Supplementary Material

Sources and oxidative potential of water-soluble humic-like substances ($HULIS_{WS}$) in fine particulate matter ($PM_{2.5}$) in Beijing

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Section S1. HPLC-ELSD analysis of total $HULIS_{WS}$.

Total $HULIS_{WS}$ was analyzed by a high-performance liquid chromatography system (HPLC, ThermoFisher Scientific, Waltham, MA, USA) coupled with an evaporative light scattering detector (Alltech ELSD 3300, Grace, Houston, TX, USA). Detailed method was provided in Lin et al. (2010) Since there is no requirement for further separation, a polyaryletheretherketone tube (15 m, 0.127 mm i.d., Alltech, Dearfield, IL, USA) instead of analytical column was used to connect the HPLC injector port and ELSD). $HULIS_{WS}$ was eluted by isocratic elution with acetonitrile: distilled deinoized water (1:4, vol/vol) at a rate of 0.6 mL min^{-1}. The ELSD was operated at a N_2 flow rate of 1.5 L min^{-1} and a drift tubing temperature of 90°C. The recoveries of representative $HULIS_{WS}$ species were provided in Lin et al. (2010)

Section S2. GC-MS analysis of individual $HULIS_{WS}$ species.

Individual $HULIS_{WS}$ species were analyzed using gas chromatography-mass spectrometry (GC-MS; Agilent 7890A-5975C, Santa Clara, CA, USA) in electron ionization (EI) mode. A HP-5MS column (30 m, 250 μm i.d., 0.25 μm film thickness, Agilent, Santa Clara, CA, USA) was used to separate individual species. Two microliter of sample was injected into GC injection in splitless mode. The GC oven temperature program was set as follows: held at 80°C for 5 min; 3°C min^{-1} to 200°C and held for 2 min; 15°C min^{-1} to 300°C and held for 15 min. For most compounds with authentic standards, they were identified and quantified by comparison to the standards. For terephthalic acid, 2-hydroxybenzoic acid, and 1,2,3-/1,2,4-benzenetricarboxylic acids, which were lack of authentic standards, isophthalic acid, 3-hydaroxybenzoic acid, and 1,3,5-benzentricarboxylic acid were used as surrogate for the calibration and recovery, respectively. Similarly, for SOA markers, surrogate compounds with similar functional groups were used for calibration and they were determined following the procedure described in Hu et al. (2008). Recoveries for all measured species were within 72%-106%.

Section S3. Positive Matrix Factorization (PMF) analysis.

PMF is a widely used receptor model for the source apportionment of fine particulate matter ($PM_{2.5}$). In this model, the original data matrix *X* could be divided into a factor contribution matrix *G* and a factor profile matrix *F*:

$$\underset{m\times n}{X} = \underset{m\times p}{G} \times \underset{p\times n}{F} + \underset{m\times n}{\varepsilon}$$

where *n* stands for the sample number, *m* stands for the species number, *p* refers to the number of factors in PMF solution, ε refers to a residual matrix.

During calculation, the sum of scaled residual *Q* was minimized:

$$Q = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{e_{ij}}{\sigma_{ij}}\right)^2$$

where e_{ij} is the residual of each sample, and σ_{ij} is the uncertainty in the j^{th} species for the sample *i*.

In this study, a total of 66 samples and 13 species was included in the final PMF solution. The uncertainty setting was referred to Hu et al.[3] Briefly, the uncertainties of total $HULIS_{WS}$, DTT activity, major ions (Mg^{2+}, Ca^{2+}, NH_4^+, SO_4^{2-}, and nss-Cl^-), SOA marker (MonoT) and individual $HULIS_{WS}$ species (4M5NC, 3M6NC, 123Ben, 124Ben, and TPha) were set as 0.4 of average annual value. Hopane and Levoglucosan (LevoG) were set as 0.2 of average annual value. The optimal PMF solution had five factors with 20% of extra modeling uncertainty.

Section S3. Calculation of particle-phase liquid water content (LWC_p) and particle acidity (H_p^+).

LWC_p was associated to both organic (LWC_{org}) and inorganic components (LWC_{inorg}) in $PM_{2.5}$. The LWC_{org} was calculated using the following equation:

$$\mathrm{LWC}_{org} = \frac{m_{org}\rho_w}{\rho_{org}}\frac{k_{org}}{(1/RH-1)}$$

where m_{org} is the concentration of organic matter (OM), and in this paper, 1.98 and 1.50 were adopted for OM/OC ratio in the heating and non-heating seasons, respectively.[4] ρ_w and ρ_{org} are the densities of water and organic, with values of 1 g cm^{-3} and 1.4 g cm^{-3}, respectively.[5] k_{org} is the organic hygroscopicity parameter (k_{org}=0.1),[6] and RH is the relative humidity (%).

Particle acidity (H_p^+) was calculated using the following equation:

$$H_P^+ = \frac{1000 H_{air}^+}{LWC_{org} + LWC_{inorg}}$$

where H_p^+ (mol/L) is the concentration of hydronium ion in the aqueous solution, interpreted as particle acidity. H_{air}^+ and LWC_{inorg} were calculated by ISORROPIA-Ⅱ using inorganic ions (Na^+, SO_4^{2-}, NH_4^+, Cl^-, Ca^{2+}, K^+, and Mg^{2+}), RH and temperature as the input

Table S1. Concentrations of individual $HULIS_{WS}$ species during the heating and non-heating seasons

Concentration	Heating season			Non-heating season		
(ng m^{-3})	Mean	Median	Range	Mean	Median	Range
			Individual $HULIS_{WS}$ species			
adipic acid	6.59	3.50	0.91 – 25.5	5.28	4.40	2.01 – 17.7
pimelic acid	2.94	1.77	0.41 -9.57	2.50	2.21	0.86 – 11.5
vanillic acid	5.88	6.32	0.47 – 12.9	1.28	0.60	n.d. – 10.6
azelaic acid	13.7	10.3	1.14 – 35.5	14.9	13.9	3.86 – 55.2
syringic acid	7.04	4.59	0.38 – 16.5	2.08	1.04	0.29 – 16.0
2-hydroxybenoic acid	6.70	5.40	0.71 – 22.4	1.00	0.69	n.d. – 3.26
3-hydroxybenoic acid	6.03	4.96	0.54 – 21.1	1.03	0.76	n.d. – 6.97
4-hydroxybenoic acid	19.3	13.7	0.99 – 57.6	4.39	1.74	0.47 – 63.3
phthalic acid	54.4	25.0	6.55 – 424	22.0	23.8	6.88 – 69.4
isophthalic acid	4.77	3.29	0.64 – 17.8	2.87	2.30	1.06 – 14.9
terephthalic acid	150	97.7	17.0 – 411	98.1	79.6	7.30 – 372
4-nitrophenol	35.1	27.7	1.49 – 105	2.86	1.56	0.45 – 14.5

4-nitrocatechol	27.1	20.6	0.62 – 103	2.91	1.54	0.50 – 28.1
2-hydroxy-5-nitrobenzoic acid	8.50	8.60	0.33 – 23.8	6.38	8.12	0.72 – 15.8
2-methyl-4-nitrophenol	27.2	24.8	1.47 – 56.9	1.91	0.85	0.32 – 9.68
4-methyl-5-nitrocatechol	7.38	7.94	0.26 – 17.6	0.51	n.d.	n.d. – 8.70
3-methyl-6-nitrocatechol	18.6	16.6	0.51 – 54.5	2.25	1.47	n.d. – 13.7
1,2,3-benzenetricarboxylic acid	27.3	12.6	2.24 – 168	16.2	13.2	n.d. – 65.2
1,2,4-benzenetricarboxylic acid	22.7	11.9	1.98 – 114	13.7	11.5	4.09 – 43.3
1,3,5-benzenetricarboxylic acid	5.95	0.98	0.23 – 134	1.35	0.93	0.26 – 4.94
Σ HULIS$_{WS\text{-}quantified}$	458	368	39.62– 1657	203	178	41.9 – 782
			SOA tracers			
3-hydroxyglutaric acid	3.66	3.50	0.36 – 9.77	1.81	1.84	0.71 – 4.85
3-acetylpentanedioic acid	2.47	1.71	n.d. – 8.40	4.44	3.83	1.16 – 10.33
3-hydroxy-4,4-dimethylglutaric acid	1.06	0.80	n.d. – 3.01	1.16	1.04	0.37 – 3.11
3-Isopropylpentanedioic acid	4.01	3.34	n.d. – 14.09	5.34	5.11	1.02 – 11.80
3-methyl-1,2,3-butanetricarboxylic acid	1.26	1.05	n.d. – 3.30	4.09	3.15	1.09 – 9.80

n.d. : not detected.

Table S2. Multilinear regression analysis of PMF-resolved $HULIS_{WS}$ from vehicle emissions ($HULIS_{WS\_VE}$), particle acidity (H_p^+), particle-phase liquid water content (LWC_p), and particle-phase SO_4^{2-}, NO_X and O_3

Variable	β-coefficient	Standard error	t value	*p* value
Intercept	0.337	0.220	1.530	0.131
H_p^+	-0.113	0.508	-0.223	0.824
LWC_p	-0.008	0.008	-0.972	0.335
SO_4^{2-}	0.018	0.013	1.381	0.172
NO_X	0.012	0.003	4.254	0.000
O_3	-0.013	0.004	-3.008	0.004

Table S3. Multilinear regression analysis of PMF-resolved $HULIS_{WS}$ from secondary aerosol formation ($HULIS_{WS\_SEC}$), particle acidity (H_p^+), particle-phase liquid water content (LWC_p), and particle-phase SO_4^{2-}, NO_X and O_3

Variable	β-coefficient	Standard error	t value	*p* value
Intercept	-0.031	0.357	-0.088	0.930
H_p^+	1.291	0.822	1.571	0.121
LWC_p	0.026	0.013	1.997	0.050
SO_4^{2-}	0.066	0.021	3.227	0.002
NO_X	-0.001	0.005	-0.267	0.790
O_3	0.028	0.007	3.942	0.000

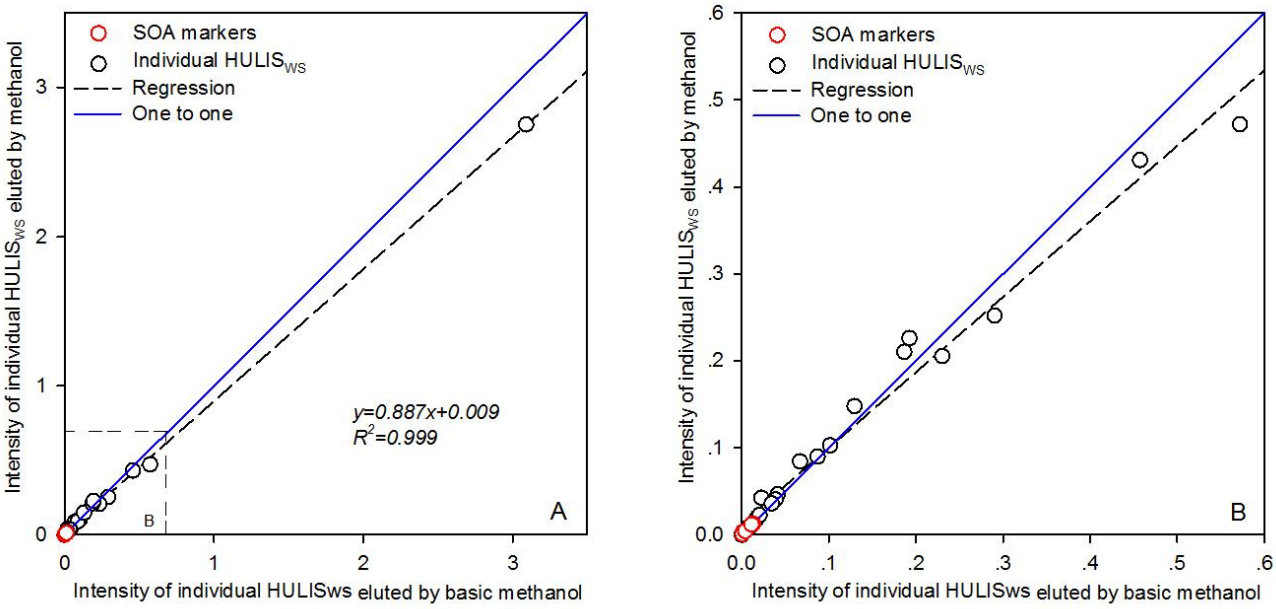

Figure S1. The comparison of GC-MS peak intensity of $HULIS_{WS}$ species eluted by methanol and basic methanol (panel B is the magnification of panel A with the intensity below 0.6)

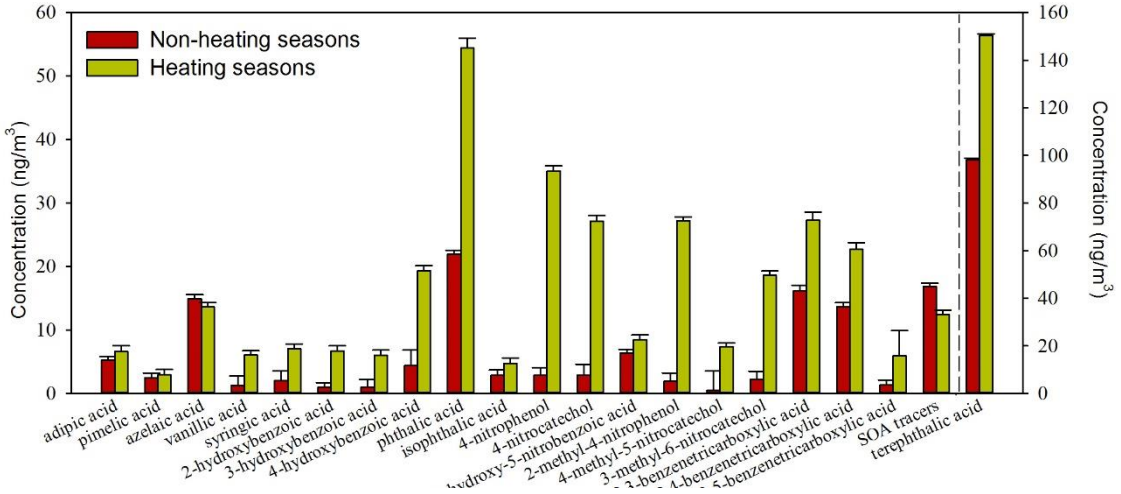

Figure S2. Difference of individual $HULIS_{WS}$ species between the heating and non-heating seasons.

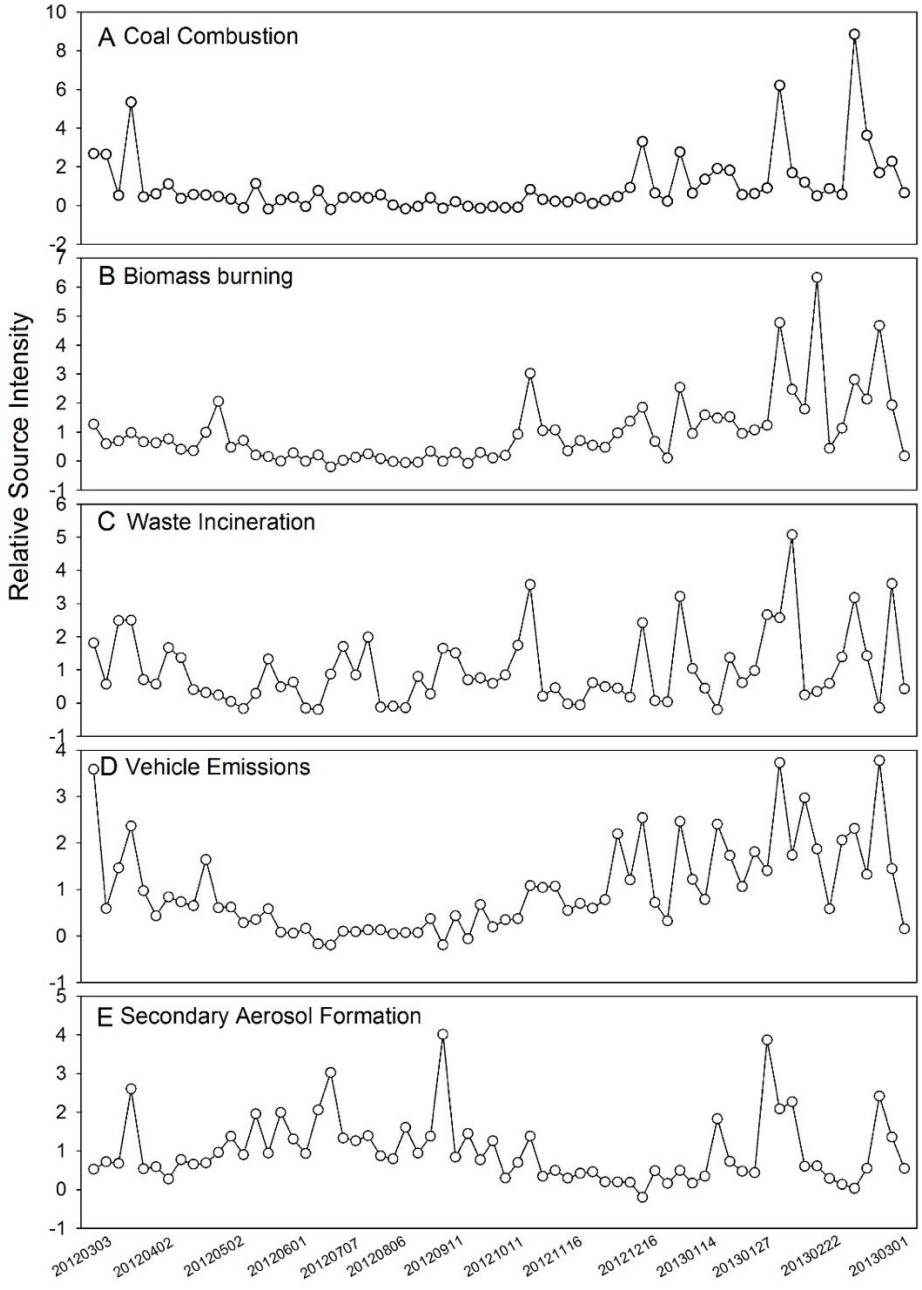

Figure S3. Relative source intensities of PMF source profiles.

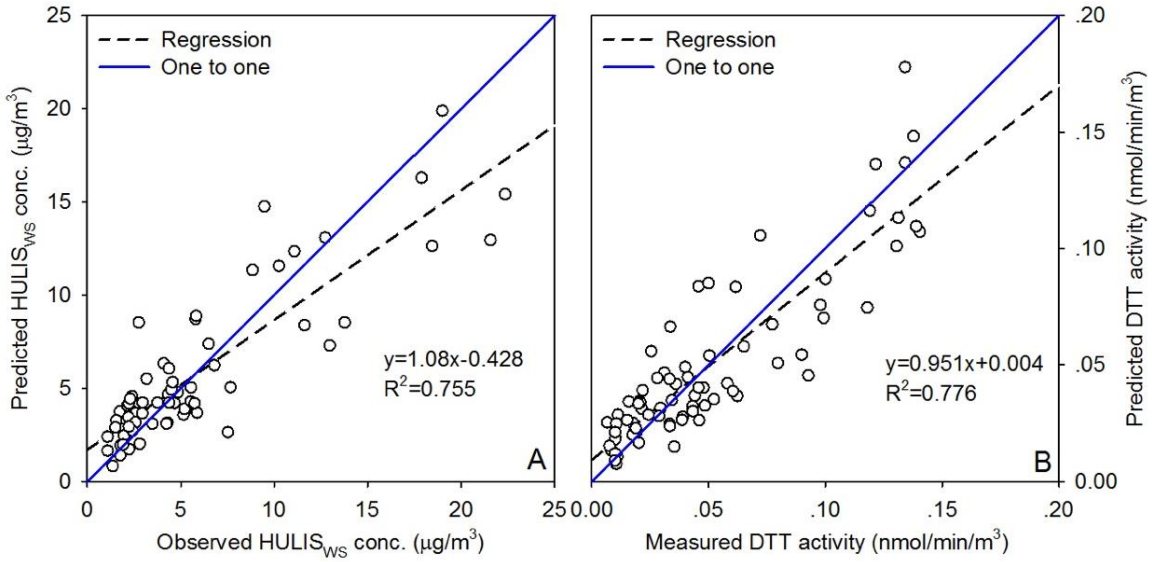

Figure S4. PMF-predicted versus measured concentrations of total HULIS$_{WS}$ (panel A) and HULIS$_{WS}$-associated DTT activity (panel B).

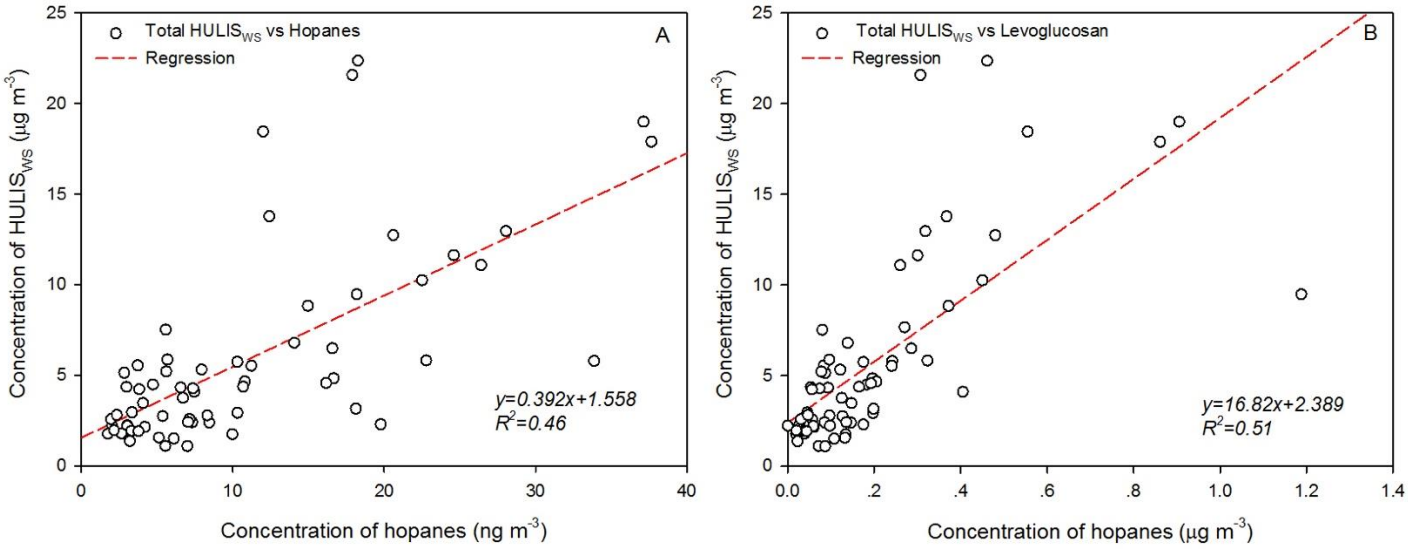

Figure S5. Total HULIS$_{WS}$ versus hopanes (panel A) and levoglucosan (panel B)

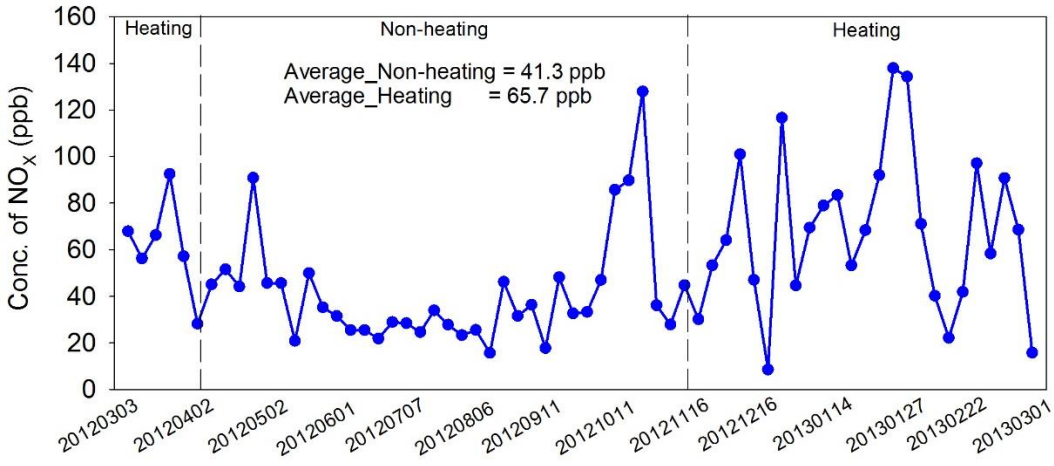

Figure S6. Temporal variation for gas-phase NO$_X$ concentration in Beijing during 2012-2013.

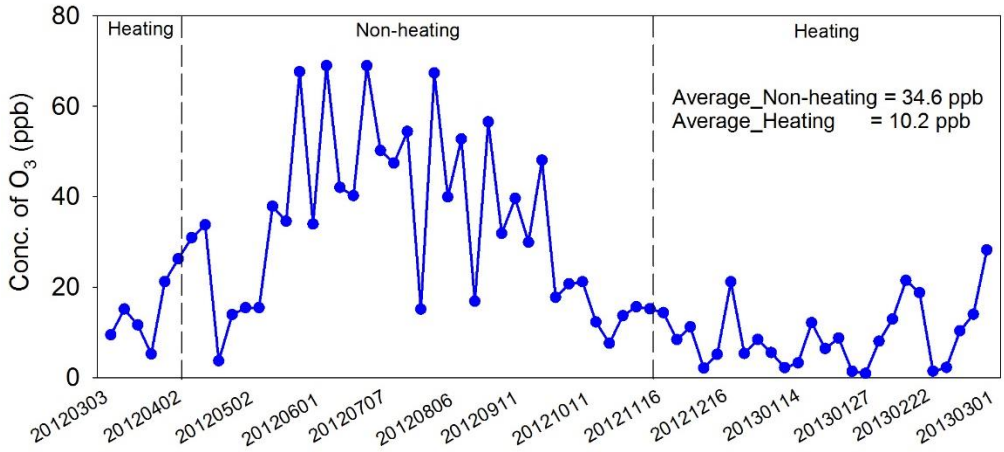

Figure S7. Temporal variation for gas-phase O_3 concentration in Beijing during 2012-2013.

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