*atmosphere*

*Supplementary Materials*

# Understanding the Sources of Ambient Fine Particulate Matter ($PM_{2.5}$) in Jeddah, Saudi Arabia

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**Table S1.** Summary of the optimum conditions for analysis of water-soluble cations and anions by ion exchange chromatography.

| Instrument Parameter | Anions Analysis | Cations Analysis |
|---|---|---|
| Instrument | Dionex ICS 3000 ion chromatography system | Dionex ICS 2500 ion chromatography system |
| Analytical column | Dionex IonPac™ AS14 4mm * 250mm | Dionex IonPac® CS14 4mm * 250mm |
| Guard column | IonPac™ AG14 4mm * 50mm | IonPac™ CG14 4mm |
| Suppressor | Anion Self-Regenerating Suppressor (ASRS) 300 | Cationic electrolytic suppressor (CAES) |
| Sampler | Automatic sampler (AS) | AS50 |
| Gradient pump | Single pump | Gradient pump (GP50) |
| Detector | Conductivity detector | Conductivity detector (CD25A) |
| Chromeleon software | Dionex Chromeleon software (version 6.80 SP4 Build 2361) | Dionex Chromeleon software (version 6.60) |
| Eluent | 1.0 mM $NaHCO_3$ \| 3.5 mM $Na_2CO_3$ | 10.0 mM methane-sulfonic acid ($CH_3SO_3H$) |
| Injection volume | 50.0 µL | 35.0 µL |
| Run time | 15.0 min | 22.0 min |
| Flow rate (ml/min) | 1.10 | 1.20 |
| Gradient pressure | 1300–1400 psi | 1000–1050 psi |
| Suppressor current | 36 mA | 40 mA |
| Baseline conductivity | 15–18 µS | 34–36 µS |

**Table S2.** Typical detection limits of elements measured on a Thermo Scientific™ ARL™ QUANT'X ED-XRF Spectrometer (based on [1]).

| | ng/cm² | ng/m³ | | ng/cm² | ng/m³ | | ng/m² | ng/m³ | | ng/m² | ng/m³ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Na** | 14.14 | 9.88 | **Mn** | 0.85 | 0.59 | **Zr** | 1.56 | 1.09 | **Eu** | 2.83 | 1.98 |
| **Mg** | 4.24 | 2.96 | **Fe** | 0.71 | 0.50 | **Nb** | 1.70 | 1.19 | **Tb** | 2.83 | 1.98 |
| **Al** | 3.68 | 2.57 | **Co** | 0.99 | 0.69 | **Mo** | 2.83 | 1.98 | **Hf** | 4.24 | 2.96 |
| **Si** | 3.54 | 2.47 | **Ni** | 0.71 | 0.50 | **Ag** | 8.49 | 5.93 | **Ta** | 2.83 | 1.98 |
| **P** | 3.39 | 2.37 | **Cu** | 0.85 | 0.59 | **Cd** | 8.49 | 5.93 | **W** | 2.26 | 1.58 |
| **S** | 2.83 | 1.98 | **Zn** | 0.85 | 0.59 | **In** | 11.31 | 7.90 | **Ir** | 1.84 | 1.29 |
| **Cl** | 2.4 | 1.68 | **Ga** | 0.85 | 0.59 | **Sn** | 14.14 | 9.88 | **Au** | 1.70 | 1.19 |
| **K** | 2.26 | 1.58 | **As** | 0.85 | 0.59 | **Sb** | 15.56 | 10.9 | **Hg** | 1.56 | 1.09 |
| **Ca** | 2.26 | 1.58 | **Se** | 0.71 | 0.50 | **Cs** | 4.24 | 2.96 | **Pb** | 1.56 | 1.09 |
| **Sc** | 1.70 | 1.19 | **Br** | 0.71 | 0.50 | **Ba** | 4.53 | 3.16 | | | |
| **Ti** | 1.41 | 0.98 | **Rb** | 0.85 | 0.59 | **La** | 3.54 | 2.47 | | | |
| **V** | 1.41 | 0.98 | **Sr** | 1.13 | 0.79 | **Ce** | 2.83 | 1.98 | | | |
| **Cr** | 0.99 | 0.69 | **Y** | 1.41 | 0.98 | **Sm** | 2.83 | 1.98 | | | |

**Table S3.** Summary of the overall variations in expected and observed $SO_4^{2-}$, $NH_4^+$ and $NO_3^-$ during the four sampling cycles in Jeddah, Saudi Arabia.

| | Total S (µg/m³) | Expected $SO_4^{2-}$ (µg/m³) | Observed $SO_4^{2-}$ (µg/m³) | Unexplained $SO_4^{2-}$ (µg/m³) | $NH_4^+$ (µg/m³) | $NO_3^-$ (µg/m³) |
|---|---|---|---|---|---|---|
| Cycle_1 | 4972 ± 2577 | 14.92 | 17.8 ± 17.0 | -2.88 | 2.49 ± 1.90 | 1.45 ± 0.90 |
| Cycle_2 | 4434 ± 1301 | 13.30 | 8.51 ± 3.23 | 4.79 | 2.43 ± 0.86 | 1.12 ± 0.80 |
| Cycle_3 | 6838 ± 2714 | 20.51 | 12.1 ± 4.94 | 8.41 | 3.20 ± 1.25 | 0.88 ± 0.55 |
| Cycle_4 | 4348 ± 2216 | 13.04 | 8.6 ± 4.69 | 4.44 | 3.16 ± 1.74 | 1.16 ± 0.55 |
| **Average** | 5148 ± 1160 | 15.44 ± 3.48 | 11.75 ± 4.36 | 3.69 ± 4.74 | 2.82 ± 0.42 | 1.15 ± 0.23 |

**Table S4.** Pearson correlations between different pollutant species measured from $PM_{2.5}$ and with meteorology—Refer to the appended excel sheet.

**Table S5.** Mean values for the elemental enrichment factors (EFs) per study cycle.

| | Cycle 1 | | | | Cycle 2 | | | | Cycle 3 | | | | Cycle 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TE** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** |
| **Si** | **0.86** | 0.10 | 0.73 | 1.20 | **1.09** | 0.42 | 0.67 | 2.93 | **0.81** | 0.07 | 0.64 | 1.11 | **1.04** | 0.30 | 0.80 | 2.23 |
| **Ti** | **1.59** | 0.25 | 1.23 | 2.35 | **2.51** | 1.20 | 1.18 | 7.14 | **1.57** | 0.28 | 1.23 | 2.55 | **2.01** | 0.69 | 1.35 | 4.50 |
| **Fe** | **1.77** | 0.34 | 1.27 | 2.92 | **2.94** | 1.39 | 1.37 | 7.79 | **1.75** | 0.29 | 1.42 | 3.05 | **2.27** | 0.85 | 1.56 | 5.67 |
| **Mg** | **1.95** | 1.16 | 0.85 | 6.11 | **4.88** | 5.15 | 0.57 | 28.9 | **2.28** | 1.43 | 1.40 | 10.07 | **1.62** | 0.83 | 0.97 | 5.41 |
| **K** | **1.98** | 1.11 | 1.02 | 6.18 | **5.27** | 4.57 | 0.61 | 24.2 | **2.37** | 1.34 | 1.07 | 8.66 | **2.04** | 1.23 | 1.06 | 7.26 |
| **Mn** | **2.49** | 0.83 | 1.32 | 4.72 | **3.88** | 2.46 | 1.46 | 13.7 | **2.47** | 0.57 | 1.75 | 3.91 | **3.08** | 1.48 | 1.19 | 7.56 |
| **Sr** | **2.62** | 1.26 | 1.37 | 6.78 | **5.36** | 4.48 | 0.72 | 21.1 | **2.24** | 0.88 | 1.20 | 6.46 | **2.72** | 1.04 | 1.37 | 7.11 |
| **Ca** | **3.31** | 1.41 | 1.66 | 7.70 | **6.35** | 4.54 | 0.68 | 22.9 | **3.22** | 1.06 | 1.85 | 8.18 | **3.78** | 1.89 | 1.65 | 11.6 |
| **Cr** | **4.21** | 1.90 | 1.79 | 9.84 | **7.86** | 6.18 | 1.34 | 25.3 | **4.23** | 3.76 | 0.74 | 25.9 | **6.85** | 6.99 | 2.29 | 41.9 |
| **Na** | **5.70** | 6.71 | 0.76 | 30.1 | **23.1** | 28.9 | 0.08 | 158 | **5.99** | 7.88 | 1.16 | 47.8 | **4.53** | 6.12 | 0.45 | 35.4 |
| **Ce** | **7.64** | 6.65 | 0.66 | 29.8 | **36.7** | 36.6 | 0.69 | 168 | **14.8** | 7.64 | 1.27 | 31.3 | **6.28** | 5.06 | 1.04 | 23.3 |
| **Ni** | **19.2** | 9.85 | 2.66 | 44.1 | **71.2** | 60.7 | 3.57 | 258 | **23.0** | 11.4 | 6.91 | 55.6 | **15.7** | 12.6 | 2.75 | 62.5 |
| **V** | **22.6** | 13.0 | 0.06 | 71.3 | **104** | 97.1 | 4.06 | 455 | **29.3** | 18.9 | 5.38 | 79.2 | **14.1** | 13.9 | 0.10 | 58.2 |
| **Cu** | **25.0** | 18.5 | 3.34 | 85.2 | **49.6** | 38.7 | 3.55 | 189 | **28.7** | 36.4 | 8.86 | 256 | **32.9** | 30.2 | 5.67 | 142 |
| **Y** | **30.7** | 44.8 | 0.58 | 216 | **37.3** | 59.1 | 0.41 | 241 | **29.9** | 30.7 | 0.85 | 119 | **44.6** | 52.2 | 0.94 | 195 |
| **Zn** | **96.5** | 135 | 10.5 | 770 | **234** | 460 | 4.79 | 2731 | **83.3** | 70.4 | 26.7 | 340 | **95.0** | 153 | 8.74 | 844 |
| **Cl** | **657** | 1546 | 0.20 | 8596 | **1027** | 2569 | 0.07 | 14,547 | **293** | 1354 | 0.34 | 8934 | **270** | 736 | 0.17 | 4500 |
| **S** | **1714** | 1025 | 134 | 4212 | **6355** | 5514 | 143 | 20,261 | **2949** | 1190 | 912 | 5664 | **1881** | 1449 | 228 | 6573 |
| **Pb** | **2140** | 2958 | 24.2 | 14,452 | **1952** | 2962 | 10.4 | 11,203 | **2330** | 2474 | 52.3 | 9841 | **3435** | 4045 | 61.4 | 15,769 |
| **Br** | **2319** | 2376 | 320 | 12,562 | **10,285** | 9912 | 136 | 46,597 | **3614** | 3125 | 1061 | 19,518 | **2548** | 2956 | 557 | 18,236 |
| **Lu** | **3572** | 2502 | 616 | 12,638 | **8802** | 7960 | 468 | 38,121 | **3476** | 1714 | 1311 | 8544 | **4086** | 3735 | 808 | 18,950 |

**Table S6.** Summary of the PMF solution in Jeddah: Sources of $PM_{2.5}$ and their overall relative contributions.

| | **Factor contribution (%)** | | | | |
|---|---|---|---|---|---|
| **Source/Factor** | **Cycle 1** | **Cycle 2** | **Cycle 3** | **Cycle 4** | **Average** |
| 1. Fossil-fuels/oil combustion | 44.3 | 30.2 | 40.7 | 31.3 | 36.6 |
| 2. Vehicular emissions | 19.0 | 19.9 | 12.9 | 11.4 | 15.8 |
| 3. Soil/dust resuspension | 16.1 | 29.0 | 16.5 | 30.2 | 23.0 |
| 4. Industrial mixed dust | 14.2 | 17.4 | 20.5 | 18.6 | 17.7 |
| 5. Sea spray | 6.4 | — | — | — | 6.9 |
| 6. Urban dust | — | 3.5 | 9.4 | 8.4 | |
| **Total** | **100** | **100** | **100** | **100** | **100** |

**Table S7.** Signal-to-Noise ratios (S/N) and classifications/categories of air pollutant species used for PMF analysis per cycle in Jeddah.

| | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | |
|---|---|---|---|---|---|---|---|---|
| **Pollutant Specie** | **Category** | **S/N** | **Category** | **S/N** | **Category** | **S/N** | **Category** | **S/N** |
| $PM_{2.5}$ | Weak | 10 | Weak | 10 | Weak | 10 | Weak | 10 |
| Black carbon (BC) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Sodium (Na) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Magnesium (Mg) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Aluminum (Al) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Silicon (Si) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Sulfur (S) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Chlorine (Cl) | Strong | 6.4 | Strong | 5.2 | Weak | 3.2 | Strong | 5.8 |
| Potassium (K) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Calcium (Ca) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Titanium (Ti) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Vanadium (V) | Strong | 9.5 | Strong | 10 | Strong | 10 | Strong | 7.8 |
| Chromium (Cr) | Strong | 8.8 | Strong | 9.6 | Strong | 9.1 | Strong | 9.9 |
| Manganese (Mn) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Iron (Fe) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Nickel (Ni) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Copper (Cu) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Zinc (Zn) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |
| Bromine (Br) | Strong | 9.3 | Strong | 9.0 | Strong | 10 | Strong | 10 |
| Strontium (Sr) | Strong | 10 | Strong | 7.8 | Strong | 10 | Strong | 10 |
| Yttrium (Y) | Strong | 7.8 | Weak | 4.4 | Strong | 7.7 | Strong | 9.3 |
| Cerium (Ce) | Weak | 3.0 | Strong | 5.1 | Weak | 3.9 | Weak | 4.4 |
| Erbium (Er) | Strong | 7.3 | Strong | 5.9 | Strong | 7.7 | Strong | 7.6 |
| Lutetium (Lu) | Strong | 9.9 | Strong | 10 | Strong | 10 | Strong | 10 |
| Lead (Pb) | Strong | 9.3 | Strong | 8.7 | Strong | 9.9 | Strong | 10 |
| Ammonium ($NH_4^+$) | Strong | 9.8 | Strong | 10 | Strong | 10 | Strong | 10 |
| Nitrate ($NO_3^-$) | Strong | 10 | Strong | 10 | Strong | 10 | Strong | 10 |

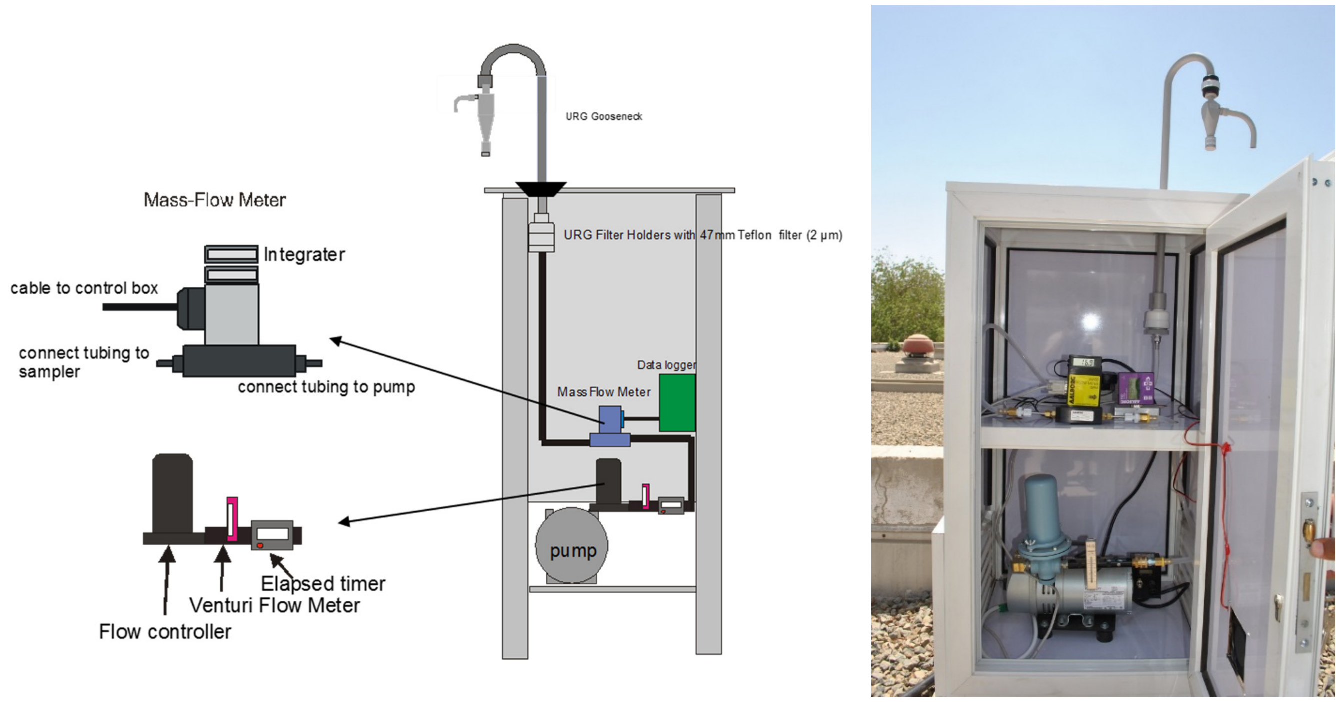


**Figure S1.** An assembled PM2.5 sampler showing the major components—Photo by author(s).

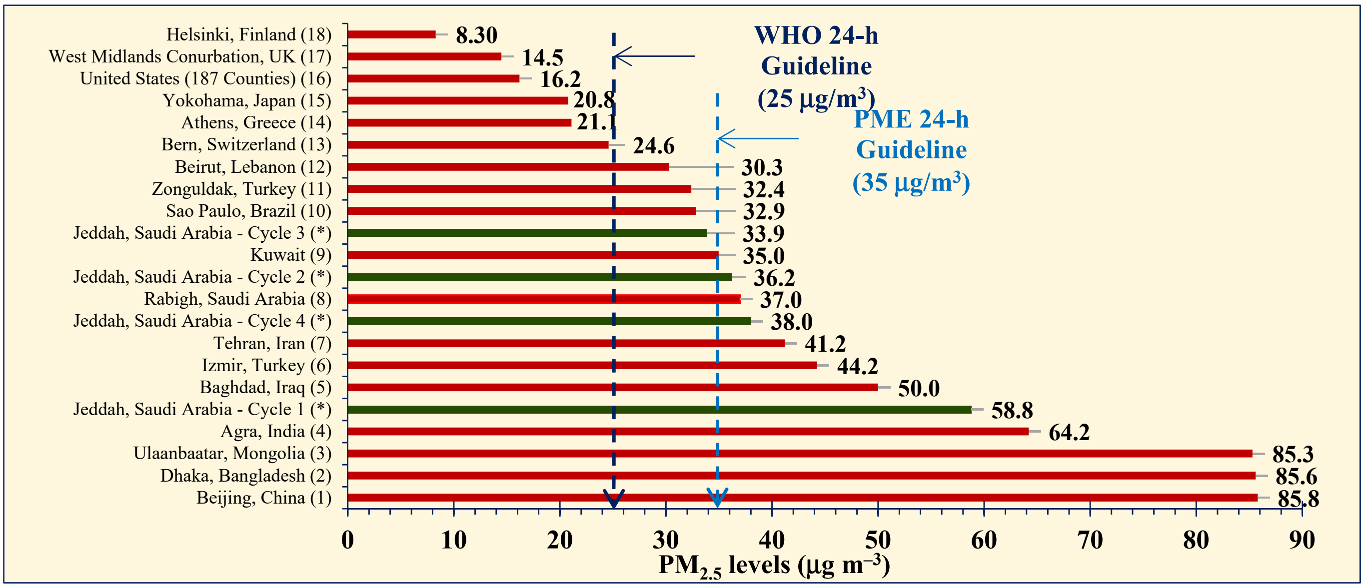


**Figure S2.** Comparison of mean PM2.5 levels measured in Jeddah with other cities worldwide. 1—[2]; 2—[3]; 3—[4]; 4—[5]; 5—[6]; 6—[7]; 7—[8]; 8—[9]; 9—[10]; 10—[11]; 11—[12]; 12—[13]; 13—[14]; 14—[15]; 15—[16]; 16—[17]; 17—[18]; 18—[19]; *—Cycles (1–4)—current study

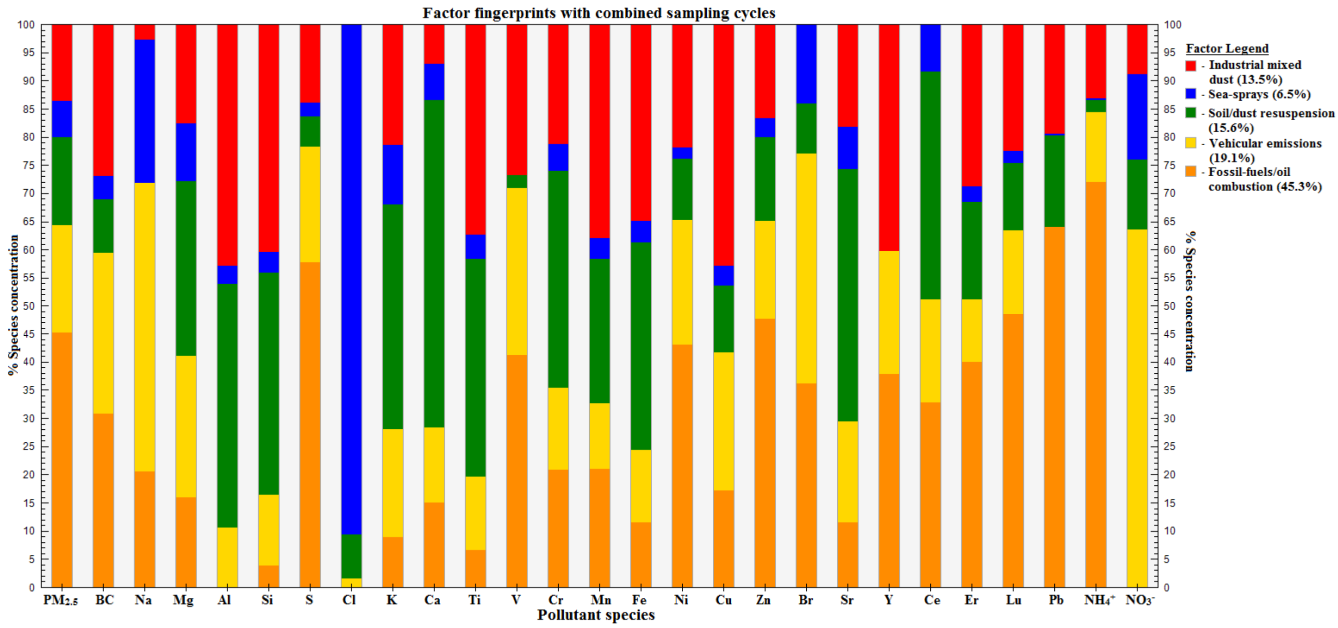


**Figure S3.** Factor fingerprints and contributions to the overall $PM_{2.5}$ in Jeddah—combined cycles.

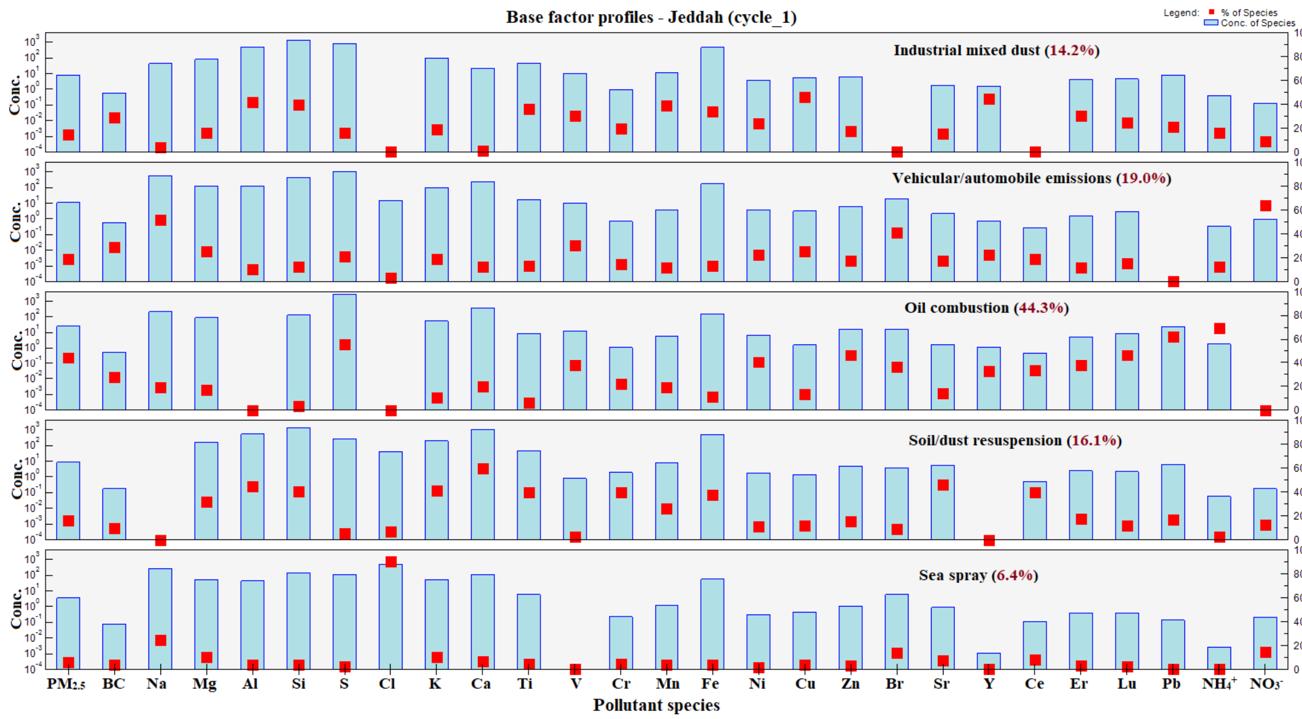


**Figure S4.** Base factor profiles and contributions to the overall $PM_{2.5}$—Jeddah cycle 1.

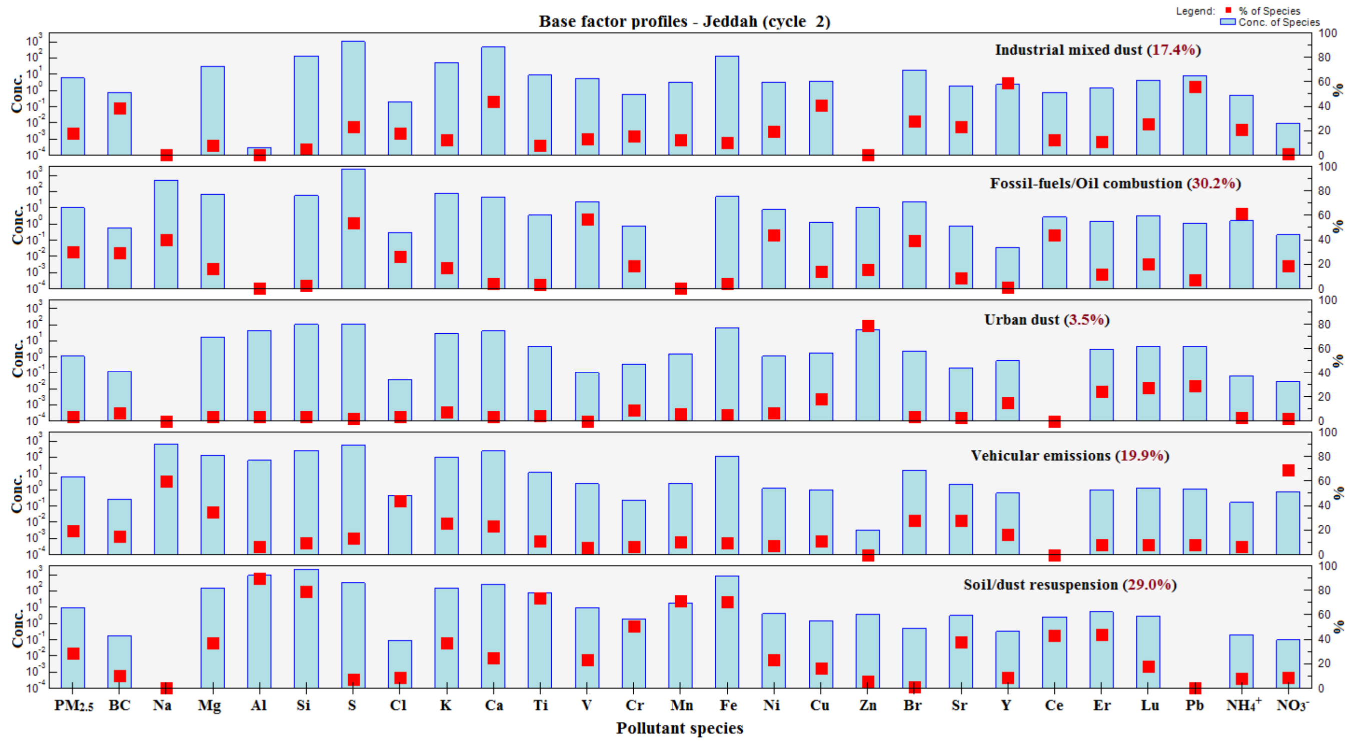


**Figure S5.** Base factor profiles and contributions to the overall $PM_{2.5}$—Jeddah cycle 2.

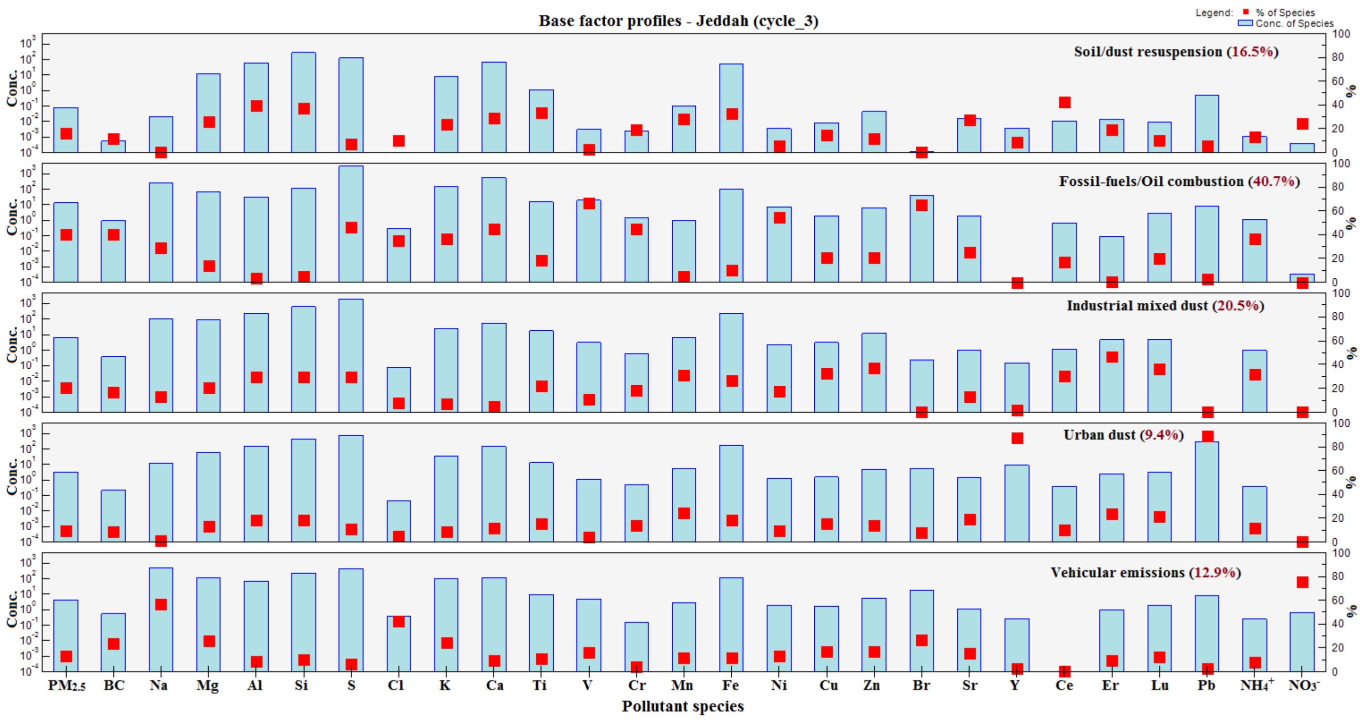


**Figure S6.** Base factor profiles and contributions to the overall $PM_{2.5}$—Jeddah cycle 3.

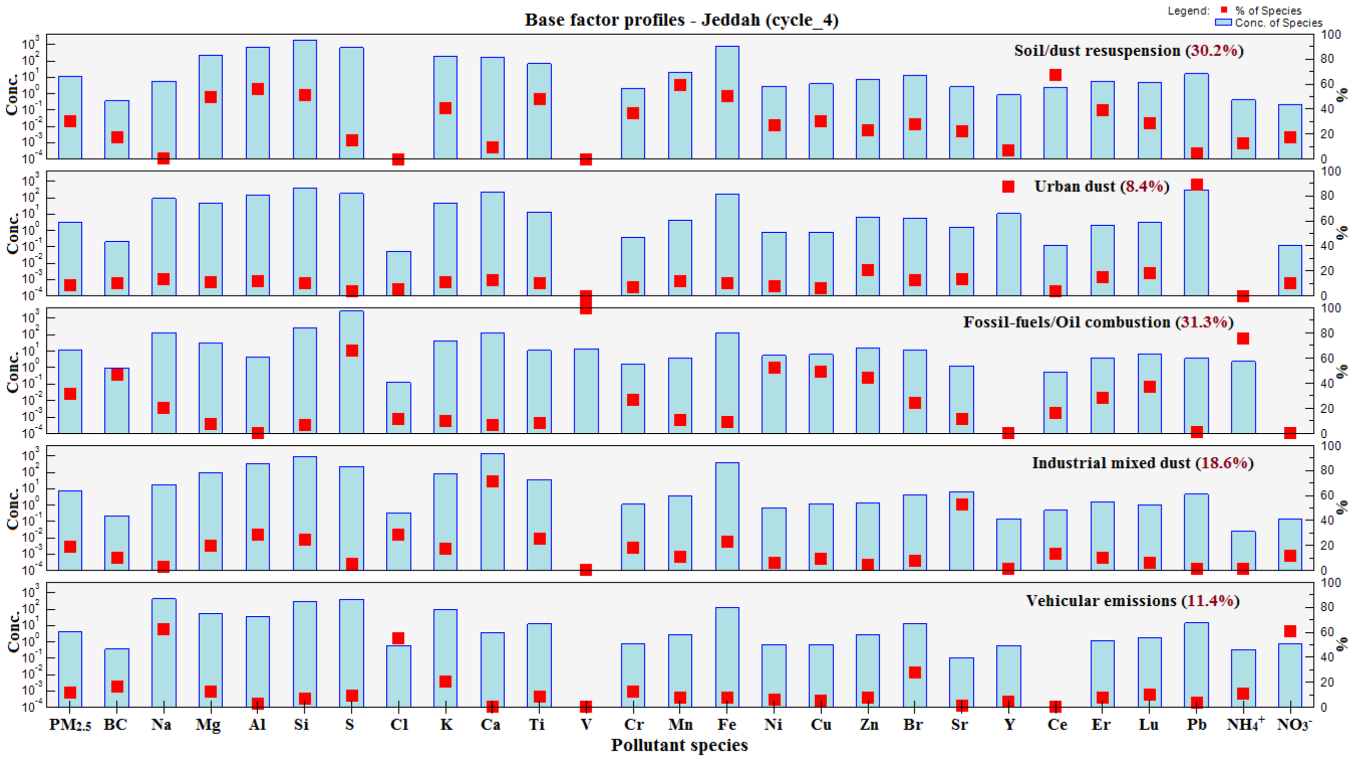


**Figure S7.** Base factor profiles and contributions to the overall $PM_{2.5}$—Jeddah cycle 4.

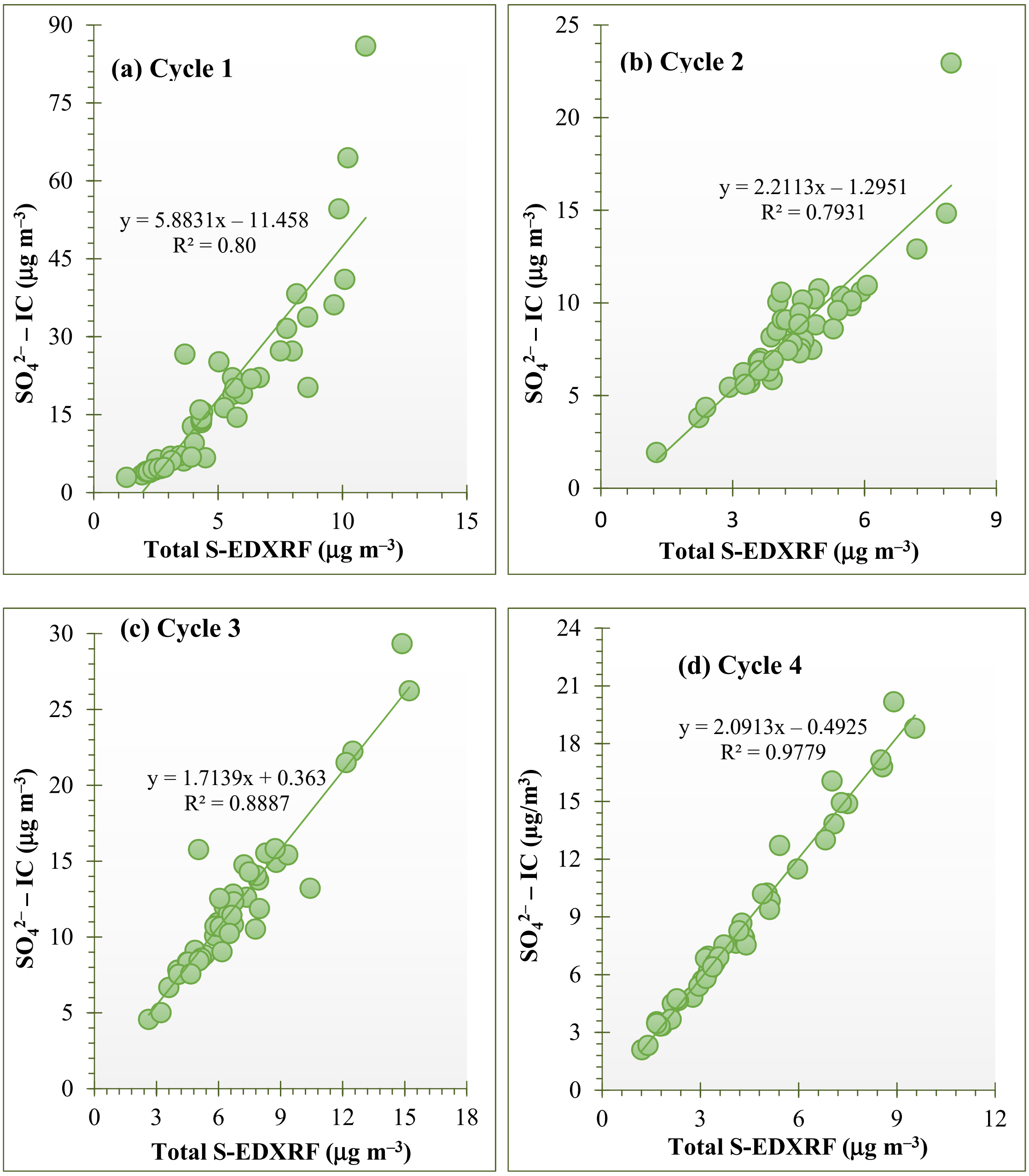


**Figure S8. Plots of water-soluble $SO_4^{2-}$ from IC analysis versus total S from ED-XRF analysis: cycle 1—(a); cycle 2—(b); cycle3—(c); cycle 4—(d).Backward-in-time trajectories**

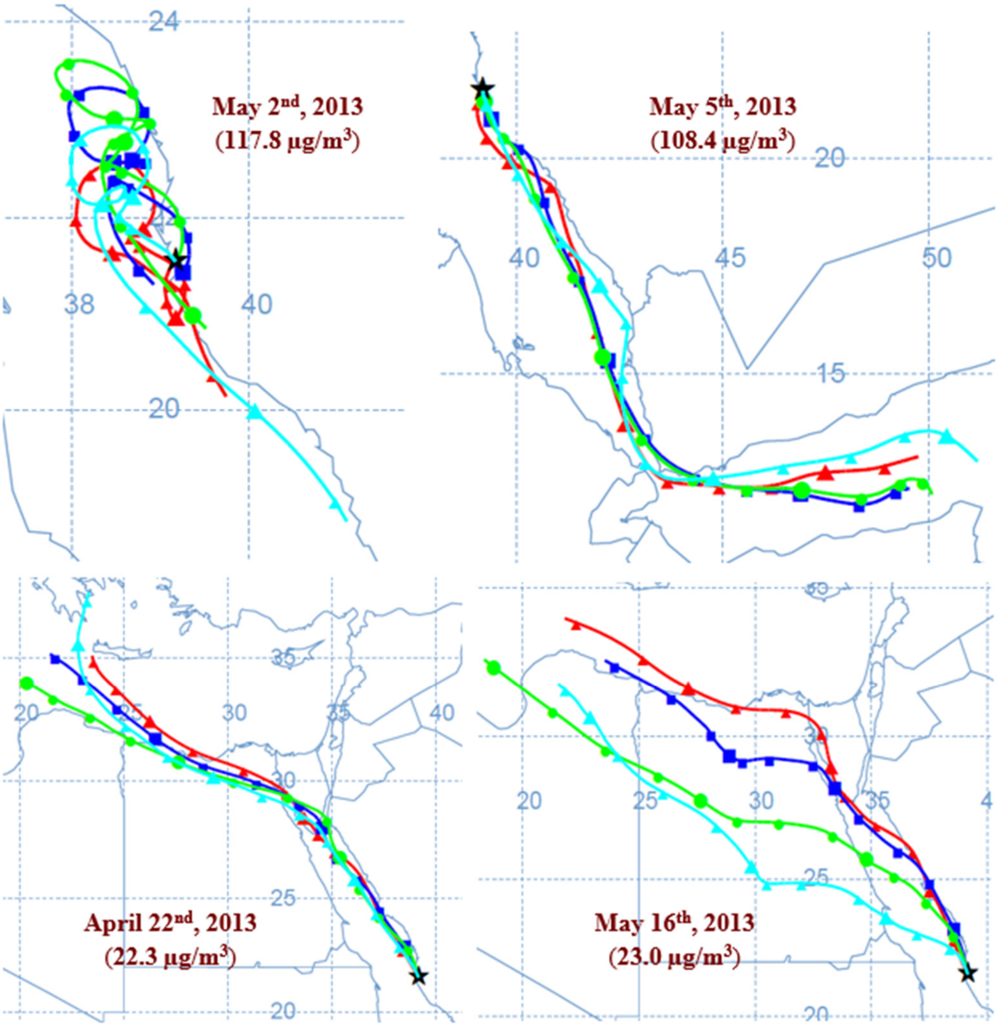


**Figure S9.** Plots of backward-in-time wind trajectories showing wind direction and its influence on daily $PM_{2.5}$ measured in Jeddah (cycle 1).

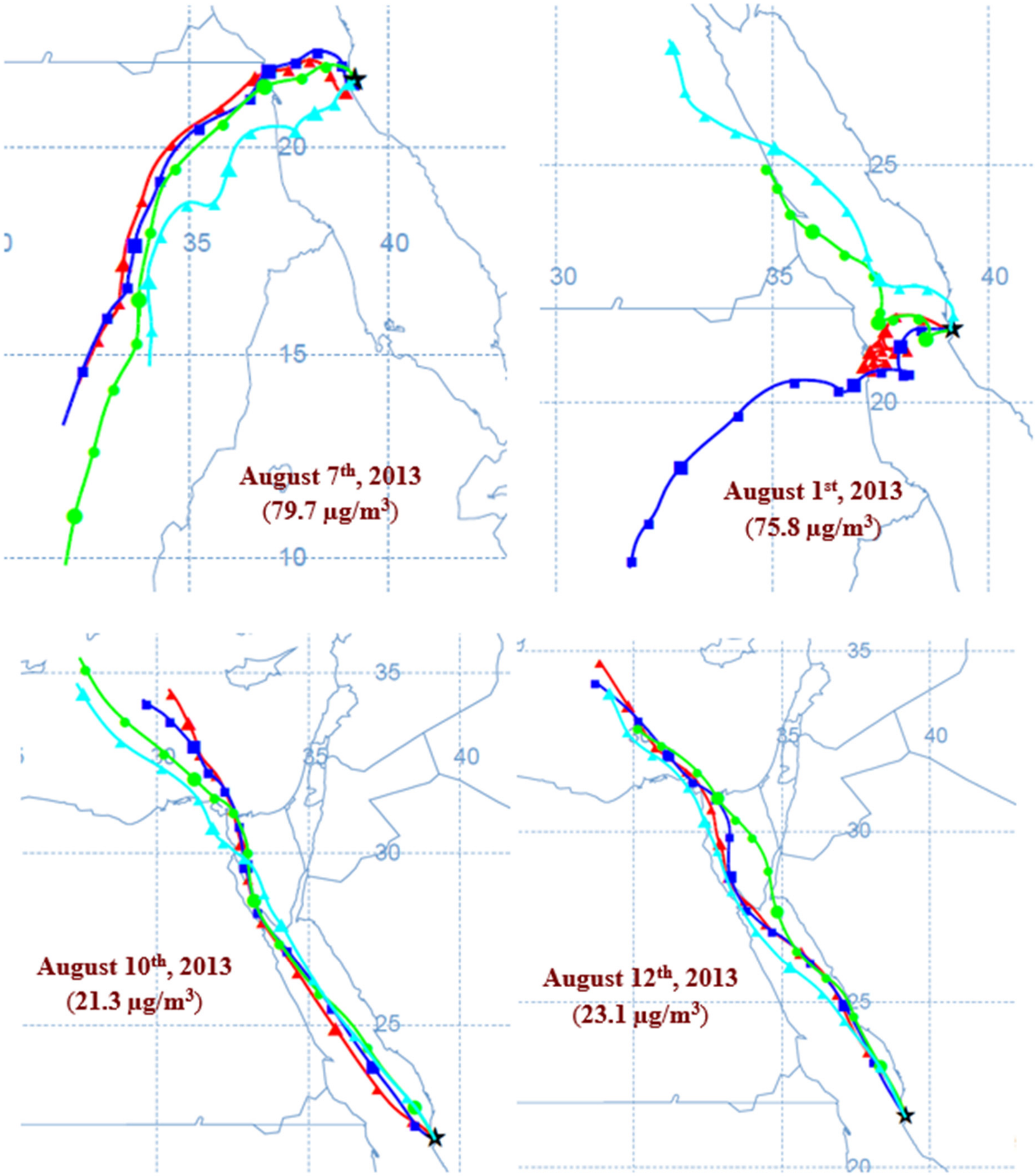


**Figure S10.** Plots of backward-in-time wind trajectories showing wind direction and its influence on daily $PM_{2.5}$ measured in Jeddah (cycle 2).

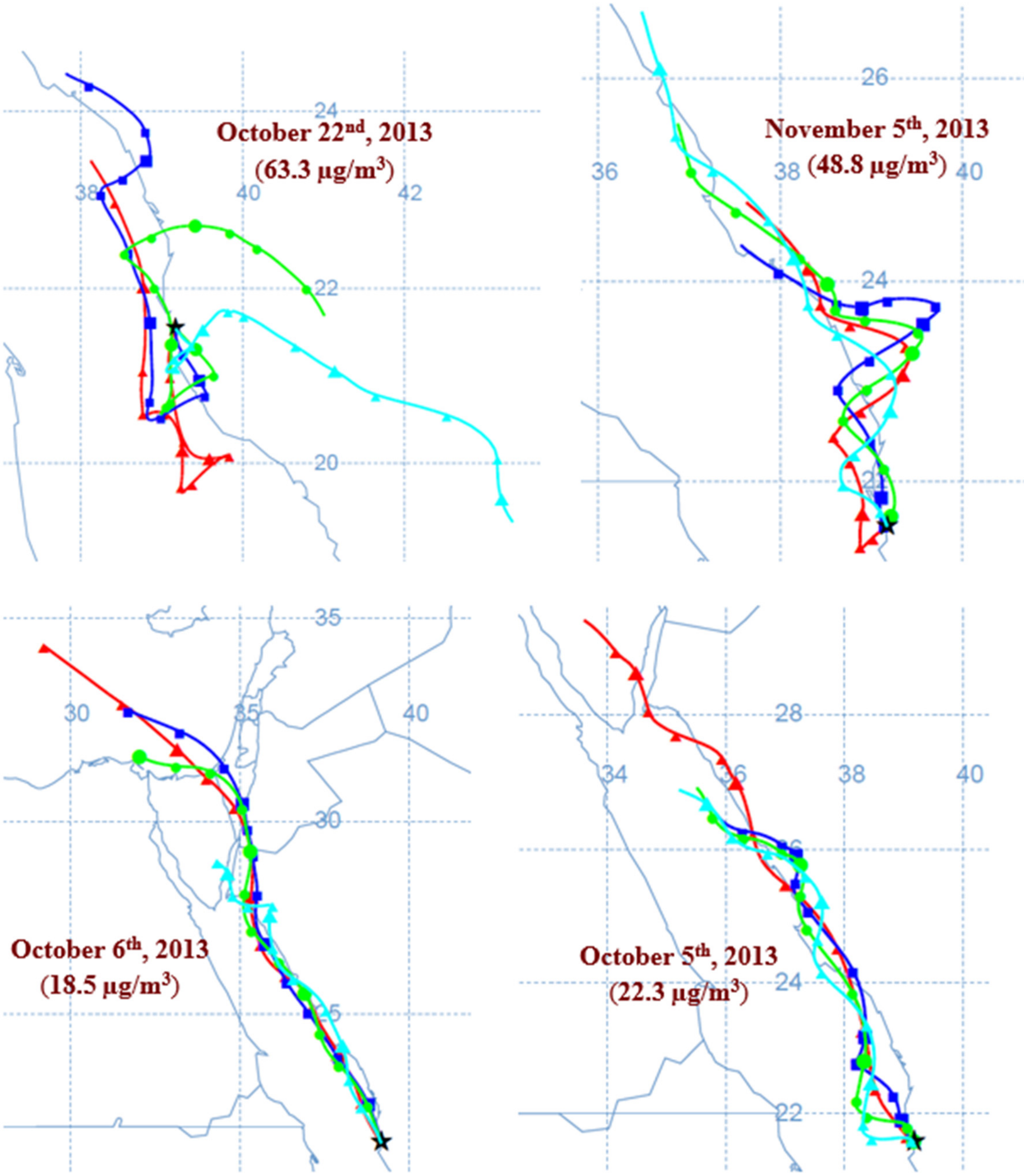


**Figure S11.** Plots of backward-in-time wind trajectories showing wind direction and its influence on daily $PM_{2.5}$ measured in Jeddah (cycle 3).

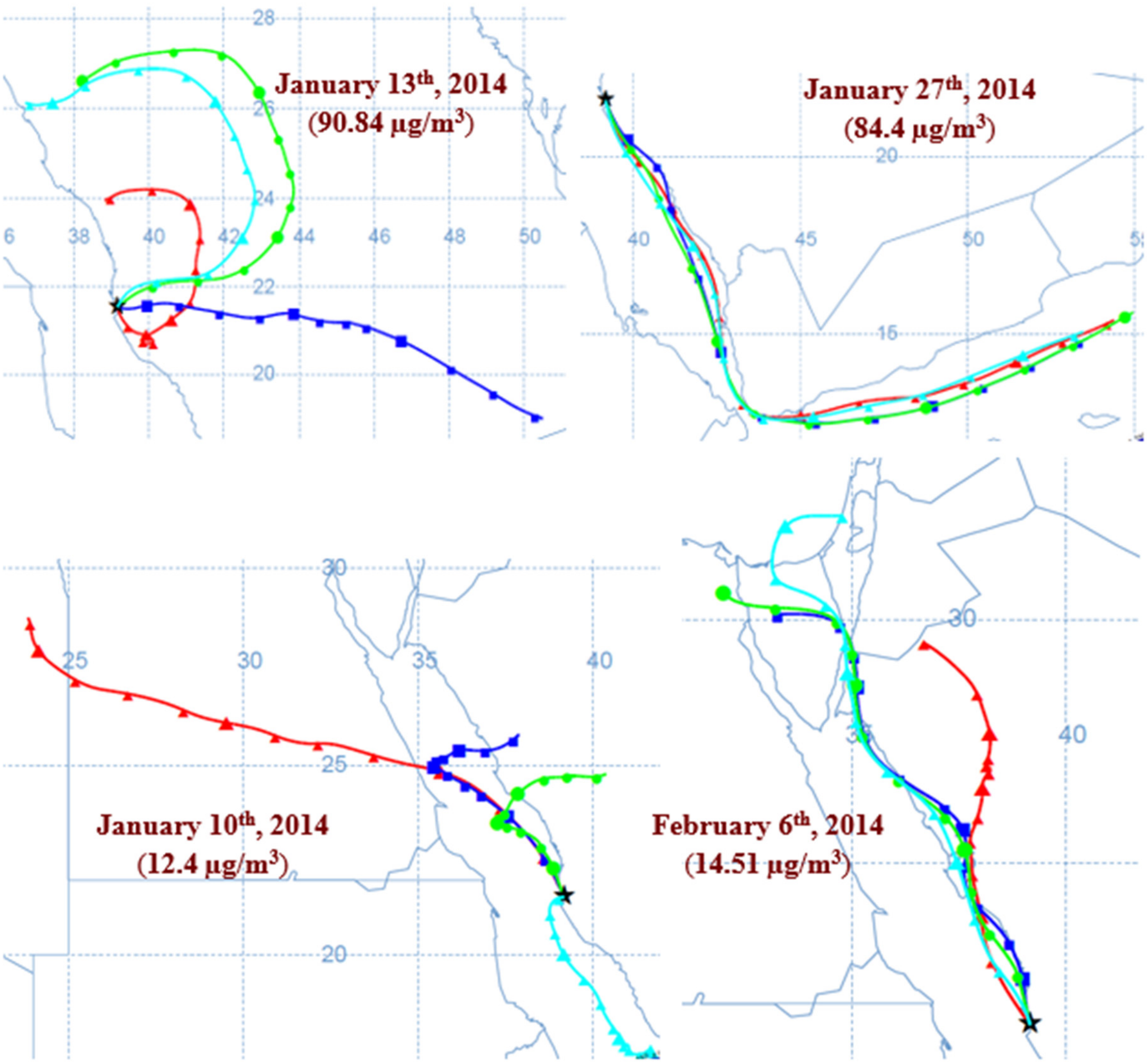


**Figure S12.** Plots of backward-in-time wind trajectories showing wind direction and its influence on daily $PM_{2.5}$ measured in Jeddah (cycle 4).

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