**Supplementary Material for**

# Source Apportionment of $PM_{2.5}$ using DN-PMF in Three Megacities in South Korea

**Yeonseung Cheong[a], Taeyeon Kim[a], Jiwon Ryu[a], Ilhan Ryoo[a], Jieun Park[c], Kwon-ho Jeon[d*], Seung-Muk Yi[a,b], Philip K. Hopke[e,f]**

[a] Institute of Health and Environment, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, 08826, Republic of Korea

[b] Graduate School of Public Health, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea

[c] Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA

[d] Department of Climate and Air Quality Research, Global Environment Research Division, National Institute of Environmental Research, Incheon, 22689, Republic of Korea

[e] Department of Public Health Sciences, University of Rochester School of Medicine and Dentistry, Rochester, NY 14642, USA

[f] Institute for a Sustainable Environment, Clarkson University, Potsdam, NY 13699, USA

*Corresponding author: Kwon-ho Jeon, National Institute of Environmental Research, 42, Hwangyeong ro, Seo gu, Incheon, 22689, Republic of Korea, Phone: +82-32-560-7320; FAX: +82-32-568-2042; Email: jeon0119@korea.kr; ORCID ID: 0009-0000-8845-6595

ORCID ID: Yeonsueng Cheong (0009-0008-7031-9478), Kwon-ho Jeon (0009-0000-8845-6595)

## Supplementary figures

**List of figure captions**

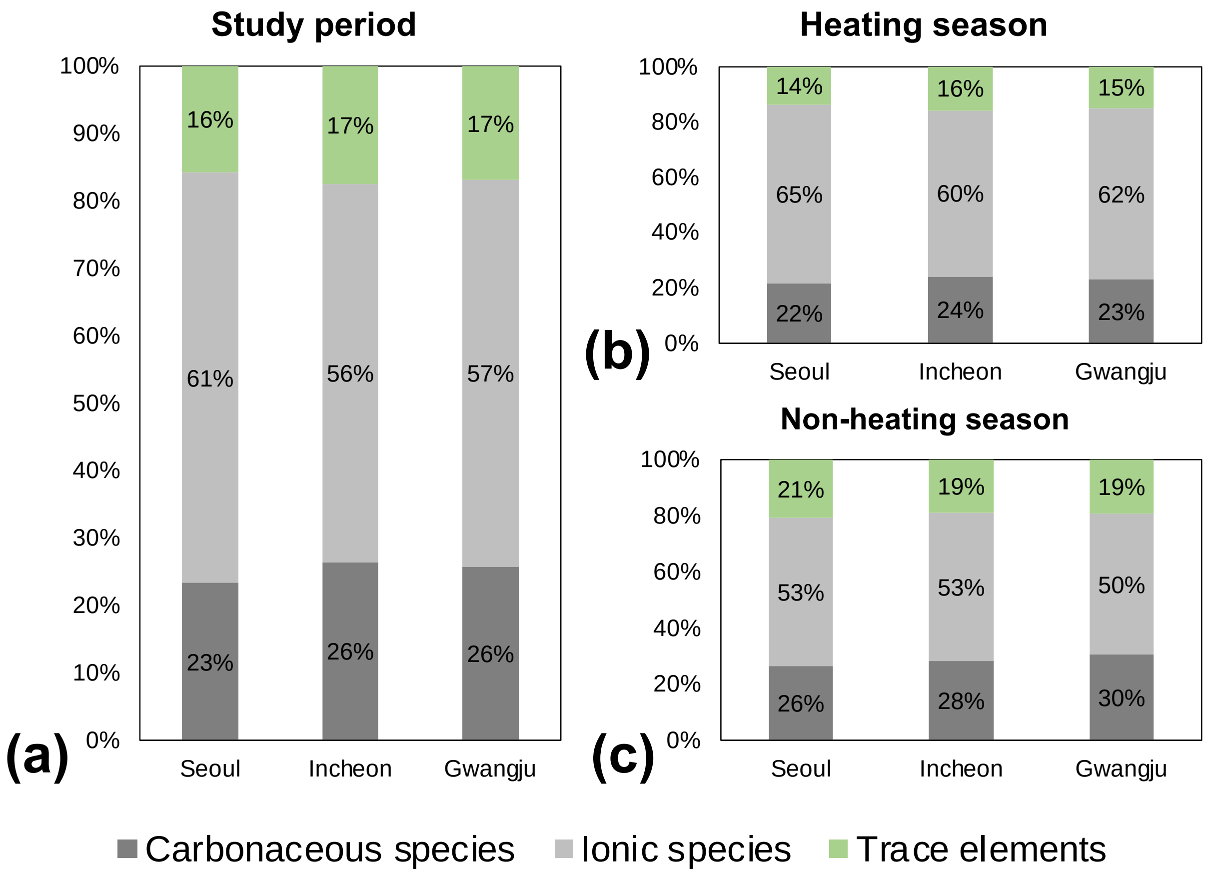
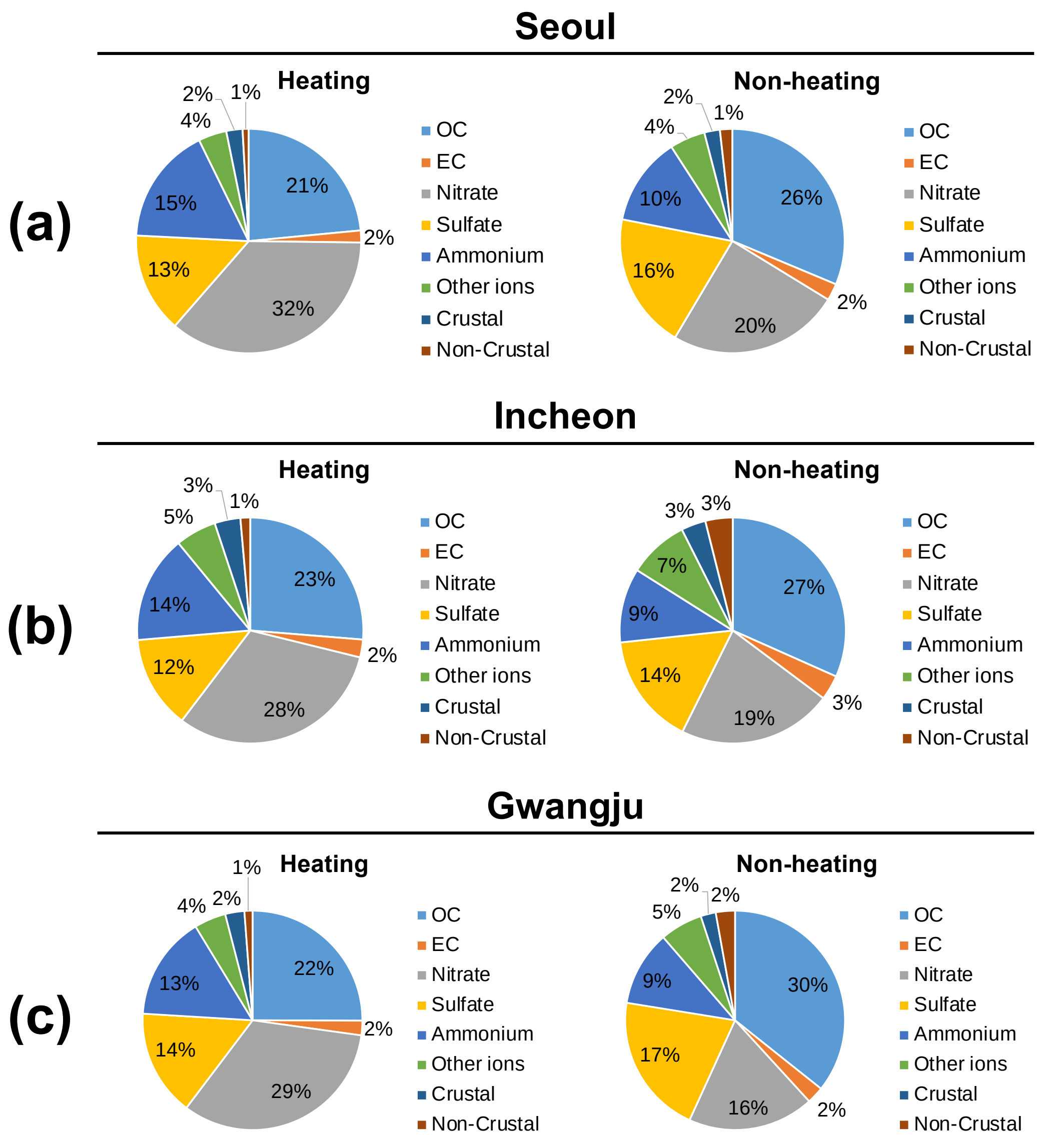



**Figure S1. Chemical fractions of $PM_{2.5}$ by (a) study period, (b) heating season, and (c) non-heating season.**




**Other ions**: $Na^+$, $K^+$, $Cl^-$
**Crustal**: Al, Si, K, Ca, Ti, Fe
**Non-crustal**: Mg, S, Cl, V, Cr, Mn, Ba, Ni, Cu, Zn, As, Se, Br, Pb

**Figure S2. Chemical composition of $PM_{2.5}$ by heating and non-heating seasons: (a) Seoul site, (b) Incheon site, (c) Gwangju site.**

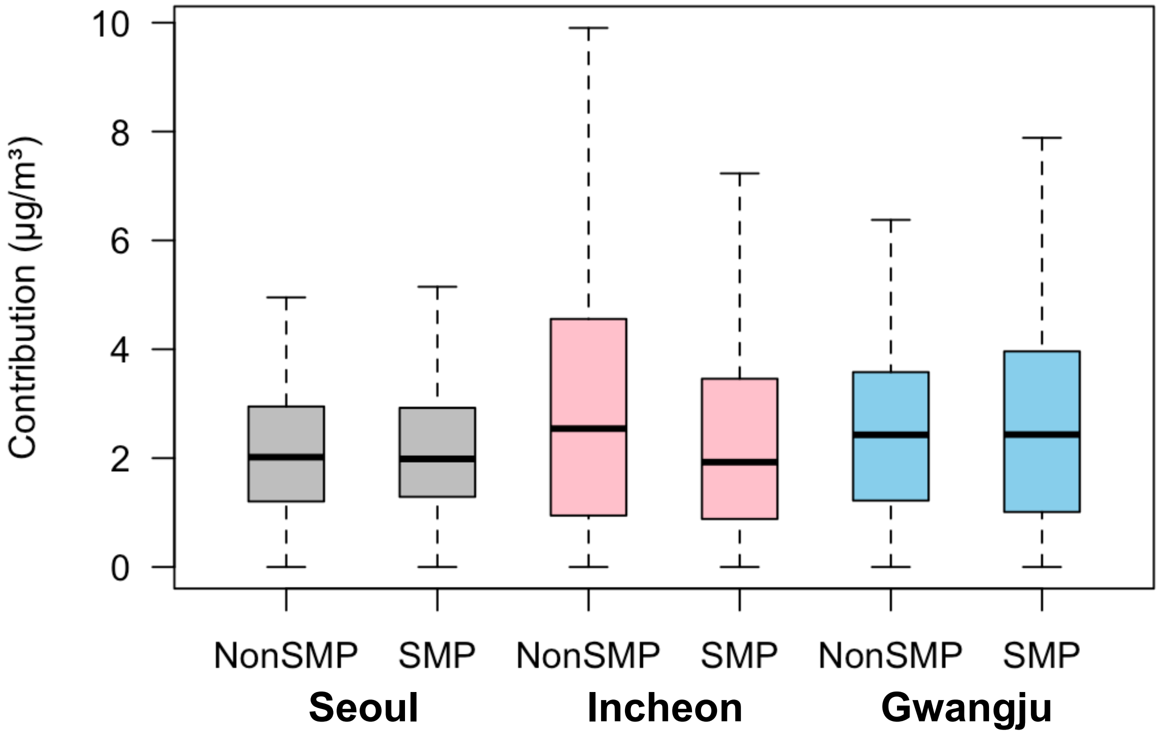



**Figure S3. Box plots of mobile source contributions during the seasonal management system implementation period at all sites. Seasonal management program periods are abbreviated as SMP.**

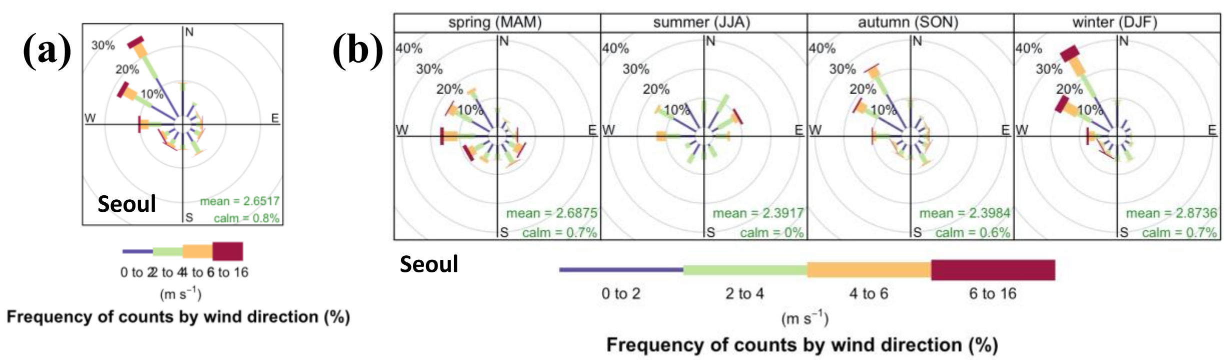



**Figure S4. Wind rose plots in Seoul: (a) wind rose plot for the whole study period, (b) wind rose plot by season.**

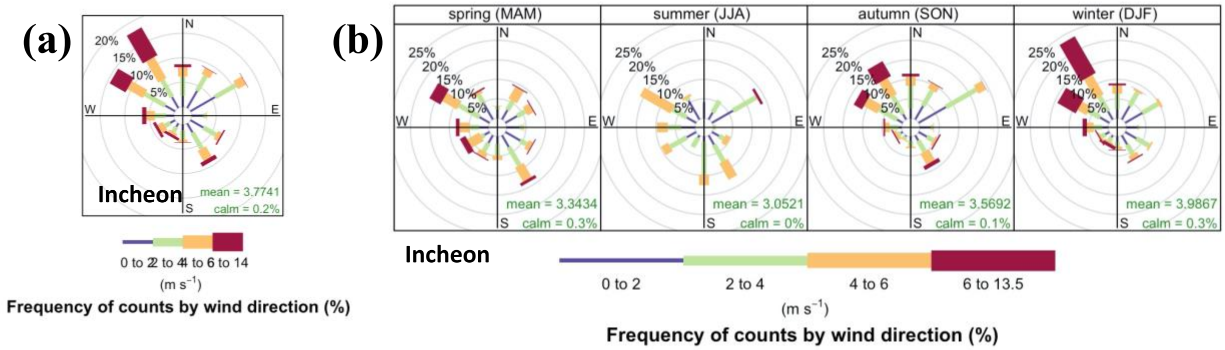



**Figure S5. Wind rose plots in Incheon: (a) wind rose plot for the whole study period, (b) wind rose plot by season.**

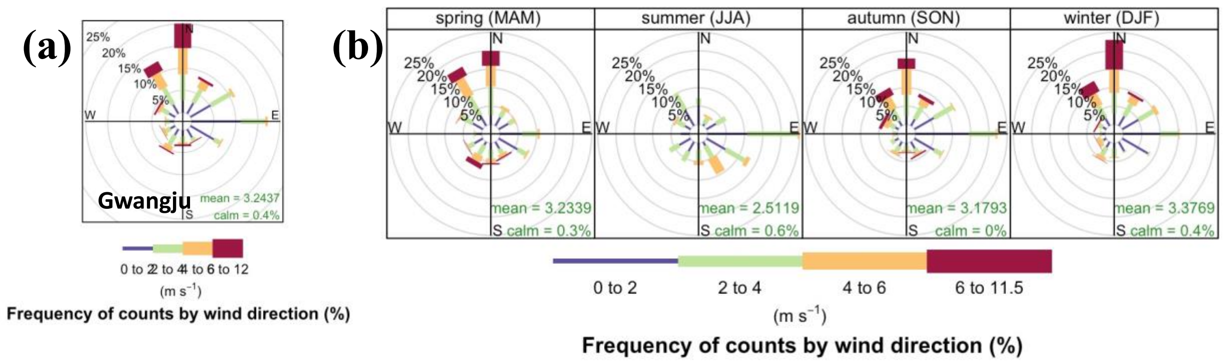



**Figure S6. Windrose plots in Gwangju: (a) wind rose plot for the whole study period, (b) wind rose plot by season.**

## Supplementary table

**List of table captions**



**Table S1. Uncertainty calculation of each species**

| Uncertainty calculation | |
|---|---|
| $PM_{2.5}$ | $4 \times conc$ |
| Carbonaceous species | $\sqrt{((0.05+E) \times conc + IDLs)^2 + (S.D.of\ Blank)^2}$ |
| Ionic species | $\sqrt{(global\ unc \times conc)^2 + (S.D.of\ Blank)^2 + (E \times conc)^2}$ |
| Trace element species | $\sqrt{((0.1+E) \times conc)^2 + (0.5 \times MDL)^2}$ |
| Flow error ($E$) | $\frac{\lvert (total\ flow) - 16.7 \rvert}{16.7}$ |

**Table S2. Dates of HCEs at each site**

| | Site | |
|---|---|---|
| Seoul | Incheon | Gwangju |
| 2020/10/19 | 2020/10/19 | 2020/10/27 |
| 2020/10/26 | 2020/10/26 | 2020/12/07 |
| 2020/10/27 | 2020/10/27 | 2020/12/22 |
| 2020/11/14 | 2020/11/12 | 2021/01/14 |
| 2020/11/16 | 2020/11/14 | 2021/02/06 |
| 2020/11/26 | 2020/11/16 | 2021/02/20 |
| 2020/12/10 | 2020/11/26 | 2021/03/10 |
| 2020/12/11 | 2020/12/10 | 2021/03/29 |
| 2020/12/22 | 2020/12/11 | 2021/05/07 |
| 2020/12/26 | 2020/12/22 | 2021/11/20 |
| 2020/12/28 | 2021/01/11 | 2021/12/16 |
| 2021/01/04 | 2021/01/15 | 2022/01/09 |
| 2021/01/11 | 2021/02/08 | 2022/01/23 |
| 2021/01/13 | 2021/03/10 | 2022/02/10 |
| 2021/01/15 | 2021/03/11 | 2022/02/12 |
| 2021/01/21 | 2021/03/12 | 2022/03/04 |
| 2021/01/27 | 2021/03/15 | 2022/03/08 |
| 2021/02/01 | 2021/03/18 | 2022/03/22 |
| 2021/02/06 | 2021/03/20 | |
| 2021/02/19 | 2021/03/26 | |
| 2021/02/20 | 2021/03/29 | |
| 2021/03/09 | 2021/05/07 | |
| 2021/03/10 | 2021/11/04 | |
| 2021/03/11 | 2021/11/18 | |
| 2021/03/13 | 2021/11/20 | |
| 2021/03/15 | 2021/12/06 | |
| 2021/03/18 | 2021/12/08 | |
| 2021/03/20 | 2021/12/16 | |
| 2021/03/26 | 2021/12/20 | |

| | |
|---|---|
| 2021/03/29 | 2021/12/28 |
| 2021/05/07 | 2022/01/05 |
| 2021/11/04 | 2022/01/10 |
| 2021/11/14 | 2022/01/15 |
| 2021/11/18 | 2022/01/21 |
| 2021/11/20 | 2022/01/25 |
| 2021/12/16 | 2022/02/10 |
| 2021/12/20 | 2022/02/12 |
| 2021/12/28 | 2022/02/18 |
| 2022/01/09 | 2022/03/04 |
| 2022/01/19 | 2022/03/10 |
| 2022/01/23 | |
| 2022/01/25 | |
| 2022/02/10 | |
| 2022/02/12 | |
| 2022/02/14 | |
| 2022/02/26 | |
| 2022/03/08 | |
| 2022/03/16 | |

**Table S3. $PM_{2.5}$ mass concentration and its chemical constituents in Seoul, Incheon, and Gwangju**

| Site | | Seoul | | Incheon | | Gwangju | |
|---|---|---|---|---|---|---|---|
| Species | Unit | Mean | SD | Mean | SD | Mean | SD |
| $PM_{2.5}$ | μg/m$^3$ | 24.2 | 21.4 | 24.6 | 20.0 | 18.8 | 16.5 |
| OC | μg/m$^3$ | 4.79 | 2.22 | 5.82 | 2.71 | 4.45 | 2.14 |
| EC | μg/m$^3$ | 0.36 | 0.17 | 0.59 | 0.30 | 0.36 | 0.22 |
| $NO_3^-$ | μg/m$^3$ | 6.54 | 7.03 | 6.27 | 6.83 | 4.82 | 4.84 |
| $SO_4^{2-}$ | μg/m$^3$ | 2.97 | 1.97 | 2.94 | 1.97 | 2.73 | 1.58 |
| $NH_4^+$ | μg/m$^3$ | 3.11 | 2.94 | 3.06 | 2.81 | 2.33 | 1.98 |
| $Cl^-$ | μg/m$^3$ | 0.45 | 0.38 | 0.77 | 0.57 | 0.43 | 0.31 |
| $Na^+$ | μg/m$^3$ | 0.20 | 0.28 | 0.41 | 0.63 | 0.25 | 0.35 |
| $K^+$ | μg/m$^3$ | 0.17 | 0.11 | 0.18 | 0.10 | 0.13 | 0.11 |
| ∑Trace elements | μg/m$^3$ | 3.48 | 5.50 | 4.23 | 5.56 | 3.13 | 5.22 |
| Crustal | ng/m$^3$ | 1448.9 | 4252.4 | 1763.2 | 4160.9 | 1277.3 | 4240.8 |
| Non-crustal | ng/m$^3$ | 2029.9 | 1246.9 | 2465.2 | 1397.9 | 1856.0 | 982.4 |
| Mg | ng/m$^3$ | 72.8 | 133.0 | 74.5 | 138.0 | 68.9 | 149.6 |
| Al | ng/m$^3$ | 178.4 | 665.4 | 208.1 | 676.7 | 167.4 | 705.8 |
| Si | ng/m$^3$ | 513.8 | 1996.2 | 617.6 | 1996.1 | 490.2 | 2067.6 |
| S | ng/m$^3$ | 1410.6 | 939.5 | 1395.8 | 842.2 | 1265.2 | 690.6 |
| Cl | ng/m$^3$ | 453.4 | 414.6 | 864.1 | 653.9 | 453.4 | 401.6 |
| K | ng/m$^3$ | 302.4 | 476.1 | 326.3 | 456.2 | 246.1 | 452.2 |
| Ca | ng/m$^3$ | 156.8 | 348.4 | 205.4 | 323.8 | 127.5 | 319.9 |
| Ti | ng/m$^3$ | 18.4 | 61.4 | 21.1 | 60.5 | 16.1 | 58.4 |
| V | ng/m$^3$ | 0.4 | 1.6 | 0.4 | 1.6 | 0.3 | 1.3 |
| Cr | ng/m$^3$ | 1.6 | 1.0 | 5.2 | 6.3 | 1.3 | 2.8 |
| Mn | ng/m$^3$ | 15.0 | 20.8 | 27.5 | 26.8 | 12.0 | 19.3 |
| Ba | ng/m$^3$ | 5.0 | 4.7 | 5.6 | 5.8 | 4.7 | 4.9 |
| Fe | ng/m$^3$ | 278.9 | 727.8 | 392.6 | 700.5 | 230.0 | 663.6 |
| Ni | ng/m$^3$ | 0.9 | 0.8 | 3.1 | 3.9 | 0.7 | 0.9 |
| Cu | ng/m$^3$ | 3.2 | 3.5 | 6.7 | 11.8 | 3.3 | 4.0 |
| Zn | ng/m$^3$ | 40.0 | 35.4 | 58.4 | 36.2 | 28.5 | 28.7 |
| As | ng/m$^3$ | 4.6 | 6.4 | 5.4 | 8.4 | 1.9 | 2.4 |
| Se | ng/m$^3$ | 0.9 | 0.9 | 0.8 | 0.8 | 0.9 | 0.8 |
| Br | ng/m$^3$ | 6.1 | 4.1 | 8.9 | 7.4 | 5.5 | 6.9 |
| Pb | ng/m$^3$ | 15.5 | 10.6 | 20.2 | 15.2 | 9.4 | 7.3 |

**Table S4. Explained values of chemical species for each source in Seoul**

| Species | Sources | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | SN | SS | BB | Mobile | Soil | Waste | CC | Ind/Oil | AGS | Ind |
| $PM_{2.5}$ | 33.592 | 15.013 | 13.622 | 10.051 | 7.817 | 6.825 | 3.981 | 2.275 | 2.275 | 4.550 |
| OC | 13.319 | 11.096 | 21.560 | 34.052 | 3.807 | 4.578 | 6.615 | 0.819 | 1.649 | 2.506 |
| EC | 4.559 | 0.000 | 17.716 | 38.019 | 14.365 | 12.477 | 10.567 | 0.000 | 0.000 | 2.297 |
| $NO_3^-$ | 67.861 | 6.341 | 15.732 | 0.000 | 0.828 | 4.126 | 2.176 | 0.000 | 0.000 | 2.936 |
| $SO_4^{2-}$ | 18.929 | 49.909 | 7.106 | 3.747 | 0.000 | 0.000 | 4.158 | 4.378 | 3.256 | 8.517 |
| $NH_4^+$ | 55.254 | 25.181 | 9.591 | 3.738 | 1.115 | 1.414 | 2.475 | 0.000 | 1.035 | 0.197 |
| $Cl^-$ | 8.251 | 0.501 | 0.000 | 0.000 | 0.000 | 80.388 | 4.440 | 6.421 | 0.000 | 0.000 |
| $Na^+$ | 6.258 | 0.000 | 0.877 | 9.479 | 0.000 | 3.394 | 0.000 | 0.207 | 79.786 | 0.000 |
| $K^+$ | 0.000 | 0.000 | 73.424 | 0.000 | 0.000 | 5.315 | 3.245 | 18.016 | 0.000 | 0.000 |
| Mg | 0.000 | 11.297 | 4.677 | 0.000 | 61.498 | 0.000 | 6.464 | 0.000 | 8.722 | 7.341 |
| Al | 1.197 | 6.788 | 0.000 | 0.000 | 77.576 | 0.234 | 8.759 | 3.978 | 1.468 | 0.000 |
| Si | 0.000 | 3.540 | 4.482 | 0.133 | 75.091 | 1.611 | 9.519 | 5.624 | 0.000 | 0.000 |
| Ca | 1.356 | 0.000 | 10.120 | 12.209 | 59.002 | 6.160 | 7.146 | 2.146 | 1.595 | 0.266 |
| Ti | 8.219 | 3.365 | 6.145 | 15.187 | 51.332 | 0.347 | 6.464 | 4.315 | 3.038 | 1.587 |
| V | 0.000 | 11.707 | 0.000 | 0.000 | 9.329 | 6.745 | 9.494 | 60.086 | 2.639 | 0.000 |
| Cr | 17.597 | 0.751 | 4.977 | 12.922 | 14.746 | 0.000 | 0.000 | 11.072 | 0.000 | 37.935 |
| Mn | 20.579 | 4.046 | 0.332 | 13.314 | 28.532 | 3.029 | 1.122 | 5.810 | 1.326 | 21.910 |
| Ba | 0.000 | 0.000 | 0.000 | 50.425 | 0.000 | 0.000 | 22.488 | 18.081 | 0.000 | 9.006 |
| Fe | 12.263 | 2.375 | 1.275 | 17.545 | 36.985 | 3.239 | 6.853 | 8.873 | 0.055 | 10.537 |
| Ni | 24.394 | 0.000 | 17.508 | 0.386 | 14.533 | 12.984 | 0.000 | 27.224 | 2.970 | 0.000 |
| Cu | 13.421 | 0.000 | 0.000 | 23.294 | 0.000 | 0.000 | 9.016 | 54.269 | 0.000 | 0.000 |
| Zn | 23.665 | 6.135 | 0.000 | 10.959 | 6.211 | 0.220 | 1.113 | 8.036 | 0.495 | 43.165 |
| As | 0.000 | 0.000 | 10.229 | 8.466 | 0.000 | 0.000 | 74.317 | 4.858 | 2.131 | 0.000 |
| Pb | 5.914 | 0.000 | 22.698 | 1.022 | 3.297 | 1.279 | 17.273 | 0.000 | 0.285 | 48.231 |

Abbreviations: SN (Secondary nitrate), SS (Secondary sulfate), BB (Biomass burning), CC (Coal combustion), Ind/Oil (Industry/Oil combustion), AGS (Aged sea salt), Ind (Industry).

**Table S5. Explained values of chemical species for each source in Incheon**

| Species | Sources | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | SN | SS | BB | Mobile | Soil | Waste | CC | Ind/Oil | AGS | MP |
| $PM_{2.5}$ | 25.694 | 18.373 | 12.805 | 11.136 | 8.898 | 12.361 | 3.897 | 1.670 | 3.341 | 1.825 |
| OC | 9.130 | 13.676 | 21.414 | 21.594 | 4.512 | 20.485 | 5.374 | 1.376 | 0.283 | 2.156 |
| EC | 0.000 | 0.000 | 22.719 | 34.788 | 11.339 | 21.755 | 5.992 | 0.000 | 0.000 | 3.406 |
| $NO_3^-$ | 71.437 | 0.000 | 8.118 | 0.000 | 3.389 | 10.641 | 2.987 | 0.000 | 2.707 | 0.721 |
| $SO_4^{2-}$ | 16.110 | 64.642 | 0.000 | 10.240 | 0.000 | 0.000 | 4.914 | 4.094 | 0.000 | 0.000 |
| $NH_4^+$ | 49.651 | 25.624 | 1.178 | 4.186 | 0.000 | 14.044 | 2.558 | 1.683 | 1.076 | 0.000 |
| $Cl^-$ | 5.209 | 9.626 | 0.000 | 15.371 | 0.477 | 59.572 | 0.255 | 0.634 | 7.414 | 1.442 |
| $Na^+$ | 4.551 | 0.000 | 3.939 | 0.000 | 0.230 | 2.043 | 1.727 | 1.834 | 85.677 | 0.000 |
| $K^+$ | 0.000 | 20.160 | 52.641 | 0.000 | 2.464 | 18.383 | 0.000 | 0.000 | 0.382 | 5.969 |
| Mg | 0.000 | 12.748 | 8.470 | 8.564 | 48.086 | 9.267 | 11.257 | 0.000 | 1.608 | 0.000 |
| Al | 5.187 | 8.019 | 4.894 | 14.730 | 52.081 | 2.683 | 8.198 | 1.985 | 1.526 | 0.696 |
| Si | 5.176 | 4.733 | 7.319 | 17.317 | 50.446 | 0.000 | 7.113 | 1.622 | 3.015 | 3.259 |
| Ca | 2.104 | 1.845 | 15.931 | 21.493 | 39.433 | 8.412 | 3.525 | 0.191 | 2.761 | 4.306 |
| Ti | 8.351 | 3.209 | 8.652 | 23.229 | 37.178 | 7.158 | 1.703 | 2.772 | 3.624 | 4.124 |
| V | 3.122 | 15.937 | 26.307 | 0.000 | 24.634 | 5.691 | 0.403 | 23.732 | 0.174 | 0.000 |
| Cr | 0.000 | 0.000 | 5.477 | 25.605 | 1.161 | 0.000 | 3.137 | 1.305 | 1.965 | 61.351 |
| Mn | 8.514 | 3.528 | 0.000 | 47.073 | 11.999 | 11.031 | 0.000 | 2.628 | 2.504 | 12.722 |
| Ba | 0.000 | 0.000 | 32.758 | 56.083 | 0.000 | 0.000 | 8.631 | 2.528 | 0.000 | 0.000 |
| Fe | 9.347 | 0.000 | 6.123 | 37.376 | 21.106 | 5.654 | 2.528 | 3.599 | 3.055 | 11.211 |
| Ni | 1.652 | 0.725 | 7.385 | 0.000 | 0.000 | 9.089 | 0.000 | 0.000 | 2.879 | 78.271 |
| Cu | 8.100 | 0.000 | 0.000 | 19.775 | 0.000 | 0.000 | 0.036 | 68.682 | 3.408 | 0.000 |
| Zn | 11.406 | 2.983 | 5.200 | 43.485 | 4.483 | 13.743 | 4.947 | 7.224 | 4.296 | 2.232 |
| As | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 89.827 | 0.098 | 6.713 | 3.362 |
| Pb | 4.043 | 1.602 | 10.052 | 10.029 | 7.262 | 15.974 | 41.600 | 3.287 | 0.000 | 6.152 |

Abbreviations: SN (Secondary nitrate), SS (Secondary sulfate), BB (Biomass burning), CC (Coal combustion), Ind/Oil (Industry/Oil combustion), AGS (Aged sea salt), MP (Metal plating).

**Table S6. Explained values of chemical species for each source in Gwangju**

| Species | Sources | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | SN | SS | BB | Mobile | Soil | Waste | CC | Ind/Oil | AGS |
| $PM_{2.5}$ | 29.152 | 16.353 | 14.931 | 12.430 | 4.209 | 10.666 | 5.932 | 2.844 | 3.484 |
| OC | 8.142 | 11.771 | 19.759 | 37.820 | 0.000 | 8.726 | 7.103 | 4.754 | 1.926 |
| EC | 0.000 | 0.000 | 20.872 | 51.263 | 1.852 | 16.680 | 9.334 | 0.000 | 0.000 |
| $NO_3^-$ | 73.054 | 0.000 | 12.747 | 0.000 | 2.037 | 6.521 | 5.641 | 0.000 | 0.000 |
| $SO_4^{2-}$ | 5.883 | 51.435 | 19.697 | 0.000 | 0.000 | 14.767 | 2.573 | 0.244 | 5.402 |
| $NH_4^+$ | 51.612 | 23.471 | 13.491 | 0.251 | 0.000 | 6.360 | 3.640 | 0.053 | 1.122 |
| $Cl^-$ | 8.973 | 0.000 | 1.983 | 6.074 | 0.000 | 71.600 | 0.915 | 10.454 | 0.000 |
| $Na^+$ | 0.000 | 0.000 | 8.161 | 1.730 | 0.000 | 9.178 | 0.000 | 0.856 | 80.075 |
| $K^+$ | 6.097 | 0.000 | 50.914 | 0.000 | 0.319 | 7.005 | 0.000 | 35.664 | 0.000 |
| Mg | 0.000 | 8.505 | 17.201 | 0.000 | 41.768 | 22.055 | 9.236 | 0.000 | 1.236 |
| Al | 7.677 | 8.532 | 11.740 | 7.754 | 55.907 | 1.729 | 5.735 | 0.000 | 0.927 |
| Si | 10.617 | 1.821 | 9.830 | 7.082 | 61.235 | 1.304 | 4.606 | 3.505 | 0.000 |
| Ca | 13.032 | 0.000 | 7.683 | 7.264 | 50.972 | 11.705 | 1.689 | 7.548 | 0.107 |
| Ti | 12.095 | 5.391 | 8.476 | 18.351 | 44.627 | 3.647 | 0.000 | 6.149 | 1.264 |
| V | 0.000 | 20.122 | 0.000 | 0.000 | 14.000 | 0.000 | 8.336 | 51.876 | 5.665 |
| Cr | 23.787 | 1.413 | 5.098 | 23.624 | 10.224 | 1.479 | 10.370 | 24.006 | 0.000 |
| Mn | 21.228 | 10.258 | 0.442 | 24.613 | 21.598 | 3.090 | 8.254 | 8.996 | 1.522 |
| Fe | 17.594 | 3.331 | 5.231 | 23.551 | 34.004 | 0.000 | 5.496 | 9.793 | 1.000 |
| Ni | 19.619 | 12.160 | 4.768 | 3.868 | 12.571 | 19.762 | 0.000 | 27.253 | 0.000 |
| Cu | 7.146 | 0.000 | 0.912 | 33.717 | 0.000 | 0.000 | 4.181 | 52.353 | 1.690 |
| Zn | 21.468 | 6.356 | 0.000 | 23.648 | 5.512 | 5.902 | 18.973 | 18.142 | 0.000 |
| As | 0.000 | 0.000 | 23.471 | 0.000 | 0.000 | 0.000 | 74.926 | 1.603 | 0.000 |
| Pb | 8.531 | 9.278 | 16.785 | 14.155 | 3.024 | 7.743 | 36.938 | 3.028 | 0.517 |

Abbreviations: SN (Secondary nitrate), SS (Secondary sulfate), BB (Biomass burning), CC (Coal combustion), Ind/Oil (Industry/Oil combustion), AGS (Aged sea salt), MP (Metal plating).

**Statistical analysis**

**Table S7. Comparison of source contributions between the heating season and non-heating season in each site (Mann-Whitney U test at $\alpha = 0.05$)**

| Source | *p*-Value | | |
|---|---|---|---|
| | Seoul | Incheon | Gwangju |
| Secondary nitrate | ≤ 0.001 | ≤ 0.001 | ≤ 0.001 |
| Secondary sulfate | 0.049 | 0.008 | 0.467 |
| Biomass burning | ≤ 0.001 | ≤ 0.001 | 0.103 |
| Mobile | 0.927 | 0.153 | 0.12 |
| Soil | 0.005 | 0.062 | 0.073 |
| Waste incinerator | ≤ 0.001 | ≤ 0.001 | ≤ 0.001 |
| Coal combustion | 0.007 | 0.923 | ≤ 0.001 |
| Industry/Oil combustion | ≤ 0.001 | ≤ 0.001 | ≤ 0.001 |
| Aged sea salt | 0.257 | 0.223 | 0.011 |
| Industry | 0.023 | - | - |
| Metal plating | - | 0.021 | - |

**Inter-site comparison of common source contributions by Kruskal-Wallis One Way Analysis of Variance on Ranks at $\alpha = 0.05$.**

**Table S8. Statistics of $PM_{2.5}$ mass concentration**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 222 | 0 | 18.300 | 11.500 | 31.850 |
| Incheon | 217 | 0 | 20.080 | 12.625 | 31.660 |
| Gwangju | 219 | 0 | 15.051 | 9.900 | 23.50 |

H = 18.271 with 2 degrees of freedom. ($p \leq 0.001$)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference ($p \leq 0.001$).

**Table S9. All Pairwise Multiple Comparison Procedures (Dunn's method) of $PM_{2.5}$**

| Comparison | Diff of Ranks | Q | P | P<0.050 |
|---|---|---|---|---|
| Incheon vs Gwangju | 72.985 | 4.008 | <0.001 | Yes |
| Incheon vs Seoul | 13.397 | 0.738 | 1 | No |
| Seoul vs Gwangju | 59.588 | 3.291 | 0.003 | Yes |

**Table S10. Statistics of secondary nitrate source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 5.449 | 1.449 | 17.041 |
| Incheon | 183 | 0 | 4.418 | 1.477 | 14.390 |
| Gwangju | 186 | 0 | 4.388 | 0.933 | 9.662 |

H = 5.204 with 2 degrees of freedom. ($p = 0.074$)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($p = 0.074$).

**Table S11. Statistics of secondary sulfate source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 1.941 | 0.548 | 3.725 |
| Incheon | 183 | 0 | 2.502 | 1.061 | 4.474 |
| Gwangju | 186 | 0 | 2.163 | 1.071 | 3.853 |

H = 4.765 with 2 degrees of freedom. ($p = 0.092$)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($p = 0.092$).

**Table S12. Statistics of biomass burning source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 2.115 | 1.138 | 3.569 |
| Incheon | 183 | 0 | 2.659 | 1.623 | 4.077 |
| Gwangju | 186 | 0 | 1.841 | 0.856 | 3.739 |

H = 10.405 with 2 degrees of freedom. ($p = 0.006$)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference ($p = 0.006$).

**Table S13. All Pairwise Multiple Comparison Procedures (Dunn's method) of biomass burning source**

| Comparison | Diff of Ranks | Q | P | P<0.050 |
|---|---|---|---|---|
| Incheon vs Gwangju | 51.136 | 3.074 | 0.006 | Yes |
| Incheon vs Seoul | 39.826 | 2.387 | 0.051 | No |
| Seoul vs Gwangju | 11.31 | 0.681 | 1 | No |

**Table S14. Statistics of mobile source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 2.002 | 1.220 | 2.925 |
| Incheon | 183 | 0 | 1.977 | 0.906 | 4.048 |
| Gwangju | 186 | 0 | 2.429 | 1.137 | 3.820 |

H = 3.751 with 2 degrees of freedom. ($p = 0.153$)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($p = 0.153$).

**Table S15. Statistics of soil source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 1.234 | 0.657 | 2.019 |
| Incheon | 183 | 0 | 1.108 | 0.410 | 2.285 |
| Gwangju | 186 | 0 | 0.254 | 0.0418 | 0.598 |

H = 95.674 with 2 degrees of freedom. ($p \leq 0.001$)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference ($p \leq 0.001$).

**Table S16. All Pairwise Multiple Comparison Procedures (Dunn's method) of soil source**

| Comparison | Diff of Ranks | Q | P | P<0.050 |
|---|---|---|---|---|
| Seoul vs Gwangju | 150.875 | 9.081 | <0.001 | Yes |
| Seoul vs Incheon | 23.734 | 1.423 | 0.464 | No |
| Incheon vs Gwangju | 127.14 | 7.642 | <0.001 | Yes |

**Table S17. Statistics of coal combustion source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 0.375 | 0.0870 | 1.152 |
| Incheon | 183 | 0 | 0.475 | 0.206 | 1.225 |
| Gwangju | 186 | 0 | 0.572 | 0.155 | 1.265 |

H = 2.614 with 2 degrees of freedom. ($p = 0.271$)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($p = 0.271$).

**Table S18. Statistics of waste incinerator source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 0.953 | 0.232 | 1.629 |
| Incheon | 183 | 0 | 2.053 | 0.735 | 3.515 |
| Gwangju | 186 | 0 | 0.957 | 0.215 | 2.107 |

H = 44.673 with 2 degrees of freedom. ($p \leq 0.001$)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference ($p \leq 0.001$).

**Table S19. All Pairwise Multiple Comparison Procedures (Dunn's method) of waste incinerator source**

| Comparison | Diff of Ranks | Q | P | P<0.050 |
|---|---|---|---|---|
| Incheon vs Seoul | 102.109 | 6.121 | <0.001 | Yes |
| Incheon vs Gwangju | 89.504 | 5.38 | <0.001 | Yes |
| Gwangju vs Seoul | 12.605 | 0.759 | 1 | No |

**Table S20. Statistics of industry/oil combustion source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 0.286 | 0.100 | 0.736 |
| Incheon | 183 | 0 | 0.242 | 0.0727 | 0.659 |
| Gwangju | 186 | 0 | 0.351 | 0.102 | 0.726 |

H = 0.481 with 2 degrees of freedom. ($p$ = 0.786)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($p$ = 0.786).

**Table S21. Statistics of aged sea salt source contribution**

| Group | N | Missing | Median | 25% | 75% |
|---|---|---|---|---|---|
| Seoul | 184 | 0 | 0.137 | 0.000 | 0.394 |
| Incheon | 183 | 0 | 0.163 | 0.000 | 0.635 |
| Gwangju | 186 | 0 | 0.249 | 0.000 | 0.609 |

H = 2.726 with 2 degrees of freedom. ($p$ = 0.256)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($p$ = 0.256).