Model analysis of secondary organic aerosol over China with a regional air quality modeling system (RAMS-CMAQ)

LI Jia-Lin\textsuperscript{a,b}, ZHANG Mei-Gen\textsuperscript{a,c}, GAO Yi\textsuperscript{b} and CHEN Lei\textsuperscript{a,b}

\textsuperscript{a}State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry (LAPC), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), Beijing, China; \textsuperscript{b}College of Earth Science, University of Chinese Academy of Sciences, Beijing, China; \textsuperscript{c}Center for Excellence in Urban Atmospheric Environment, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, China

ABSTRACT
The regional air quality modeling system RAMS-CMAQ was updated to incorporate secondary organic aerosol (SOA) production from isoprene and sesquiterpene and to account for the SOA production rate dependence on NO\textsubscript{x} and SOA aging. The system was then used to simulate spatiotemporal distributions of SOA concentration and its major constituents over China in winter. Modeled monthly mean SOA concentrations were high in central and eastern China and low in western regions. The highest SOA appeared in regions from Beijing–Tianjin–Hebei (BTH) to the middle reaches of the Yangtze River and areas from Sichuan Basin to the southwest border of China, where SOA contributions were less than 10\% of the organic aerosol (OA). The lowest concentration was in the Qinghai–Tibet Plateau, accounting for 20\%–30\% of OA. It is notable that contributions from anthropogenic precursors to SOA were significant in winter, especially the wide areas of central and eastern China with contributions generally varying from 50\% to 80\% of the total SOA. Beijing was used as an example location representative of the heavily polluted BTH area for analysis of major components of SOA. Though the modeled concentration of SOA was still underestimated compared to the observations, it still showed that xylene and toluene were the two greatest contributors to anthropogenic SOA, which was in agreement with the observations. SOA produced from monoterpene was the greatest contributor to biogenic SOA due to the high mass yield of monoterpene, followed by isoprene. More than 57\% of SOAs were aged, which may increase the extinction effect of SOA.

1. Introduction
Organic aerosols (OAs) comprise a significant fraction (20\%–90\%) of the total fine particulate mass in the atmosphere (Zhang et al. 2007). It is well known that OAs significantly influence human health, air quality, and climate change; thus, it has attracted increasing attention in recent years. OAs can be divided into two categories: primary organic aerosol (POA) and secondary organic aerosol (SOA). POA is emitted directly from anthropogenic and biogenic sources, whereas SOA is formed from the oxidation of volatile or semi-volatile organic compounds (SVOCs) in the atmosphere (Seinfeld and Pankow 2003). Because of the poor understanding of the various sources, chemical formation and transformation mechanisms, and physicochemical characterization (Hallquist et al. 2009; Zhang et al. 2007), there are many uncertainties remaining in our knowledge of OAs, among which the formation and evolution of SOAs are the least known.

During the past twenty years, significant efforts have been made to investigate SOAs. A number of field observational studies and laboratory chamber experiments of SOAs have been carried out domestically and abroad.
to investigate their properties, sources, chemical aging characteristics as well as diurnal and seasonal variations (Cao et al. 2007; Duan et al. 2007; Huang et al. 2014; Riva et al. 2015; Zhang et al. 2008). Additionally, models have been used to predict spatiotemporal distribution and the properties of SOAs (Fu et al. 2008; Han et al. 2008; Jiang et al. 2012). However, it has been noted that current atmospheric models underestimate SOA mass. Heald et al. (2005) showed that concentrations of measured organic carbon (OC) over the northwest Pacific during the ACE-Asia campaign were 10–100 times higher than that simulated by a global chemical transport model with large differences in SOA estimations. As we can see, the underestimation of SOA in models is still quite common, and the most likely causes are (1) the uncertainty in emission inventories of volatile organic gases; (2) missing precursors, e.g. emissions of semi-volatile organic gases (Robinson et al. 2007); (3) the exclusion of emissions from regions outside of the studied areas (Jiang et al. 2012); (4) missing physical/chemical processes that contribute to SOA formation (Fu et al. 2008; Robinson et al. 2007); and (5) limited model resolution (e.g. Qian, Gustafson, and Fast 2010).

In order to improve SOA simulation, much work has been conducted. The use of the volatility basis-set (VBS) approach (Donahue et al. 2006), instead of the traditional two-product method (Odum et al. 1996), has been a major improvement (Han et al. 2016; Lin et al. 2016). In their results, the VBS method indeed increased SOA concentrations, but the models do not capture time variation well. So, further understanding and improvement of SOA mechanisms are needed to enhance the performance of SOA simulation.

In this study, RAMS-CMAQ was updated to use the most recent SOA production mechanisms, which include incorporating SOA production from isoprene and sesquiterpene, accounting for SOA production rate dependence on nitrogen oxides and SOA aging. The improved model was applied to investigate the spatiotemporal distributions of SOA concentration as well as its contribution to atmospheric aerosols over China in February 2014.

### 2. Model description

In this study, CMAQ version 4.7.1 was chosen as the base model and was configured to use the gas-phase chemical mechanism model SAPRC99 (the 1999 Statewide Air Pollutant Research Center) (Carter 2000). Compared to previous versions, CMAQ v4.7.1 has been modified to incorporate two new groups of SOA production pathways: (1) SOA formation from new precursors such as benzene, isoprene, and sesquiterpenes; and (2) SOA formation from new mechanisms, such as NOx-dependent SOA yields from aromatics, acid-catalyzed SOA yields from isoprene, in-cloud SOA formation, and aging of SOA. Furthermore, it allows for the assignment of SOA mass to individual volatile organic compounds (VOCs).

In this version, SOA is produced from seven VOCs species: long-chain alkanes, high-yield aromatics (toluene), low-yield aromatics (xylene), benzene, isoprene, monoterpenes and sesquiterpenes. There are 19 secondary organic products during the formation process, of which 12 species are semi-volatile. Semi-volatile VOCs (SVOCs), produced from the oxidation of VOCs, are represented by the two-product model and then absorbed into an organic particulate phase (i.e. semi-volatile SOA) through gas/particle partitioning behavior (Pankow 1994). Unlike the semi-volatile SOA, nonvolatile SOA do not partition back to the gas phase. There are four types of nonvolatile SOAs: (1) low-NOx aromatic SOA, (2) acid-enhanced isoprene, (3) oligomers formed through particle-phase reactions, and (4) SOAs from in-cloud oxidation processes. A detailed description was depicted in (Carlton et al. 2010).

The emission sources used in this model were obtained by several ways. Anthropogenic emissions of VOCs, black carbon (BC), OC, SO2, NOx, and particle matters were obtained from monthly-based emission inventory of China in 2010 with a spatial resolution of 0.25° × 0.25° and divided into four categories, namely power, industry, residential, and transport (Lu, Zhang, and Streets 2011). NOx and ammonia from soil were provided by the Global Emissions Inventory Activity (GEIA) 1° × 1° monthly inventory (Benkovitz et al. 1996). The open biomass burning emissions (from forest wildfires, savanna burning, and agriculture waste burning) were adopted from the Global Fire Emissions Database Version 2 (Randerson et al. 2007). Besides, emissions of dust and sea salt were estimated online (Gong 2003; Han et al. 2004) in the modeling system.

Our CMAQ model was driven by meteorology fields simulated by RAMS. The model domain was 6654 × 5440 km² for CMAQ (shown in Figure 1) on a rotated polar-stereographic map projection centered at (35°N, 110°E) with a 64-km-grid-cell. The other detailed model configuration information can be found in Han et al. (2014).

### 3. Results and discussion

In this study, we chose the month of February 2014 as the modeling period because many places in China experienced heavy haze pollution during this episode, especially the region of Huabei.

#### 3.1. Model evaluation

Meteorological factors have important effects on photochemical and aerosol processes. In order to understand the model performance, daily mean meteorological data of 12
stations were used for comparison. The monitoring data from the twelve surface stations (as shown in Figure 1) of the Chinese National Meteorological Center (CNMC) were downloaded from the website (http://www.escience.gov.cn/metdata/page/index.html).

The observations and model predictions of the daily-average temperature ($T$), relative humidity (RH), wind speed (WS), and direction of maximum wind speed (WD) at the 12 stations in February are presented in the figures that not shown. RAMS generally predicted the magnitude and day-to-day variation of $T$, RH, and WS well. As shown in Table 1(a), average for all 12 stations, the monthly mean observations of $T$, RH, and WS were 2.74 °C, 67.12%, and 2.21 m s$^{-1}$, respectively, while mean simulations for these three factors were 2.47 °C, 67.31%, and 2.14 m s$^{-1}$, respectively. The differences of the standard deviations of the three factors between measurements and simulations were small. The values of normalized mean bias (NMB) for $T$, RH, and WS were $-9.92\%$, $0.28\%$, and $-3.10\%$, respectively, with the correlation coefficients ($R$) being $0.97$, $0.84$, and $0.62$, respectively. However, the simulated directions of maximum wind speed did not coincide well with the observed data. As presented in Table 1(b), the fraction of samples with an absolute error $\leq 22.5^\circ$ between simulation and observation was 29.46%, and the fraction of samples with an absolute error $\leq 11.25^\circ$ was 14.28%. The most probable reason is the different time resolution (every 10 min for measurements and 1 h for simulations). Nevertheless, variance of the predicted wind direction was similar to the measurements at most sites with $R = 0.53$. As a whole, the predicted and measured meteorological data showed good consistency, and the model can reasonably simulate the variations of meteorological phenomena.

**Figure 1.** Geographic locations of CNMC measurement stations in the model domain.

Note: 1: Huhhot; 2: Datong; 3: Shijiazhuang; 4: Tianjin; 5: Baoding; 6: Jinan; 7: Changsha; 8: Hangzhou; 9: Nanchang; 10: Fuzhou; 11: Guangzhou; 12: Beijing.

**Table 1.** Statistical summary of the comparison of the daily average meteorological factors and the hourly PM$_{2.5}$ mass concentrations between observations and simulations at 12 stations in February 2014.

| (a) | | | | | | |
|---|---|---|---|---|---|---|
| | $N$ | $C_{\text{obs}}$ | $C_{\text{mod}}$ | $\sigma_{\text{obs}}$ | $\sigma_{\text{mod}}$ | NMB (%) | $R$ |
| $T$ (°C) | 336 | 2.74 | 2.47 | 7.52 | 7.38 | $-9.92$ | 0.97 |
| RH (%) | 336 | 67.12 | 67.31 | 17.97 | 18.22 | 0.28 | 0.84 |
| WS (m s$^{-1}$) | 336 | 2.21 | 2.14 | 1.11 | 1.38 | $-3.10$ | 0.62 |
| PM$_{2.5}$ (µg m$^{-3}$) | 3563 | 105.36 | 146.27 | 90.72 | 103.86 | 38.83 | 0.62 |

| (b) | | | | | |
|---|---|---|---|
| | $N$ | $|\Delta x| \leq 22.5^\circ$ (%) | $|\Delta x| \leq 11.25^\circ$ (%) | $R$ |
| WD | 336 | 29.46 | 14.28 | 0.53 |

Notes: $N =$ Number of samples; $C_{\text{obs}} =$ total mean of observations; $C_{\text{mod}} =$ total mean of simulations; $\sigma_{\text{obs}} =$ standard deviation of observations; $\sigma_{\text{mod}} =$ standard deviation of simulations; NMB = normalized mean bias; $R =$ correlation coefficient between observation and simulation; $|\Delta x| \leq 22.5^\circ =$ the fraction of simples that the absolute error is not more than $22.5^\circ$; $|\Delta x| \leq 11.25^\circ =$ same as $|\Delta x| \leq 22.5^\circ$ but for $11.25^\circ$. 
Figure 2(a) shows the spatial distribution of monthly averaged SOA mass concentration and wind field. As a whole, in China, the concentration of SOA was high in central and eastern regions and low in the western region. SOA concentration generally varied from 0.5 to 1 μg m⁻³ in central and eastern areas, with maximum (1–2 μg m⁻³) in portion of regions from the Beijing–Tianjin–Hebei (BTH) area to the middle reaches of the Yangtze River, regions from southeast of Sichuan province to the China–Vietnam border and China–Burma border as well as Hainan Province. The model results were lower than the observed ranges of 3.1–29.9 and 1.4–19.6 μg m⁻³, respectively (Cao et al. 2007; Dan et al. 2004; Li and Bai 2009; Wang et al. 2015), due to the uncertainties in the ratio of OC to elemental carbon (EC) when calculating observed SOC, and the underestimation of emission inventories in our model. The simulated SOA concentration in western region of China was less than 0.2 μg m⁻³, mainly due to low emissions of related precursors. Outside China, in northeast India, central Burma, Thailand and Cambodia etc., we can also find high SOA concentrations (≥3 μg m⁻³) because of large amount

To further evaluate the performance of the model during the period, simulated hourly PM₉.₅ results were compared with the observations provided by the China National Environmental Monitoring Centre (CNEMC). For all the stations, though simulated values were mostly higher than the observations (with mean bias being approximately 40 μg m⁻³), the model had a relatively good ability to capture the variations and trends of fine aerosol mass concentrations. As presented in Table 1(a), the correlation coefficient was 0.62 between the measurements and simulations, with the standard deviations being 90.72 and 103.86 μg m⁻³ for the observed and predicted concentrations, respectively. Above all, it indicated a generally good ability of the model to predict aerosol concentrations.

3.2. Spatial distribution characteristics of predicted SOA

The OA mass concentrations were simulated in μg m⁻³, but measured in μgC m⁻³. For comparison, SOA and OA in Figure 2(a) and (b) were actually SOC and OC.
of biomass combustion which may release biogenic VOCs (Rouviere et al. 2006) to produce SOA.

Figure 2(b) presents the spatial distribution of monthly averaged OA mass concentration and the monthly mean fraction of SOA to OA (SOA/OA). The distribution of OA is similar to SOA: high in the central and eastern regions and low in the western region. The simulated OA concentration was generally in the range of 1–25 μg m⁻³ in central and east China and reached the highest levels (25–35 μg m⁻³) in the BTH area due to large amount of anthropogenic emissions. The model result in BTH area is comparable to values of (27.2 ± 15.3–38.9 ± 18.4) μg m⁻³ observed by Cao et al. (2007). OA concentrations in eastern Sichuan Basin were also high (25–35 μg m⁻³), within the observed range of (18.3 ± 8.6–76.7 ± 24.6) μg m⁻³ (Cao et al. 2007; Chen et al. 2014). The reason for the high concentrations is that Sichuan Basin is surrounded by mountains and has some of the lowest wind speeds (Chen and Xie 2012), which is not conducive to the diffusion of pollutants. In addition to the increased carbon emissions from domestic heating and the stable atmospheric conditions, high relative humidity may also contribute to the high OA concentration. In western China, OA concentrations were generally lower than 2 μg m⁻³, although concentrations in some northwestern areas were 2–10 μg m⁻³ mainly due to relatively high anthropogenic emissions from surrounding areas with dense population. The lowest concentration (≤0.2 μg m⁻³) appeared in the center of Qinghai–Tibet Plateau resulting from very low source emissions. Outside China, in western Burma, northeastern India and the Thailand–Burma border, we also found high OA concentrations (>25 μg m⁻³) because of biomass combustion, including burning of agricultural waste and fuel wood in Southeast Asia.

As illustrated in Figure 2(b), the SOA fraction ranged from less than 6% to 30% in China, with a relatively higher contribution (generally 10%–30%) in western regions and lower fraction (<10%) mostly in central and eastern developed areas. The contribution of SOA to OA in south China (6%–20%) and north China (<10%) were within the range of field measurements of 6%–60% and 8%–32%, respectively (Cao et al. 2003, 2007; Niu et al. 2006; Zhao, Dong, Yang et al. 2013). Both the simulated and observed results indicated that the fraction in the north was lower than in the south due to the lower temperatures and reduced sunlight. The lowest fraction (<6%) mainly appeared in regions where the concentrations of OA were relatively high (e.g. Sichuan Basin and BTH area etc.). Similarly, in the western regions, the SOA/OA fraction was also the lowest in areas where OA concentration was the highest. This illustrates that emission of POA was the main contributor to high OA. The highest fraction (20%–30%) appeared in Tibet–Qinghai area due to low primary source emissions. Outside China, the SOA fraction was quite large (20%–50%) over wide areas of the western Pacific Ocean and the northern Indian Ocean due to relatively lower POA emissions and greater oxidation of SOA transported from upwind areas. However, among the areas of high OA concentrations, such as northeast India and central Burma, SOA/OA was less than 20%.

As shown in Figure 2(c), the distribution of PM$_{2.5}$ mass concentration was also similar to the OA and SOA concentrations. The highest concentration (100–135 μg m⁻³) occurred in BTH and Sichuan Basin and were within the observed range of (126.5 ± 66.1–179.4 ± 87.8) μg m⁻³ and (158 ± 51–311.8 ± 114.1) μg m⁻³ (Cao et al. 2007; Tao et al. 2014) respectively. The lowest (<2 μg m⁻³) occurred in the Tibet–Qinghai Plateau. Outside China, PM$_{2.5}$ in east India was relatively high with the concentration varying from 40 μg m⁻³ to 80 μg m⁻³ due to biomass burning and transportation in the western India with its high fossil fuel consumption and particulate emissions (Reddy and Venkataraman 2002). As is evident in Figure 2(c), as a whole, the OA fraction was high in central and eastern China (generally 20%–30%) and low (approximately 10%–20%) in western regions. As a result, the contribution of SOA to PM$_{2.5}$ (SOA/PM$_{2.5}$) in the areas with low and high concentrations were less than 6% and less than 3%, respectively. Outside China, the OA/PM$_{2.5}$ ratio was the highest in central and south Burma and reached up to 80%–90% due to large amount of biomass burning in these areas.

As presented in Figure 2(d), because of large amount of anthropogenic VOCs emissions, anthropogenic SOA (ASOA) dominated SOA over wide areas of central and east China (50%–80%) in the winter time, with the fraction reaching more than 60% in the regions from the Huabei plain to the upper reaches of the Yellow River as well as the middle and lower reaches of the Yangtze River. The modeled distribution was similar to that predicted by Jiang et al. (2012). It was notable that the contribution to SOA from anthropogenic sources was significant in the regions of north of the Huabei plain, the Bohai Sea, and the Yellow Sea with contributions up to 80%, resulting from the atmospheric barrier of the Taihang Mountains and transport of clockwise horizontal airflow. The fraction of ASOA to SOA in portions of western remote areas of China can also reach 40%–50% because of the transport of ASOA from neighboring areas. Outside China, the ASOA fraction was also quite high (50%–70%) in eastern India, resulting from the transport from the western India as well as the Himalayas preventing pollutant transmission to the northeast. In the western Pacific Ocean and the northern Indian Ocean, the fraction of anthropogenic SOA can reach 60%. However, the fraction in south Burma and Cambodia was small (<10%) because of high biomass burning (Rouviere et al. 2006).
3.3. Major components of SOA

The BTH area always experiences heavy pollution in winter, so we took Beijing (BJ, 39.8° N, 116.47°E) as an example site to analyze the major components of SOA in this area. SOA was seriously underestimated compared to the observation (0.93 μg m⁻³ vs. 8.66–23.1 μg m⁻³) with the concentration difference being a multiple of 9.3–24.8 (Dan et al. 2004; Duan et al. 2005; Zhao, Dong, He et al. 2013). This discrepancy may result from the underestimation of emission inventories in the areas with dense population and high anthropogenic emissions (Liu et al. 2012). In Beijing, the contribution to SOA from anthropogenic sources was approximately 72.39% with the two most important anthropogenic VOC precursors being xylene and toluene. This is consistent with the observations that the benzene series is one of the main VOCs compounds in the BTH area, with the major constituents including benzene, xylene and toluene (Cao et al. 2012; Jiang et al. 2015; Zhou, Hao, and Wang 2011). Here, SOA that formed from aromatic compounds (including benzene, xylene, and toluene) accounted for more than 27% of total SOA, which was approximately 6.0 times more than the contribution from long-chain alkanes. Among BSOA components, SOA formed from monoterpenes was the major contributor, followed by that from isoprene, with fractions being 8.74% and 1.27%, respectively. This may result from the higher mass yield from monoterpenes (Lane, Donahue, and Pandis 2008). SOA produced from sesquiterpenes was negligible, with a fraction of approximately 0.04%, probably due to its low emission among biogenic VOCs (Oderbolz et al. 2013). Aged SOA was produced from oligomerization of SOA in the condensed phase. Its properties, especially the optical property, may change through the aging process. In this study, aged SOA accounted for more than 57% of the total SOA, suggesting the greater extinction effect of SOA in Beijing, which may give rise to the lower visibility during heavy pollution days.

4. Conclusions

In this study, we used RAMS-CMAQ with the most recent SOA production mechanisms to investigate spatial mass concentration distributions of SOAs as well as their contribution to total atmospheric aerosols over China in February 2014.

In China, the distribution of the mean SOA concentration for the month was similar to OA and PM$_{2.5}$ concentrations, which were high in the central and eastern regions and low in the western region. The highest concentrations were mainly concentrated in the areas around the middle reaches of the Yellow River and the Yangtze River (e.g. BTH area) as well as Sichuan Basin, while the lowest generally occurred in the Qinghai-Tibet Plateau. SOA concentration generally varied from 0.5 μg m⁻³ to 1 μg m⁻³ in the central and eastern areas with maximum concentrations being 1–2 μg m⁻³, and were not more than 0.2 μg m⁻³ in western China because of low emissions of precursors. Though the high SOA concentration was accompanied by high OA and PM$_{2.5}$, SOA/OA and SOA/PM$_{2.5}$ in these areas (like BJ regions and Sichuan Basin) were less than 10% and less than 3%, respectively. SOA/OA, and SOA/PM$_{2.5}$ were 10%–30% and less than 6%, respectively, in the low concentration areas like the Tibet–Qinghai Plateau.

Anthropogenic SOA dominated SOA over wide areas of central and eastern China, with contributions of more than 60%. In portions of the remote western areas of China, the fraction can also reach 40%–50%.

In terms of Beijing, the contribution to SOA from anthropogenic sources was approximately 72.39% with the two greatest contributions coming from xylene and toluene. Among BSOA components, SOA produced from monoterpenes was the major contributor, followed by SOA from isoprene, with fractions of 8.74% and 1.27%, respectively. In this study, aged SOA, produced from oligomerization reactions of SOA, accounted for more than 57%, suggesting the greater extinction effect of SOA.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the ‘Strategic Priority Research Program (B)’ of the Chinese Academy of Sciences [XDB05030105, XDB05030102], [XDB05030103]; the National Basic Research Program of China [2014CB953802].

References

Benkovitz, C. M., M. T. Scholtz, J. Pacyna, L. Tarrason, J. Dignon, E. C. Voldner, P. A. Sprio, J. A. Logan, and T. E. Graedel. 1996. “Global Gridded Inventories of Anthropogenic Emissions of Sulfur and Nitrogen.” *Journal of Geophysical Research: Atmospheres* 101 (D22): 29239–29253.

Cao, J. J., S. C. Lee, K. F. Ho, X. Y. Zhang, S. C. Zou, K. Fung, J. C. Chow, and J. G. Watson. 2003. “Characteristics of Carbonaceous Aerosol in Pearl River Delta Region, China during 2001 Winter Period.” *Atmospheric Environment* 37 (11): 1451–1460.

Cao, J. J., S. C. Lee, J. C. Chow, J. G. Watson, K. F. Ho, R. J. Zhang, Z. D. Jin, et al. 2007. “Spatial and Seasonal Distributions of Carbonaceous Aerosols over China.” *Journal of Geophysical Research-Atmospheres* 112 (D22), doi:10.1029/2006jd008205.

Cao, W., J. Shi, B. Han, X. Wang, Y. Peng, W. Qiu, L. Zhao, and Z. Bai. 2012. “Composition and Distribution of Vocs in the Ambient Air of Typical Cities in Northern of China.” *China Environmental Science* 32 (2): 200–206.
Riva, M., E. S. Robinson, E. Perraudin, N. M. Donahue, and E. Villenave. 2015. “Photochemical Aging of Secondary Organic Aerosols Generated from the Photooxidation of Polycyclic Aromatic Hydrocarbons in the Gas-phase.” Environmental Science & Technology 49 (9): 5407–5416.

Robinson, A. L., N. M. Donahue, M. K. Shrivastava, E. A. Weitkamp, A. M. Sage, A. P. Griephop, T. E. Lane, J. R. Pierce, and S. N. Pandis. 2007. “Rethinking Organic Aerosols: Semivolatile Emissions and Photochemical Aging.” Science 315 (5816): 1259–1262.

Rouviere, A., G. Brulfert, P. Baussand, and J. P. Chollet. 2006. “Monoterpene Source Emissions from Chamonix in the Alpine Valleys.” Atmospheric Environment 40 (19): 3613–3620.

Seinfeld, J. H., and J. F. Pankow. 2003. “Organic Atmospheric Particulate Material.” Annual Review of Physical Chemistry 54: 121–140.

Tao, J., J. Gao, L. Zhang, R. Zhang, H. Che, Z. Zhang, Z. Lin, J. Jing, J. Cao, and S. C. Hsu. 2014. “PM$_{2.5}$ Pollution in a Megacity of Southwest China: Source Apportionment and Implication.” Atmospheric Chemistry and Physics 14 (16): 8679–8699.

Wang, J., S. S. H. Ho, J. Cao, R. Huang, J. Zhou, Y. Zhao, H. Xu, et al. 2015. “Characteristics and Major Sources of Carbonaceous Aerosols in PM$_{2.5}$ from Sanya, China.” Science of the Total Environment 530: 110–119.

Zhang, Q., J. L. Jimenez, M. R. Canagaratna, J. D. Allan, H. Coe, I. Ulbrich, M. R. Alfarra, et al. 2007. “Ubiquity and Dominance of Oxygenated Species in Organic Aerosols in Anthropogenically-Influenced Northern Hemisphere Midlatitudes.” Geophysical Research Letters 34 (13). doi:10.1029/2007gl029979.

Zhao, P., F. Dong, Y. Yang, D. He, X. Zhao, W. Zhang, Q. Yao, and H. Liu. 2013. “Characteristics of Carbonaceous Aerosol in the Region of Beijing, Tianjin, and Hebei, China.” Atmospheric Environment 71: 389–398.

Zhao, P. S., F. Dong, D. He, X. J. Zhao, X. L. Zhang, W. Z. Zhang, Q. Yao, and H. Y. Liu. 2013. “Characteristics of Concentrations and Chemical Compositions for PM$_{2.5}$ in the Region of Beijing, Tianjin, and Hebei, China.” Atmospheric Chemistry and Physics 13 (9): 4631–4644.

Zhou, Y., Z. Hao, and H. Wang. 2011. “Pollution and Source of Atmospheric Volatile Organic Compounds in Urban-rural Juncture Belt Area in Beijing.” Chinese Journal of Environmental Science 32 (12): 3560–3565.