Supplement of Atmos. Chem. Phys., 17, 9187–9203, 2017
https://doi.org/10.5194/acp-17-9187-2017-supplement

Atmospheric Chemistry and Physics
Open Access
EGU

Supplement of

Chemical composition of ambient $PM_{2.5}$ over China and relationship to precursor emissions during 2005–2012

Guannan Geng et al.

Correspondence to: Qiang Zhang (qiangzhang@tsinghua.edu.cn)

Collection of ground-based $PM_{2.5}$ and chemical compositions measurements from literatures

In this study, we collected $PM_{2.5}$ and chemical composition measurements for 2005–2012 from literatures to evaluate our estimations. The sources of the data, site locations, sampling period, and other information are all listed in Table S1.

GEOS-Chem model

In this work, we used the nested-grid GEOS-Chem model v9-01-02 over Southeast Asia to simulate the conversion factors between $PM_{2.5}$ species and AOD, as well as tropospheric SO_2 and NO_2 column densities. The nested-grid model, which covers China and most of its surrounding countries (11°S–55N, 70–150E), has a spatial resolution of 0.5° lat × 0.667° lon with 47 vertical layers (Chen et al., 2009). The lateral boundary conditions for the nested model were provided by the associated global simulations with horizontal resolution of 2° lat × 2.5° lon. Both global and nested simulations were driven by the assimilated GEOS-5 meteorology from the Goddard Earth Observing System (GEOS) at the NASA Global Modeling and Assimilation Office (GMAO; http://gmao.gsfc.nasa.gov/). A correction to the GEOS-5 predicted nocturnal mixed layer depth was applied, as described in Heald et al. (2012) and Walker et al. (2012).

The model was run with the full HO_x-NO_x-VOC-ozone-aerosol chemistry (Bey et al., 2001; Park et al., 2004), which includes the sulfate-nitrate-ammonium system (Park et al., 2006), primary (Park et al., 2003) and secondary (Liao et al., 2007) carbonaceous aerosols, mineral dust (Fairlie et al., 2007) and sea salt (Alexander et al., 2005). The ISORROPIA II thermodynamic scheme (Fountoukis et al., 2007) was used for partitioning of gases and aerosols (Pye et al., 2009). The nitric acid was reduced to 75% of its value for each time step to correct for an overestimation in HNO_3 suggested by Heald et al. (2012). AOD at 550 nm were calculated using the RH-dependent aerosol

optical extinctions (Martin et al., 2003) with an updated growth factor for organic matter, and updates to the dust (Ridley et al., 2012) and ammonium sulfate optics.

Anthropogenic emissions over China used in the GEOS-Chem model were year-by-year emissions during 2005–2012 taken from the MEIC inventory, including SO_2, NO_x, NH_3, CO, OC, BC and NMVOCs. Anthropogenic emissions over Southeast Asia outside China were taken from the INTEX-B inventory (Zhang et al., 2009). Other non-anthropogenic emissions include biomass burning (Mu et al., 2011), soil NO_x (Yienger et al., 1995) and lightning NO_x (Martin et al., 2007; Murray et al., 2012). A total of eight years simulations were conducted (2005–2012) with initialization on January 1, 2005 after a one year spin-up simulation. The study time period could not be expanded due to the restrictions by GEOS-5 meteorology data.

Satellite observations of SO_2 and NO_2 column densities

Satellite observation of SO_2 and NO_2 columns retrieved from the OMI instrument were used to better understand the emissions changes of SO_2 and NO_x in this work. OMI is a nadir-viewing UV-visible spectrometer, which observes the atmosphere in ground pixels varying from 13 × 24 km^2 at nadir to about 28 × 150 km^2 at edges.

The SO_2 products used in this study were taken from Wang et al. (2015), which were improved based on the standard NASA products to reduce the uncertainties. The latitude-dependent offsets in the SO_2 slant columns were removed using the reference sector method on a daily basis (Lee et al., 2009). Local AMFs were recalculated using the LIDORT radiative transfer model (Spurr et al., 2001) weighted by the relative vertical SO_2 profile taken from the global GEOS-Chem model. In addition, the NASA Cloud Pressure and Fraction products using O_2-O_2 absorption (OMCLDO2 v003) were used to replace the original Cloud Pressure and Fraction retrievals using Raman scattering (OMCLDRR v003) used in the operational NASA SO_2 products to diminish their effects on the inter-annual

variations of the AMFs for OMI retrievals, which would have impacts on the trend of SO_2 columns (Wang et al., 2015).

The NO_2 products used in this work were the OMI standard product, OMNO2 (version 2.1) (Bucsela et al., 2013), which is publicly available from the NASA Goddard Earth Sciences Data Active Archive Center (GES DISC, http://disc.sci.gsfc.nasa.gov). This version is significantly improved compared to previous versions (Bucsela et al., 2006; Celarier et al., 2008). The uncertainties in the final products were suggested to be 20% for clear-sky conditions (Lamsal et al., 2014).

For both SO_2 and NO_2 retrievals, we only used pixels with cloud radiance fraction $\leq$ 0.3, solar zenith angle (SZA) $\leq 70°$ and surface albedo ≤ 3. Those five pixels at each edges were also excluded. Since June 2007, an anomaly happened to the CCD detectors, which can affect the quality of the radiance data at all wavelengths (i.e., row anomaly, http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/index.shtml#info). The row anomaly has been expanded and changed over time ever since. In this work, we restricted all pixels affected by the row anomaly as suggested by NASA.

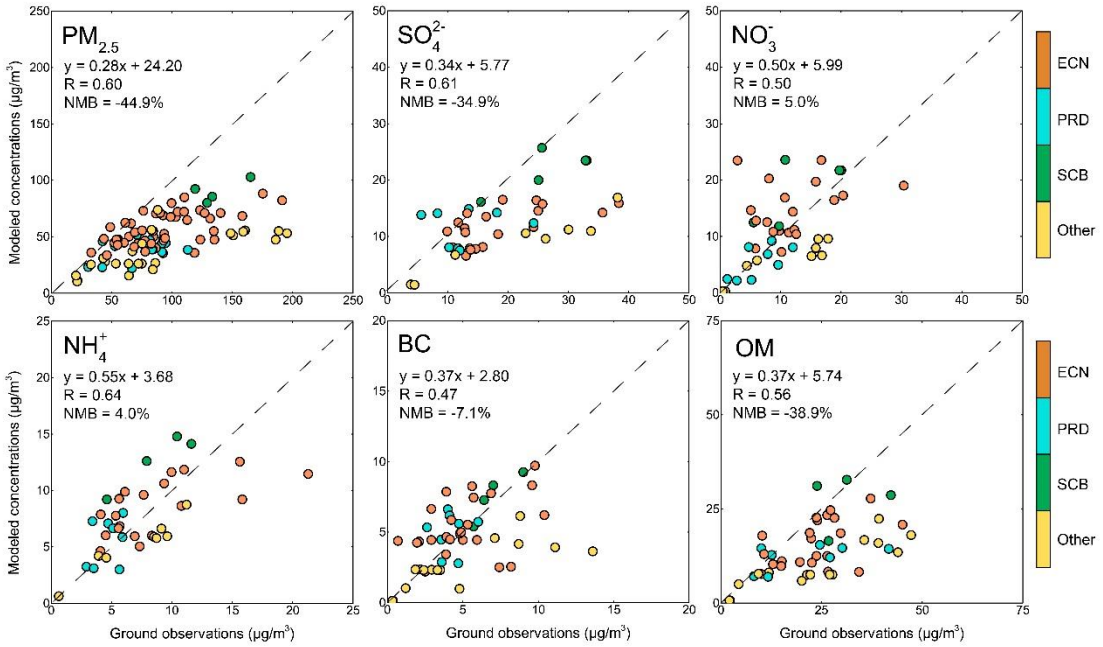

Figure S1. Evaluation of the GEOS-Chem modeled $PM_{2.5}$ and chemical compositions concentrations using in situ data collected from publications. The dashed lines show the 1:1 line.

Table S1. Ground measurements collected from publications.

City	Lat	Lon	($\mu g/m^3$)						Sample Period	Source
			$PM_{2.5}$	SO_4^{2-}	NO_3^-	NH_4^+	OM	BC		
Baotou	40.65	109.85	66.6	10.3	3.2	2.7	18.1	2.7	Sep 2011 - Jun 2012	(Zhang and Zhang, 2014)
Beijing	40.32	116.32	118.5	15.8	10.1	7.3	24.5	8.2	Mar 2005 - Feb 2006	(Yang et al., 2011)
Beijing	39.99	116.30	55.4						2010	(Yu et al., 2013)
Beijing	39.99	116.30	135.0	13.6	11.3	6.9	16.9	5.0	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhang et al., 2013)
Beijing	39.98	116.34	131.5	18.4	10.7	10.8	32.2	9.6	2009 summer and winter	(Song et al., 2012)
Beijing	39.97	115.43	33.0						2009 - 2011	(Xin et al., 2014)
Beijing	39.95	116.30	92.6	14.6	9.7	8.3	18.8	5.9	Jun 2009, Sep 2009, Dec 2009, Mar 2010	(Liu et al., 2014)
Beijing	39.93	116.28	64.2					4.8	2007	(Yu et al., 2011)
Beijing	39.93	116.28	84.5						2007	(Zhao et al., 2009)
Beijing	39.90	116.30	123.4	19.1	20.5	6.4	18.2	6.3	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhao et al., 2013)
Beijing	39.98	116.35	112.4	24.2	20.3	15.8	17.1	5.6		(Wang et al., 2015)
Benxi	41.19	123.47	78.2						2007	(Guo et al., 2009)
Changsha	28.16	112.95	92.3						Jun - Oct 2009	(Yang et al., 2010)
Chengde	40.97	117.93	92.4	13.0	5.8	4.1	19.0	7.4	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhao et al., 2013)
Chengdu	30.66	104.00	165.0	33.0	20.0	10.4	22.3	9.0	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Tao et al., 2013)
Chengdu	30.61	104.04	133.2	15.5	9.7	4.6	19.1	5.7	Apr - May 2009	(Yang et al., 2012)
Chengdu	30.66	104.00		32.8	19.7	10.4			Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Li et al., 2014)
Chengdu	30.65	104.03	119.0	25.0	10.7	11.6	17.0	7.0	Jan 2011, Apr 2011, Jul 2011, Oct 2011	(Tao et al., 2014)
Chonging	29.57	106.53	129.0	25.6	5.5	7.9	30.1	6.4	Mar 2005 - Feb 2006	(Yang et al., 2011)
Duolun	42.20	116.52	64.1						Mar - Apr 2007	(Deng et al., 2011)
Fuzhou	26.10	119.31	44.3	10.8	4.4	3.9	8.5	2.2	Apr 2007 - Jan 2008	(Xu et al., 2012)
Guangzhou	23.09	113.30	42.4				7.1	4.0	Aug 2006 - Jul 2007	(Huang et al., 2010)

Guangzhou	23.25	113.60	81.7	5.6	12.0	4.7	17.5	4.1	Dec 2008 - Feb 2009	(Yang et al., 2011)
Guangzhou	23.14	113.36	94.7	8.3	4.7	3.4	21.5	4.7	Jan 2008	(Tan et al., 2009)
Guangzhou	23.12	113.35	76.8	18.1	7.8	5.1	9.0	6.0	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Tao et al., 2014)
Guangzhou	23.10	113.35	91.4						Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Lin et al., 2013)
Guangzhou	22.71	113.55	70.8	13.5	8.5	5.9	29.7	2.6	Nov - Dec 2010	(Wang et al., 2012)
Guangzhou	22.71	113.55	113.0	24.2	9.5	5.9	19.3	3.6	Oct - Nov 2007	(Ding et al., 2011)
Guangzhou	22.70	113.53	91.6						Aug - Dec 2008	(Ding et al., 2012)
Gucheng	39.13	115.80	86.6						2007	(Guo et al., 2009)
Guilin	25.32	110.30	66.9						2007	(Guo et al., 2009)
Hangzhou	30.27	120.15	84.3						Sep 2010 - Jul 2011	(Sun et al., 2013)
Hangzhou	30.27	120.15	69.0						2006 - 2008	(Hong et al., 2013)
Hangzhou	30.24	120.12	77.5	12.8	5.9	5.3				(Bao et al., 2010)
Hong kong	22.33	114.10	30.5	10.2	1.1	2.9	5.8	3.6	Aug - Sep 2009, Jan - Feb 2010	(Yau et al., 2013)
Huai'an	33.61	119.01	75.0						2008	(Cai et al., 2009)
Jinan	36.67	117.03	123.2	24.7	8.0	11.0	21.2	4.2	Mar 2006 - Feb 2007	(Yang et al, 2012)
Jinan	36.74	117.07		38.3	15.8	21.3			Dec 2007, Apr 2008, Jun 2008, Sep 2008	(Gao et al., 2011)
Jinan	36.67	117.12	158.1				16.0	5.3	2010	(Gu et al., 2014)
Jinsha	29.63	114.20	48.7	13.2	5.0	5.6	7.3	0.7	Mar 2012 - Mar 2013	(Zhang et al., 2014)
Lin'an	30.30	119.73	93.3						2007	(Guo et al., 2009)
Lushan	29.57	115.99	43.4						2007	(Guo et al., 2009)
Nanjing	32.12	118.95	90.0						Nov 2011 - Mar 2012	(Herrmann et al., 2013)
Nanjing	32.05	118.76	103.0						Jun 2007 - May 2008	(Yang et al., 2010)
Nanjing	32.05	118.76	98.8				15.7	10.4	Jun 2007 - May 2008	(Chen et al., 2010)
Nanjing	32.06	118.74	104.7	16.3	2.8	9.9			2010	(Zhang et al., 2013)
Nanjing	32.05	118.78	76.1						Jan 2011 - Apr 2011	(Zhuang et al., 2014)
Nanning	22.82	108.35	42.8						2007	(Guo et al., 2009)

Ningbo	29.68	121.60	46.0				7.1	2.5	Jul 2009 - Mar 2010	(Liu et al., 2013)
Panyu	23.00	113.35	52.6						2007	(Guo et al., 2009)
Qingdao	36.06	120.34	86.6						Jun 2007 - May 2008	(Li et al., 2012)
Qinghai Lake	36.98	99.90	21.5	3.9	0.8	0.6	1.6	0.4	Jun - Aug 2010	(Li et al., 2013)
Qinghai Lake	36.98	99.90	21.3	4.5	0.4		1.5	0.3	Jun - Sep 2010	(Zhang et al., 2014)
Qingyuan	23.70	113.06	84.1						Aug 2009 - Jan 2010	(Wei et al., 2011)
Qingyuan	23.60	113.08	83.2						Aug 2009 - Jan 2010	(Wei et al., 2011)
Sanya	18.30	109.52	20.4				3.1	1.2	Jan - Feb 2012	(Zhou et al., 2012)
Shangdianzi	40.70	117.10	71.8	13.8	12.2	4.5	10.8	3.9	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhao et al., 2013)
Shangdianzi	40.65	117.12	60.2						2007	(Guo et al., 2009)
Shangdianzi	40.65	117.12	51.9						2007	(Zhao et al., 2009)
Shanghai	31.33	121.35	92.9				16.1	2.9	Oct 2005, Jan 2006, Apr 2006, Jul 2006	(Feng et al., 2009)
Shanghai	31.30	121.40	77.7						Nov 2011 - Dec 2011	(Jahn et al., 2013)
Shanghai	31.30	121.40	82.7						Jul 2009 - Sep 2010	(Wang et al., 2013)
Shanghai	31.23	121.48	54.8						2007	(Waheed et al., 2010)
Shanghai	31.22	121.55	53.9					3.9	Apr 2007 - Dec 2008	(Geng et al., 2013)
Shanghai	31.17	121.43	54.9	9.9	8.7	5.7	9.2	2.1	2011 - 2012	(Qiao et al., 2014)
Shanghai	31.15	121.43	94.0	11.7	7.7	4.1	14.0	4.1	Apr 2009 - Feb 2010	(Zhao et al., 2015)
Shanghai	31.15	121.43	68.4	12.9	12.6	5.6	10.7	2.0	Dec 2011 - Nov 2012	(Zhao et al., 2015)
Shenyang	41.73	123.41	75.0						2006 - 2008	(Ma et al., 2011)
Shenzhen	22.59	113.97	42.2	11.7	2.7	3.5	8.3	4.7	2009	(Huang et al., 2014)
Shenzhen	22.58	113.97	66.9	12.0	5.1	5.6			Jul - Aug 2009 - 2010, Nov - Dec 2009 - 2010	(Dai et al., 2013)
Shijiazhuang	38.02	114.52	99.4						Jun - Oct 2008	(Du et al., 2010)
Shijiazhuang	38.00	114.40	191.2	35.6	30.4	9.3	26.5	9.8	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhao et al., 2013)
Shijiazhuang	38.02	114.54	66.0						Jun - Jul 2012	(Ning et al., 2012)
Taishan	36.27	117.10	61.2						Mar - Jul 2007	(Zhou et al., 2012)

Taiyuan	37.80	112.58	334.5	35.1	12.1				Dec 2011 - Jan 2012	(Jia et al., 2013)
Tianjin	39.10	117.20	140.0	25.0	18.8	7.6	18.8	6.9	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhao et al., 2013)
Tianjin	39.10	117.20	109.8				16.9	5.7	Apr 2008, Jul 2008, Oct 2008, Jan 2009	(Gu et al., 2010)
Tianjin	39.10	117.15	134.5				7.6	4.9	Jun - Aug 2011	(Wei et al., 2012)
Tianjin	39.01	117.17		19.1	12.0	6.1			Jan 2008, Apr 2008, Jul 2008, Oct 2008	(Gu et al., 2013)
Urumqi	43.83	87.60		33.1	13.2	13.3	25.2	5.5	Mar 2013 - Feb 2014	(Zhao et al., 2015)
Wuhan	30.50	114.35	127.0				19.4	2.9	Jul 2011 - Feb 2012	(Cheng et al., 2012)
Wuhan	30.50	114.35	110.7	18.0	13.9	9.6	27.0	2.3	Aug 2012 - Jul 2013	(Zhang et al., 2015)
Xiamen	24.61	118.06	32.7						2012	(Niu et al., 2013)
Xiamen	24.58	118.09	86.2	11.2	6.0	4.5	15.2	2.9	Jun 2009 - May 2010	(Zhang et al., 2012)
Xiamen	24.58	118.09	63.9				15.8	2.4	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhang et al., 2011)
Xiamen	24.48	118.04	74.8				19.7	3.5	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhang et al., 2011)
Xiamen	24.48	118.11	72.1				19.3	3.3	Apr 2009, Jul 2009, Oct 2009, Jan 2010	(Zhang et al., 2011)
Xiamen	24.43	118.08	53.4				6.7	1.9	2008 - 2011	(Chen et al., 2012)
Xi'an	34.31	108.95					28.0	8.8	2006 - 2008	(Huang et al., 2011)
Xi'an	34.31	108.95		38.1	16.2	11.2			2006	(Huang et al., 2011)
Xi'an	34.30	108.93	88.1						2007	(Guo et al., 2009)
Xi'an	34.23	108.89	185.9	33.7	16.8	8.5	31.4	13.6	2005	(Cao, 2014)
Xi'an	34.23	108.89	195.2						2006	(Cao, 2014)
Xi'an	34.23	108.89	188.4	30.0	15.1	9.6	27.9	11.1	2007	(Cao, 2014)
Xi'an	34.23	108.89	150.4						2008	(Cao, 2014)
Xi'an	34.23	108.89	160.4	26.2	15.8	8.7	25.4	8.7	2009	(Cao, 2014)
Xi'an	34.23	108.89	148.4						2010	(Cao, 2014)
Xi'an	34.23	108.89	159.0	22.9	17.8	9.1	33.7	7.1	2011	(Cao, 2014)
Yong'an	25.97	117.36	84.1				14.3	4.8	Apr 2007 - Jan 2008	(Yin et al., 2012)
Yulin	38.29	109.74	83.0						Mar - Apr 2007	(Deng et al., 2011)

Zhengzhou	34.80	113.52	175.0	25.7	16.7	15.6	20.1	3.9	2010		(Geng et al., 2013)
Zhengzhou	34.78	113.68	110.2						2007		(Guo et al., 2009)

References

Alexander, B., Park, R. J., Jacob, D. J., Li, Q. B., Yantosca, R. M., Savarino, J., Lee, C. C. W., and Thiemens, M. H.: Sulfate formation in sea-salt aerosols: Constraints from oxygen isotopes, J. Geophys. Res., 110, D10307, 2005.

Bao, Z., Feng, Y. C., Jiao, L., Hong, S. M., and Liu, W. G.: Characterization and Source Apportionment of $PM_{2.5}$ and PM_{10} in Hangzhou, Environmental Monitoring of China, 26, 44-48, 2010 (in Chinese).

Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., Li, Q. B., Liu, H. G. Y., Mickley, L. J., and Schultz, M. G.: Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation, J. Geophys. Res., 106, 23073-23095, 2001.

Bucsela, E. J., Celarier, E. A., Wenig, M. O., Gleason, J. F., Veefkind, J. P., Boersma, K. F., and Brinksma, E. J.: Algorithm for NO_2 vertical column retrieval from the ozone monitoring instrument, IEEE T. Geosci. Remote Sens., 44, 1245-1258, 2006.

Bucsela, E. J., Krotkov, N. A., Celarier, E. A., Lamsal, L. N., Swartz, W. H., Bhartia, P. K., Boersma, K. F., Veefkind, J. P., Gleason, J. F., and Pickering, K. E.: A new stratospheric and tropospheric NO_2 retrieval algorithm for nadir-viewing satellite instruments: applications to OMI, Atmos. Meas. Tech., 6, 2607-2626, 2013.

Cai, H., Lin, S. S., Wu, J. B., and You, X. J.: $PM_{2.5}$ and PM_{10} air pollution in the urban area of Huai'an, Environmental Research and Mornitoring, 22, 25-27, 2009 (in Chinese).

Celarier, E. A., Brinksma, E. J., Gleason, J. F., Veefkind, J. P., Cede, A., Herman, J. R., Ionov, D., Goutail, F., Pommereau, J. P., Lambert, J. C., van Roozendael, M., Pinardi, G., Wittrock, F., Schoenhardt, A., Richter, A., Ibrahim, O. W., Wagner, T., Bojkov, B., Mount, G., Spinei, E., Chen, C. M., Pongetti, T. J., Sander, S. P., Bucsela, E. J., Wenig, M. O., Swart, D. P. J., Volten, H., Kroon, M., and Levelt, P. F.: Validation of ozone monitoring instrument nitrogen dioxide columns, J. Geophys. Res., 113, 2008.

Chen, B., Du, K., Wang, Y., Chen, J., Zhao, J., Wang, K., Zhang, F., and Xu, L.: Emission and transport of carbonaceous aerosols in urbanized coastal areas in China, Aerosol Air Qual. Res., 12, 371-378, 2012.

Chen, D., Wang, Y., McElroy, M. B., He, K., Yantosca, R. M., and Le Sager, P.: Regional CO pollution and export in China simulated by the high-resolution nested-grid GEOS-Chem model, Atmos. Chem. Phys., 9, 3825-3839, 2009.

Chen, K., Yin, Y., Wei, Y. X., and Yang, W. F.: Characteristics of Carbonaceous Aerosols in $PM_{2.5}$ in Nanjing, China Environmental Science, 30, 1015-1020, 2010 (in Chinese).

Cheng, H. R., Wang, Z. W., Feng, J. L., Chen, H. L., Zhang, F., and Liu, J.: Carbonaceous species composition and source apportionment of $PM_{2.5}$ in urban atmosphere of Wuhan, Ecology and Environmental Sciences, 21, 1574-1579, 2012 (in Chinese).

Dai, W., Gao, J., Cao, G., and Ouyang, F.: Chemical composition and source identification of $PM_{2.5}$ in the suburb of Shenzhen, China, Atmos. Res., 122, 391-400, 2013.

Deng, C., Zhuang, G., Huang, K., Li, J., Zhang, R., Wang, Q., Liu, T., Sun, Y., Guo, Z., Fu, J. S., and Wang, Z.: Chemical characterization of aerosols at the summit of Mountain Tai in Central East China, Atmos. Chem. Phys., 11, 7319-7332, 2011.

Ding, X., Wang, X. M., Gao, B., Fu, X. X., He, Q. F., Zhao, X. Y., Yu, J. Z., and Zheng, M.: Tracer-based estimation of secondary organic carbon in the Pearl River Delta, south China, J. Geophys. Res., 117, 2012.

Ding, X., Wang, X.-M., and Zheng, M.: The influence of temperature and aerosol acidity on biogenic secondary organic aerosol tracers: Observations at a rural site in the central Pearl River Delta region, South China, Atmos. Environ., 45, 1303-1311, 2011.

Du, W. P., Wang, Y. S., Song, T., Xin, J. Y., Cheng, Y. S., and Ji, D. S.: Characteristics of Atmospheric Pollutants During the Period of Summer and Autumn in Shijiazhuang, Environmental Science, 31, 1409-1416, 2010 (in Chinese).

Fairlie, D. T., Jacob, D. J., and Park, R. J.: The impact of transpacific transport of mineral dust in the United States, Atmos. Environ., 41, 1251-1266, 2007.

Feng, Y., Chen, Y., Guo, H., Zhi, G., Xiong, S., Li, J., Sheng, G., and Fu, J.: Characteristics of organic and elemental carbon in $PM_{2.5}$ samples in Shanghai, China, Atmos. Res., 92, 434-442, 2009.

Fountoukis, C. and Nenes, A.: ISORROPIA II: a computationally efficient thermodynamic equilibrium model for K^+–Ca^{2+}–Mg^{2+}–NH^{4+}–Na^+–SO_4^{2-}–NO_3^-–Cl^-–H_2O aerosols, Atmos. Chem. Phys., 7, 4639-4659, 2007.

Gao, X., Yang, L., Cheng, S., Gao, R., Zhou, Y., Xue, L., Shou, Y., Wang, J., Wang, X., and Nie, W.: Semi-continuous measurement of water-soluble ions in $PM_{2.5}$ in Jinan, China: temporal variations and source apportionments, Atmos. Environ., 45, 6048-6056, 2011.

Geng, F., Hua, J., Mu, Z., Peng, L., Xu, X., Chen, R., and Kan, H.: Differentiating the associations of black carbon and fine particle with daily mortality in a Chinese city, Environ. Res., 120, 27-32, 2013.

Geng, N., Wang, J., Xu, Y., Zhang, W., Chen, C., and Zhang, R.: $PM_{2.5}$ in an industrial district of Zhengzhou, China: Chemical composition and source apportionment, Particuology, 11, 99-109, 2013.

Gu, J., Bai, Z., Liu, A., Wu, L., Xie, Y., Li, W., Dong, H., and Zhang, X.: Characterization of atmospheric organic carbon and element carbon of $PM_{2.5}$ and PM_{10} at Tianjin, China, Aerosol Air Qual. Res., 10, 167-176, 2010.

Gu, J., Du, S., Han, D., Hou, L., Yi, J., Xu, J., Liu, G., Han, B., Yang, G., and Bai, Z.-P.: Major chemical compositions, possible sources, and mass closure analysis of $PM_{2.5}$ in Jinan, China, Air Qual. Atmos. Health, 7, 251-262, 2014.

Gu, J. X., Wu, L. P., Huo, G. Y., Bai, Z. P., Du, S. Y., Liu, A. X., and Xie, Y. Y.: Pollution Character and Source of Water-Soluble Inorganic Ions in $PM_{2.5}$ over Tianjin, Environmental Monitoring in China, 29, 30-34, 2013 (in Chinese).

Guo, J.-P., Zhang, X.-Y., Che, H.-Z., Gong, S.-L., An, X., Cao, C.-X., Guang, J., Zhang, H., Wang, Y.-Q., Zhang, X.-C., Xue, M., and Li, X.-W.: Correlation between PM

concentrations and aerosol optical depth in eastern China, Atmos. Environ., 43, 5876-5886, 2009.

Heald, C. L., Collett, J. L., Jr., Lee, T., Benedict, K. B., Schwandner, F. M., Li, Y., Clarisse, L., Hurtmans, D. R., Van Damme, M., Clerbaux, C., Coheur, P. F., Philip, S., Martin, R. V., and Pye, H. O. T.: Atmospheric ammonia and particulate inorganic nitrogen over the United States, Atmos. Chem. Phys., 12, 10295-10312, 2012.

Herrmann, E., Ding, A., Petäjä, T., Yang, X., Sun, J., Qi, X., Manninen, H., Hakala, J., Nieminen, T., and Aalto, P.: New particle formation in the western Yangtze River Delta: first data from SORPES-station, Atmos. Chem. Phys. Discuss., 13, 1455-1488, 2013.

Hong, S., Jiao, L., and Ma, W.: Variation of $PM_{2.5}$ concentration in Hangzhou, China, Particuology, 11, 55-62, 2013.

Huang, H., Cao, J. J., Tsang, P. K., Li, S. C., He, J. H., Zou, C. W., Zou S. C., and Li S. M.: Characterization of Organic Carbon, Elemental Carbon and Water-Soluble Organic Carbon in $PM_{2.5}$ of Guangzhou City, J. Anal. Sci., 26, 255-260, 2010 (in Chinese).

Huang, W., Cao, J., Tao, Y., Dai, L., Lu, S.-E., Hou, B., Wang, Z., and Zhu, T.: Seasonal variation of chemical species associated with short-term mortality effects of $PM_{2.5}$ in Xi'an, a central city in China, Am. J. Epidemiol., 2012. kwr342, 2012.

Huang, X., Yun, H., Gong, Z., Li, X., He, L., Zhang, Y., and Hu, M.: Source apportionment and secondary organic aerosol estimation of $PM_{2.5}$ in an urban atmosphere in China, Sci. China Earth Sci., 57, 1352-1362, 2014.

Jahn, H. J., Kraemer, A., Chen, X.-C., Chan, C.-Y., Engling, G., and Ward, T. J.: Ambient and personal $PM_{2.5}$ exposure assessment in the Chinese megacity of Guangzhou, Atmos. Environ., 74, 402-411, 2013.

Jia, X. H., Xie, J. F., Ma, X., Di, Z. D., and Wu, Y. N.: Analysis of water-soluble constituents in winter of $PM_{2.5}$ in Taiyuan City, China Environmental Science, 2013. 599-604, 2013 (in Chinese).

Lamsal, L. N., Krotkov, N. A., Celarier, E. A., Swartz, W. H., Pickering, K. E., Bucsela, E. J., Gleason, J. F., Martin, R. V., Philip, S., Irie, H., Cede, A., Herman, J., Weinheimer, A., Szykman, J. J., and Knepp, T. N.: Evaluation of OMI operational standard NO_2 column retrievals using in situ and surface-based NO_2 observations, Atmos. Chem. Phys., 14, 11587-11609, 2014.

Lee, C., Martin, R. V., van Donkelaar, A., O'Byrne, G., Krotkov, N., Richter, A., Huey, L. G., and Holloway, J. S.: Retrieval of vertical columns of sulfur dioxide from SCIAMACHY and OMI: Air mass factor algorithm development, validation, and error analysis, J. Geophys. Res., 114, D22303, 2009.

Li, J. J., Wang, G. H., Wang, X. M., Cao, J. J., Sun, T., Cheng, C. L., Meng, J. J., Hu, T. F., and Liu, S. X.: Abundance, composition and source of atmospheric $PM_{2.5}$ at a remote site in the Tibetan Plateau, China, Tellus B, 65, 2013.

Li, X. Z., Sheng, L. F., Xu, H., and Qu, W. J.: Element Compositions and Source of $PM_{2.5}$ Aerosols in Qingdao, Environmental Science, 33, 1438-1445, 2012 (in Chinese).

Li, Y. P., Zhou, H., Zhang, Z. S., Wang, Q. Y., and Luo, L.: Pollution Characteristics of Secondary Water-soluble Inorganic Ions of $PM_{2.5}$ in Urban Chengdu, China, Environ. Sci., 35(12), 4439-4445, 2014 (in Chinese).

Liao, H., Henze, D. K., Seinfeld, J. H., Wu, S., and Mickley, L. J.: Biogenic secondary organic aerosol over the United States: Comparison of climatological simulations with observations, J. Geophys. Res., 112, D06201, 2007.

Lin, Z., Tao, J., Chai, F., Fan, S., Yue, J., Zhu, L., Ho, K., and Zhang, R.: Impact of relative humidity and particles number size distribution on aerosol light extinction in the urban area of Guangzhou, Atmos. Chem. Phys., 13, 1115-1128, 2013.

Liu, D., Li, J., Zhang, Y., Xu, Y., Liu, X., Ding, P., Shen, C., Chen, Y., Tian, C., and Zhang, G.: The use of levoglucosan and radiocarbon for source apportionment of $PM_{2.5}$ carbonaceous aerosols at a background site in East China, Environ. Sci. Tech., 47, 10454-10461, 2013.

Liu, Y.-J., Zhang, T.-T., Liu, Q.-Y., Zhang, R.-J., Sun, Z.-Q., and Zhang, M.-G.: Seasonal variation of physical and chemical properties in TSP, PM_{10} and $PM_{2.5}$ at

a roadside site in Beijing and their influence on atmospheric visibility, Aerosol Air Qual. Res., 14, 954-969, 2014.

Ma, Y., Chen, R., Pan, G., Xu, X., Song, W., Chen, B., and Kan, H.: Fine particulate air pollution and daily mortality in Shenyang, China, Sci. Total Environ., 409, 2473-2477, 2011.

Martin, R. V., Jacob, D. J., Yantosca, R. M., Chin, M., and Ginoux, P.: Global and regional decreases in tropospheric oxidants from photochemical effects of aerosols, J. Geophys. Res., 108, 2003.

Martin, R. V., Sauvage, B., Folkins, I., Sioris, C. E., Boone, C., Bernath, P., and Ziemke, J.: Space-based constraints on the production of nitric oxide by lightning, J. Geophys. Res., 112, D09309, 2007.

Mu, M., Randerson, J. T., van der Werf, G. R., Giglio, L., Kasibhatla, P., Morton, D., Collatz, G. J., DeFries, R. S., Hyer, E. J., Prins, E. M., Griffith, D. W. T., Wunch, D., Toon, G. C., Sherlock, V., and Wennberg, P. O.: Daily and 3-hourly variability in global fire emissions and consequences for atmospheric model predictions of carbon monoxide, J. Geophys. Res., 116, D24303, 2011.

Murray, L. T., Jacob, D. J., Logan, J. A., Hudman, R. C., and Koshak, W. J.: Optimized regional and interannual variability of lightning in a global chemical transport model constrained by LIS/OTD satellite data, J. Geophys. Res., 117, D20307, 2012.

Ning, X. Y.: Characteristic and source identifications of $PM_{2.5}$ at Shijiazhuang, National Business: Economic Theory, 2012. 13-14, 2012 (in Chinese).

Niu, Z., Chen, J., Xu, L., Yin, L., and Zhang, F.: Application of the Environmental Internet of Things on monitoring $PM_{2.5}$ at a coastal site in the urbanizing region of southeast China, Int. J. Sust. Dev. World, 20, 231-237, 2013.

Park, R. J., Jacob, D. J., Chin, M., and Martin, R. V.: Sources of carbonaceous aerosols over the United States and implications for natural visibility, J. Geophys. Res., 108, 4355, 2003.

Park, R. J., Jacob, D. J., Field, B. D., Yantosca, R. M., and Chin, M.: Natural and transboundary pollution influences on sulfate-nitrate-ammonium aerosols in the United States: Implications for policy, J. Geophys. Res., 109, 2004.

Park, R. J., Jacob, D. J., Kumar, N., and Yantosca, R. M.: Regional visibility statistics in the United States: Natural and transboundary pollution influences, and implications for the Regional Haze Rule, Atmos. Environ., 40, 5405-5423, 2006.

Pye, H. O. T., Liao, H., Wu, S., Mickley, L. J., Jacob, D. J., Henze, D. K., and Seinfeld, J. H.: Effect of changes in climate and emissions on future sulfate-nitrate-ammonium aerosol levels in the United States, J. Geophys. Res., 114, D01205, 2009.

Qiao, L., Cai, J., Wang, H., Wang, W., Zhou, M., Lou, S., Chen, R., Dai, H., Chen, C., and Kan, H.: $PM_{2.5}$ constituents and hospital emergency-room visits in Shanghai, China, Environ. Sci. Tech., 48, 10406-10414, 2014.

Ridley, D. A., Heald, C. L., and Ford, B.: North African dust export and deposition: A satellite and model perspective, J. Geophys. Res., 117, D02202, 2012.

Song, S., Wu, Y., Jiang, J., Yang, L., Cheng, Y., and Hao, J.: Chemical characteristics of size-resolved $PM_{2.5}$ at a roadside environment in Beijing, China, Environ. Pollut., 161, 215-221, 2012.

Spurr, R. J. D., Kurosu, T. P., and Chance, K. V.: A linearized discrete ordinate radiative transfer model for atmospheric remote-sensing retrieval, J. Quant. Spectrosc. Ra., 68, 689-735, 2001.

Sun, G., Yao, L., Jiao, L., Shi, Y., Zhang, Q., Tao, M., Shan, G., and He, Y.: Characterizing $PM_{2.5}$ Pollution of a Subtropical Metropolitan Area in China, Atmos. Clim. Sci., 3, 100, 2013.

Tan, J., Duan, J., He, K., Ma, Y., Duan, F., Chen, Y., and Fu, J.: Chemical characteristics of $PM_{2.5}$ during a typical haze episode in Guangzhou, J. Environ. Sci., 21, 774-781, 2009.

Tao, J., Cheng, T., Zhang, R., Cao, J., Zhu, L., Wang, Q., Luo, L., and Zhang, L.: Chemical composition of $PM_{2.5}$ at an urban site of Chengdu in southwestern China, Adv. Atmos. Sci., 30, 1070-1084, 2013.

Tao, J., Gao, J., Zhang, L., Zhang, R., Che, H., Zhang, Z., Lin, Z., Jing, J., Cao, J., and Hsu, S.-C.: $PM_{2.5}$ pollution in a megacity of southwest China: source apportionment and implication, Atmos. Chem. Phys., 14, 8679-8699, 2014.

Tao, J., Zhang, L., Engling, G., Zhang, R., Yang, Y., Cao, J., Zhu, C., Wang, Q., and Luo, L.: Chemical composition of $PM_{2.5}$ in an urban environment in Chengdu, China: Importance of springtime dust storms and biomass burning, Atmos. Res., 122, 270-283, 2013.

Tao, J., Zhang, L., Ho, K., Zhang, R., Lin, Z., Zhang, Z., Lin, M., Cao, J., Liu, S., and Wang, G.: Impact of $PM_{2.5}$ chemical compositions on aerosol light scattering in Guangzhou—the largest megacity in South China, Atmos. Res., 135, 48-58, 2014.

Waheed, A., Zhu, Y., Tan, M., Bao, L., Zhang, G., Li, Y., Iida, A., and Li, X.: Characterization and source identification of fine particulate matter in the atmosphere of downtown Shanghai using mu-SXRF and ICP-MS, Nucl. Sci. and Tech., 21, 197-197-203, 2010.

Walker, J. M., Philip, S., Martin, R. V., and Seinfeld, J. H.: Simulation of nitrate, sulfate, and ammonium aerosols over the United States, Atmos. Chem. Phys., 12, 11213-11227, 2012.

Wang, H., Tian, M., Li, X., Chang, Q., Cao, J., Yang, F., Ma, Y., and He, K.: Chemical composition and light extinction contribution of $PM_{2.5}$ in urban Beijing for a 1-year period, Aerosol Air Qual. Res., 15, 2200-2211, 2015.

Wang, J., Hu, Z., Chen, Y., Chen, Z., and Xu, S.: Contamination characteristics and possible sources of PM_{10} and $PM_{2.5}$ in different functional areas of Shanghai, China, Atmos. Environ., 68, 221-229, 2013.

Wang, S., Zhang, Q., Martin, R. V., Philip, S., Liu, F., Li, M., Jiang, X., and He, K.: Satellite measurements oversee China's sulfur dioxide emission reductions from coal-fired power plants, Environ. Res. Lett., 10, 2015.

Wang, X., Ding, X., Fu, X., He, Q., Wang, S., Bernard, F., Zhao, X., and Wu, D.: Aerosol scattering coefficients and major chemical compositions of fine particles observed at a rural site in the central Pearl River Delta, South China, J. Environ. Sci., 24, 72-77, 2012.

Wei, S., Liu, M., Huang, B., Bi, X., Sheng, G., and Fu, J.: Polycyclic aromatic hydrocarbons with molecular weight 302 in $PM_{2.5}$ at two industrial sites in South China, J. Environ. Monitor., 13, 2568-2574, 2011.

Wei, X., Bi, X. H., Dong, H. Y., Chen, K., Sun, R., and Feng, Y. C.: Characteristics and Sources of Particulate Matter during Hazy and Non-Hazy Episodes in Tianjin City in Summer, Research of Environmental Sciences, 25, 1193-1200, 2012 (in Chinese).

Xin, J., Zhang, Q., Wang, L., Gong, C., Wang, Y., Liu, Z., and Gao, W.: The empirical relationship between the $PM_{2.5}$ concentration and aerosol optical depth over the background of North China from 2009 to 2011, Atmos. Res., 138, 179-188, 2014.

Xu, L., Chen, X., Chen, J., Zhang, F., He, C., Zhao, J., and Yin, L.: Seasonal variations and chemical compositions of $PM_{2.5}$ aerosol in the urban area of Fuzhou, China, Atmos. Res., 104, 264-272, 2012.

Yang, F., Tan, J., Zhao, Q., Du, Z., He, K., Ma, Y., Duan, F., and Chen, G.: Characteristics of $PM_{2.5}$ speciation in representative megacities and across China, Atmos. Chem. Phys., 11, 5207-5219, 2011.

Yang, L., Zhou, X., Wang, Z., Zhou, Y., Cheng, S., Xu, P., Gao, X., Nie, W., Wang, X., and Wang, W.: Airborne fine particulate pollution in Jinan, China: Concentrations, chemical compositions and influence on visibility impairment, Atmos. Environ., 55, 506-514, 2012.

Yang, T. Z.: Chemical Compositions and Source Apportionment of $PM_{2.5}$ in Changsha, 2010 (in Chinese).

Yang, W. F., Yin, Y., Wei, Y. X., and Chen, K.: Characteristics and sources of metal elements in $PM_{2.5}$ during hazy days in Nanjing, China Environmental Science, 30, 12-17, 2010 (in Chinese).

Yang, Y., Chan, C.-y., Tao, J., Lin, M., Engling, G., Zhang, Z., Zhang, T., and Su, L.: Observation of elevated fungal tracers due to biomass burning in the Sichuan Basin at Chengdu City, China, Sci. Total Environ., 431, 68-77, 2012.

Yau, P., Lee, S., Cheng, Y., Huang, Y., Lai, S., and Xu, X.: Contribution of ship emissions to the fine particulate in the community near an international port in Hong Kong, Atmos. Res., 124, 61-72, 2013.

Yienger, J. J. and Levy, H.: Empirical model of global soil-biogenic NO_χ emissions, J. Geophys. Res., 100, 11447-11464, 1995.

Yin, L., Niu, Z., Chen, X., Chen, J., Xu, L., and Zhang, F.: Chemical compositions of $PM_{2.5}$ aerosol during haze periods in the mountainous city of Yong'an, China, J. Environ. Sci., 24, 1225-1233, 2012.

Yu, L., Wang, G., Zhang, R., Zhang, L., Song, Y., Wu, B., Li, X., An, K., and Chu, J.: Characterization and Source Apportionment of $PM_{2.5}$ in an Urban Environment in Beijing, Aerosol Air Qual. Res., 13, 574-583, 2013.

Yu, Y., Schleicher, N., Norra, S., Fricker, M., Dietze, V., Kaminski, U., Cen, K., and Stüben, D.: Dynamics and origin of $PM_{2.5}$ during a three-year sampling period in Beijing, China, J. Environ. Monitor., 13, 334-346, 2011.

Zhang, B. and Zhang, W.: Source apportionment of $PM_{2.5}$ in ambient air of Baotou, Environmental Engineering, 2014 (in Chinese).

Zhang, F., Cheng, H.-r., Wang, Z.-w., Lv, X.-p., Zhu, Z.-m., Zhang, G., and Wang, X.-m.: Fine particles ($PM_{2.5}$) at a CAWNET background site in Central China: Chemical compositions, seasonal variations and regional pollution events, Atmos. Environ., 86, 193-202, 2014.

Zhang, F., Wang, Z.-w., Cheng, H.-r., Lv, X.-p., Gong, W., Wang, X.-m., and Zhang, G.: Seasonal variations and chemical characteristics of $PM_{2.5}$ in Wuhan, central China, Science of The Total Environment, 518–519, 97-105, 2015.

Zhang, F., Xu, L., Chen, J., Yu, Y., Niu, Z., and Yin, L.: Chemical compositions and extinction coefficients of $PM_{2.5}$ in peri-urban of Xiamen, China, during June 2009–May 2010, Atmos. Res., 106, 150-158, 2012.

Zhang, F., Zhao, J., Chen, J., Xu, Y., and Xu, L.: Pollution characteristics of organic and elemental carbon in $PM_{2.5}$ in Xiamen, China, J. Environ. Sci., 23, 1342-1349, 2011.

Zhang, N., Cao, J., Liu, S., Zhao, Z., Xu, H., and Xiao, S.: Chemical composition and sources of $PM_{2.5}$ and TSP collected at Qinghai Lake during summertime, Atmos. Res., 138, 213-222, 2014.

Zhang, Q., Streets, D. G., Carmichael, G. R., He, K. B., Huo, H., Kannari, A., Klimont, Z., Park, I. S., Reddy, S., Fu, J. S., Chen, D., Duan, L., Lei, Y., Wang, L. T., and Yao, Z. L.: Asian emissions in 2006 for the NASA INTEX-B mission, Atmos. Chem. Phys., 9, 5131-5153, 2009.

Zhang, R., Jing, J., Tao, J., Hsu, S. C., Wang, G., Cao, J., Lee, C. S. L., Zhu, L., Chen, Z., Zhao, Y., and Shen, Z.: Chemical characterization and source apportionment of $PM_{2.5}$ in Beijing: seasonal perspective, Atmos. Chem. Phys., 13, 7053-7074, 2013.

Zhang, Y. Y., Ren, L., Sun, J., Zhu, Z. F., and Chen, Y. Y.: Features of Water-Soluble Components Pollution of Atmospheric Fine Particles in Nanjing, Environmental Monitoring in China, 29, 25-27, 2013 (in Chinese).

Zhao, K. L: Study on characteristics of $PM_{2.5}$ in Urumqi (based on meteorological administration and heishantou sites). Xinjiang University, 25-46, 2015 (in Chinese).

Zhao, M., Qiao, T., Huang, Z., Zhu, M., Xu, W., Xiu, G., Tao, J., and Lee, S.: Comparison of ionic and carbonaceous compositions of $PM_{2.5}$ in 2009 and 2012 in Shanghai, China, Sci. Total Environ., 536, 695-703, 2015.

Zhao, P. S., Dong, F., He, D., Zhao, X. J., Zhang, X. L., Zhang, W. Z., Yao, Q., and Liu, H. Y.: Characteristics of concentrations and chemical compositions for $PM_{2.5}$ in the region of Beijing, Tianjin, and Hebei, China, Atmos. Chem. Phys., 13, 4631-4644, 2013.

Zhao, X., Zhang, X., Xu, X., Xu, J., Meng, W., and Pu, W.: Seasonal and diurnal variations of ambient $PM_{2.5}$ concentration in urban and rural environments in Beijing, Atmos. Environ., 43, 2893-2900, 2009.

Zhou, J. M., Zhao, Y. Z., Liu, S. X., Xu, Y. S., and Cao, J. J.: Characteristic and source identifications of $PM_{2.5}$ and carbonaceous aerosol at Sanya during 2011 winter, J. Earth Environ., 3, 1060-1065, 2012 (in Chinese).

Zhou, Y., Xue, L., Wang, T., Gao, X., Wang, Z., Wang, X., Zhang, J., Zhang, Q., and Wang, W.: Characterization of aerosol acidity at a high mountain site in central eastern China, Atmos. Environ., 51, 11-20, 2012.

Zhuang, B., Wang, T., Li, S., Liu, J., Talbot, R., Mao, H., Yang, X., Fu, C., Yin, C., and Zhu, J.: Optical properties and radiative forcing of urban aerosols in Nanjing, China, Atmos. Environ., 83, 43-52, 2014.