**Response to the *Interactive comments from Referees on* "The Role of Meteorological Conditions and Pollution Control Strategies in Reducing Air Pollution in Beijing during APEC 2014 and Parade 2015" *by* Pengfei Liang et al.**

We thank the referees for the helpful comments. We have revised the manuscript according to the suggestions and responded to their concerns below.

**Referee #1:**

**General Comments:**

***General Comment 1:*** *Too many tables were included in the main text, so I suggest the authors adjust the structures of the manuscript and move some of the tables and figures to the supplement to make it more concise and clear.*

**Response to General Comment 1:** Accepted. We move a number of tables and figures to the supplement or other sections of the manuscript.

Table 2 (Table 1 at present) remains in "Introduction", since it illustrates the background of the GLM in this study. By comparing the GLM with the statistic models used in other studies, the theoretical basis and advantages of the GLM can be better illustrated.

**Changes in the Manuscript:** Table 1 (Table 2 at present) is moved to "Measurements and Methods". Table 5 (Table S5 at present) and Table 6 (Table S7 at present), Figure 5 (Figure S3 at present), Figure 6 (Figure S4 at present), Figure 9 (Figure S8 at present), and Figure 12 (Figure S9 at present) are moved from the main text to supplement. Please refer to Page 9 Line 178-180 and Page 12 Line 237-242.

***General Comment 2:*** *The authors used two methods to separate out the influence of meteorological conditions on the air pollutant concentrations to give a fairly and accurate evaluation of effectiveness of pollution control strategies. It seems that the authors think the GLM method is better than the "stable meteorological condition" method? If so, why the authors focused on the explanations of the results of "stable meteorological condition" method?*

**Response to General Comment 2:** Agree. The discussion of the results of the GLM method is weak and need more in-depth discussion. .

**Changes in the Manuscript:** The results of the "stable meteorological condition" method are simplified. Please refer to Page 17 Line 351-356. The results of the GLM method is emphasized in Section 3.3. Figure S4 (Figure 8 at present) "Time series of the observed and GLM-predicted pollutant concentrations" is moved from the supplement to the manuscript. Please refer to Page 18 Line 382-384. Table 8 is added to the manuscript. Please refer to Page 21 Line 450 to Page 22 Line 462. The discussion of pollutant concentrations variations is emphasized. Please refer to Page 24 Line 496-499 and Page 24 Line 506-509. Section 3.3.4 "Uncertainties of the GLM" is added to the manuscript. Please refer to Page 26 Line 544-557.

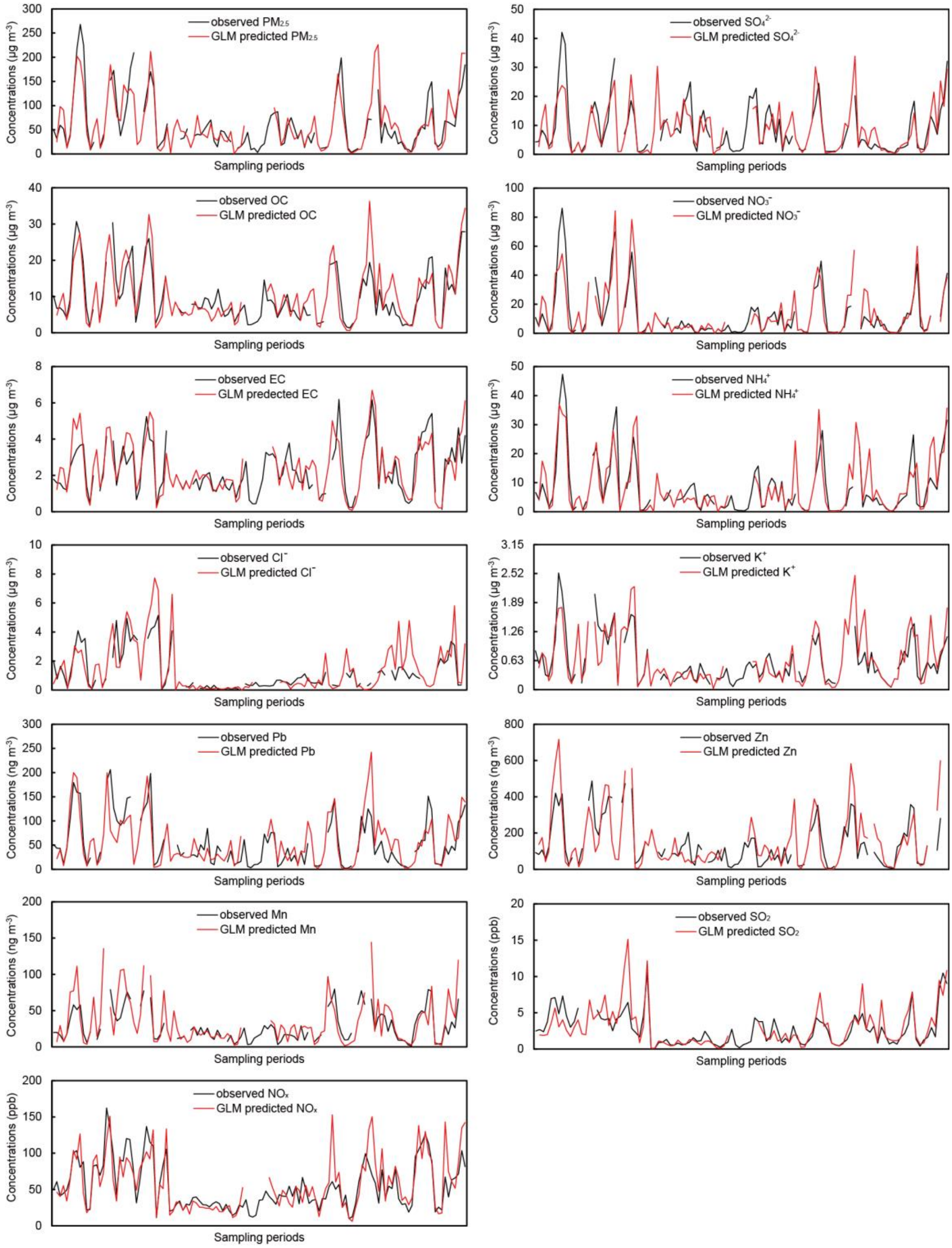


Figure 8. Time series of the observed (in black line) and GLM-predicted pollutant concentrations (in red line).

Table 8. The influence of the meteorological parameters included in the GLMs on pollutant concentrations[1].

| Parameters | Included in the GLM (times)[2] | $PM_{2.5}$ | EC | OC | $SO_4^{2-}$ | $NO_3^-$ | $NH_4^+$ | $Cl^-$ | $K^+$ | Pb | Zn | Mn | $SO_2$ | $NO_x$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PBL | 13 | - | - | - | - | +- | - | - | +- | - | - | - | - | - |
| $WS_{(lag)}$ | 9 | - | - | | - | - | - | | - | - | - | | - | |
| $PREC_{(lag)}$ | 8 | - | - | - | - | | | | | - | | - | - | - |
| PREC | 7 | - | | | - | - | - | | - | | | | - | - |
| WS | 7 | - | | - | + | + | | | - | - | - | | | |
| RH | 6 | | | | + | + | + | | + | | | - | - | |
| $PBL_{(lag)}$ | 5 | + | + | | + | | | | - | | | + | | |
| $RH_{(lag)}$ | 5 | | | - | | - | - | - | - | | | | | |
| T | 5 | | + | + | + | +- | | | | | | | | -+ |
| $T_{(lag)}$ | 5 | + | | | | | + | - | + | + | | | | |
| $WD/WS_{(lag)}$ | 4 | + | | + | | | | + | | | | + | | |
| SLP | 3 | - | | | | | | | | | | - | + | |
| WD | 3 | | | + | | + | | + | | | | | | |
| WD/WS | 3 | | + | | | | | | | | | + | | + |
| $WD_{(lag)}$ | 1 | | | | | | | | | | | | + | |

[1] "+" represents the positive correlation, and "-" represents the negative correlation between meteorological parameters and pollutant concentrations.

[2]If a parameter is included in the model for several times, it will be counted as one time.

**Detailed Comments:**

***Detailed Comment 1:*** *The abstract is too long, please give a concise and clearly written. Line 28, delete "dramatically". Line 23, the authors state that "During the APEC (1 October to 31 December 2014) and Parade (1 August to 31 December 2015) sampling periods", but in Figure1, 4, 6 and Line235-240, the study periods were from 18/10/2014-22/11/2014 and 01/08/2015-23/09/2015. Please give more clear and consistent definition of your research periods in your manuscript, such as during, before and after "APEC" or "Parade", "AAPEC", "APEC", "BAPEC", "AParade", "Parade" and "BParade".*

**Response to Detailed Comment 1:** Accepted. "Abstract" has been simplified. For the definition of our research periods, 1) the control periods of APEC and Parade are 03/11/2014-12/11/2014 and 20/08/2015-03/09/2015; 2) the APEC/Parade campaigns consist of before, during, and after APEC/Parade, from 18/10/2014-22/11/2014 and 01/08/2015-23/09/2015; 3) the sampling periods are 01/10/2014-31/12/2014 and 01/08/2015-31/12/2015, which are used to better match the statistical model (GLM). In correspondence, we give more clear and consistent definition of our research periods in the tables and figures.

**Changes in the Manuscript:** The sentence "We therefore developed a generalized linear regression model (GLM) to establish the relationship between the concentrations of air pollutants and meteorological parameters" has been deleted. The sentence "During the APEC (1 October to 31 December 2014) and Parade (1 August to 31 December 2015) sampling periods" has been deleted. The sentence "The concentrations of all pollutants except ozone decreased dramatically (by more than 20%) during both events, compared with the levels during non-control periods" has been deleted. The sentence "(i.e. when the daily average wind speed (WS) was less than 2.50 m $s^{-1}$ and planetary boundary layer (PBL) height was lower than 290 m)" has been deleted. The sentence " We found that the average $PM_{2.5}$ concentration during APEC decreased by 45.7% compared with the period before APEC and by 44.4% compared with the period after APEC. This difference was attributed to emission reduction efforts during APEC" has been deleted.

Section 2.2 “Research Periods Definition and Control Strategies” is added to the manuscript. Please refer to Page 8 Line 168 to Page 9 Line 177.

***Detailed Comment 2:*** *For the “Introduction” section, I suggest the authors move Table 1 and Table 2 and some related context to the “Methods” Section. Line 55, “(2013)” is the reference citation format correct? Please check the format of the references throughout the whole manuscript more carefully. Line59“2012levels”to“levelsof2012”. Line71-72, please cite some scientific literatures here instead of “(SEPB, 2010)”, “(GEPB, 2009)”and “(CEPB, 2013)”. Line73-75, only need to define abbreviations at their first occurrence. e.g. “APEC”, “Parade”, “GLM” etc. Line 78, delete “control (Table1)”. Line 83 “from” to “to”. Line 86-90, please rewrite these two sentences. You mean 54 % in Beijing, 26 % in Shijiazhuang, and 39 % in Tangshan. What is “the average concentration of total elements in PM2.5”? Line 92, what is “before” represent? Line 95, delete “e.g.”*

**Response to Detailed Comment 2:** Accepted. “the State Council of China (2013)” is equal to “(the State Council of China, 2013)”. We have checked the format of the references throughout the whole manuscript. The air pollution control measures implemented for the events come from the public documents and some scientific literatures have been added.

**Changes in the Manuscript:** The control strategies in Table 1 (Table 2 at present) are moved to "Measurements and Methods". Please refer to Page 9 Line 178-180 and Page 12 Line 237-242. "2012 levels" is changed to "levels of 2012". Please refer to Page 3 Line 50. A number of scientific literatures are added to support the air pollution control measures implemented for the events. Please refer to Page 3 Line 61-63. The abbreviations of "APEC", "Parade", and "GLM" are used after being defined at their occurrence in "Abstract". Please refer to Page 3 Line 64. The decreased ratios of the concentrations of total elements reported by Wen et al. (2016) are deleted. Please to Page 4 Line 73-75.In the study of Han et al. (2015), "before" is changed to "before APEC". Please refer to Page 4 Line 77.

***Detailed Comment 3:*** *For the "Measurement and Methods", I just recommend the authors include the measurement, the research periods definition and control strategies, and the methods for the meteorological conditions separation in this section. Section 2.1, 2.2 and 2.3 can be combined, and some content in introduction and Section 3 can be moved to this part. Line 141, change to "the 4th Ring Road of Beijing". Section 2.2, why the authors used the meteorological data from NCDC of the airport not the corresponding data from PKU site? Line 172, what is "AX105DR" represent for? Line 203-205, why define the variable WD? And what is the difference between (1) and (2). Line 208, change "Figure S2" to "Fig. S1", the tables and the figures should be labeled separately. Line 216, use the equation editor to give the proper format of the formulas.*

**Response to Detailed Comment 3:** Accepted. The structure of "Measurement and Methods" is accordingly adjusted. We use the meteorological data from NCDC of the airport rather than the corresponding data from PKU site, because the data of WS and WD is influenced by the building northern of the observation site and these two meteorological parameters might influence the pollutant concentrations significantly. The meteorological data from NCDC are integrated and continuous, which can represent the meteorological influences on the daily average pollutant concentrations at PKU site. "AX105DR" is the instrument model of the electronic balance. The definition of "variable WD" is given by the JetStream Glossary of NOAA (http://www.srh.weather.gov/srh/jetstream/append/glossary_v.html). For the WD data of NCDC, it is invalid when the wind is calm or keeps fluctuating during a time period. Thus, the data of WD indicated with "calm and variable" are grouped into an independent category.

**Changes in the Manuscript:** The structure of "Measurement and Methods" is adjusted. "Measurements of Air Pollutants", "Meteorological Data", and "Analysis of the $PM_{2.5}$ Filter Samples" are combined into Section 2.1 "Measurements". Section 2.2 "Research Periods Definition and Control Strategies" is added. The introduction of the "stable meteorological condition" method is moved to "Measurement and Methods" and combined with the GLM method into Section 2.3 "Methods for the Meteorological Conditions Separation". Please refer to Page 6 Line 116, Page 8 Line 168 to Page 9 Line 180, and Page 9 Line 181 to Page 10 Line 196. "the fourth ring road" is replaced by "the 4$^{th}$ Ring Road of Beijing". Please refer to Page 6 Line 122. The citation of the JetStream Glossary of NOAA is added. Please refer to Page 10 Line 208-209.

***Detailed Comment 4:*** *For Section 3, the authors are suggested to rearrange the structure of the manuscript and give in-depth discussions of the results, not just mentioned the results. Line 235-240, move the annotations to the figure captions and keep the annotations in the Figure and the main text consistent,* *such as "Before APEC" means "BAPEC" in the main text? Line245, delete "during the whole control period". Line255-268, and Figure 2, the authors give detail explanations of the changes of the PM2.5 components for the "AAPEC", "APEC" and "BAPEC" etc., in my opinion, Figure 2 revealed a part of information of Figure1,why the authors give this part of analysis? And why the components changes for different periods? Line284-289, change"(SNA)/PM2.5"to"(SNA/PM2.5)". And why the proportion of SNA change like this? Line 290-296 Please give more clear and consistent definition of your research periods in your manuscript, such as during, before and after "APEC" or "Parade", "AAPEC", "APEC", "BAPEC", "AParade", "Parade" and "BParade". Line 311, add "(Fig. 1)" after sulphate information. Line 325-326 "during BParade and 326 AParade (25.7% and 20.3%, respectively)." to "during BParade (25.7%) and AParade (20.3%). Line 331-333, did the authors mean "the PBL heights during APEC and Parade were constantly high", but during these two periods, the PBL heights sometimes were low, please rewrite this sentence to give more clear statement. Section 3.2.1, Move this part to the methods section. What is the theoretical basis of this identification method? This method from previous study or developed by the authors? Did the authors combined the data of APEC and Parade, why not give the identification separately? Line 383, add "(S3)" after "Supplementary Information" Line 398-497, this part just description of the figures and lacks in-depth discussions of the results. What is Similarities and differences of the changes for different species and what caused the results?*

**Response to Detailed Comment 4:** Accepted. "BAPEC", "APEC", and "AAPEC" mean before, during, and after APEC; "BParade", "Parade", and "AParade" mean before, during, and after Parade.

We discuss the proportions of the measured components in $PM_{2.5}$ before, during, and after APEC/Parade. Although all the component concentrations decrease during APEC and Parade, the proportions of different components in $PM_{2.5}$ show different changing patterns. The proportions of OC and elements in $PM_{2.5}$ tend to increase and the proportion of SNA in $PM_{2.5}$ tends to decrease. This indicates that secondary formation of SNA from primary gaseous pollutants contributes to high pollution level significantly. During APEC/Parade, emission reduction results in decreased proportions of SNA and increased proportions of other components in $PM_{2.5}$.

The PBL heights increase on 5, 11, and 12 November during APEC and are mostly higher than 400 m during Parade. The identification of stable meteorological periods is based on the empirical and mathematical relationship between air pollution levels and both WS and PBL height. We combine the data of APEC and Parade so that different pollution levels can be included in the scattering plot for better influences of WS and PBL height on $PM_{2.5}$.

**Changes in the Manuscript:** “BAPEC”, “APEC”, and “AAPEC” are replaced by before, during, and after APEC; “BParade”, “Parade”, and “AParade” are replaced by before, during, and after Parade. Please refer to Page 13 Line 258-261, 268-270, and 272-273, Page 14 Line 300, and Page 15 Line 301, 306-308, 310-311, and 313-314.“during the whole control period” is deleted. Please refer to Page 12 Line 253. “(SNA)/$PM_{2.5}$” is changed to“(SNA/$PM_{2.5}$)”. Please refer to Page 14 Line 296, 299, and 300. “(Figure 1)” is added after sulphate information. Please refer to Page 15 Line 322. The figures “The prevalence of WD during the APEC and Parade campaigns” and “Time series of daily average $PM_{2.5}$ concentrations and PBL heights during the APEC and Parade campaigns” are moved to the supplement S3 and S4. “during BParade and AParade (25.7% and 20.3%, respectively)” is changed to “during BParade (25.7%) and AParade (20.3%)”. The statement of the PBL heights has been rewritten. Please refer to the supplement S3 and S4. The introduction of the “stable meteorological condition” method is moved to “Measurements and Methods”. Please refer to Page 9 Line 182 to Page 10 Line 196. “(S6)” is added after “Supplementary Information”. Please refer to Page 17 Line 358.

The discussion of the results of the GLM method has been improved. Figure S4 (Figure 8 at present) is moved from the supplement to the manuscript in Section 3.3.1, showing the time series of the observed pollutant and GLM-predicted pollutant concentrations. Please refer to Page 18 Line 382-384. The description of the model results is emphasized. Table 8 is added to Section 3.3.2, summarizing the meteorological parameters included in the models and their influence on pollutant concentrations. Please refer to Page 21 Line 450 to Page 22 Line 462. The changes for different pollutant concentrations are further discussed. Please refer to Page 24 Line 496-499 and 506-509. Section 3.3.4 “Uncertainties of the GLM” is added to the manuscript. Please refer to Page 26 Line 544-557.

***Detailed Comment 5:*** *Section 3.3 have structural problem, and I just recommend the authors adjust the manuscript in this section. Firstly, the authors should give a clear description of the model constructing and parameterization process (Table 8); Secondly, the authors should give the modeling results (FigureS4 should be moved to the main text) and give the validation check of the models (Figure 10-12); and then the authors can use the models to give the evaluations (this part in Section 3.3 is weak compared to the “stable meteorological condition method” and this part should be more emphasized in the manuscript). Line 548-550, “decreased by 58% and 63%” compared with what? Line 549-550, please correct the expressions like the following in the whole manuscript “the meteorological conditions and pollution control strategies contributed 30% and 28% to the reduction of the $PM_{2.5}$ concentrations during APEC 2014, respectively, and 38% and 25% during*

*Parade 2015, respectively". Did the authors mean the meteorological conditionsdecreasedthePM2.5concentrationsby30%andpollutioncontrolstrateg ies decreased the PM2.5 concentration by 28%? Please check the manuscript and make more accurate statement. Line 568 and table 10, why the sulfate increased by 44%? The results is opposite to the "stable meteorological condition method" (Figure 9)?*

**Response to Detailed Comment 5:** Accepted. The structure of Section 3.3 is adjusted accordingly and the results of the GLM method have been more emphasized in the manuscript. We apply the GLM to predict air pollutant concentrations during APEC and Parade based on meteorological parameters. The difference between the observed and GLM-predicted concentrations is attributed to emission reduction through the implementation of air pollution control strategies.

The concentrations of sulphate are determined by primary emissions and secondary transformation from $SO_2$; thus, the changes in sulphate concentrations may not reflect the effectiveness of emission control strategies. One needs to also include the changes in $SO_2$ concentrations by adding the concentration of total S to discussion.

**Changes in the Manuscript:** The structure of Section 3.3 is adjusted accordingly, including the model performance and cross-validation test, model description, quantitative estimates of the contribution of meteorological conditions to air pollutant concentrations, and uncertainties of the GLM. Please refer to Page 18 Line 380, Page 21 Line 430, Page 22 Line 463, and Page 26 Line 544. The assumption of the GLM is added when discussing the contributions of meteorological conditions and pollution control strategies to the reduction of pollutant concentrations. Please refer to Page 23 Line 479-480. The reduction of sulphate concentrations is discussed in the manuscript. Please refer to Page 24 Line 510 to Page 25 Line 524.

***Detailed Comment 6:*** *For figures and tables, the authors should give more accurate captions. Table 2, give the annotation of "AOD" ("AOT"), "(MODIS/MISR)" (what does it mean?), Table 3 add "in this study" after "in the GLM", and clarified the minimum and maximum data is for daily or others? Table 4 give more accurate annotation of "BAPEC", "APEC", "AAPEC", "Bparade", "parade", and "AParade". Delete the ambiguous annotation "B: before; A: after". The same for other tables and Figures. Figure 1 "grey-shaded" to "blue-shaded", "Before APEC" to "BAPEC" and so on. Figure 8, what does this figure stand for? Not just give the explanations of "the black/red bars" or "the whiskers" stand for? Figure 9 delete "(SNA)" or "SNA=sulphate + nitrate + ammonium". FigureS4 move this figure to the main text and give the exactly labels of the x-axis, use the date format not just "the sampling period".*

**Response to Detailed Comment 6:** Accepted. We give more accurate captions for figures and tables accordingly. Figure 8 (Figure 6 at present) stands for the improvements and uncertainties of the "stable meteorological condition" method, indicating that by considering only days with stable meteorological conditions, the uncertainties associated with the percentage reduction figures are reduced and the reliability of the changes of air pollutants concentrations are improved. However, uncertainties still remain.

**Changes in the Manuscript:** The annotations of "MODIS/MISR", ""MOD/MYD" are given in Table 2 (Table 1 at present). Please refer to Page 38 Line 828. "in this study" is added after "in the GLM" in Table 3. Please refer to Page 40 Line 834. More accurate annotations of "BAPEC", "APEC", "AAPEC", "Bparade", "parade", and "AParade" are given in relevant tables and figures. "B: before; A: after" is replaced by "BAPEC/BParade: before APEC/Parade, AAPEC/AParade: after

APEC/Parade”. Please refer to Page 41 Line 839-840 and Page 48 Line 882-883. “grey-shaded” is changed to “blue-shaded”. Please refer to Page 47 Line 875. The caption of Figure 8 (Figure 6 at present) is modified, illustrating the purpose of the figure. Please refer to Page 52 Line 914-915. Figure S4 (Figure 8 at present) is moved from the supplement to the manuscript. Please refer to Page 54 Line 929. Figure S4 (Figure 8 at present) is moved from the supplement to the main text and the date format in the labels of x-axis is given. Please refer to Page 54 Line 927-929.

**Referee #2:**

**Major Comments:**

***Major Comment 1:*** *Why the authors chose the stable meteorological condition identification method to give the evaluation first? It seems GLM method is more effective for the meteorological influence separation. Which method is focused on?*

*If the stable meteorological condition identification method has limitations in quantifying the meteorological influences, why the authors give so many discussions on the quantifying results in this part, i.e. Line 393-436? Compared to the stable meteorological condition identification method, the GLM method mainly focused on the evaluation of the model performance and lack in-depth discussions.*

*Furthermore, the validations of the GLM method is still weak in the manuscript, the authors just compared the model results of* $PM_{2.5}$ *in literatures, line 551-552. Please give more in-depth analysis for the results of GLM method*

**Response to Major Comment 1:** Agree. We focus on the GLM method rather than the “stable meteorological condition” method, because the GLM method has been proved to be more effective for the meteorological influence separation. We firstly introduce the “stable meteorological condition” method for the reasons as following. The “stable meteorological condition” method and the “statistical models (e.g. GLM)” method are two major methods to help separate the meteorological influences on pollutant concentrations in the former studies. The “stable meteorological condition” method is easier to achieved and more widely applied. However, there still exists limits of the application of the “stable meteorological condition” method that the stable meteorological conditions are determined subjectively e.g. by meteorological maps and weather systems. Thus, we determine the days with stable meteorological conditions based on specific meteorological parameters of wind speed and PBL height quantitatively and evaluate the improvement of the “stable meteorological condition” method.

As a result, uncertainties of the “stable meteorological condition” method still remain in quantifying the meteorological influences, although the size of these uncertainties has been reduced. This may be due to the limited sample size on days with stable meteorological conditions during the control periods. It is therefore necessary to further quantify the meteorological influences with the GLM method. Indeed, the discussion of the results of the GLM method is weak compared to the “stable meteorological condition” method.

In fact, we give systematic validation check of the $PM_{2.5}$ GLM, including the $R^2$ values of the linear regression equations showing the correlations between GLM-predicted and observed concentrations of pollutants, and the results of the cross-validation test (Figure 10 (Figure 7 at present), Figure 11 (Figure 9 at present), and Table 7 (Table 5 at present)). As the referee suggested, the results of the GLM method have been more emphasized in the manuscript.

**Changes in the Manuscript:** The results of the “stable meteorological conditions” method is simplified in Section 3.2. Figure 5 (Figure S3 at present), Figure 6 (Figure S4 at present), and Table 5 (Table S5 at present) are moved from the main text. Please refer to Page 16 Line 331-333 and 340-342. The variations of pollutant concentrations under stable meteorological conditions in Figure 9 (Figure S8 at present) are simplified and moved from the main text. Please refer to Page 17 Line 351-356. Table 6 (Table S7 at present) is moved from the main text, listing the percentage differences among the mean $PM_{2.5}$ concentrations of four periods that are randomly selected from within the non-control days of the APEC and Parade campaigns. Please refer to Page 18 Line 368-370.

The results of GLM method is emphasized in Section 3.3. The structure of Section 3.3 is adjusted accordingly, including the model performance and cross-validation test, model description, quantitative estimates of the contribution of meteorological conditions to air pollutant concentrations, and uncertainties of the GLM. Please refer to Page 18 Line 380, Page 21 Line 430, Page 22 Line 463, and Page 26 Line 544. Figure S4 (Figure 8 at present) is moved from the supplement to the manuscript in Section 3.3.1, showing the time series of the observed pollutant and GLM-predicted pollutant concentrations. Please refer to Page 18 Line 382-384.The description of the model results is emphasized. Table 8 is added to Section 3.3.2, summarizing the meteorological parameters included in the models and their influence on pollutant concentrations. Please refer to Page 21 Line 450 to Page 22 Line 462. The changes for different pollutant concentrations are further discussed. Please refer to Page 24 Line 496-499 and 506-509. Section 3.3.4 "Uncertainties of the GLM" is added to the manuscript. Please refer to Page 26 Line 544-557.

***Major Comment 2:*** *The authors are recommended to adjust the structure of the manuscript to give more clear and concise abstract and introduction. Some part of the "introduction" and "Results and discussions" can be moved to the method section. The "Results and discussions" should give more in-depth analysis without just give statement of the tables and Figures. See the following comments in detail.*

**Response to Major Comment 2:** Accepted. The "Abstract" and "Introduction" are modified to be clearer and more concise.

**Changes in the Manuscript:** For the "Abstract", the variations of pollutant concentrations are deleted. The results of the "stable meteorological condition" method are deleted. Please refer to Page 2 Line 23-26. For the "Introduction", Table 1 (Table 2 at present) is moved to "Measurements and Methods". Please refer to Page 9 Line 178-180. For the "Measurements and Methods", "Measurements of Air Pollutants", "Meteorological Data", and "Analysis of the $PM_{2.5}$ Filter Samples" are combined into Section 2.1 "Measurements". Section 2.2 "Research Periods Definition and Control Strategies" is added. The introductions of the "stable meteorological condition" method has been moved to "Measurement and Methods" and combined with the GLM method into Section 2.3 "Methods for the Meteorological Conditions Separation". Please refer to Page 6 Line 116, Page 8 Line 168 to Page 9 Line 180, and Page 9 Line 181 to Page 10 Line 196.

***Major Comment 3:*** *Some annotations of the Figures and Tables should be more precise and accurate.*

**Response to Major Comment 3:** Accepted. Please refer to the following responses in detail.

**Changes in the Manuscript:** For the tables, "in the study" is added after "in the GLM" in Table 3. Please refer to Page 40 Line 834. "B:before; A: after" is replaced by "BAPEC/BParade: before APEC/Parade, AAPEC/AParade: after APEC/Parade" in Table 4. Please refer to Page 41 Line 839-840.

For the figures, "grey-shaded" is replaced by "blue-shaded" in Figure 1. Please refer to Page 47 Line 875. "B:before; A: after" is replaced by "BAPEC/BParade: before APEC/Parade, AAPEC/AParade: after APEC/Parade" in Figure 2. Please refer to Page 48 Line 882-883. "(SNA)/$PM_{2.5}$" is changed to"(SNA/$PM_{2.5}$)" in Figure 4. Please refer to Page 50 Line 894-895. "The percentage reductions of pollutant concentrations under similar meteorological conditions." is added in front of the annotation of Figure 8 (Figure 6 at present). Please refer to Page 52 Line 914-915.

**Detailed Comments:**

***Detailed Comment 1:*** *Line 47-48, this sentence is confusion and misunderstanding. If "meteorological conditions and pollution control strategies contributed 30% and 28% to the reduction of the $PM_{2.5}$ concentrations", is there any other reason to cause the reduction? Please rewrite sentences like this in the manuscript.*

**Response to Detailed Comment 1:** Agree. The concentrations of air pollutants could be influenced by meteorological parameters, emission intensities, and chemical transformation. In our study, the results of the GLM method are based on the assumption that the pollutant concentrations are only the function of meteorological conditions and emission intensities during the control periods of APEC and Parade.

**Changes in the Manuscript:** The assumption that "the concentrations of air pollutants are only determined by meteorological conditions and emission intensities" is added after the reduction of the $PM_{2.5}$ concentrations. Please refer to Page 2 Line 38-39 and Page 23 Line 479-480.

***Detailed Comment 2:*** *Line 62-63, what do you mean here?*

**Response to Detailed Comment 2:** The long-term strategies cannot improve the air quality in the short term, thus it is difficult to evaluate the effectiveness of these strategies.

**Changes in the Manuscript:** "in the short term" is added after the sentence. Please refer to Page 3 Line 55.

***Detailed Comment 3:*** *Line64-80, the authors list the special events for air pollution control, are there related studies on these events? Please add some scientific references here.*

**Response to Detailed Comment 3:** Accepted. There are related studies on these events and the references have been added.

**Changes in the Manuscript:** "Huang et al., 2012" and "Liu et al., 2013" are added after the 41$^{st}$ Shanghai World Expo in 2010 and the 16$^{th}$ Guangzhou Asian Games and Asian Para Games in 2010. Please refer to Page 3 Line 61-63, Page 30 Line 659-662, and 665-667.

***Detailed Comment 4:*** *Line 90-91, the statement here is quite obscure. Please give a clear and accurate summary of the previous studies.*

**Response to Detailed Comment 4:** Accepted. The decreased ratios of the extinction and absorbance coefficients during APEC are compared with those before APEC.

**Changes in the Manuscript:** "before APEC" is added after the sentence. Please refer to Page 4 Line 77.

***Detailed Comment 5:*** *Line 95, add more references here to back your statement.*

**Response to Detailed Comment 5:** Accepted. More references are added.

**Changes in the Manuscript:** "Calkins et al., 2016" is added. Please refer to Page 4 Line 80 and Page 29 Line 606-609.

***Detailed Comment 6:*** *Line 130-134, the authors give the advantages of the GLM methods. "(3) in addition to predicting $PM_{2.5}$ mass concentrations, our model could also predict concentrations of gaseous pollutants and individual $PM_{2.5}$ components." Other methods cannot predict concentrations of gaseous pollutants and individual $PM_{2.5}$ components? However, I think for most reader, they more concern about the correctness and effectiveness of the method.*

**Response to Detailed Comment 6:** The concentrations of $PM_{2.5}$, gaseous pollutants, and individual components can be predicted precisely because of the corresponding models for different pollutants, solely based on meteorological conditions.

**Changes in the Manuscript:** "by corresponding models for different pollutants" is added after the sentence. Please refer to Page 12 Line 242.

***Detailed Comment 7:*** *Line 162-168, why the authors used the data from BCIA? Did the meteorological data can match with the observation data of the pollutants?*

**Response to Detailed Comment 7:** We use the meteorological data from NCDC of the airport rather than the corresponding data from PKU site, because the data of WS and WD may be influenced by the building northern of the observation site and these two meteorological parameters can influence the pollutant concentrations significantly. The meteorological data from NCDC are integrated and continuous, which can represent the meteorological influences on the daily average pollutant concentrations at PKU site.

**Changes in the Manuscript:** Please refer to the response of the comment.

***Detailed Comment 8:*** *Line 183, "OCEC" to "OC/EC".*

**Response to Detailed Comment 8:** Accepted.

**Changes in the Manuscript:** "OCEC" has been changed to "OC/EC". Please refer to Page 8 Line 161.

***Detailed Comment 9:*** *Line201-205, why the authors define "variable WD" and separate to (1) and (2).*

**Response to Detailed Comment 9:** The definition of "variable WD" is given by the JetStream Glossary of NOAA (http://www.srh.weather.gov/srh/jetstream/append/glossary_v.html) rather than given by our study. For the WD data of NCDC, it is invalid when the wind is calm or keeps fluctuating during a time period. Thus, the data of WD indicated with "calm and variable" are grouped into an independent category.

**Changes in the Manuscript:** The statement of "the JetStream Glossary of NOAA" is added. Please refer to Page 10 Line 208-209.

***Detailed Comment 10:*** *What the physical meaning of $\beta_0$ i.e. in the intercept?*

**Response to Detailed Comment 10:**The non-linear functions are natural log transformed and introduced into the GLM, then the coefficients in the non-linear functions are transformed into β, including $\beta_0$, $\beta_{1k}$, $\beta_{2k}$, $\beta_{3k}$, and $\beta_{4k}$, which represent the non-linear relationships between meteorological parameters and pollutant concentrations.

**Changes in the Manuscript:** Please refer to the response of the comment.

***Detailed Comment 11:*** *Line 233, what is the study period? 2014.10.01-2014.12.31 and 2015.08.01-2015.12.31 not match with the data shown in Figure 1.*

**Response to Detailed Comment 11:**For the definition of our research periods, 1) the control periods of APEC and Parade are 03/11/2014-12/11/2014 and 20/08/2015-03/09/2015; 2) the APEC/Parade campaigns consist of before, during, and after APEC/Parade, from 18/10/2014-22/11/2014 and 01/08/2015-23/09/2015; 3) the sampling periods are 01/10/2014-31/12/2014 and 01/08/2015-31/12/2015, which are used to better match the statistical model (GLM). In correspondence, we give clearer and more consistent definition of our research periods in the tables and figures.

**Changes in the Manuscript:** Section 2.2 “Research Periods Definition and Control Strategies” is added. Please refer to Page 8 Line 168 to Page 9 Line 177.

***Detailed Comment 12:*** *Line 255-268, what does the results imply?*

**Response to Detailed Comment 12:** The results imply the similarities of the chemical characteristics during these two events that the proportions of OC and elements in $PM_{2.5}$ tend to increase and the proportion of SNA in $PM_{2.5}$ tends to decrease during APEC and Parade.

**Changes in the Manuscript:** Please refer to the response of the comment.

***Detailed Comment 13:*** *Line 276-278, "indicating that OC and EC were mainly derived from the same sources during both pollution control periods, and were from different sources during the non-control periods." Why and how the sources changes?*

**Response to Detailed Comment 13:** Li et al. (2017) reported that the residential burning of coal and open and domestic combustion of wood and crop residuals could contribute to more than 50% of total organic aerosol of the North China Plain during winter. During the control periods, it might be difficult to fully control the emission of residential burning. The sources of OC and EC remain to be proved by referring to more studies researching into the source apportionment and distribution during these two events.

**Changes in the Manuscript:** The citation of "Li et al., 2017" is added to support the discussion of the sources of OC. Please refer to Page 14 Line 286-290 and Page 30 Line 668-672.

***Detailed Comment 14:*** *Line 280-281, why the secondary OC (SOC) formation contribution from residential solid fuel (coal and biomass) are higher in the control period?*

**Response to Detailed Comment 14:** The control periods of APEC and Parade are 03/11/2014-12/11/2014 and 20/08/2015-03/09/2015, mainly during early winter and early autumn respectively. During the control periods, it might be difficult to fully control the emission of residential burning. Residential solid fuel, like bulk coal and biomass burning might contribute to the higher level of SOC formation (Liu et al., 2016).

**Changes in the Manuscript:** Please refer to the response of the comment.

***Detailed Comment 15:*** *Line 341-353, what is the basis for this method?*

**Response to Detailed Comment 15:** The identification of stable meteorological periods is based on the empirical and mathematical relationship between air pollution levels and both WS and PBL height. The meteorological parameters of WS and PBL height are decided by the scatter plot and correlation between $PM_{2.5}$ concentrations and meteorological parameters shown in Figure S2.

**Changes in the Manuscript:** Please refer to the response of the comment.

***Detailed Comment 16:*** *Line 568-597, please give in-depth discussion of the results. Why the authors use positive value to represent decrease? Why the sulfate increase during APEC?*

**Response to Detailed Comment 16:** Agree. The discussion of the results of the GLM method is weak compared to the “stable meteorological condition” method and it has been more emphasized in the manuscript.

We apply the GLM to predict air pollutant concentrations during APEC and Parade based on meteorological parameters. The difference between the observed and GLM-predicted concentrations, which is the positive value, is attributed to emission reduction through the implementation of air pollution control strategies.

The concentrations of sulphate are determined by primary emissions and secondary transformation from $SO_2$; thus, the changes in sulphate concentrations may not reflect the effectiveness of emission control strategies. One needs to also include the changes in $SO_2$ concentrations by adding the concentration of total S to discussion.

**Changes in the Manuscript:** The results of GLM method is emphasized in Section 3.3. The structure of Section 3.3 is adjusted accordingly, including the model performance and cross-validation test, model description, quantitative estimates of the contribution of meteorological conditions to air pollutant concentrations, and uncertainties of the GLM. Please refer to Page 18 Line 380, Page 21 Line 430, Page 22 Line 463, and Page 26 Line 544. Figure S4 (Figure 8 at present) is moved from the supplement to the manuscript in Section 3.3.1, showing the time series of the observed pollutant and GLM-predicted pollutant concentrations. Please refer to Page 18 Line 382-384. The description of the model results has been emphasized. Table 8 is added to Section 3.3.2, summarizing the meteorological parameters included in the models and their influence on pollutant concentrations. Please refer to Page 21 Line 450 to Page 22 Line 462. The changes for different pollutant concentrations are further discussed. Please refer to Page 24 Line 496-499, 506-509. Section 3.3.4 “Uncertainties of the GLM” is added to the manuscript. Please refer to Page 26 Line 544-557.

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# The Role of Meteorological Conditions and Pollution Control Strategies in Reducing Air Pollution in Beijing during APEC 2014 and Parade 2015

Pengfei Liang[1], Tong Zhu[1*], Yanhua Fang[1], Yingruo Li[1, 2], Yiqun Han[1], Yusheng Wu[1], Min Hu[1], and Junxia Wang[1]

[1]SKL-ESPC and BIC-ESAT, College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China

[2]Environmental Meteorology Forecast Center of Beijing-Tianjin-Hebei, China Meteorological Administration, Beijing, 100089, China

[*]Correspondence to: Tong Zhu (tzhu@pku.edu.cn)

## Abstract

To control severe air pollution in China, comprehensive pollution control strategies have been implemented throughout the country in recent years. To evaluate the effectiveness of these strategies, the influence of meteorological conditions on levels of air pollution needs to be determined. Using the intensive air pollution control strategies implemented during the Asia-Pacific Economic Cooperation Forum in 2014 (APEC 2014) and the Victory Parade for the Commemoration of the 70th Anniversary of the Chinese Anti-Japanese War and the World Anti-Fascist War in 2015 (Parade 2015) as examples, we estimated the role of meteorological conditions and pollution control strategies in reducing air pollution levels in Beijing. Atmospheric particulate matter of aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) samples were collected and gaseous pollutants ($SO_2$, NO, $NO_x$, and $O_3$) were measured online at a site in Peking University (PKU). To determine the influence of meteorological conditions on the levels of air pollution, we first compared the air pollutant concentrations during days with stable meteorological conditions. However, there were few days with stable meteorological conditions during Parade. As such, we were unable to estimate the level of emission reduction efforts during this period. Finally, a generalized linear regression model (GLM) based only on meteorological parameters was built to predict air pollutant concentrations, which could explain more than 70% of the variation in air pollutant concentration levels, after incorporating the nonlinear relationships between certain meteorological parameters and the concentrations of air pollutants. Evaluation of the GLM performance revealed that the GLM, even based only on meteorological parameters, could be satisfactory to estimate the contribution of meteorological conditions in reducing air pollution, and hence the contribution of control strategies in reducing air pollution. Using the GLM, we found that the meteorological conditions and pollution control strategies contributed 30% and 28% to the reduction of the $PM_{2.5}$ concentration during APEC, and 38% and 25% during Parade, based on the assumption that the concentrations of air pollutants are only determined by meteorological conditions and emission intensities. We also estimated the contribution of meteorological conditions and control strategies in reducing the concentrations of gaseous pollutants and $PM_{2.5}$ components with the GLMs, revealing the effective control of anthropogenic emissions.

# 1 Introduction

Air pollution poses serious health risks to human populations and is one of the most important global environmental problems. To control air pollution in China, the State Council of China (2013) has released the Action Plan for Air Pollution Prevention and Control, which sets pollution control targets for different regions, e.g. atmospheric particulate matter of aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) concentrations in 2017 shall fall in Beijing–Tianjin–Hebei (BTH) by 25%, in the Yangtze River Delta by 20%, and in the Pearl River Delta by 15%, compared with the levels of 2012. To meet these targets, comprehensive pollution control strategies have been implemented at the national, provincial, and city levels. However, it is not clear how effective these strategies are in reducing air pollution. One of the challenges in evaluating the effectiveness of these strategies is that the long-term strategies cannot improve air quality in the short term. The efforts made to ensure satisfactory air quality for special events in the short term, such as the Beijing 2008 Olympics, provide a unique opportunity to evaluate the effectiveness of pollution control strategies (Kelly and Zhu, 2016). During the Beijing Olympics comprehensive pollution control strategies were implemented intensively over a short period of time. Based on the successful experience during this event, the Chinese government implemented similar air pollution control measures for the 41st Shanghai World Expo in 2010 (Huang et al., 2012; SEPB, 2010), the 16th Guangzhou Asian Games and Asian Para Games in 2010 (GEPB, 2009; Liu et al., 2013), and the Chengdu Fortune Forum 2013 (CEPB, 2013). To ensure satisfactory air quality in Beijing during the two most recent events: APEC 2014 and Parade 2015, the Chinese central government and the local government in Beijing, together with its surrounding provinces, implemented comprehensive air pollution control strategies. These two events provide a good opportunity to evaluate the effectiveness of air pollution control strategies.

One challenge when evaluating the effectiveness of air pollution control strategies over a short period of time is separating out the contribution of meteorological conditions to the reduction in air pollution levels.

Most previous studies have only provided a descriptive analysis of the changing concentrations of air pollutants during these events. Wen et al. (2016) reported that the average $PM_{2.5}$ concentration during APEC decreased by 54%, 26%, and 39% compared with the levels before APEC in Beijing, Shijiazhuang, and Tangshan, respectively. Han et al. (2015) observed that the extinction coefficient and absorbance coefficient decreased significantly during APEC compared with the values before APEC.

An increasing number of studies have recognized the importance of meteorological conditions in determining air pollution in Beijing and North China Plain (Calkins et al., 2016; Zhang et al., 2012). A northerly wind is considered to be favourable for pollutant diffusion, while a southerly wind is considered to be favourable for the transport of pollutants to Beijing (Zhang et al., 2014). When assessing the effectiveness of air pollution control strategies, a few studies have distinguished between the contribution of meteorological conditions and pollution control strategies in reducing air pollution by comparing air pollutant concentrations under similar meteorological conditions (Wang et al., 2015; Zhang et al., 2009). However, in these studies, days with stable meteorological conditions were determined subjectively, which may introduce uncertainties and inconsistencies when estimating changes in air pollutant concentrations.

Statistical models have been developed to establish the relationship between air pollutant concentrations and meteorological parameters. Table 1 summarizes these models, with their respective $R^2$ values. Multiple linear regression models have been widely applied to demonstrate the quantitative relationship between air pollutant concentrations and meteorological parameters, by assuming a linear relationship. However, these relationships are often non-linear (Liu et al., 2007; Liu et al., 2012). Most of the models with good explanation ($R^2 > 0.6$) have actually adopted visibility, aerosol optical depth (AOD), and air quality index (AQI) as independent variables to improve the performance of the regression models (Liu et al., 2007; Sotoudeheian and Arhami, 2014; Tian and Chen, 2010; You et al., 2015). This could cause problems in the prediction of air pollutant concentrations during intensive emission control periods because visibility, AOD, and AQI are also dependent on air pollution levels; hence, the statistical models may not function when air pollutant levels are drastically reduced over a short period. A statistical model based solely on meteorological parameters to predict air pollutant concentrations is therefore required.

In this study, we used the air pollution control periods during APEC 2014 and Parade 2015 to estimate the role of meteorological conditions and pollution control strategies in reducing air pollution in the megacity of Beijing. We first measured the changes in air pollutant concentrations, including $PM_{2.5}$, gaseous pollutants, and the components of $PM_{2.5}$. We then estimated the role of meteorological conditions and pollution control strategies in reducing air pollution by comparing the pollutant concentrations during days with stable meteorological conditions. Finally, we developed a statistical model based only on meteorological parameters to evaluate the role of meteorological conditions and pollution control strategies in reducing the levels of air pollution in Beijing.

# 2 Measurements and Methods

## 2.1 Measurements

### 2.1.1 Measurements of Air Pollutants

Gaseous pollutants ($SO_2$, NO, $NO_x$, and $O_3$) were measured online, and $PM_{2.5}$ samples were collected on filters at an urban monitoring station in the campus of Peking University (39.99°N, 116.33°E) northwest of Beijing (Huang et al., 2010). The station is located on the roof of a six-floor building, about 20 m above the ground and about 550 m north of the 4$^{th}$ Ring Road of Beijing.

A $PM_{2.5}$ four-channel sampler (TH-16A, Wuhan Tianhong Instruments Co., Ltd., Hubei, China) was used to collect $PM_{2.5}$ samples. The sampling duration was 23.5 h (from 09:30 to 09:00 LT the next day). Both 47-mm quartz filters (QM/A, Whatman, Maidstone, England) and Teflon filters (PTFE, Whatman) were used. The flow rate was calibrated to 16.7 L min$^{-1}$ each week and a blank $PM_{2.5}$ sample was collected once a month. The quartz filters were baked at 550°C for 5.5 h before use. Immediately after collection, the filter samples were stored at −25°C until analysis.

Sulphur dioxide ($SO_2$) was measured with an $SO_2$ analyzer (43i TL, Thermo Fisher Scientific, Waltham, MA, USA), with a precision of 0.05 ppb. Nitric oxide (NO) and nitrogen oxides ($NO_x$) were measured with a NO-$NO_x$ analyzer (42i TL, Thermo Fisher Scientific), with precisions of 0.05 ppb for NO and 0.17 ppb for $NO_2$. Ozone ($O_3$) was measured with an $O_3$ analyzer (49i, Thermo Fisher Scientific), with a precision of 1.0 ppb. The $SO_2$ and NO-$NO_x$ analyzers both had a detection limit of 0.05 ppb, and the $O_3$ analyzer had a detection limit of 0.50 ppb. All of the gaseous pollutant analyzers had a time resolution of 1 min, and were maintained and calibrated weekly following the manufacturer's protocols.

### 2.1.2 Meteorological Data

Meteorological data were obtained from the National Climate Data Center (www.ncdc.noaa.gov) dataset. The meteorological parameters were monitored at a station located in the Beijing Capital International Airport, and consisted of temperature (T), relative humidity (RH), wind direction (WD), wind speed (WS), sea level pressure (SLP), and precipitation (PREC). The PBL height was computed from the simulation results of the National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) model (www.ready.arl.noaa.gov/READYamet.php).

### 2.1.3 Analysis of the $PM_{2.5}$ Filter Samples

To obtain daily average $PM_{2.5}$ mass concentrations, Teflon filters were weighed before and after sampling using an electronic balance, with a detection limit of 10 μg (AX105DR) in a super-clean lab (T: 20 ± 1°C, RH: 40 ± 3%). A portion of each Teflon filter was extracted with ultrapure water for the measurement of water-soluble ions ($Na^+$, $NH_4^+$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, $SO_4^{2-}$, $NO_3^-$, and $Cl^-$), with an ion-chromatograph (IC-2000 & 2500, Dionex, Sunnyvale, CA, USA). The detection limits of $Na^+$, $NH_4^+$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, $SO_4^{2-}$, $NO_3^-$, and $Cl^-$ were 0.03, 0.06, 0.10, 0.10, 0.05, 0.01, 0.01, and 0.03 mg $L^{-1}$, respectively. A portion of each Teflon filter was digested with a solution consisting of nitric acid ($HNO_3$), hydrochloric acid (HCl), and hydrofluoric acid (HF) for the measurement of trace elements (Na, Mg, Al, Ca, Mn, Fe, Co, Cu, Zn, Se, Mo, Cd, Ba, Tl, Pb, Th and U), with inductively coupled plasma-mass spectrometry (ICP-MS, Thermo X series, Thermo Fisher Scientific). The recoveries for all measured elements fell within ±20% of the certified values. A semi-continuous organic carbon/elemental carbon (OC/EC) analyzer (Model 4, Sunset Laboratory, Tigard, OR, USA) was used to analyze organic and elemental carbon from a round punch (diameter: 17 mm) from each quartz filter sample. The T protocol of the National Institute for Occupational Safety and Health (NIOSH) thermal-optical method was applied (see details in Table S1).

All analytical instruments were calibrated before each series of measurements. The $R^2$ values of the calibration curves for ions, elements, and sucrose concentrations were higher than 0.999.

### 2.2 Research Periods Definition and Control Strategies

In our study, the APEC 2014 campaign consisted of three distinct periods: before APEC (18 October to 2 November 2014), during APEC (3 to 12 November 2014), and after APEC (13 to 22 November 2014). The Parade 2015 campaign was also divided into three distinct periods: before Parade (1 to 19 August 2015), during Parade (20 August to 3 September 2015), and after Parade (4 to 23 September 2015). A total of 225 $PM_{2.5}$ filter samples were collected from 1 October to 31 December 2014 and from 1 August to 31 December 2015. Sufficient number of sampling days are used to establish the relationship between air pollutant concentrations and meteorological parameters. 20 days of $PM_{2.5}$ samples were missed due to rain or sampler failures.

Table 2 shows the control periods and control strategies of APEC and Parade. , including the control of emissions from traffic, industry, and coal combustion, as well as dust pollution.

## 2.3 Methods for the Meteorological Conditions Separation

### 2.3.1 Identify Stable Meteorological Periods

Stable conditions can be defined based on the relationship between air pollution levels and both WSs and PBL height. Figure 5 shows scatter plots between $PM_{2.5}$ concentrations and WS and PBL heights. The relationship can be fitted with a power function. A stable condition could be defined by identifying the turning points when the slopes changed from large to relatively small values, and stable conditions could be defined when WSs and PBL heights were lower than the values of the turning points.

The slopes of the power function were monotone, varying with no inflection point. Thus, we used piecewise functions to identify the turning points. As Figure 5 shows, the intersections of two fitting lines represented the turning points of the meteorological influence on $PM_{2.5}$; thus, we defined days with stable meteorological conditions to be those with a daily average WS less than 2.50 m $s^{-1}$ and a daily average PBL height lower than 290 m. We could then compare the corresponding pollutant concentrations between days with stable meteorological conditions.

Figure 5 here

### 2.3.2 Generalized Linear Regression Model (GLM)

A GLM was used to establish the relationship between air pollutant concentrations and meteorological parameters. The objective dependent variables included concentrations of $PM_{2.5}$, individual $PM_{2.5}$ components, and gaseous pollutants.

To match the 23.5-h (09:30–09:00 LT the next day) sampling time of the $PM_{2.5}$ filter samples, metrological parameters were averaged over the same time span (Table 3) and used in the GLM alongside other parameters, e.g. the daily maximum of certain meteorological parameters. The meteorological parameters used in the GLM were T, RH, WD, WS, PBL height, SLP, and PREC. WDs were grouped into three categories, with relevant values and assigned to each category: north (NW, W and NE) as 1, south (SW, SE and E) as 2, and “calm and variable” as 3. A calm wind was defined as when the WS was less than 0.5 m $s^{-1}$. According to the JetStream Glossary of NOAA (http://www.srh.weather.gov/srh/jetstream/append/glossary_v.html), a variable WD was defined as a condition when: (1) the WD fluctuated by 60° or more during a 2-min evaluation period, with a WS greater than 6 knots (11 km $h^{-1}$); or (2) the WD was variable and the WS was less than 6 knots (11 km $h^{-1}$).

A preliminary analysis showed that the concentrations of air pollutants and meteorological parameters fitted best with an exponential function or power function (Figure S2); therefore, these functions were natural log transformed and introduced into the GLM.

We applied the stepwise method to evaluate the level of multicollinearity between the independent variables based on relevant judgement indexes, such as the variance inflation factor (VIF) or tolerance. Based on the assumption that the regression residuals followed a normal distribution and homoscedasticity, which is discussed in a later section, we developed the following model to calculate the concentrations of air pollutants and chemical components of $PM_{2.5}$ based on meteorological parameters:

$$ln\, C_{ij} = \beta_0 + \sum_{k=1}^{m} \beta_{1k} x_k + \sum_{k=1}^{n} \beta_{2k}\, ln\, x_k + \sum_{k=1}^{m'} \beta_{3k} x_k (lag) + \sum_{k=1}^{n'} \beta_{4k}\, ln\, x_k (lag) \quad (1)$$

where $C_{ij}$ is the concentration of the $j^{th}$ air pollutant averaged over the $i^{th}$ day, $x_k$ is the $k^{th}$ meteorological parameter, $\beta_k$ is the regression coefficient of the $k^{th}$ meteorological parameter, and $\beta_0$ is the intercept. For meteorological parameters containing both positive and negative values (i.e. T), only the exponential form was applied. *m*, *n*, *m'*, and *n'* are the number of different forms of meteorological parameters that were eventually included in the model, and were determined based on the stepwise entering method of the regression model. The suffix of *(lag)* refers to the meteorological parameters of the previous day. The main assumption for equation (1) was that the concentrations of air pollutants were only a function of the meteorological parameters, and the emission intensities were constant. Hence, we only used the data before and after APEC 2014 and Parade 2015 control periods in equation (1), excluding the data collected during each period and during the heating season, e.g. after 15 November

2014.

Compared with the models used in previous studies (Table 1), our statistical model had the following advantages: (1) all of the independent variables were meteorological parameters; (2) we considered the non-linear relationships between air pollutant concentrations and meteorological parameters; and (3) in addition to predicting $PM_{2.5}$ mass concentrations, our model could also predict concentrations of gaseous pollutants and individual $PM_{2.5}$ components by corresponding models for different pollutants.

# 3 Results and Discussion

## 3.1 Changes of Air Pollutant Concentrations during the APEC 2014 and Parade 2015 Campaigns

Figure 1 shows the time series of $PM_{2.5}$ and the concentrations of its components, as well as the meteorological parameters during the APEC 2014 and Parade 2015 campaigns.

There were two pollution episodes during APEC, on 4 November and 7–10 November 2014, which corresponded to two relatively stable periods with low WS, mainly from the south. The T declined gradually from 12.2°C before APEC to 4.9°C after APEC, and the RH was above 60% during the two pollution episodes. During Parade, the $PM_{2.5}$ concentrations were low, with the prevailing WD from the north and low WS. The T was mostly higher than 20°C, which differed from that during the APEC campaign when it was lower than 20°C.

Table 4 lists the mean concentrations and standard deviations of $PM_{2.5}$, gaseous pollutants, and $PM_{2.5}$ components during the APEC and Parade campaigns. The mean concentration of $PM_{2.5}$ during APEC was 48 ± 35 μg $m^{-3}$, 58% lower than before APEC (113 ± 62 μg $m^{-3}$), and 51% lower than after APEC (97 ± 84 μg $m^{-3}$). The mean concentration of $PM_{2.5}$ during Parade was 15 ± 6 μg $m^{-3}$, 63% lower than before Parade (41 ± 14 μg $m^{-3}$), and 62% lower than after Parade (39 ± 28 μg $m^{-3}$).

Figure 1 here

Figure 2 shows the proportion of the measured $PM_{2.5}$ components, including OC; EC; the sum of the sulphate, nitrate, and ammonia (SNA); and chloride ion ($Cl^-$) and trace elements, which together accounted for 70–80% of the total $PM_{2.5}$ mass concentration. The proportions of OC (23.5%) and EC (3.5%) in $PM_{2.5}$ were highest during APEC. The proportion of SNA in $PM_{2.5}$ during APEC (40.6%) was lower than before APEC (50.7%) and higher than after APEC (37.2%). The proportions of $Cl^-$ (4.3%) and elements (6.8%) in $PM_{2.5}$ during APEC were higher than before APEC and lower than after APEC. For the Parade campaign, the proportions of OC (26.6%) and elements (6.6%) in $PM_{2.5}$ were highest during Parade. The proportions of EC (4.9%) and $Cl^-$ (1.1%) in $PM_{2.5}$ during Parade were higher than before Parade and lower than after Parade. The proportion of SNA in $PM_{2.5}$ was lowest during Parade (37.3%). Similarly, during the pollution control periods of APEC and Parade, the proportions of OC and elements in $PM_{2.5}$ tended to increase and the proportion of SNA in $PM_{2.5}$ tended to decrease.

Figure 2 here

EC is usually considered to be a marker of anthropogenic primary sources, while the sources of OC include both primary and secondary organic aerosols. The correlation between OC and EC can reflect the origin of carbonaceous fractions (Chow et al., 1996). Figure 3 shows the correlation between EC and OC concentrations during the APEC and Parade campaigns. During the APEC and Parade campaigns, the correlation coefficient during both control periods ($R^2$ = 0.9032) was larger than that during non-control periods ($R^2$ = 0.6468), indicating that OC and EC were mainly derived from the same sources during both pollution control periods, and were from different sources during the non-control periods. Li et al. (2017) reported that the residential burning of coal and open and domestic combustion of wood and crop residuals could contribute to more than 50% of total organic aerosol of the North China Plain during winter. During the control periods, it might be difficult to fully control the emission of residential burning. The slope of the OC/EC correlation during the pollution control period was 6.86, which was higher than that during the non-control period (3.97). This could be due to high levels of secondary OC (SOC) formation during the control periods, and/or the higher contribution from residential solid fuel (coal and biomass) burning (Liu et al., 2016).

Figure 3 here

Figure 4 shows the proportion of SNA in $PM_{2.5}$ ($\rho(SNA/PM_{2.5})$), the sulphur (S) oxidation ratio (SOR = $[SO_4^{2-}]/([SO_2]+[SO_4^{2-}])$), and nitrogen oxidation ratio (NOR = $[NO_3^-]/([NO_x]+[NO_3^-])$), along with $PM_{2.5}$ concentrations during the APEC (a) and Parade (b) campaigns. During APEC, the average $\rho(SNA/PM_{2.5})$ was 27%, which was significantly lower than before APEC (42%). During Parade, the average $\rho(SNA/PM_{2.5})$

was 35%, which was also significantly lower than before Parade (47%).

During the APEC campaign, the average $SO_2$ concentration was 11.3 μg $m^{-3}$ before APEC, 9.5 μg $m^{-3}$ during APEC, and 34.8 μg $m^{-3}$ after APEC, respectively. The average $NO_x$ concentration was 151 μg $m^{-3}$ before APEC, 81 μg $m^{-3}$ during APEC, and 220 μg $m^{-3}$ after APEC, respectively. During the Parade campaign, the average $SO_2$ concentration during Parade was 1.6 μg $m^{-3}$, lower than both before Parade (2.7 μg $m^{-3}$) and after Parade (5.9 μg $m^{-3}$). The average $NO_x$ concentration was also lower during Parade (26 μg $m^{-3}$), than before Parade (57 μg $m^{-3}$) and after Parade (63 μg $m^{-3}$).

During the APEC campaign, both the SOR and NOR declined gradually. The average SOR was 42%, 27%, and 17% before, during, and after APEC, respectively. The average NOR was 13%, 8%, and 5% before, during, and after APEC, respectively. SOR and NOR exhibited different patterns during the Parade campaign. The average SOR was 75%, 64%, and 55% before, during, and after Parade, respectively. The average NOR was 8%, 5%, and 8% before, during, and after Parade, respectively. The SOR was higher during the Parade campaign (64%) than during the APEC campaign (30%). For NOR, a higher average value was found during the APEC campaign (9%) than during the Parade campaign (7%).

The APEC campaign occurred during autumn and early winter, while the Parade campaign occurred during late summer and autumn. The active photochemical oxidation during the Parade campaign resulted in high $SO_2$-to-sulphate transformation rates, as indicated by the high SOR. In addition, the higher RH in summer favoured the heterogeneous reaction of sulphate formation (Figure 1). For NOR, the T was higher during Parade than during APEC, which favoured the volatilization of nitric acid and ammonia from the particulate phase of nitrate.

These results indicate significant reductions of air pollution during the pollution control periods of APEC 2014 and Parade 2015. However, it is necessary to evaluate if meteorological conditions contributed to this improvement.

Figure 4 here

## 3.2 Variation of Air Pollutant Concentrations under Similar Meteorological Conditions

Figure S3 shows the prevalence of WD during the APEC and Parade campaigns. Figure S4 shows a time series of daily average $PM_{2.5}$ concentrations and PBL heights during the APEC and Parade campaigns. Both WS and PBL height during APEC and Parade were favourable for pollutant diffusion. Therefore, it is necessary to consider meteorological conditions when assessing the impacts of pollution control. One way to do this is to compare air pollution concentrations during periods when meteorological conditions were the same, i.e. under stable conditions (Wang et al., 2015; Zhang et al., 2009).

The days with stable meteorological conditions were determined with the method introduced in Section 3.2.1. As a result, eight days before APEC, six days during APEC, and seven days after APEC were defined as having stable meteorological conditions (Table S5).

Figure 6 shows the percentage reductions calculated by comparing the decreased average concentrations for all days during APEC to the average concentrations before

APEC in black bars, and the percentage reductions based on the days with stable meteorological conditions in red bars. For the difference between the periods during APEC and before APEC, the percentage reduction on days with stable meteorological conditions was much lower than the reduction calculated when considering all days, except for Ca and NO. This indicates that the method applied to days with stable meteorological conditions excluded part of the meteorological influence on pollutant concentrations. The average $PM_{2.5}$ concentration was 70 μg $m^{-3}$ during APEC, which represented a 45.7% decrease compared with the concentration in the BAPEC period (129 μg $m^{-3}$) and a 44.4% decrease compared with the concentration in the AAPEC period (126 μg $m^{-3}$) (Figure S8). Changes of other pollutant concentrations on days with stable meteorological conditions during the APEC campaign are shown in Figure S8.

The standard deviations were also calculated with an error transfer formula that is described in detail in the Supplementary Information (S6). Figure 6 shows that the standard deviations of the percentage reduction based on days with stable meteorological conditions decreased significantly. For example, the standard deviation of the percentage reduction in $PM_{2.5}$ based on the days with stable meteorological conditions decreased from 39% to 26% compared with the same measurement when all days were considered. This indicates that by considering only days with stable meteorological conditions, the uncertainties associated with the percentage reduction figures were reduced and the reliability of the changes of air pollutants concentrations were improved. However, uncertainties remain within the percentage differences based on the days with stable meteorological conditions, although the size of these uncertainties was reduced. Table S7 lists the percentage differences among the mean $PM_{2.5}$ concentrations of four periods that were randomly selected from within the non-control days of the APEC and Parade campaigns. This may be due to the limited sample size on days with stable meteorological conditions during the APEC campaign. It is therefore necessary to further quantify the meteorological influences.

Figure 6 here

### 3.3 Emission Reductions during APEC and Parade Based on GLM Predictions

The previous section showed that the number of days with stable meteorological conditions could be limited; it was therefore impossible to estimate quantitatively the contribution of meteorological conditions to the reduction of air pollutant concentrations. We developed a GLM based only on meteorological parameters to meet this requirement.

#### 3.3.1 Model Performance and Cross-Validation Test

Figure 7 shows the scatter plot and correlation between the GLM-predicted and observed concentrations of air pollutants transformed to a natural log. Figure 8 demonstrates the time series of the observed pollutant and GLM-predicted pollutant concentrations, which displayed a good correlation. The $R^2$ values of the linear regression equations ranged from 0.6638 to 0.8542, most of them are higher than 0.7 except for Zn and Mn, indicating that the GLM-predicted concentrations correlated well with the observed concentrations. Specifically, the $R^2$ value of the linear regression equation for $PM_{2.5}$ is as high as 0.8154.

Figure 7 here

Figure 8 here

Before applying the GLM to predict the air pollutant concentrations, the cross-validation (CV) method was used to evaluate the performance of the $PM_{2.5}$ model, with the assumption that it was representative of all air pollutants. The data input to the $PM_{2.5}$ model was allocated randomly into five equal periods, namely CV1, CV2, CV3, CV4, and CV5. For each test, one period was removed from the input data and the remaining data were applied to establish the CV model, which was then used to predict the $PM_{2.5}$ concentrations for the removed period. After five rounds, all input data were included in the CV test. Figure 9 shows the time series of the observed and CV-predicted $PM_{2.5}$ concentrations, which demonstrates a good performance for the $PM_{2.5}$ GLM.

Figure 9 here

Table 5 shows the CV-predicted $PM_{2.5}$ concentrations. The adjusted $R^2$ values for the five CV periods ranged from 0.710 to 0.807, which was lower than the value (0.808) derived from the $PM_{2.5}$ model, due to the lack of input data. The observed mean $PM_{2.5}$ concentrations were 94, 59, 44, 54, and 41 μg $m^{-3}$ for the five CV periods, respectively. The corresponding CV-predicted mean $PM_{2.5}$ concentrations were 82, 57, 52, 65, and 47 μg $m^{-3}$, respectively. The relative error (RE) between the observed mean $PM_{2.5}$ concentrations and the CV-predicted mean $PM_{2.5}$ concentrations ranged from −17% to 15%, with a mean RE of −5%. The RMSE of the RE was 14.6%, reflecting the uncertainties of the GLM method in quantitatively estimating the contribution of the meteorological conditions to the air pollutant concentrations.

Table 5 also lists the daily RMSE for each CV period and the total RMSE. The daily RMSE for each CV period was calculated with the daily average $PM_{2.5}$ concentrations during each CV period, and the total RMSE was calculated with the daily average $PM_{2.5}$ concentration throughout all five CV periods combined. The daily RMSE ranged from 19 to 53 μg $m^{-3}$, and the total RMSE was 33 μg $m^{-3}$, indicating that the model prediction accuracy at the daily level needs to be improved. Liu et al. (2012) used a generalized additive model (GAM) to predict $PM_{2.5}$, which had a total daily RMSE of 23 μg $m^{-3}$. Compared with their results, the CV performance in our study was satisfactory considering that the independent variables in our model were only based on meteorological parameters, while the model of Liu et al. (2012) included AOD.

The relative error calculated with the CV method for GLM was −5% (Table 5), which was smaller than the mean percentage difference (−16%) calculated based on days with stable meteorological conditions (Table S7). Moreover, the RMSE of relative error calculated with the CV method for GLM (Table 5) was 14.6%, which was also smaller than the RMSE of percentage difference (18%) calculated based on days with stable meteorological conditions (Table S7).

These indicate that the GLM reduced uncertainties of the method in quantitatively estimating the contribution of the meteorological conditions to the pollutant concentrations.

### 3.3.2 Model Description

Table 6 shows the concentrations of air pollutants for the GLM with adjusted $R^2$ values higher than 0.6. The adjusted $R^2$ of the $PM_{2.5}$, $NO_3^-$, $NH_4^+$, and $SO_2$ models are higher than 0.8, indicating that these models could explain more than 80% of the variation in air pollutant concentrations.

Again, we used the $PM_{2.5}$ model as an example. Table 7 lists the output indexes of the $PM_{2.5}$ GLM, including a model summary, analysis of variance (ANOVA), coefficients, and other indexes. The values of R, $R^2$, and adjusted $R^2$ were 0.910, 0.828, and 0.808, respectively, indicating that the $PM_{2.5}$ model can explain 80.8% of the variability of the daily average $PM_{2.5}$ concentrations. The model was statistically significant according to the p-value ($<0.05$) from an F-test, and the meteorological parameters eventually selected as the independent variables of the model were statistically significant according to the p-values ($<0.05$) from a t-test. The meteorological parameters eventually included in the model were lnWS, $lnWS_{max(lag)}$, $PBL_{max}$, PREC, $ln\Delta T_{(lag)}$, $WS_{mode}$, $WD/WS_{(lag)}$, $PBL_{min(lag)}$, $PREC_{(lag)}$, and $SLP_{min}$. According to the collinearity statistics, all the VIF values were within 5 and tolerance values were larger than 0.1, indicating that no serious multicollinearity existed between the independent parameters. The Durbin–Watson value (1.910) was close to 2, accounting for the good independence of the variance. Figure S9 shows the graphic residual analysis of the $PM_{2.5}$ GLM.

Table 8 summarizes the meteorological parameters included in the models and their influence on pollutant concentrations. As a result, PBL, $WS_{(lag)}$, $PREC_{(lag)}$, PREC, and WS are included in the models more frequently, accounting for 13, 9, 8, 7, and 7 times. This indicates that these parameters have important influence on pollutant concentrations, especially for PBL included in all of the models. The parameters of the previous day also have important influence on pollutant concentrations, i.e. $WS_{(lag)}$, $PREC_{(lag)}$, $PBL_{(lag)}$, $RH_{(lag)}$, $T_{(lag)}$, $WD/WS_{(lag)}$, and $WD_{(lag)}$. Meteorological parameters have different influence on pollutant concentrations (Table 8). For example, PBL, $WS_{(lag)}$, and $PREC_{(lag)}$ represent the negative correlation with pollutant concentrations. This may be because the higher values of these meteorological parameters are in favour of pollution diffusion. On the contrary, RH, T, $WD/WS_{(lag)}$, and WD represent the positive correlation with pollutant concentrations, because the higher values of these meteorological parameters are beneficial for pollution formation and accumulation.

### 3.3.3 Quantitative Estimates of the Contribution of Meteorological Conditions to Air Pollutant Concentrations

We applied the GLM to predict air pollutant concentrations during APEC 2014 and Parade 2015 based on meteorological parameters. The difference between the observed and GLM-predicted concentrations was attributed to emission reduction through the implementation of air pollution control strategies.

Table 9 lists the percentage differences between the observed and GLM-predicted concentrations of air pollutants during APEC and Parade. The mean concentrations of the observed and predicted $PM_{2.5}$ were 48 and 67 μg $m^{-3}$ during APEC, i.e. a 28% difference. The mean concentrations of the observed and predicted $PM_{2.5}$ were 15 and 20 μg $m^{-3}$ during Parade, i.e. a 25% difference. These differences are attributed to the emission reduction through the implementation of air pollution control strategies. As described in Section 3.1, during APEC and Parade, the mean concentrations of $PM_{2.5}$ decreased by 58% and 63% compared with before APEC and Parade. Therefore, the meteorological conditions and pollution control strategies contributed 30% and 28% to the reduction of the $PM_{2.5}$ concentration during APEC 2014, and 38% and 25% during Parade 2015, based on the assumption that the concentrations of air pollutants are only determined by meteorological conditions and emission intensities.

The emission reduction during APEC in this study is comparable to the results of other studies where meteorological influences were considered. For example, the $PM_{2.5}$ concentration decreased by 33% under the same weather conditions during APEC in Beijing as modelled by the Weather Research and Forecasting model and Community Multiscale Air Quality (WRF/CMAQ) model (Wu et al., 2015). In addition, emission control implemented in Beijing during APEC resulted in a 22% reduction in the $PM_{2.5}$ concentration, as modelled by WRF-Chem (Guo et al., 2016).

Same as $PM_{2.5}$, the differences listed in Table 9 for other pollutants show the reduction in emission of these pollutants and/or their precursors. The differences for EC were 37% (from 2.7 to 1.7 μg $m^{-3}$) during APEC and 33% (from 1.2 to 0.8 μg $m^{-3}$) during Parade. In contrast, the differences for OC were 11% (from 12.6 to 11.2 μg $m^{-3}$) during APEC and 8% (from 3.7 to 4.0 μg $m^{-3}$) during Parade. The differences for carbonaceous components (OC + EC) were 16% (from 15.3 to 12.9 μg $m^{-3}$) during APEC and 2% (from 4.9 to 4.8 μg $m^{-3}$) during Parade. This indicates that the emission reduction for OC and its precursors were smaller than the reduction of EC during APEC and Parade. This may be because OC can originate from both primary emission and secondary transformation. The slope of the OC/EC correlation during the pollution control period reached 6.86 (Figure 3), indicating the higher levels of secondary OC (SOC) formation during the control periods.

Table 9 also shows the differences for sulphate were 44% (from 2.7 to 3.9 μg $m^{-3}$) during APEC and 50% (from 5.2 to 2.6 μg $m^{-3}$) during Parade. The differences for nitrate were 44% (from 19.0 to 10.6 μg $m^{-3}$) during APEC and 56% (from 3.4 to 1.5 μg $m^{-3}$) during Parade. The differences for ammonium were 13% (from 5.5 to 4.8 μg $m^{-3}$) during APEC and 38% (from 2.4 to 1.5 μg $m^{-3}$) during Parade. In total, the differences for SNA were 29% (from 27.2 to 19.3 μg $m^{-3}$) during APEC and 49% (from 11.0 to 5.6 μg $m^{-3}$) during Parade. The control of the SNA concentration was very effective during APEC and Parade, leading to a significant decrease of $PM_{2.5}$ during both events. The significant differences for sulphate and nitrate may indicate the control of coal combustion and/or vehicle emission were effective during APEC and Parade.

The concentration of sulphate is determined by primary emissions and secondary transformation from $SO_2$; thus, the changes in sulphate concentrations may not well reflect the effectiveness of emission control strategies. One needs to also include the changes in $SO_2$ concentrations. By adding the molar concentrations of $SO_2$ and $SO_4^{2-}$ (S = $[SO_2] + [SO_4^{2-}]$), the concentration of total S was calculated. Table 9 shows the differences for $SO_2$ were 50% (from 6.59 to 3.32 ppb) during APEC and 2% (from 0.56 to 0.57 ppb) during Parade, while the differences for total S were 41% (from 0.322 to 0.189 μmol $m^{-3}$) during APEC and 33% (from 0.079 to 0.053 μmol $m^{-3}$) during Parade.

Coal combustion emissions is the major contributor to total S, this demonstrates the effective control of coal combustion during both APEC 2014 and Parade 2015. The difference for $SO_2$ during APEC was larger than that during Parade, while the difference for sulphate during Parade was larger than that during APEC. As discussed in Section 3.1, the mean SOR was 27% and 64% during APEC and Parade, respectively, indicating that the $SO_2$-to-sulphate transformation rate during APEC (autumn and early winter) was much lower than during Parade (late summer and autumn).

Table 9 shows $NO_x$ and other $PM_{2.5}$ components also had significant emission reduction during APEC 2014 and Parade 2015. The differences between the observed and GLM-predicted concentrations of $NO_x$ were 56% (from 102 to 45 ppb) during APEC and 35% (from 20 to 13 ppb) during Parade. The differences for $Cl^-$ were 20% (from 2.58 to 2.06 μg $m^{-3}$) during APEC and 6% (from 0.17 to 0.16 μg $m^{-3}$) during Parade. The differences for $K^+$ were 37% (from 1.03 to 0.65 μg $m^{-3}$) during APEC and 25% (from 0.24 to 0.18 μg $m^{-3}$) during Parade. The differences for Pb, Zn, and Mn ranged from 21% to 53% during APEC and Parade. The concentrations of $Cl^-$ have been found to be high in the fine particles produced from coal combustion (Takuwa et al., 2006), while the concentrations of $K^+$ are high in particles derived from combustion activities, e.g. biomass burning and coal combustion. Lead is typically considered to be a marker of emissions from coal combustion, power stations, and metallurgical plants (Dan et al., 2004; Mukai et al., 2001; Schleicher et al., 2011). Zinc can be produced by the action of a car braking and by tire wearing (Cyrys et al., 2003; Sternbeck et al., 2002). Manganese mainly originates from industrial activities. Major sources of $NO_x$

emissions include power plants, industry, and transportation (Liu and Zhu, 2013). The differences for the concentrations of total S, $Cl^-$, $K^+$, Pb, Zn, Mn, and $NO_x$, indicate that the control of anthropogenic emissions, especially coal combustion, was very effective during APEC and Parade.

### 3.3.4 Uncertainties of the GLM

In this study, the uncertainties of the GLM when estimating the contributions of meteorological conditions and pollution control strategies in reducing air pollution were assessed with the method of cross-validation test (Table 5) in Section 3.3.1. All the GLMs were developed following the same procedure, thus the $PM_{2.5}$ model was used as an example representative of all the pollutants. As a result, the relative error between the observed mean $PM_{2.5}$ concentrations and the CV-predicted mean $PM_{2.5}$ concentrations were within ±20%, averaging with −5%. This indicates that the $PM_{2.5}$ concentrations could be predicted with the GLM based on the meteorological conditions. The uncertainties of the GLM could refer to the RMSE of relative error for GLM of 14.6% (Table 5). It should be mentioned that the data input to the $PM_{2.5}$ model was allocated randomly into several periods, thus the RMSE of relative error for GLM would vary accordingly. In the future, we could test the uncertainties of the GLMs for other pollutants with the CV test.

## 4 Conclusions

During the pollution control periods of APEC 2014 and Parade 2015, the concentrations of air pollutants except ozone decreased dramatically compared with the concentrations during non-control periods, accompanied by meteorological conditions favourable for pollutant dispersal.

To estimate the contributions of meteorological conditions and pollution control strategies in reducing air pollution, comparing the concentrations of air pollutants during days with stable meteorological conditions is a useful method, but has limitation due to high uncertainty and lack of a sufficient number of days with stable meteorological conditions

Our study shows that, if including the nonlinear relationship between meteorological parameters and air pollutant concentrations, GLMs based only on meteorological parameters could provide a good explanation of the variation of pollutant concentrations, with adjusted $R^2$ values mostly larger than 0.7. Since the GLMs contained no parameters dependent on air pollution levels as independent variables, they could be used to estimate the contributions of meteorological conditions and pollution control strategies to the air pollution levels during emission control periods.

With the GLMs method, we found meteorological conditions and pollution control strategies played almost equally important roles in reducing air pollution in megacity Beijing during APEC 2014 and Parade 2015, e.g. 30% and 28% to the reduction of the $PM_{2.5}$ concentration during APEC 2014, as well as 38% and 25% during Parade 2015. We also found that the control of the SNA concentration was more effective than carbonaceous components. The differences between the observed and GLM-predicted concentrations of specific pollutants ($Cl^-$, $K^+$, Pb, Zn, Mn, $NO_x$, and S) related to coal combustion and industrial activities revealed the effective control of anthropogenic emissions.

In the future, combining the methods of source apportionment, the contributions of emission reductions for different sources in reducing air pollution could be estimated, enabling further analysis of pollution control strategies.

**Data availability.** The data of stationary measurements are available upon requests.

**Author contribution.** T. Zhu and P. F. Liang designed the experiments. P. F. Liang collected and weighed the $PM_{2.5}$ filter samples. P. F. Liang, Y. H. Fang, Y. Q. Han, and J. X. Wang carried out the analysis of the components in $PM_{2.5}$. Y. S. Wu and M. Hu provided the data of gaseous pollutant concentrations. Y. R. Li computed the data of planetary boundary layer heights from GDAS and P. F. Liang developed the GLM. J. X. Wang managed the data. P. F. Liang analyzed the data with contributions from all co-authors. P. F. Liang prepared the manuscript with helps from T. Zhu.

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**Figure Captions:**

Figure 1. Time series of atmospheric particulate matter of aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) and the concentrations of its components, wind direction (WD), wind speed (WS), temperature (T), and relative humidity (RH) before, during, and after (a) APEC 2014 and (b) Parade 2015. The blue-shaded areas highlight the pollution control periods of APEC 2014 (3 November to 12 November 2014) and Parade 2015 (20 August to 3 September 2015).

Figure 2. Proportions of the measured components in $PM_{2.5}$ during (a) APEC 2014 and (b) Parade 2015 campaigns, including organic carbon (OC), elemental carbon (EC), $SO_4^{2-}$, $NO_3^-$, $NH_4^+$, $Cl^-$ and elements. BAPEC/BParade: before APEC/Parade, AAPEC/AParade: after APEC/Parade.

Figure 3. Scatter plot and correlations between organic carbon (OC: *y*-axis) and elemental carbon (EC: *x*-axis) concentrations of $PM_{2.5}$ during the APEC 2014 and Parade 2015 campaigns. The red symbols denote the non-control period and the black symbols denote the pollution control period. The linear regression equations and $R^2$ values are given for these two campaigns.

Figure 4. Upper panel: time series of the proportion of sulphate, nitrate, and ammonia (SNA) in $PM_{2.5}$ ($\rho(SNA/PM_{2.5})$) and $PM_{2.5}$ mass concentrations (the black bar represents $PM_{2.5}$ concentration and the red line represents $\rho(SNA/PM_{2.5})$). Middle panel: $SO_2$, $SO_4^{2-}$, and SOR ($[SO_4^{2-}]/([SO_2]+[SO_4^{2-}])$). Lower panel: $NO_x$, $NO_3^-$, and NOR

($[NO_3^-]/([NO_x]+[NO_3^-])$). Data collected during the (a) APEC 2014 and (b) Parade 2015 campaigns. The hollow bars represent gaseous pollutants (red for $SO_2$, blue for $NO_x$), and solid bars represent secondary inorganic ions (red for sulphate, blue for nitrate).

Figure 5. Scatter plot showing the correlation between daily $PM_{2.5}$ concentrations (*y*-axis) and (a) daily PBL heights (*x*-axis) and (b) daily WSs (*x*-axis) during the sampling periods. The red and black scattered points represent different distribution areas. The piecewise function regression equations and the corresponding values of PBL height and WS according to the intersections are given.

Figure 6. The percentage reductions of pollutant concentrations under similar meteorological conditions. The black bars represent the percentage reductions calculated by comparing the decreased average concentrations during APEC to the average concentrations before APEC. The red bars represent the percentage reductions calculated by comparing the decreased average concentrations during APEC to the average concentrations before APEC based only on the days with stable meteorological conditions. The whiskers represent the standard deviations of the percentage reductions.

Figure 7. Scatter plot and correlations between GLM-predicted (*y*-axis) and observed (*x*-axis) concentrations of pollutants transformed to a natural log. The linear regression equations and $R^2$ values are given.

Figure 8. Time series of the observed (in black line) and GLM-predicted pollutant concentrations (in red line).

Figure 9. Time series of the observed and cross-validation (CV) predicted $PM_{2.5}$ concentrations during five CV periods. The black line represents the observed $PM_{2.5}$ concentration and the red line represents the CV-predicted $PM_{2.5}$ concentration.

Table 1. Summary of statistical models applied to predict air pollutant concentrations with meteorological parameters.

| Dependent variables | Independent variables | $R^2$ | Methods[1] | Applications |
|---|---|---|---|---|
| $PM_{2.5}$ | meteorological parameters (T/RH/PBL/WS/cloud fraction), AOT | 0.47 | MLR | Gupta and Christopher, 2009 |
| $PM_{10}$ | meteorological parameters (T/WD/RH/PBL/WS), AOD | 0.21/0.30 (MODIS/MISR[2]) | MLR | Sotoudeheian and Arhami, 2014 |
| $PM_{10}$ | meteorological parameters (RH/WS/T), AOD | 0.49-0.88 (spatial-temporal variability) | MLR | Chitranshi et al., 2015 |
| $PM_{2.5}$ | meteorological parameters (T/RH/PREC), AOT | 0.60/0.58 (MOD/MYD[3]) | MLR | Nguyen et al., 2015 |
| $\ln(PM_{2.5})$, $\ln(PM_{2.5\text{-}10})$ | meteorological parameters (ln(PREC)/ln(RH)/ln(WS)/ln(SUN)/ln(T)), atmospheric turbulence parameters ($\ln(\Delta u/\Delta z)/\ln(\Delta\theta/\Delta z)$) | 0.60-0.74 | GLM | Hien et al., 2002 |
| $\ln(PM_{2.5})$ | meteorological parameters (T/WD/ln(WS)/ln(PBL)), ln(AOT), categorical parameters | 0.51/0.62 (MODIS/MISR) | GLM | Liu et al., 2007 |
| $\log(PM_{2.5})$, log(BC) | meteorological parameters (T/wind index), traffic-related parameters | 0.62/0.42 ($PM_{2.5}$/BC) | GLM | Richmond-Bryant et al., 2009 |
| $\ln(PM_{2.5})$ | meteorological parameters (ln(PBL)/GEO-4 RH/ln(surface RH)/T), ln(AOD) | 0.65 | GLM | Tian and Chen, 2010 |
| $\ln(PM_{10})$ | meteorological parameters (T/WD/RH/ln(PBL)/ln(WS)), ln(AOD) | 0.18/0.38 (MODIS/MISR) | GLM | Sotoudeheian and Arhami, 2014 |
| $\ln(PM_{2.5})$ | meteorological parameters (ln(PBL)/RH/Vis/ln(T)/ln(WS)), ln(AOD) | 0.67/0.72 (MODIS/MISR) | GLM | You et al., 2015 |
| $\ln(PM_{2.5})$ | meteorological parameters (WS/WD/T/RH/pressure), optical properties (absorption/scattering/attenuation co-efficient) | 0.54/0.31/0.32/0.88 (winter/pre-monsoon/monsoon/post-monsoon) | GLM | Raman and Kumar, 2016 |
| $PM_{10}$, $PM_{2.5}$ | smooth non-parametric functions of spatial/temporal variates | 0.58 | GAM | Barmpadimos et al., 2012 |
| $PM_{2.5}$, $PM_{10}$, $PM_{2.5\text{-}10}$ | smooth non-parametric functions of spatial/temporal variates | 0.77/0.58/0.46-0.52 ($PM_{2.5}$/$PM_{10}$/$PM_{2.5\text{-}10}$) | GAM | Yanosky et al., 2014 |
| $PM_{10}$ | meteorological parameters ($WS/T_{min}/T_{max}$), previous day $PM_{10}$ | 0.78 | ANN | Diaz-Robles et al., 2008 |
| $PM_{2.5}$ | meteorological parameters (WS/RH/PBL/WS*PBL), AOD, spatial | 0.89 | LUR | Chudnovsky et al., 2014 |

| | | | | |
|---|---|---|---|---|
| | explanatory variables | | | |
| $PM_{10}$, $NO_2$ | meteorological parameters (T/RH/WS/air pressure/cloud cover/percentage of haze/mist/rain/sun), spatial explanatory variables | 0.45/0.43 ($PM_{10}$/$NO_2$) | LUR | Liu et al., 2015 |

[1]MLR: multiple linear regression model, GLM: generalized linear regression model, GAM: generalized additive model, ANN: artificial neural networks, LUR: land use regression model.

[2]MODIS: Moderate resolution imaging spectroradiometer, MISR: Multi-angle imaging spectroradiometer.

[3]MOD/MYD: MODIS Terra (AM overpass) and Aqua (PM overpass).

Table 2. Air pollution control strategies during APEC 2014 and Parade 2015.

| Periods | Control measures | Detail of measures |
|---|---|---|
| **APEC 2014** (3 to 12 November 2014) and **Parade 2015** (20 August to 3 September 2015) | Traffic control | The odd/even plate number rule for traffic control in Beijing, Tianjin, Hebei and Shandong; 70% (APEC 2014)/80% (Parade 2015) of official vehicle and “yellow label vehicles” were banned from Beijing’s roads; Trucks limited to run inside the 6th Ring Road between 6 AM to 24 PM. |
| | Industrial emission control | More than 10,000 factories production limited or halted in Beijing and Hebei, Tianjin, Shandong, Shanxi and Inner Mongolia which surround Beijing city. |
| | Dust pollution control | Dust emission factories and outdoor constructions shut down or limited in Beijing and near area; Enhancing road cleaning and spray and aspirating in Beijing. |
| | Coal-fired control | State-owned enterprise productions enhancing limited and 40% coal-fired boilers shut down in Beijing; more special pollutant emission factory limited around Beijing. |

Table 3. Meteorological parameters used in the GLM in this study. The calculation of each meteorological parameter is based on the sample duration of 23.5 h (09:30–09:00 LT the next day).

| Parameters | Abbreviations | Description |
|---|---|---|
| Wind direction value* | WD | The average of wind direction values. |
| | $WD_{sum}$ | The sum of wind direction values. |
| | $WD_{mode}$ | The mode of wind direction values. |
| Wind speed (m $s^{-1}$) | WS | The average of wind speed. |
| | $WS_{mode}$ | The mode of wind speed. |
| | $WS_{max}$ | The maximum of wind speed. |
| Temperature (°C） | T | The average of temperature. |
| | $T_{max}$ | The maximum of temperature. |
| | $T_{min}$ | The minimum of temperature. |
| | ∆T | The difference of temperature. |
| Sea level pressure (hPa) | SLP | The average of sea level pressure. |
| | $SLP_{max}$ | The maximum of sea level pressure. |
| | $SLP_{min}$ | The minimum of sea level pressure. |
| Relative humidity (%) | RH | The average of relative humidity. |
| | $RH_{max}$ | The maximum of relative humidity. |
| Precipitation (mm) | PREC | The accumulation of precipitation. |
| Wind index | WD/WS | The average of wind direction value/wind speed. |
| | $WD/WS_{sum}$ | The sum of wind direction value/wind speed. |
| Planetary boundary layer height (m) | PBL | The average of 3-h planetary boundary layer height. |
| | $PBL_{min}$ | The minimum of 3-h planetary boundary layer height. |
| | $PBL_{max}$ | The maximum of 3-h planetary boundary layer height. |

* Since the degree data of wind direction cannot be applied directly, the values of wind directions are donated such that value = 1, 2, 3 for north, south, and "calm and variable", respectively.

Table 4. Statistical summary showing the mean concentrations and standard deviations of $PM_{2.5}$, gaseous pollutants, and $PM_{2.5}$ components. BAPEC/BParade: before APEC/Parade, AAPEC/AParade: after APEC/Parade.

| Pollutants | Units | BAPEC | APEC | AAPEC | BParade | Parade | AParade |
|---|---|---|---|---|---|---|---|
| $PM_{2.5}$ | $\mu g\ m^{-3}$ | 113±62 | 48±35 | 97±84 | 41±14 | 15±6 | 39±28 |
| OC | | 15.3±8.7 | 11.2±7.2 | 21.3±15.5 | 7.4±1.9 | 4.0±1.0 | 6.3±3.1 |
| EC | | 2.7±1.4 | 1.7±1.0 | 3.5±1.8 | 1.6±0.3 | 0.8±0.1 | 2.0±1.0 |
| $SO_4^{2-}$ | | 12.6±9.1 | 3.9±3.0 | 9.6±12.4 | 10.6±6.2 | 2.6±1.3 | 7.9±7.3 |
| $NO_3^-$ | | 29.4±21.4 | 10.6±11.0 | 16.3±19.4 | 5.0±3.9 | 1.5±1.5 | 6.4±6.2 |
| $NH_4^+$ | | 15.0±10.6 | 4.8±4.2 | 10.3±11.9 | 5.2±2.6 | 1.5±1.0 | 5.4±5.4 |
| $Cl^-$ | | 3.19±1.61 | 2.06±2.11 | 6.59±6.67 | 0.20±0.16 | 0.16±0.12 | 0.53±0.24 |
| $Na^+$ | | 0.50±0.26 | 0.26±0.15 | 0.57±0.46 | 0.16±0.09 | 0.10±0.05 | 0.16±0.08 |
| $K^+$ | | 1.20±0.63 | 0.65±0.51 | 1.52±1.43 | 0.30±0.13 | 0.18±0.08 | 0.38±0.20 |
| $Mg^{2+}$ | | 0.07±0.03 | 0.09±0.02 | 0.13±0.07 | 0.01±0.01 | 0.01±0.00 | 0.02±0.01 |
| $Ca^{2+}$ | | 0.52±0.34 | 0.28±0.19 | 0.53±0.40 | 0.14±0.07 | 0.10±0.04 | 0.17±0.05 |
| $SO_2$ | | 11.3±5.0 | 9.5±6.8 | 34.8±15.3 | 2.7±1.6 | 1.6±1.4 | 5.9±5.2 |
| NO | | 54.2±30.5 | 21.9±13.8 | 112.3±63.2 | 3.2±2.1 | 1.2±0.9 | 9.3±7.5 |
| $NO_x$ | | 151±62 | 81±46 | 220±107 | 57±11 | 26±13 | 63±24 |
| $O_3$ | | 23±16 | 38±19 | 17±14 | 116±33 | 79±22 | 74±27 |
| Ca | $ng\ m^{-3}$ | 582±431 | 591±335 | 1536±579 | 202±64 | 108±36 | 188±130 |
| Co | | 0.48±0.21 | 0.34±0.18 | 0.90±0.52 | 0.21±0.08 | 0.05±0.02 | 0.16±0.10 |
| Ni | | 3.20±1.56 | 5.07±7.42 | 5.17±2.50 | 1.75±1.16 | 0.63±0.72 | 1.16±0.67 |
| Cu | | 35.7±16.2 | 19.1±12.6 | 43.3±31.2 | 12.4±5.1 | 3.7±1.3 | 9.6±6.5 |
| Zn | | 320±146 | 128±120 | 315±310 | 97±46 | 20±9 | 71±54 |
| Se | | 6.45±3.46 | 3.76±3.84 | 5.22±6.56 | 7.06±3.41 | 3.19±2.76 | 3.17±2.76 |
| Mo | | 2.20±1.12 | 1.63±1.14 | 2.85±2.67 | 0.62±0.41 | 0.16±0.14 | 0.53±0.46 |
| Cd | | 3.86±2.53 | 1.41±1.25 | 3.11±2.52 | 2.35±5.72 | 0.22±0.17 | 0.71±0.74 |
| Tl | | 1.87±0.90 | 0.87±1.01 | 2.03±1.96 | 0.50±0.31 | 0.05±0.06 | 0.33±0.39 |
| Pb | | 121±59 | 55±52 | 104±81 | 36±19 | 9±6 | 29±26 |
| Th | | 0.09±0.05 | 0.06±0.03 | 0.09±0.06 | 0.02±0.01 | 0.01±0.01 | 0.01±0.01 |
| U | | 0.06±0.02 | 0.05±0.03 | 0.09±0.06 | 0.02±0.01 | 0.00±0.00 | 0.01±0.02 |
| Na | | 529±261 | 355±209 | 907±632 | 182±71 | 96±39 | 181±96 |
| Mg | | 153±94 | 105±47 | 236±143 | 43±13 | 15±8 | 24±15 |
| Al | | 516±324 | 338±154 | 588±406 | 141±82 | 130±60 | 136±93 |
| Mn | | 55.5±23.3 | 34.5±24.1 | 61.6±52.4 | 17.3±6.4 | 3.6±1.8 | 14.8±9.2 |
| Fe | | 755±314 | 573±336 | 883±538 | 269±71 | 98±28 | 234±139 |
| Ba | | 16.3±8.0 | 11.0±8.4 | 13.8±8.1 | 4.7±1.6 | 1.9±0.6 | 4.1±2.3 |

846 Table 5. The cross-validation (CV) performance of the $PM_{2.5}$ GLM.

| Periods | Adjusted $R^2$ | Observed mean values (μg $m^{-3}$) | Predicted mean values (μg $m^{-3}$) | Daily RMSE (μg $m^{-3}$) | Total RMSE (μg $m^{-3}$) | Relative errors (RE)* | Mean RE | RMSE of RE |
|---|---|---|---|---|---|---|---|---|
| CV1 | 0.748 | 94 | 82 | 53 | | 15% | | |
| CV2 | 0.798 | 59 | 57 | 20 | | 4% | | |
| CV3 | 0.783 | 44 | 52 | 19 | 33 | -15% | -5% | 14.6% |
| CV4 | 0.710 | 54 | 65 | 27 | | -17% | | |
| CV5 | 0.807 | 41 | 47 | 30 | | -13% | | |

*Relative error (RE) = (Predicted mean value - Observed mean value)/Predicted mean value × 100%.

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Table 6. The concentrations of air pollutants for the GLM with adjusted $R^2$ values higher than 0.6.

| Pollutants | Model descriptions | Adjusted $R^2$ |
|---|---|---|
| $PM_{2.5}$ | $\ln(PM_{2.5})=-0.48\ln WS-0.43\ln WS_{max(lag)}-0.00076PBL_{max}-0.11PREC+0.25\ln\Delta T_{(lag)}-0.14WS_{mode}+0.48WD/WS_{(lag)}+0.0043PBL_{min(lag)}-0.025PREC_{(lag)}-0.015SLP_{min}+19.51$ | 0.808 |
| EC | $\ln(EC)=0.60\ln WD/WS_{sum}-0.59\ln PBL-0.017PREC_{(lag)}+0.22\ln\Delta T-0.50\ln WS_{(lag)}+0.25\ln PBL_{max(lag)}-0.17$ | 0.780 |
| OC | $\ln(OC)= -0.44\ln WS+0.47WD/WS_{(lag)}-0.67\ln PBL-0.020PREC_{(lag)}+0.67\ln WD+0.17\ln\Delta T-0.65\ln RH_{max(lag)}+7.84$ | 0.751 |
| $SO_4^{2-}$ | $\ln(SO_4^{2-})=-0.99\ln WS_{(lag)}+0.066T_{min}-0.040PREC_{(lag)}-1.20\ln PBL+0.0011PBL_{(lag)}+0.019RH-0.12PREC+0.087WS_{max}+6.68$ | 0.795 |
| $NO_3^-$ | $\ln(NO_3^-)=-1.90\ln PBL-0.96\ln WS_{(lag)}+0.88WD+0.0045PBL_{min}-0.20PREC+0.12WS_{max}+1.57\ln RH+0.60\ln\Delta T_{(lag)}-1.22\ln RH_{max(lag)}-0.047\Delta T+9.32$ | 0.833 |
| $NH_4^+$ | $\ln(NH_4^+)=0.040RH-1.27\ln WS_{(lag)}-1.03\ln RH_{(lag)}-0.00075PBL_{max}-0.16PREC+0.33\ln\Delta T_{(lag)}+4.28$ | 0.813 |
| $Cl^-$ | $\ln(Cl^-)= -1.12\ln PBL-0.072T_{(lag)}+1.60\ln WD-2.32\ln RH_{max(lag)}+0.53\ln WD/WS_{sum(lag)}+14.69$ | 0.737 |
| $K^+$ | $\ln(K^+)= -0.75\ln PBL-0.66\ln WS_{(lag)}-0.020RH_{(lag)}+0.0056PBL_{min}-0.20WS_{mode}+0.33\ln\triangle T_{(lag)}-0.47\ln PBL_{max(lag)}-0.087PREC+0.66\ln RH+5.46$ | 0.717 |
| Pb | $\ln(Pb)= -0.61\ln WS-0.67\ln WS_{max(lag)}+0.36\ln\Delta T_{(lag)}-0.00062PBL_{max}-0.19WS_{mode}-0.030PREC_{(lag)}+5.39$ | 0.721 |
| Zn | $\ln(Zn)=-0.81\ln WS-0.41\ln WS_{max(lag)}-0.0016PBL-0.36\ln WS_{mode(lag)}+6.56$ | 0.627 |
| Mn | $\ln(Mn)=0.80WD/WS-0.98\ln PBL-0.043PREC_{(lag)}+0.57WD/WS_{(lag)}-0.017RH-0.023SLP+0.0030PBL_{min(lag)}+31.04$ | 0.656 |
| $SO_2$ | $\ln(SO_2)=-1.32\ln PBL-0.071PREC_{(lag)}-0.047PREC+0.29WD_{mode(lag)}-0.026RH-0.47\ln WS_{(lag)}+14.12\ln SLP_{max}-87.56$ | 0.803 |
| $NO_x$ | $\ln(NO_x)=0.014WD/WS_{sum}-0.030T_{min}+0.27\ln\Delta T-0.44\ln PBL-0.015PREC-0.012PREC_{(lag)}+5.30$ | 0.772 |

Table 7. The output indexes of the $PM_{2.5}$ GLM, including a model summary, analysis of variance (ANOVA), coefficients, and other indexes.

| Model Summary and ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| R | $R^2$ | Adjusted $R^2$ | Std. Error of the Estimate | Durbin-Watson | F | Sig.* |
| 0.910 | 0.828 | 0.808 | 0.411 | 1.910 | 41.763 | 0.000 |

| Coefficients | | | | | | |
|---|---|---|---|---|---|---|
| Model | Unstandardized Coefficients | | t | Sig.* | Collinearity Statistics | |
| | B | Std. Error | | | Tolerance | VIF |
| (Constant) | 19.512 | 6.871 | 2.840 | 0.006 | | |
| lnWS | -0.483 | 0.162 | -2.971 | 0.004 | 0.313 | 3.194 |
| $lnWS_{max(lag)}$ | -0.431 | 0.153 | -2.818 | 0.006 | 0.300 | 3.331 |
| $PBL_{max}$ | -0.001 | 0.000 | -6.747 | 0.000 | 0.395 | 2.534 |
| PREC | -0.110 | 0.029 | -3.735 | 0.000 | 0.618 | 1.618 |
| $ln\triangle T_{(lag)}$ | 0.247 | 0.083 | 2.975 | 0.004 | 0.662 | 1.512 |
| $WS_{mode}$ | -0.135 | 0.050 | -2.726 | 0.008 | 0.493 | 2.027 |
| $WD/WS_{(lag)}$ | 0.476 | 0.148 | 3.222 | 0.002 | 0.353 | 2.829 |
| $PBL_{min(lag)}$ | 0.004 | 0.001 | 3.510 | 0.001 | 0.407 | 2.459 |
| $PREC_{(lag)}$ | -0.025 | 0.009 | -2.796 | 0.006 | 0.707 | 1.415 |
| $SLP_{min}$ | -0.015 | 0.007 | -2.176 | 0.032 | 0.707 | 1.414 |

*The significance level is 0.05.

Table 8. The influence of the meteorological parameters included in the GLMs on pollutant concentrations[1].

| Parameters | Included in the GLM (times)[2] | $PM_{2.5}$ | EC | OC | $SO_4^{2-}$ | $NO_3^-$ | $NH_4^+$ | $Cl^-$ | $K^+$ | Pb | Zn | Mn | $SO_2$ | $NO_x$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PBL | 13 | - | - | - | - | +- | - | - | +- | - | - | - | - | - |
| $WS_{(lag)}$ | 9 | - | - | | - | - | - | | - | - | - | | - | |
| $PREC_{(lag)}$ | 8 | - | - | - | - | | | | | - | | - | - | - |
| PREC | 7 | - | | | - | - | - | | - | | | | - | - |
| WS | 7 | - | | - | + | + | | | - | - | - | | | |
| RH | 6 | | | | + | + | + | | + | | | - | - | |
| $PBL_{(lag)}$ | 5 | + | + | | + | | | | - | | | + | | |
| $RH_{(lag)}$ | 5 | | | - | | - | - | - | - | | | | | |
| T | 5 | | + | + | + | +- | | | | | | | | -+ |
| $T_{(lag)}$ | 5 | + | | | | | + | - | + | + | | | | |
| $WD/WS_{(lag)}$ | 4 | + | | + | | | | + | | | | + | | |
| SLP | 3 | - | | | | | | | | | | - | + | |
| WD | 3 | | | + | | + | | + | | | | | | |
| WD/WS | 3 | | + | | | | | | | | | + | | + |
| $WD_{(lag)}$ | 1 | | | | | | | | | | | | + | |

[1] "+" represents the positive correlation, and "-" represents the negative correlation between meteorological parameters and pollutant concentrations.

[2] If a parameter is included in the model for several times, it will be counted as one time.

Table 9. The percentage differences between the observed and GLM-predicted concentrations of the air pollutants during APEC and Parade.

| Pollutants | Units | During APEC | | | During Parade | | |
|---|---|---|---|---|---|---|---|
| | | Observed | Predicted | Percentage differences[1] | Observed | Predicted | Percentage differences[1] |
| $PM_{2.5}$ | | 48 | 67 | 28% | 15 | 20 | 25% |
| OC | | 11.2 | 12.6 | 11% | 4.0 | 3.7 | -8% |
| EC | | 1.7 | 2.7 | 37% | 0.8 | 1.2 | 33% |
| $SO_4^{2-}$ | μg $m^{-3}$ | 3.9 | 2.7 | -44% | 2.6 | 5.2 | 50% |
| $NO_3^-$ | | 10.6 | 19.0 | 44% | 1.5 | 3.4 | 56% |
| $NH_4^+$ | | 4.8 | 5.5 | 13% | 1.5 | 2.4 | 38% |
| $Cl^-$ | | 2.06 | 2.58 | 20% | 0.16 | 0.17 | 6% |
| $K^+$ | | 0.65 | 1.03 | 37% | 0.18 | 0.24 | 25% |
| Pb | | 55 | 70 | 21% | 9 | 17 | 47% |
| Zn | ng $m^{-3}$ | 128 | 171 | 25% | 20 | 41 | 51% |
| Mn | | 34.5 | 51.5 | 33% | 3.6 | 7.6 | 53% |
| $SO_2$ | ppb | 3.32 | 6.59 | 50% | 0.57 | 0.56 | -2% |
| $NO_x$ | | 45 | 102 | 56% | 13 | 20 | 35% |
| OC+EC | μg $m^{-3}$ | 12.9 | 15.3 | 16% | 4.8 | 4.9 | 2% |
| SNA | μg $m^{-3}$ | 19.3 | 27.2 | 29% | 5.6 | 11.0 | 49% |
| total S[2] | μmol $m^{-3}$ | 0.189 | 0.322 | 41% | 0.053 | 0.079 | 33% |

[1]Percentage difference = (Predicted - Observed)/Predicted × 100%.

[2]total S = $[SO_2] + [SO_4^{2-}]$.

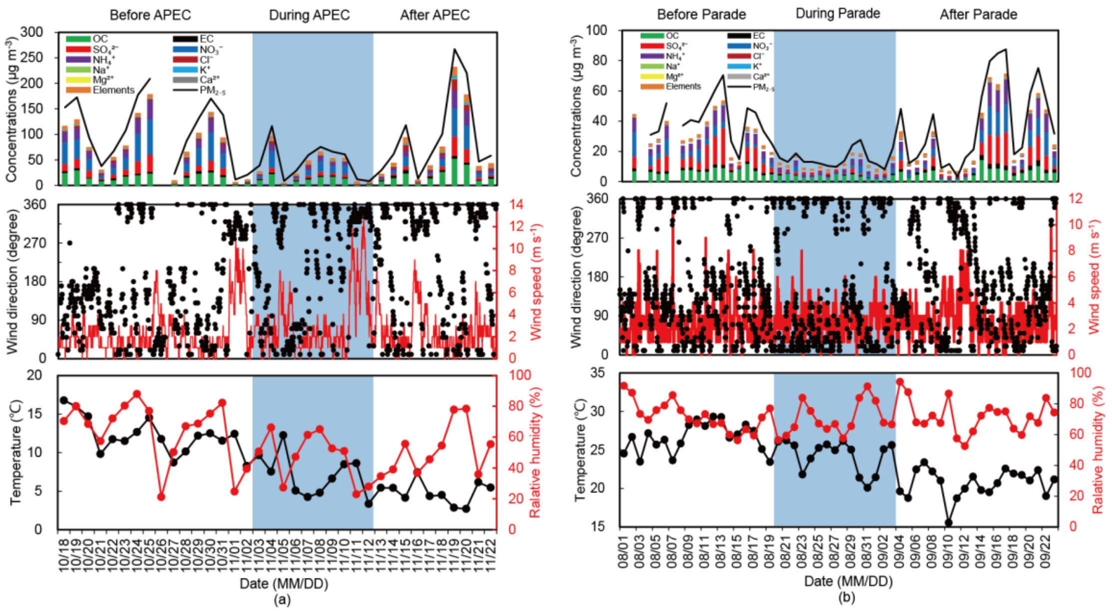



Figure 1. Time series of atmospheric particulate matter of aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) and the concentrations of its components, wind direction (WD), wind speed (WS), temperature (T), and relative humidity (RH) before, during, and after (a) APEC 2014 and (b) Parade 2015. The blue-shaded areas highlight the pollution control periods of APEC 2014 (3 November to 12 November 2014) and Parade 2015 (20 August to 3 September 2015).

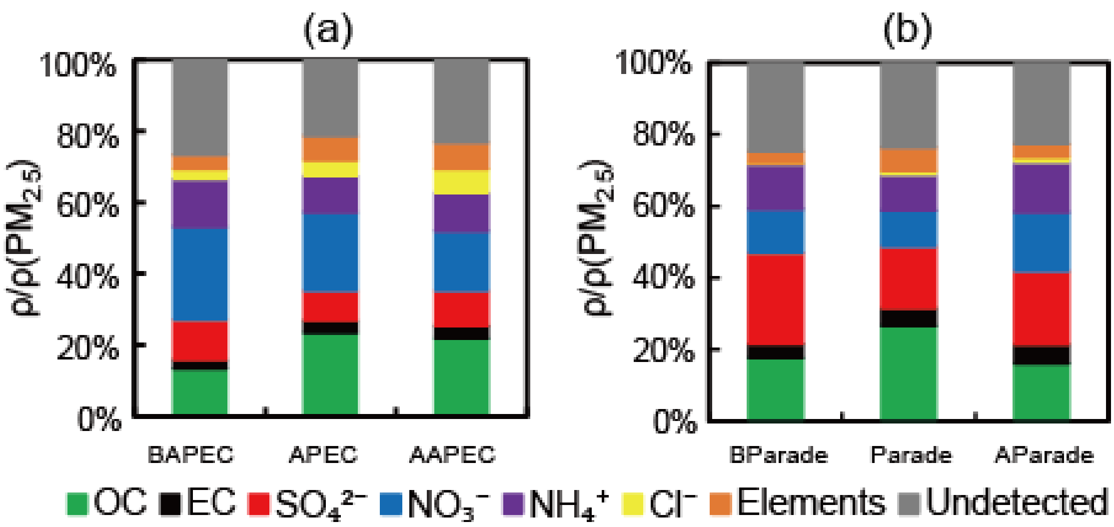



Figure 2. Proportions of the measured components in $PM_{2.5}$ during (a) APEC 2014 and (b) Parade 2015 campaigns, including organic carbon (OC), elemental carbon (EC), $SO_4^{2-}$, $NO_3^-$, $NH_4^+$, $Cl^-$ and elements. BAPEC/BParade: before APEC/Parade, AAPEC/AParade: after APEC/Parade.

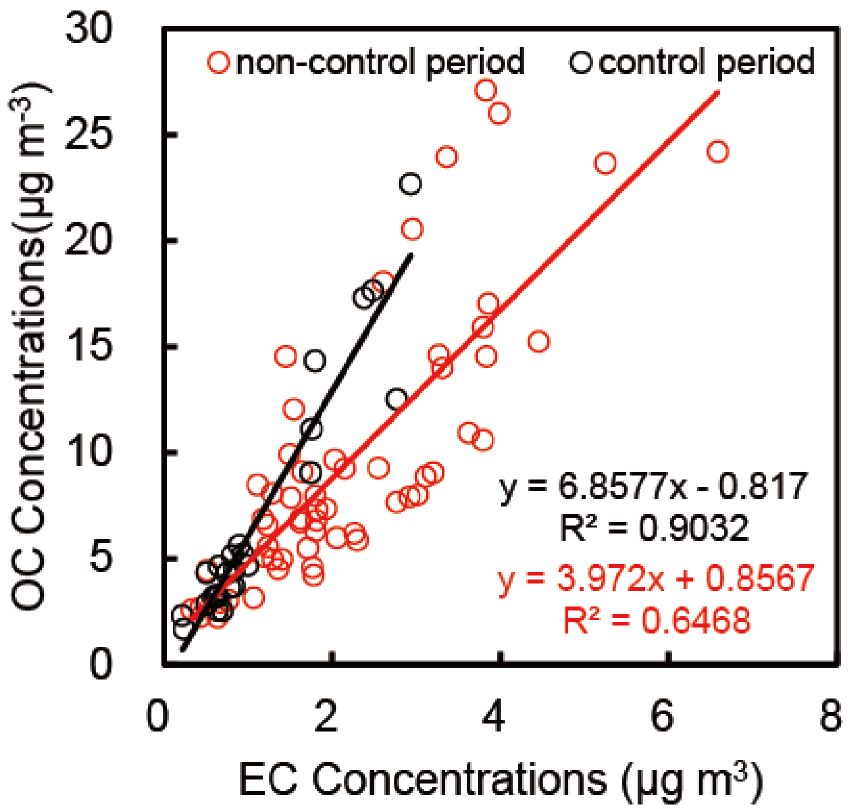



Figure 3. Scatter plot and correlations between organic carbon (OC: *y*-axis) and elemental carbon (EC: *x*-axis) concentrations of $PM_{2.5}$ during the APEC 2014 and Parade 2015 campaigns. The red symbols denote the non-control period and the black symbols denote the pollution control period. The linear regression equations and $R^2$ values are given for these two campaigns.

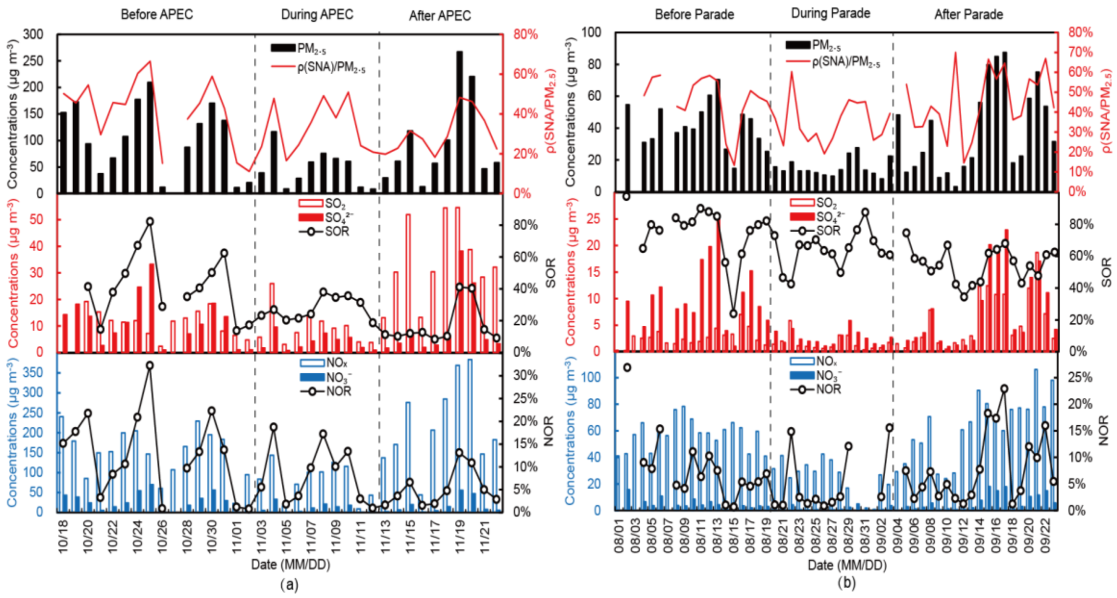
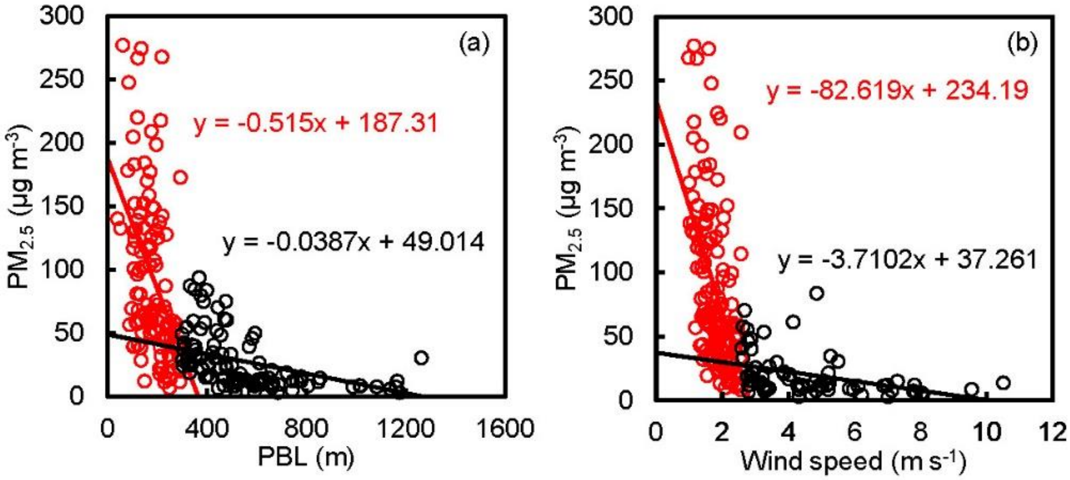



Figure 4. Upper panel: time series of the proportion of sulphate, nitrate, and ammonia (SNA) in $PM_{2.5}$ ($\rho(SNA/PM_{2.5})$) and $PM_{2.5}$ mass concentrations (the black bar represents $PM_{2.5}$ concentration and the red line represents $\rho(SNA/PM_{2.5})$). Middle panel: $SO_2$, $SO_4^{2-}$, and SOR ($[SO_4^{2-}]/([SO_2]+[SO_4^{2-}])$). Lower panel: $NO_x$, $NO_3^-$, and NOR ($[NO_3^-]/([NO_x]+[NO_3^-])$). Data collected during the (a) APEC 2014 and (b) Parade 2015 campaigns. The hollow bars represent gaseous pollutants (red for $SO_2$, blue for $NO_x$), and solid bars represent secondary inorganic ions (red for sulphate, blue for nitrate).




Values of intersections

| PBL (m) | Wind speed (m $s^{-1}$) |
|---|---|
| 290 | 2.50 |

Figure 5. Scatter plot showing the correlation between daily $PM_{2.5}$ concentrations (*y*-axis) and (a) daily PBL heights (*x*-axis) and (b) daily WSs (*x*-axis) during the sampling periods. The red and black scattered points represent different distribution areas. The piecewise function regression equations and the corresponding values of PBL height and WS according to the intersections are given.

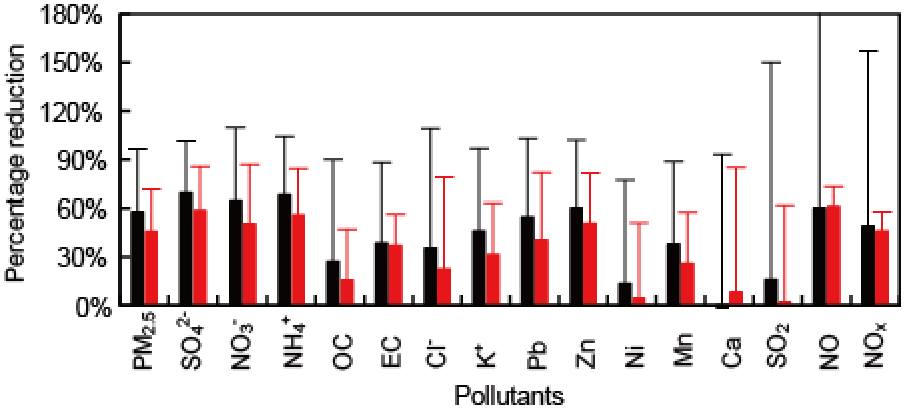



Figure 6. The percentage reductions of pollutant concentrations under similar meteorological conditions. The black bars represent the percentage reductions calculated by comparing the decreased average concentrations during APEC to the average concentrations before APEC. The red bars represent the percentage reductions calculated by comparing the decreased average concentrations during APEC to the average concentrations before APEC based only on the days with stable meteorological conditions. The whiskers represent the standard deviations of the percentage reductions.

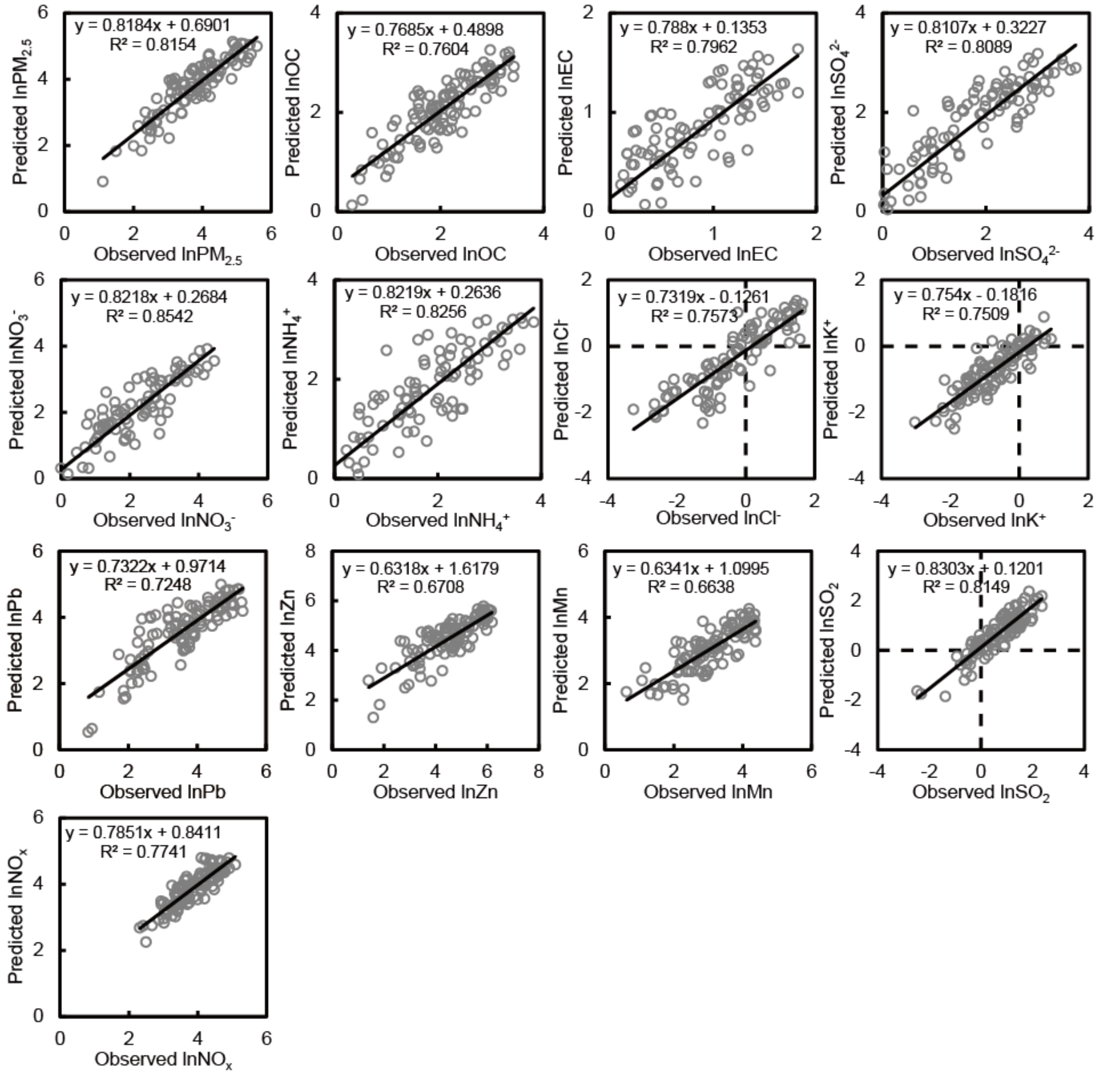



Figure 7. Scatter plot and correlations between GLM-predicted (*y*-axis) and observed (*x*-axis) concentrations of pollutants transformed to a natural log. The linear regression equations and $R^2$ values are given.

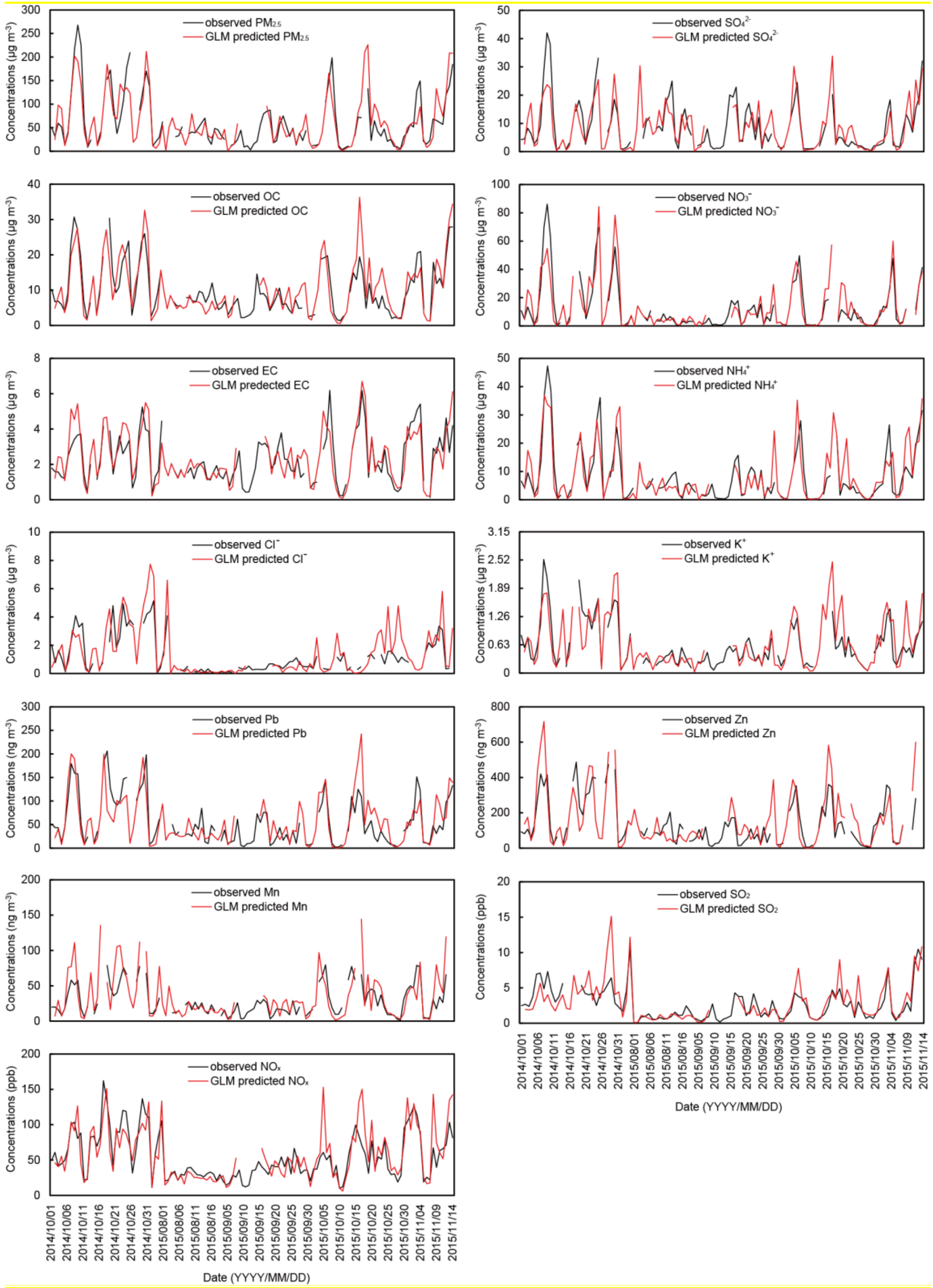



Figure 8. Time series of the observed (in black line) and GLM-predicted pollutant concentrations (in red line).

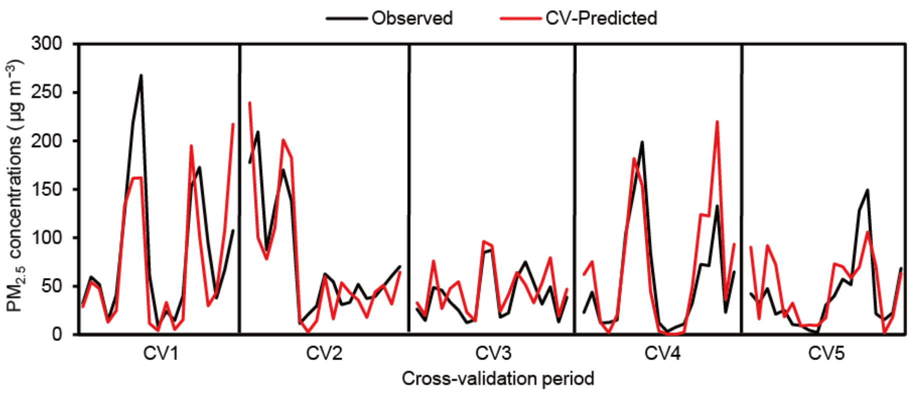



Figure 9. Time series of the observed and cross-validation (CV) predicted $PM_{2.5}$ concentrations during five CV periods. The black line represents the observed $PM_{2.5}$ concentration and the red line represents the CV-predicted $PM_{2.5}$ concentration.