10.3 | -39% | 0.63 |
| noHet_2NH$_3$ | all | 12.7 | 11.6 | -1.2 | -9% | 0.84 |
| | clean | 4.9 | 6.4 | 1.6 | 32% | 0.70 |
| | transition | 11.0 | 12.0 | 1.1 | 10% | 0.66 |
| | polluted | 26.2 | 18.1 | -8.1 | -31% | 0.68 |
| Het_2NH$_3$ | all | 12.7 | 12.4 | -0.4 | -3% | 0.87 |
| | clean | 4.9 | 6.6 | 1.8 | 36% | 0.70 |
| | transition | 11.0 | 12.6 | 1.7 | 15% | 0.67 |
| | polluted | 26.2 | 20.0 | -6.2 | -24% | 0.75 |

**Table S9.** Statistical metrics of PM$_{2.5}$ for different scenarios at SAES site during 1 to 29 December 2013

| Scenario | Period | Mean observed PM$_{2.5}$ [μg m$^{-3}$] | Mean modeled PM$_{2.5}$ [μg m$^{-3}$] | MB [μg m$^{-3}$] | NMB [-] | IOA [-] |
|---|---|---|---|---|---|---|
| noHet | all | 118.7 | 106.7 | -12.0 | -10% | 0.78 |
| | clean | 52.8 | 69.4 | 16.6 | 31% | 0.73 |
| | transition | 103.1 | 112.9 | 9.7 | 9% | 0.74 |
| | polluted | 232.3 | 149.2 | -83.0 | -36% | 0.63 |
| Het | all | 118.7 | 107.7 | -11.0 | -9% | 0.79 |
| | clean | 52.8 | 69.8 | 16.9 | 32% | 0.73 |
| | transition | 103.1 | 113.9 | 10.8 | 10% | 0.74 |
| | polluted | 232.3 | 151.2 | -81.0 | -35% | 0.64 |
| noHet_2NH$_3$ | all | 118.7 | 116.0 | -2.7 | -2% | 0.80 |
| | clean | 52.8 | 74.8 | 22.0 | 42% | 0.68 |
| | transition | 103.1 | 122.5 | 19.3 | 19% | 0.67 |
| | polluted | 232.3 | 163.7 | -68.5 | -30% | 0.66 |
| Het_2NH$_3$ | all | 118.7 | 119.4 | 0.7 | 1% | 0.82 |
| | clean | 52.8 | 75.7 | 22.9 | 43% | 0.68 |
| | transition | 103.1 | 125.1 | 22.0 | 21% | 0.68 |
| | polluted | 232.3 | 171.7 | -60.6 | -26% | 0.71 |
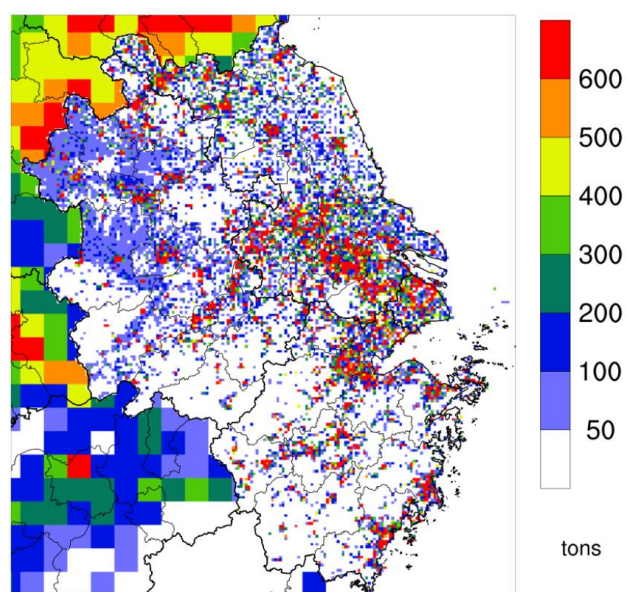
**Figure S1** Spatial distribution of primary sulfate emissions (tons) over the 4 km domain during December 2013 (for emissions outside the YRD region, emissions from the MEIC inventory with a spatial resolution of 12 km was used).
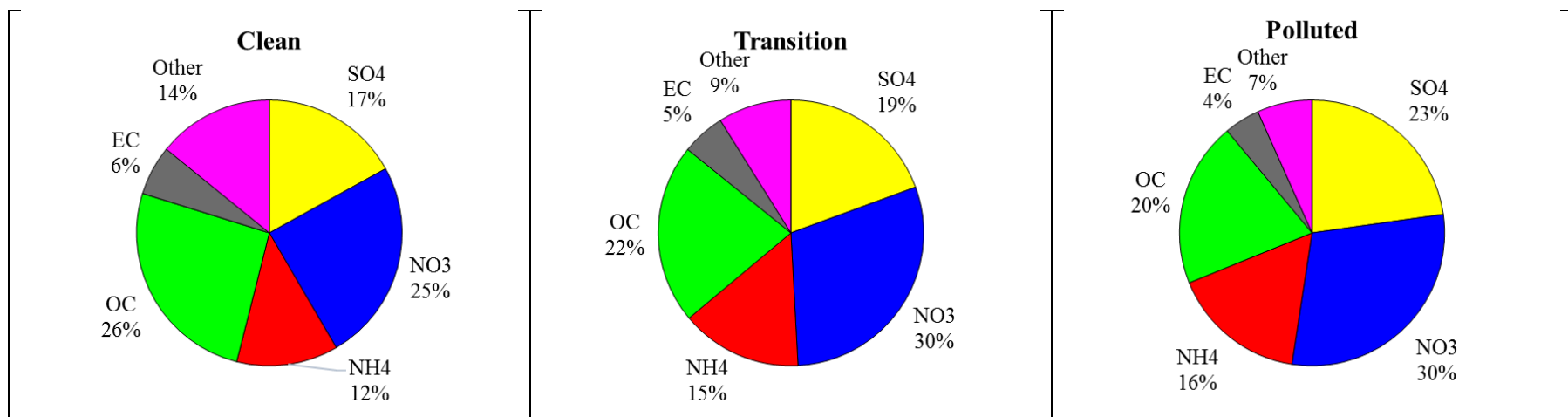
**Figure S2.** Mass fractions of major PM species for clean, transition, and polluted periods during 1 to 29 December 2013 at SAES site.
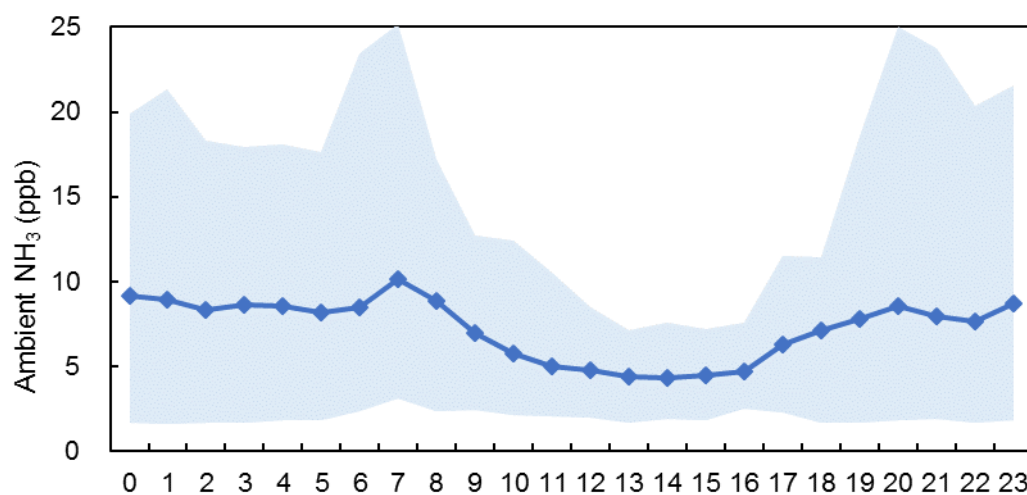
**Figure S3.** Diurnal profiles of ammonia concentrations (ppb) at FDU site during 1 to 29 December 2013. Shaded areas constrain maximum and minimum concentrations.
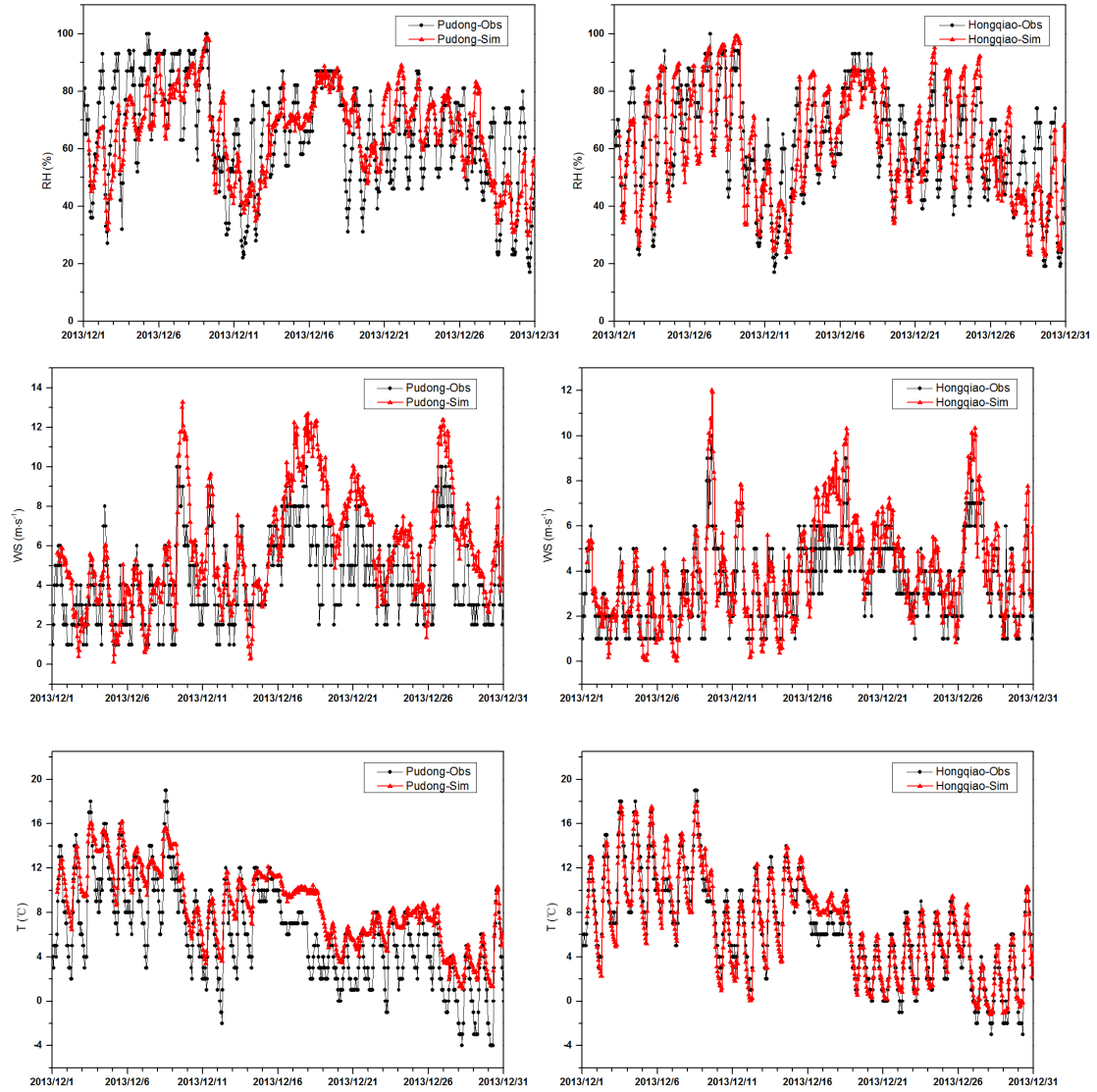
**Figure S4.** Comparison of observed (black dot-line) and simulated (red dot-line) hourly relative humidity (top row), wind speed (WS, middle row) and temperature (bottom row) at Pudong (left column) and Hongqiao (right column) airport monitoring site.
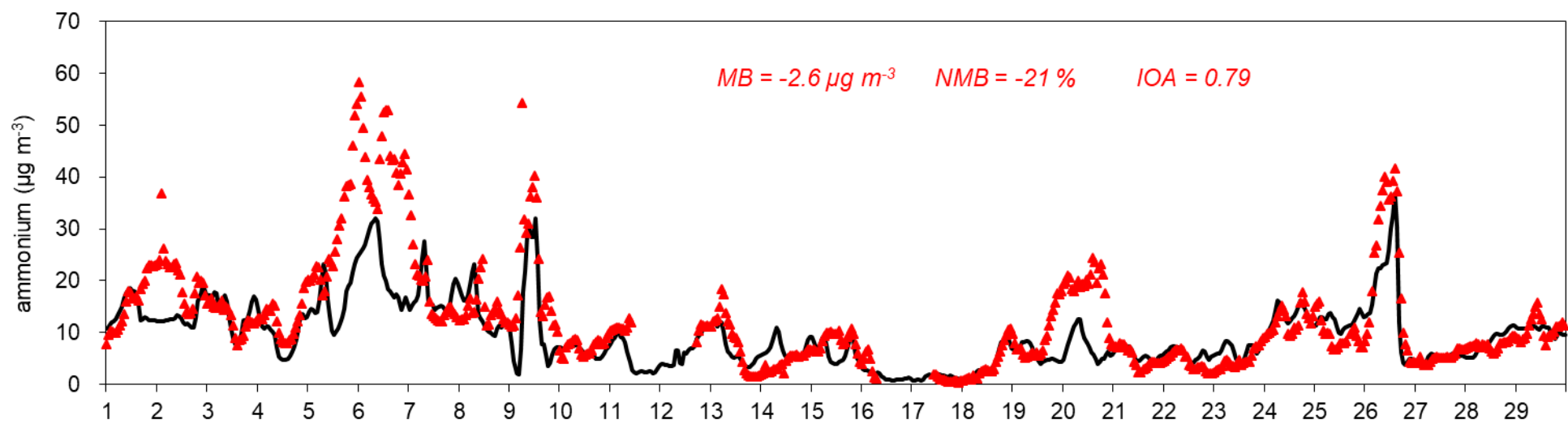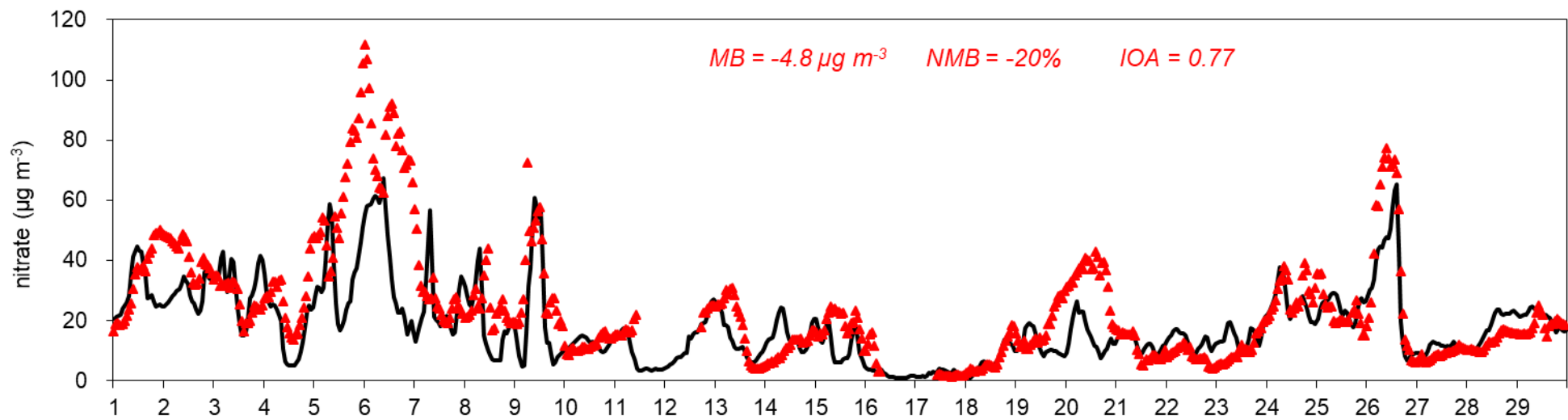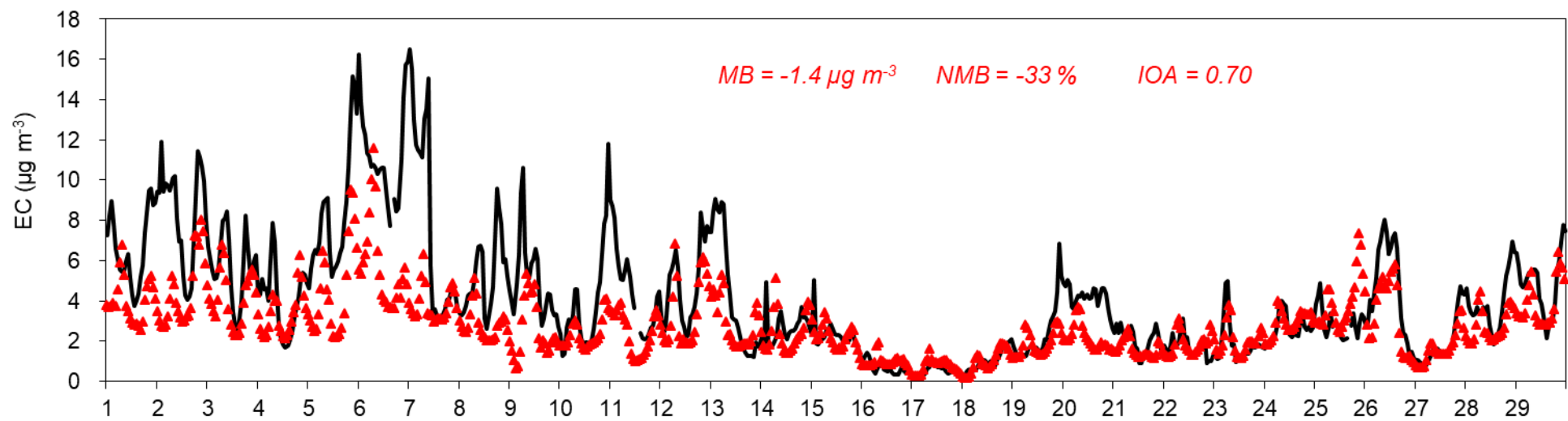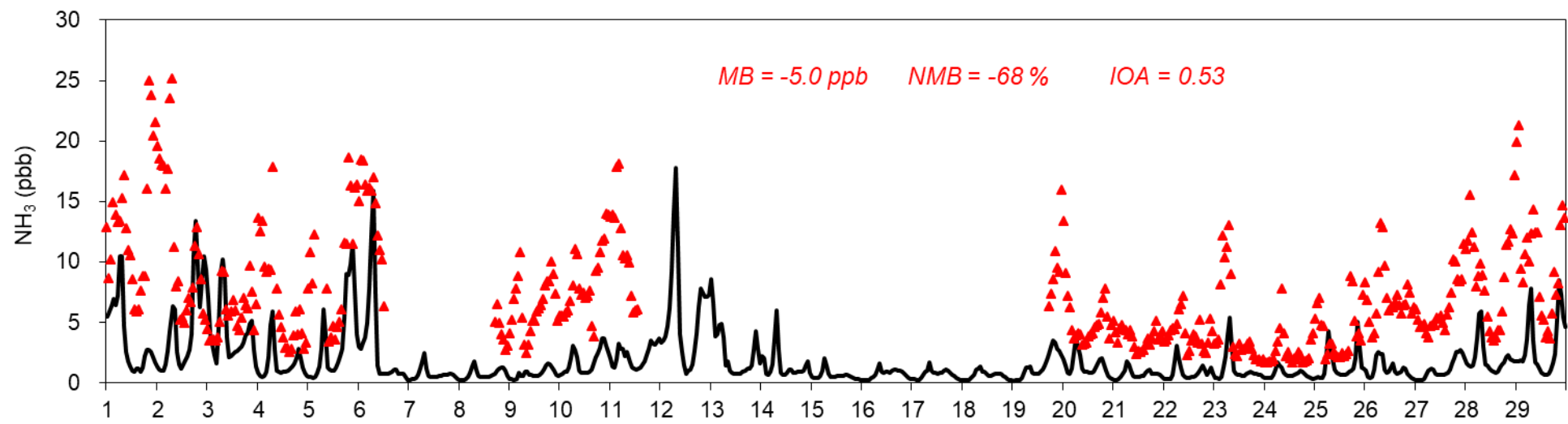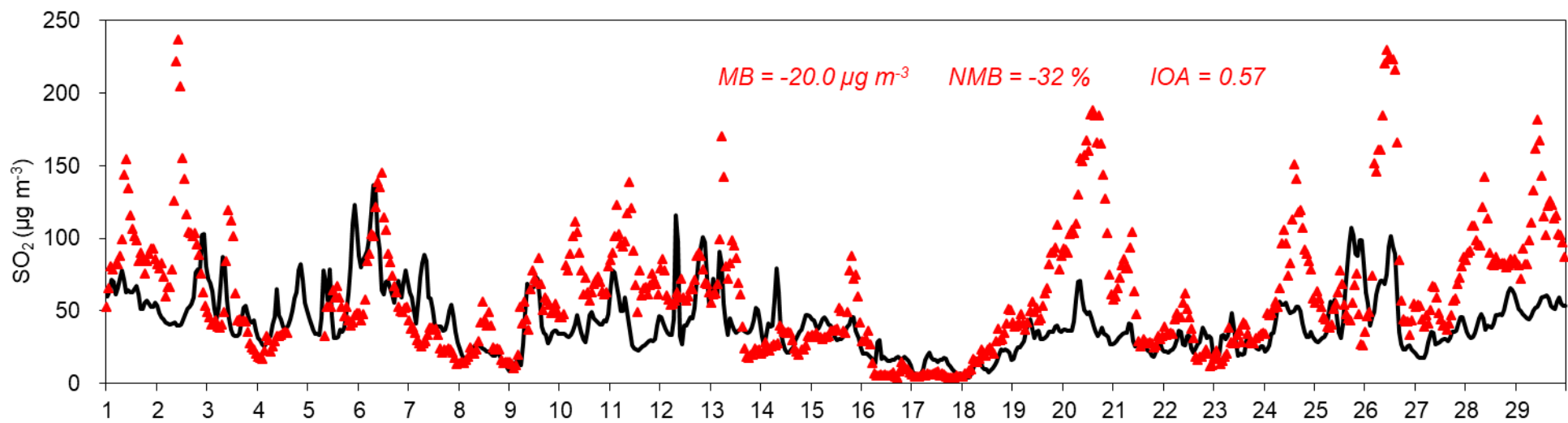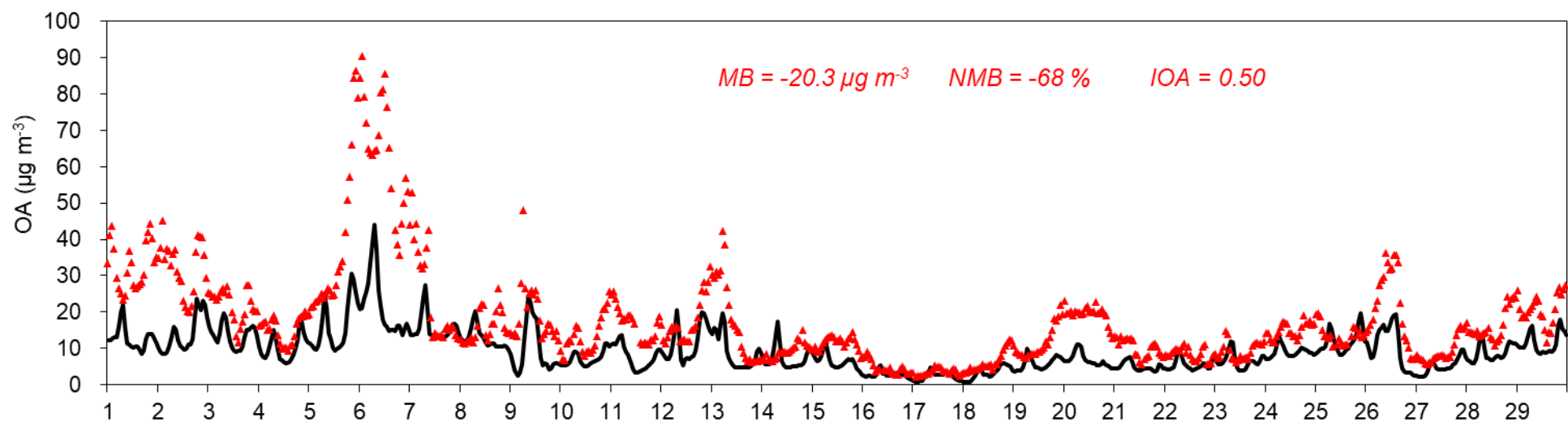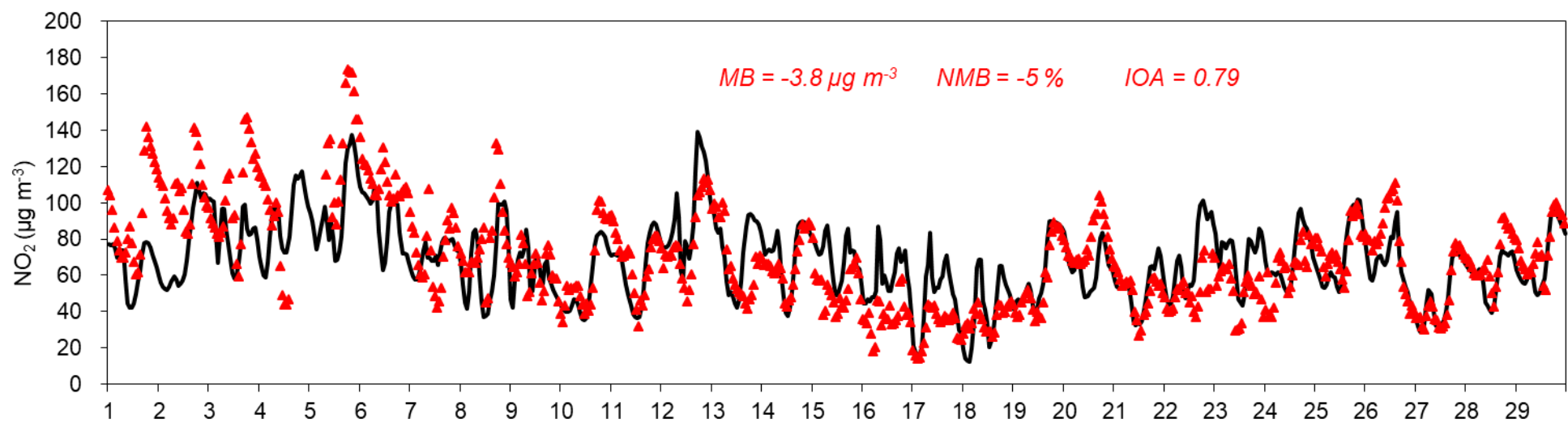
**Figure S5**. Time series of observed and modeled concentrations for ozone, NH₃, nitrate, ammonium, EC, OA, SO₂ and NO₂ at SAES site during 1 to 29 December 2013
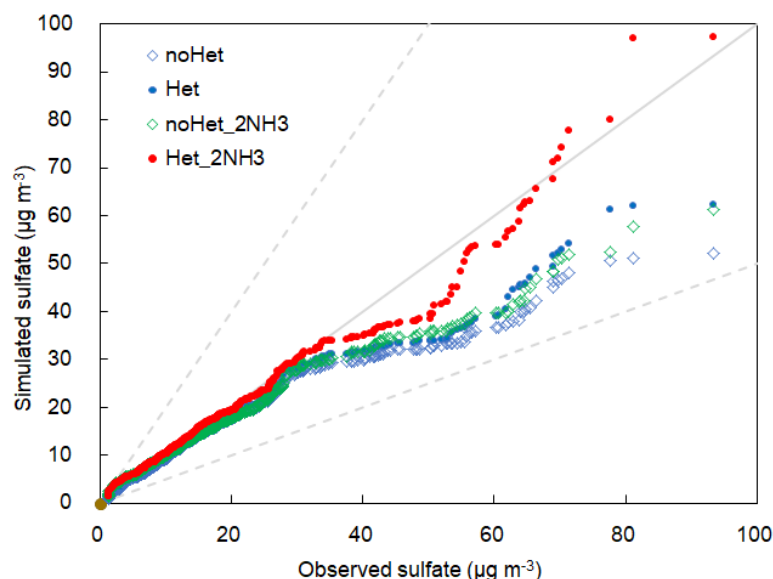
**Figure S6:** Q-Q (quantile-quantile) plot of simulated hourly sulfate concentrations for different scenarios at SAES site during December 1 to 29, 2013. Solid lines indicate 1:1 lines and dashed lines are 1:2 and 2:1 lines.
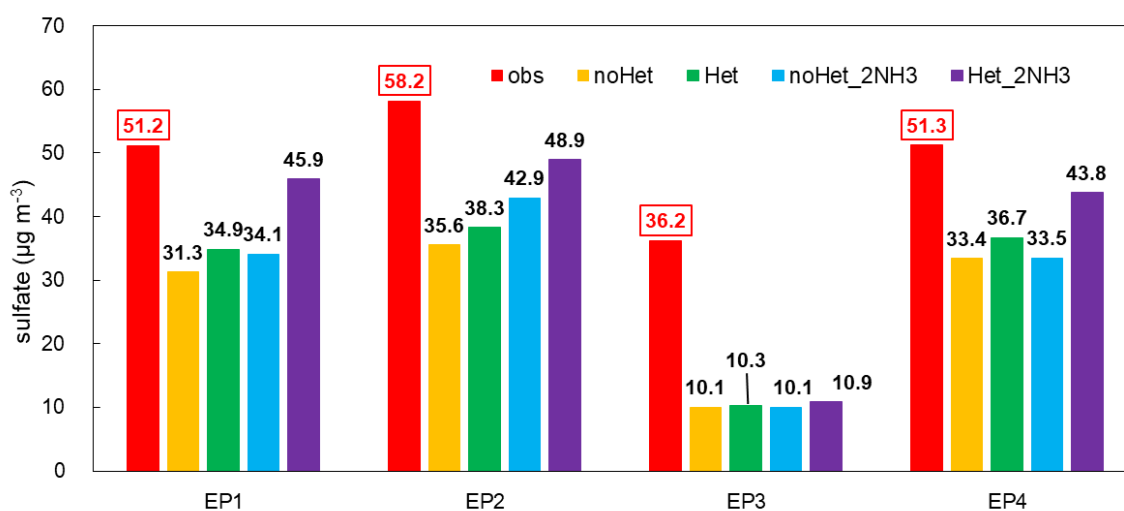
**Figure S7.** Observed and predicted average sulfate concentrations for four selected heavy haze episodes during 1 to 29 December 2013.
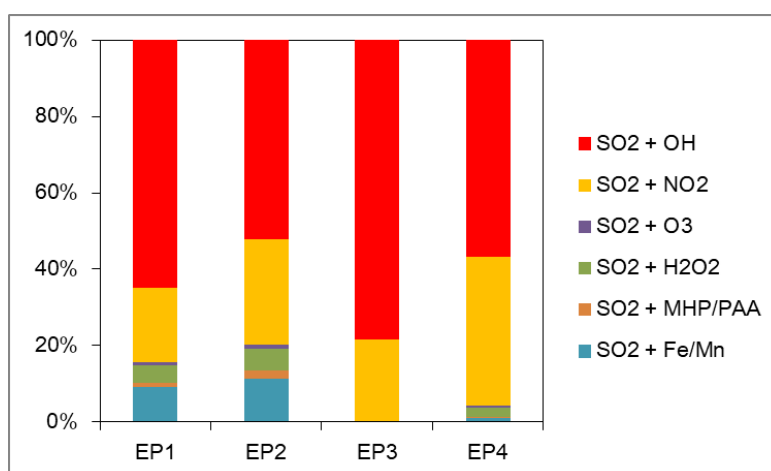
**Figure S8.** Relative contribution of different sulfate formation pathways to secondary sulfate formation at SAES site during selected pollution episodes
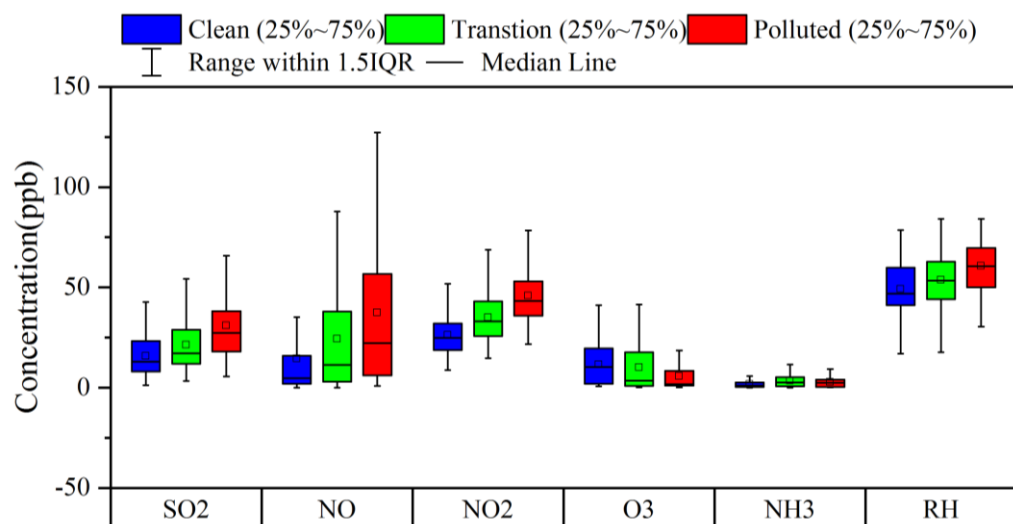
**Figure S9.** Box and whisker plot of observations by clean, transition and polluted periods during 1 to 29 December 2013 at SAES site.
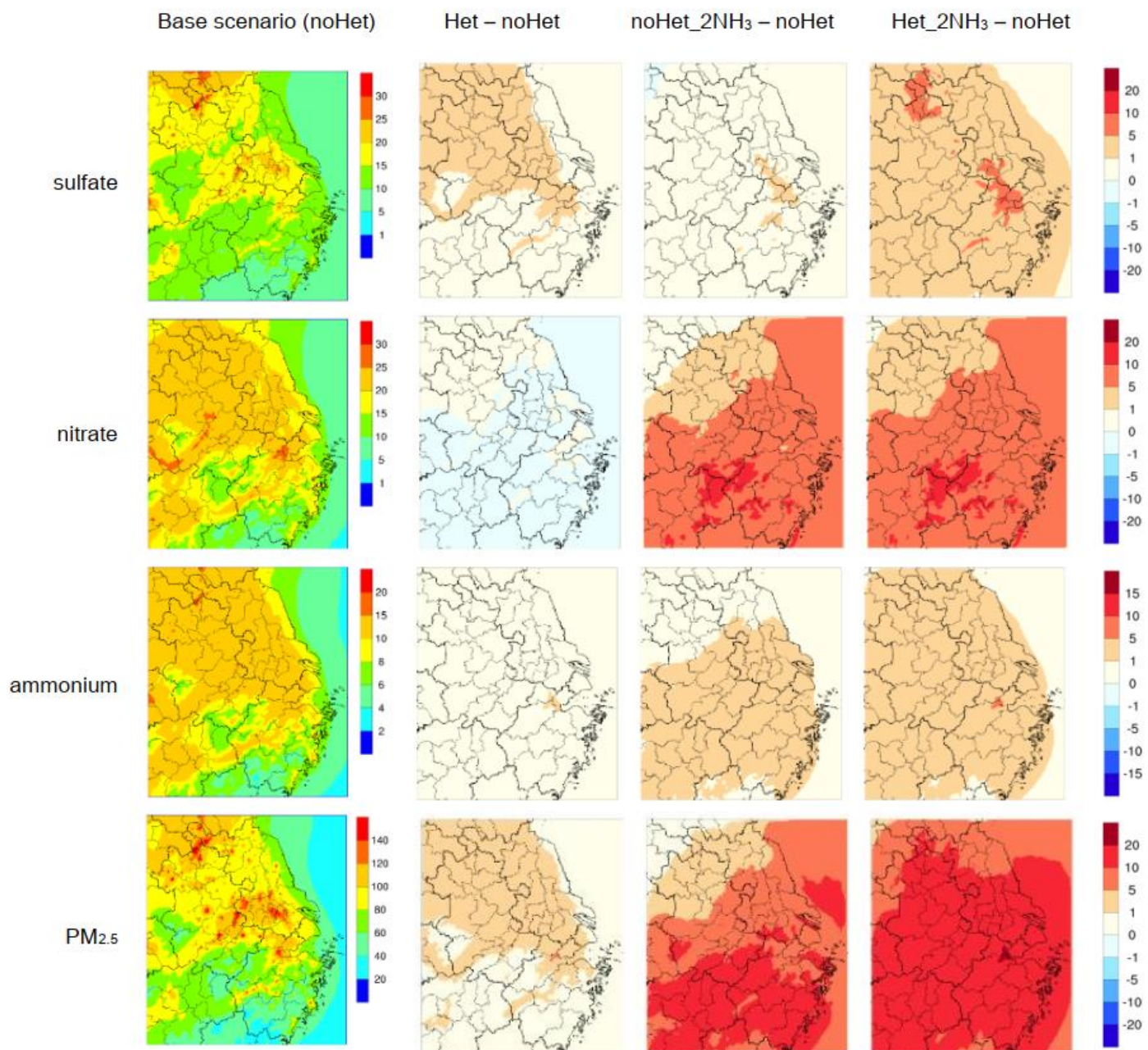
**Figure S10:** Spatial distribution of simulated monthly average sulfate (first row), nitrate (second row), ammonium and PM$_{2.5}$ (bottom row) in µg m$^{-3}$ over the YRD region for the base case scenario (first column) and the changes between the base case and the other three sensitivity runs: Het (second column), noHet_2NH$_3$ (third column) and Het_2NH$_3$ (fourth column).