Wintertime trends of fine particulate matter ($PM_{2.5}$) in South Korea, 2012-2022: response of nitrate and organic components to decreasing NO_x emissions

Drew. C. Pendergrass[1], Daniel J. Jacob[1,2], Yujin J. Oak[1], Ruijun Dang[1], Laura Hyesung Yang[1], Ellie Beaudry[1], Nadia K. Colombi[2], Shixian Zhai[3], Hwajin Kim[4,5], Jin-soo Choi[6], Jin-soo Park[6], Soontae Kim[7], Ke Li[8], and Hong Liao[8]

[1]School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA.
[2]Department of Earth and Planetary Science, Harvard University, Cambridge, MA 02138, USA.
[3]Earth and Environmental Sciences Programme and Graduation Division of Earth and Atmospheric Sciences, Faculty of Science, The Chinese University of Hong Kong, Sha Tin, Hong Kong SAR, China
[4]Department of Environmental Health Sciences, Graduate School of Public Health, Seoul National University, 08826 Seoul, South Korea
[5]Institute of Health and Environment, Graduate School of Public Health, Seoul National University, 08826 Seoul, South Korea
[6]Air Quality Research Division, National Institute of Environmental Research, Incheon 22689, South Korea
[7]Department of Environmental and Safety Engineering, Ajou University, Suwon, South Korea.
[8]Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, Jiangsu Collaborative Innovation, Center of Atmospheric Environment and Equipment Technology, School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, China.

Correspondence to: Drew C. Pendergrass (pendergrass@g.harvard.edu)

Abstract. We analyze 2011-2022 trends in wintertime fine particulate matter ($PM_{2.5}$) and its composition in South Korea. $PM_{2.5}$ concentrations decreased nationwide by 1.2 μg m^{-3} a^{-1} after correcting for meteorology. However, Seoul $PM_{2.5}$ only declines after 2019 and has shifted toward particulate nitrate (pNO_3^-) and secondary organic aerosol (SOA) which have been resistant to decrease. Surface nitrogen dioxide (NO_2) and ozone (O_3) trends including weekday versus weekend suggest nighttime formation of the nitrate radical (NO_3) from the $NO_2 + O_3$ reaction is a key driver of pNO_3^- and OA formation. Increasing O_3 as nitrogen oxide (NO_x) emissions decline has increased NO_3 production promoting pNO_3^- and SOA formation. As NO_x emissions in South Korea decrease, we see a crossover from NO_x-saturated to NO_x-limited conditions for both NO_3 formation and pNO_3^- gas-particle partitioning, explaining the pNO_3^- decrease after 2019. Further NO_x and volatile organic compound (VOC) emissions decreases should reduce pNO_3^- and SOA.

Plain language summary. Fine particulate matter ($PM_{2.5}$) is a severe air pollution problem in South Korea and is worst in winter. Strong local emissions controls and emissions reductions upwind have led

winter $PM_{2.5}$ to decline throughout South Korea. However, $PM_{2.5}$ around Seoul (where half the population lives) has been resistant to decrease and only declined after 2019. With an ensemble of surface observations augmented by machine learning, we find that $PM_{2.5}$ composition in Seoul has shifted toward two kinds of secondary $PM_{2.5}$, meaning that they are formed in the atmosphere through chemical reactions rather than emitted directly, and that these species are both resistant to decrease. Both species, particulate nitrate (pNO_3^-) and secondary organic aerosol (SOA), can be formed by nighttime chemistry. We find that as nitrogen oxide (NO_x) pollution (largely from combustion) has declined due to emissions controls, this nighttime chemistry accelerates and increases the formation of pNO_3^- and SOA. However, pNO_3^- appears to have begun responding to NO_x controls after 2019 and we propose a physical driver of this decrease. We argue that further decreases in NO_x combined with reductions in emissions of volatile organic compounds should drive faster pNO_3^- reductions and also SOA reductions because the nighttime chemistry may decelerate.

Key points.

- Fine particulate matter ($PM_{2.5}$) has declined throughout South Korea due to emissions controls but only decreases in Seoul after 2019
- Nighttime nitrate radical chemistry in Seoul accelerated with nitrogen oxide emissions controls, increasing nitrate and organic $PM_{2.5}$
- Nitrate radical and nitrate $PM_{2.5}$ chemistry are increasingly sensitive to nitrogen oxide emissions and its decrease should improve $PM_{2.5}$

1 Introduction

Fine particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) is a leading cause of mortality, responsible in South Korea for 34,000 annual deaths (Y.-H. Lim et al., 2020; N. R. Kim & Lee, 2024; Oh et al., 2024). $PM_{2.5}$ concentrations in South Korea have decreased over the past decade (Pendergrass et al., 2022, 2025), driven by domestic pollution controls (Joo, 2018; Ministry of the Environment, 2019) and by reduced transport from China where pollution controls have driven $PM_{2.5}$ declines as well (Zhai et al., 2019). However, wintertime $PM_{2.5}$ in South Korea remains high and particularly in the Seoul Metropolitan Area (SMA), where over half of the population lives. $PM_{2.5}$ is highest in winter and early spring because of suppressed vertical mixing, long-range transport, and local emissions (H. Kim et al., 2017; Lee et al., 2024; E. Kim et al., 2025; Kwon et al., 2025).

$PM_{2.5}$ can be emitted directly (primary) or can be formed in the atmosphere following oxidation of precursor gases (secondary). $PM_{2.5}$ mass concentrations have been monitored hourly by the AirKorea surface network beginning in 2015, while oxidants including nitrogen dioxide (NO_2) and ozone (O_3) have been monitored since 2001. $PM_{2.5}$ speciation has also been measured at six supersites since 2015 (Kumar et al., 2021; NIER, 2022). The data show rapid decrease of black carbon (BC) and sulfate (SO_4^{2-}) $PM_{2.5}$ components, while particulate nitrate (pNO_3^-) and secondary organic aerosol (SOA) contribute an increasing fraction of $PM_{2.5}$ mass (Y. Kim et al., 2020; Lee et al., 2024). The decreases of BC and SO_4^{2-} are consistent with decreasing primary emission from fuel combustion and decreasing emission of sulfur dioxide (SO_2) (E. Kim et al., 2025). pNO_3^- and SOA originate from emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs), respectively. NO_x emissions in South Korea (mainly from fuel combustion) decreased by 30% over the 2015-2023 period while VOC emissions have been flat (Oak et al., 2025).

pNO_3^- in South Korea has not responded to the decrease of NO_x emissions and is now a major component of extreme winter haze events in the SMA (Bae et al., 2020; B.-U. Kim et al., 2017; S. Lim et al., 2022; J. Park et al., 2022). Formation of pNO_3^- requires alkalinity (largely from ammonia, NH_3) beyond that needed to neutralize SO_4^{2-}. In the absence of alkalinity, pNO_3^- partitions to the gas phase as nitric acid (HNO_3). NH_3 is mainly emitted by agriculture, with a small urban source from vehicles (T. Park et al., 2023). pNO_3^- formation in South Korea was limited in the past by the supply of NH_3 (Dang et al., 2023, 2024) but is now increasingly limited by the supply of NO_x as NO_x emissions have decreased (Oak et al., 2025). The decrease of NO_x emissions has increased wintertime ozone (Colombi et al., 2023), which would promote nighttime formation of pNO_3^- by way of the nitrate radical (NO_3) (Shah et al., 2020; Zhang et al., 2024). Oxidation of VOCs to form SOA would also be enhanced by the increase of O_3 and NO_3 (Hu et al., 2023; Ng et al., 2017; H. Wang et al., 2023).

Here we analyze 2012-2022 trends in wintertime $PM_{2.5}$ and its composition in South Korea using a combination of data sources from surface networks, supersites, and satellites, augmented by machine learning. We examine trends in oxidants as drivers of pNO_3^- and SOA trends and draw implications for future pollution control priorities.

2 Data and methods

We use hourly 2015-22 $PM_{2.5}$ and 2012-22 NO_2 and O_3 data from the AirKorea surface network (https://www.airkorea.or.kr/). We supplement the national network data with 2012-2014 hourly $PM_{2.5}$ data collected at 25 sites in the city of Seoul by the Seoul Research Institute of Public Health and Environment (NIER, 2022). Outside of Seoul between 2012 and 2014, we use the synthetic $PM_{2.5}$ network produced by Pendergrass et al. (2025) with a random forest (RF) algorithm trained on AirKorea measurements available for related pollutants including PM_{10}. We also use a daily continuous $PM_{2.5}$ product produced using aerosol optical depth (AOD) data from the GOCI geostationary satellite (Pendergrass et al., 2025).

$PM_{2.5}$ composition measurements are sparse in South Korea. We obtain SO_4^{2-}, pNO_3^-, NH_4^+, organic carbon (OC), and BC data from an ambient ion monitor at the Seoul supersite (37.62°N, 126.93°E) managed by the National Institute for Environmental Research (NIER). We obtain inorganic particle-phase (SO_4^{2-}, pNO_3^-, and NH_4^+) and gas-phase (HNO_3 and NH_3) components from the Kanghwa site (37.71°N, 126.27°E) of the Acid Deposition Monitoring Network in East Asia (EANET). Kanghwa is an agricultural island northwest of Seoul. We analyze diurnal variability in PM_1 composition data from an aerosol mass spectrometer deployed in 2016-2018 at the Korea Institute of Science and Technology (KIST) in northeast Seoul (37.60°N, 127.05°E) (H. Kim et al., 2017).

Meteorology plays a substantial role in controlling interannual variability in $PM_{2.5}$ (Koo et al., 2020; Jeong et al., 2024). To remove meteorological influence and thus capture the long-term trend in $PM_{2.5}$ due to emission changes, we use multi-linear regression (MLR) to relate AirKorea and synthetic $PM_{2.5}$ network data to meteorological fields from the ECMWF hourly 9×9 km^2 resolution ERA5-Land replay of the ERA5 global reanalysis and hourly 30×30 km^2 from ERA5 (Hersbach et al., 2020; Muñoz-Sabater et al., 2021). To increase statistical robustness, we only use sites with continuous 2011-22 records and average the data on a 0.25°×0.3125° grid (Shen et al., 2017; Tai et al., 2010; Zhai et al., 2019). Predictor meteorological variables in the MLR include boundary layer height, mean sea-level pressure, precipitation, 2 m temperature, 10 m wind speed, 2 m relative humidity (RH), and 850 hPa meridional wind velocity, which have been identified in previous studies to correlate with $PM_{2.5}$ in the region (Leung et al., 2018; Pendergrass et al., 2019; Zhai et al., 2019). To construct our MLR model, we follow the methodology of Zhai et al. (2019) by deseasonalizing and detrending input datasets and then fitting the MLR to the $PM_{2.5}$ observations. We determine the best model for each grid cell by finding the MLR fit with at most three meteorological variables that has the highest Akaike Information Criterion (AIC) value (Akaike, 1974). We then subtract the prediction from the observed $PM_{2.5}$ and use the residual to obtain emission-driven trends (Zhai et al., 2019). The Pearson's correlation coefficient of the MLR model with 24-h $PM_{2.5}$ observations in 0.25°×0.3125° grid cells ranges between 0.41 and 0.72 with a median value of 0.60, in line with previous studies (Tai et al., 2010; Zhai et al., 2019).

3 Results and discussion

Figure 1 shows mean DJF $PM_{2.5}$ in South Korea in 2012 and 2022, together with emission-driven trends. Emission changes have driven a 1.2 μg m^{-3} a^{-1} decrease in DJF $PM_{2.5}$ that is spatially consistent across the country. Although emissions of precursor species SO_2 and NO_x have declined steadily and nationwide throughout the study period (Oak et al., 2025), DJF emission-driven $PM_{2.5}$ trends in Seoul showed an increase in the 2015-2019 period before dropping in 2020 and remaining low afterwards (Figure 1e). This 2015-2019 increase is confined to the SMA (Pendergrass et al., 2022) and is most pronounced on weekend nights (Figure 1d). The impact of COVID-19 lockdowns is not manifest in the overall $PM_{2.5}$ trends (Pendergrass et al., 2025).

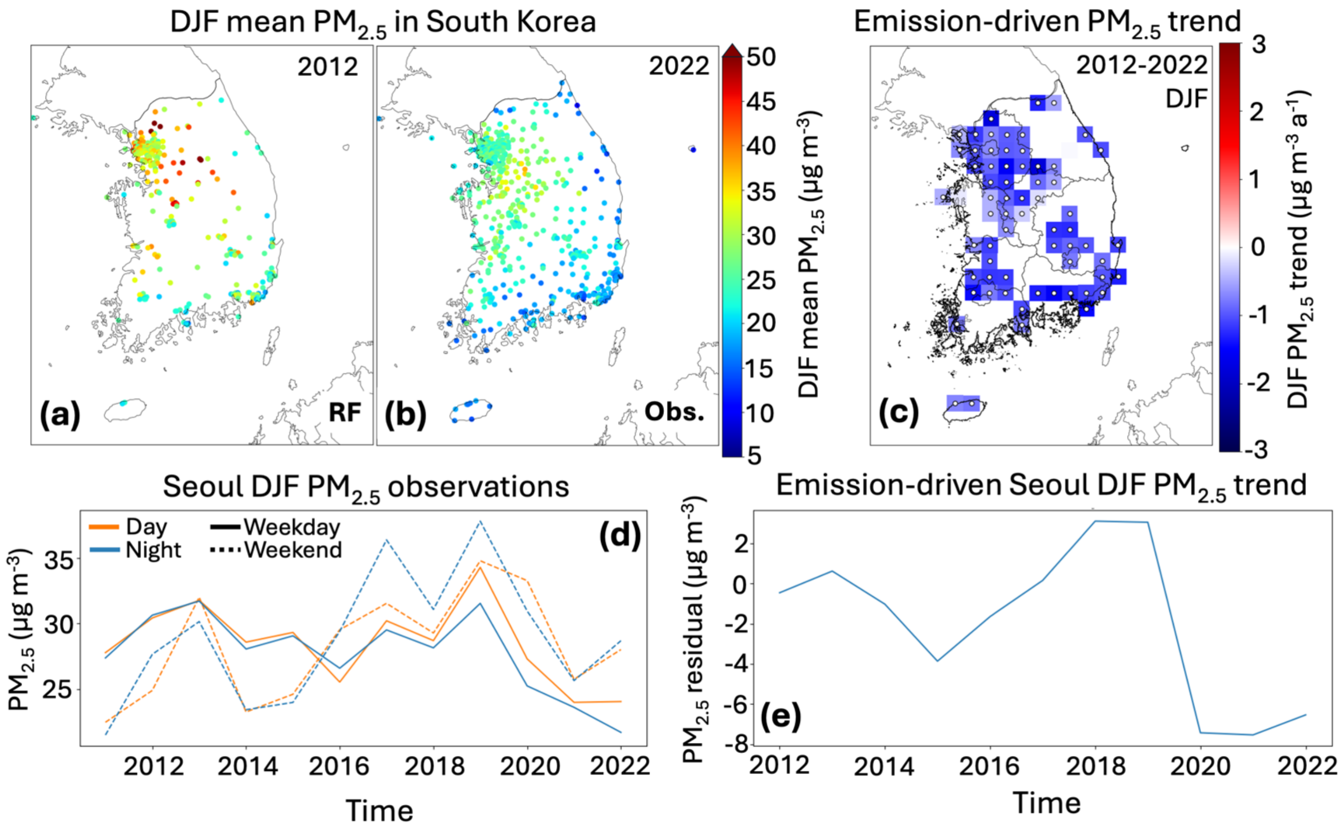

Figure 1: DJF $PM_{2.5}$ and trends in South Korea. Panels (a) and (b) show DJF mean $PM_{2.5}$ at AirKorea surface stations in (a) 2012 and (b) 2022. $PM_{2.5}$ monitoring at these stations started in 2015, and data for 2012 is from a synthetic $PM_{2.5}$ network produced using a random forest (RF) algorithm applied to the station data including PM_{10} (Pendergrass et al., 2025). Panel (c) shows the DJF emission-driven trend in $PM_{2.5}$ after removing meteorological influence with a multi-linear regression (MLR) fit. Panel (d) shows observed DJF $PM_{2.5}$ averaged over 25 sites in the city of Seoul, disaggregated into daytime (8-18 LT) and nighttime (22-5 LT) for weekdays and weekends. Panel (e) shows the emission-driven $PM_{2.5}$ timeseries (residual from the meteorological MLR model) for the Seoul 0.25°×0.3125° grid cell (centered at 37.5°N,127.0°E) and averaging data from 37 sites.

In the 2015-2019 period, reductions in SO_4^{2-} in Seoul were more than compensated by increasing pNO_3^- (Figure 2, top panel), but pNO_3^- grew faster than simple acid substitution for SO_4^{2-}. The Kangwha data show that the fraction of total nitrate ($NO_3^T \equiv HNO_3 + pNO_3^-$) in the particle phase increased from 85% to 95% between 2013 and 2019 (Figure 2, bottom panel). The pNO_3^-/NO_3^T fraction remained above 92% after 2019 when Seoul pNO_3^- begins to decline. The NH_3/NO_2 satellite indicator (Dang et al., 2023, 2024) shows that pNO_3^- sensitivity shifted from a NH_3-limited to a NO_x-limited regime around 2019 (Oak et al., 2025), consistent with a high pNO_3^-/NO_3^T fraction. OC has both primary and secondary (SOA) components (Brewer et al., 2023), did not decrease over the 2015-2022 period, and by 2022 comprised a similar fraction of $PM_{2.5}$ as pNO_3^- (Figure 2, middle panel), while BC declined substantially. Other contributions to $PM_{2.5}$ mass include sea salt, dust, and metals, which show a decline in the later phase of the record. Dust emissions from construction and road traffic have been decreasing rapidly in South Korea (Zhai et al., 2023).

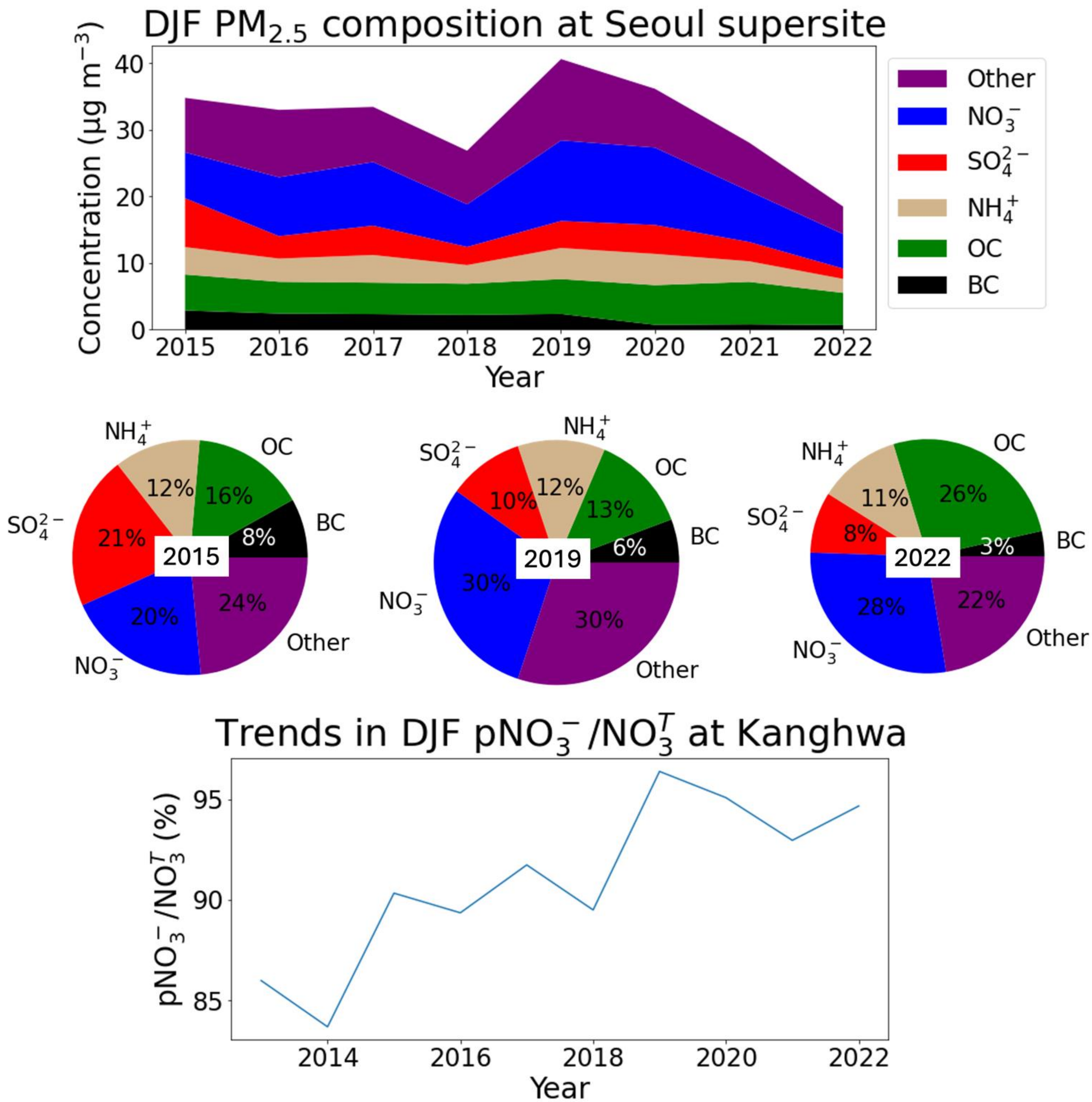

Figure 2: Wintertime $PM_{2.5}$ speciation at the Seoul supersite (37.62°N, 126.93°E) and pNO_3^-/NO_3^T gas-particle fractionation at the Kanghwa EANET site NW of Seoul (37.71°N, 126.27°E), where $NO_3^T \equiv HNO_3 + pNO_3^-$ is total (gas + particle) nitrate. Contributions to $PM_{2.5}$ mass labeled as "Other" include sea salt, dust, and metals. Values are DJF seasonal means.

The increase of wintertime pNO_3^- over the 2015-2019 period despite reductions in NO_x emissions can be explained in part by an increase in nighttime oxidants, which would also explain an increase in SOA. At night, pNO_3^- mainly forms through N_2O_5 heterogeneous chemistry, as described in the mechanism below. NO_x emission is mainly as NO, which is oxidized to NO_2 by (R1). Subsequent oxidation of NO_2 by O_3 produces the NO_3 radical, which can either react with NO_2 to form pNO_3^- via N_2O_5 or with VOCs to form SOA:

$$\mathrm{NO} + \mathrm{O_3} \rightarrow \mathrm{NO_2} + \mathrm{O_2} \qquad \textbf{(R1)}$$

$$\mathrm{NO_2} + \mathrm{O_3} \rightarrow \mathrm{NO_3} + \mathrm{O_2} \qquad \textbf{(R2)}$$

$$\mathrm{NO_3} + \mathrm{NO_2} + \mathrm{M} \rightarrow \mathrm{N_2O_5} + \mathrm{M} \qquad \textbf{(R3)}$$

$$\mathrm{NO_3} + \mathrm{VOC} \rightarrow \mathrm{SOA} \qquad \textbf{(R4)}$$

$$\mathrm{N_2O_5} + \mathrm{H_2O} \xrightarrow{\text{aerosol}} 2\ \mathrm{pNO_3^-} \qquad \textbf{(R5)}$$

The mechanism operates only at night because NO_3 photolyzes on a time scale of a minute in the daytime.

Figure 3ab shows 2012-2022 trends and diurnal variations of NO_2 and O_3 concentrations in Seoul. Decrease in NO_x emissions drives a decrease in nighttime NO_2 concentrations over the 2012-2022 period but an increase in nighttime O_3 concentrations. When NO_2 is observed to be in excess of 50 ppb, O_3 is titrated by reaction (R1) (Figure 3c) and NO_3 production by reaction (R2) cannot take place. As NO_2 drops to lower concentrations, O_3 increases rapidly which stimulates NO_3 production. We calculate the NO_3 production rate $P(NO_3)$ from the rate of reaction (R2) (Atkinson et al., 2004; H. Wang et al., 2021, 2023; Y. Wang et al., 2023):

$$\mathrm{P(NO_3)} = k[\mathrm{O_3}][\mathrm{NO_2}]; \qquad k = 1.4 \times 10^{-13} \exp(-2470/T) \qquad \textbf{(1)}$$

Plotting $P(NO_3)$ versus the NO_2 concentrations indicates a sharp maximum for 25 ppb NO_2 (Figure 3c). At lower NO_2 concentrations $P(NO_3)$ is limited by the supply of NO_x, while at higher NO_2 concentrations it is limited by the supply of O_3.

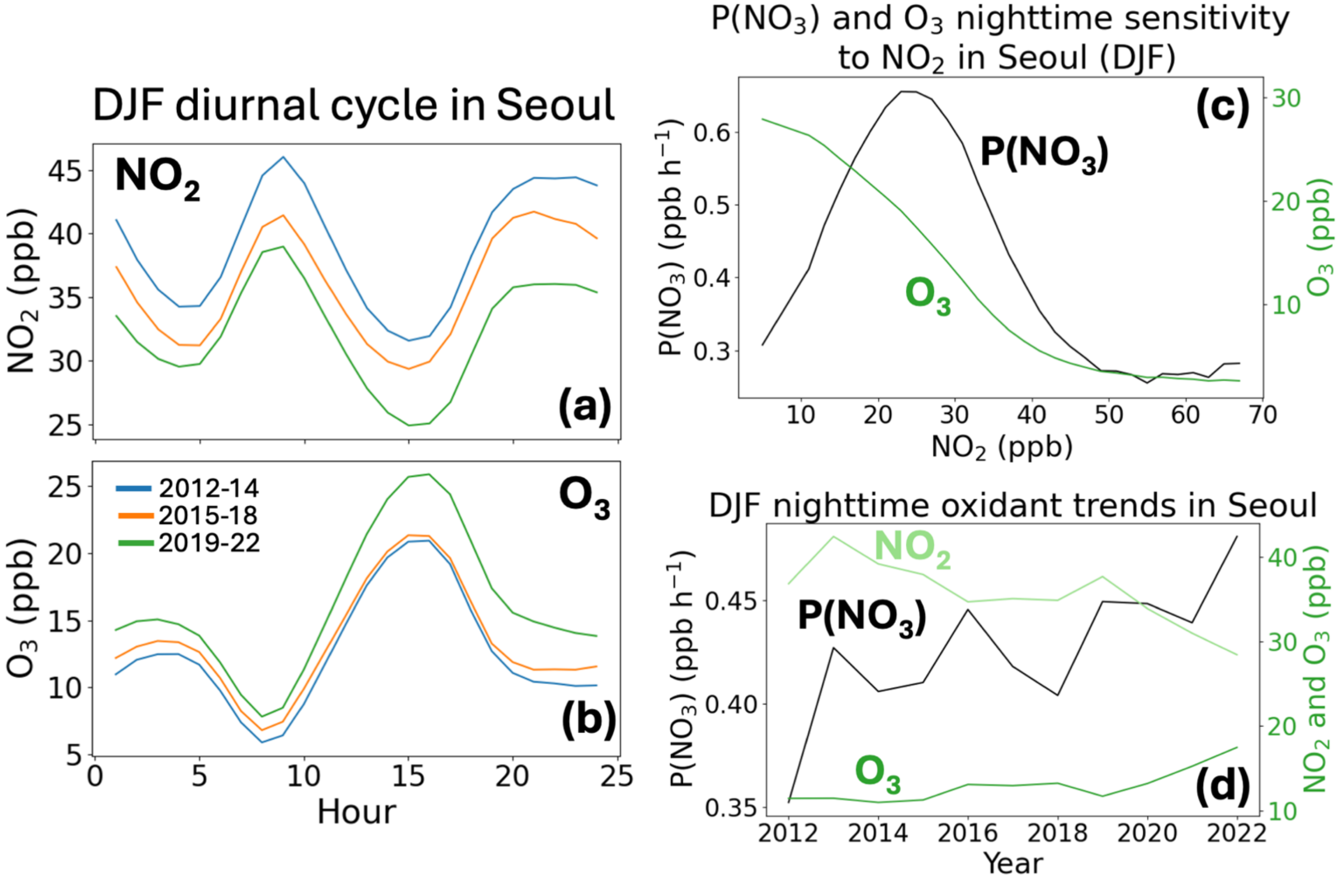

Figure 3: Mean diurnal and nighttime (22-05 LT) trends of oxidants in Seoul in winter (DJF). Values are averages for the 25 AirKorea surface sites in Seoul with continuous 2012-2022 records. Left panels show the average diurnal cycles of (a) NO_2 and (b) O_3 concentrations aggregated for the 2012-2014, 2015-2018, and 2019-2022 periods. Panel (c) shows mean nighttime O_3 concentrations and production rates of the nitrate radical $P(NO_3)$ binned as a function of NO_2 concentrations (2 ppb bins). $P(NO_3)$ is calculated from equation (1). Panel (d) shows 2012-2022 trends of nighttime NO_2 and O_3, concentrations, and $P(NO_3)$

Declining NO_x emissions has led to decreases in NO_2 with nighttime mean values in Seoul dropping just below 30 ppb by 2022 (Figure 3d). This remains in the regime where decreasing NO_2 continues to increase $P(NO_3)$, and indeed $P(NO_3)$ has steadily grown over the 2012-2022 period (Figure 3d). Such growth in $P(NO_3)$ increases the nighttime production of pNO_3^-, SOA, and organonitrates that may hydrolyze to pNO_3^- (Farmer et al., 2010; Fisher et al., 2016; Kiendler-Scharr et al., 2016; Ng et al., 2017; H. Wang et al., 2021, 2023; Y. Wang et al., 2023). As NO_2 declines, growing $P(NO_3)$ makes more NO_3 available to react with VOCs and form SOA (R4), which may explain why OC is not decreasing while pNO_3^- is. NO_2 concentrations in the SMA decline in sync with NO_x emissions (Oak et al., 2025), and if NO_x emissions decrease by another 20% they will clear the 25 ppb threshold below which $P(NO_3)$ should decline rapidly to decrease both pNO_3^- and SOA.

Further evidence of this oxidant limitation is apparent in the difference between weekdays and weekends. O_3 is higher on the weekends than on weekdays over the study period, a result of titration by vehicle NO emissions and VOC-saturated conditions. The $PM_{2.5}$ data show a weekend effect consistent with the oxidants. Figure 4 shows the DJF 2012-2022 trend in the difference between weekday and weekend $PM_{2.5}$ concentrations in South Korea for an AOD-inferred $PM_{2.5}$ product (Pendergrass et al. 2025) and for direct measurements of $PM_{2.5}$ within Seoul. Use of the AOD-inferred $PM_{2.5}$ product allows us to go back to before 2015 outside of Seoul. Previous work has observed a weekend effect in Seoul and in some Chinese cities where $PM_{2.5}$ levels are higher on weekends than weekdays as would be driven by higher oxidant levels (Choi et al., 2022; Y. Wang et al., 2019; Zhao et al., 2018). But we find that the opposite in South Korea for the period prior to 2015, with weekdays more polluted by weekends, and with our AOD-inferred $PM_{2.5}$ product we also find that the weekend effect transition in 2015 occurred everywhere in South Korea. Early air pollution controls targeting primary $PM_{2.5}$ emissions from vehicles (OC and BC) would have more effect on weekdays than weekends, and indeed the BC fraction of $PM_{2.5}$ in Seoul declined from 14% in 2003 to less than 3% by 2017 (Y. Kim et al., 2020).

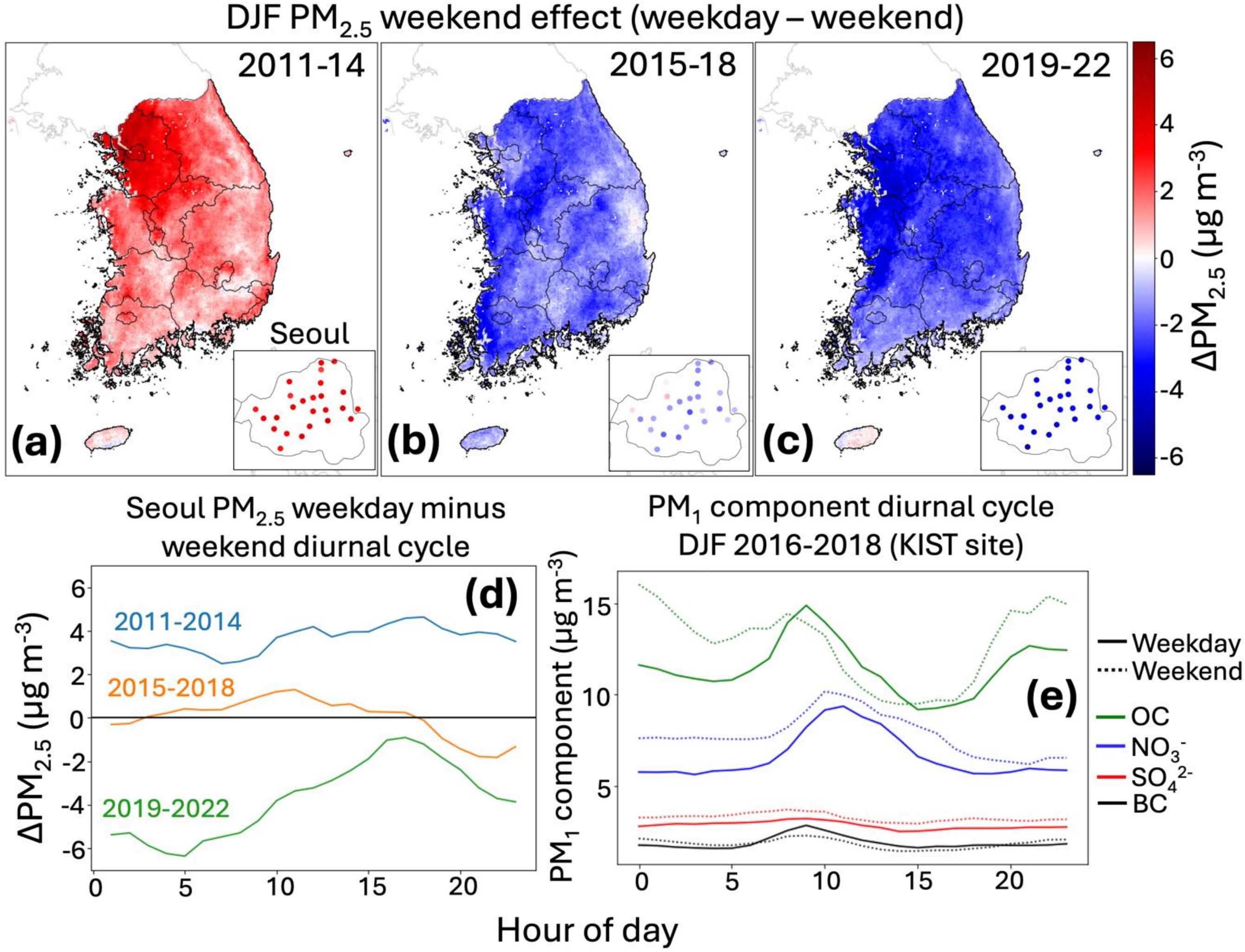

Figure 4: Wintertime (DJF) $PM_{2.5}$ weekend effect in South Korea. $\Delta PM_{2.5}$ denotes the difference between mean weekday and weekend $PM_{2.5}$ concentrations. Panels (a) through (c) show maps of $\Delta PM_{2.5}$ for (a) 2011-2014, (b) 2015-2018, and (c) 2019-2022, where red (positive $\Delta PM_{2.5}$) indicates that weekdays are more polluted than weekends. $PM_{2.5}$ concentrations are inferred using machine learning from geostationary satellite AOD data (Pendergrass et al., 2025), except for Seoul (inset) where direct continuous measurements are available from sites through the 2011-2022 period. Panel (d) shows the diurnal variation of $\Delta PM_{2.5}$ in Seoul for 2011-2014, 2015-2018, and 2019-2022. Panel (e) shows the diurnal cycle of PM_1 composition observed at the KIST site in Seoul for 2016-2018 (H. Kim et al., 2017).

Figure 4d shows that the post-2015 weekend effect is most pronounced at night (i.e. weekends are most polluted than weekdays particularly at night) especially after 2019. This means that nighttime production of $PM_{2.5}$ has become faster on weekends, consistent with an increase in the secondary component (pNO_3^- , SOA) driven by the faster production of NO_3 radicals at night. Figure 4e shows the diurnal cycle of PM_1 observations available for DJF 2016-2018 in Seoul (H. Kim et al., 2017), indicating that organic aerosols and pNO_3^- account for the weekend effect and its diurnal cycle.

In summary, we analyzed 2012-2022 trends in wintertime (DJF) $PM_{2.5}$ and its composition in South Korea using surface observations interpreted with statistical methods and machine learning. Declining anthropogenic emissions have led DJF mean $PM_{2.5}$ to decrease at a rate of 1.2 $\mu g\ m^{-3}\ a^{-1}$ in South Korea but with significant variability including a 2015-2019 increase in Seoul driven by particulate nitrate (pNO_3^-) even as NO_x emissions decreased. pNO_3^- and organic aerosol now contribute over half of total $PM_{2.5}$. pNO_3^- would not respond to NO_x emission controls if its formation was limited by the supply of NH_3, but EANET observations of total (gas + particulate) nitrate indicates a switch to NO_x-limited conditions during the 2010s. A major factor driving increased pNO_3^- and secondary organic aerosol (SOA) formation as NO_x emissions decrease is the nighttime formation of the nitrate radical (NO_3), which increases due to weaker titration of O_3. Using AirKorea hourly network observations of NO_2 and O_3, we show that the nighttime NO_3 production rate $P(NO_3)$ in Seoul increased rapidly over the 2012-2022 period. We see evidence for a resulting nighttime increase in pNO_3^- and SOA formation by comparing weekend versus weekday concentrations and their trends. We infer from the AirKorea observations a 25 ppb NO_2 threshold below which $P(NO_3)$ should begin to decrease rapidly as NO_x emissions decrease. NO_2 concentrations in Seoul in 2019-2022 were approaching that threshold, implying that further NO_x emission reductions should accrue immediate benefits for reducing pNO_3^- and SOA and therefore total $PM_{2.5}$.

Acknowledgements

This work was funded by the Harvard-NUIST Joint Laboratory for Air Quality and Climate (JLAQC) and the Samsung $PM_{2.5}$ Strategic Research Program. DCP was funded in part by a US National Science Foundation Graduate Fellowship.

References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Atkinson, R., Baulch, D. L., Cox, R. A., Crowley, J. N., Hampson, R. F., Hynes, R. G., Jenkin, M. E., Rossi, M. J., & Troe, J. (2004). Evaluated kinetic and photochemical data for atmospheric chemistry: Volume I - gas phase reactions of O_x, HO_x, NO_x and SO_x species. *Atmospheric Chemistry and Physics*, *4*(6), 1461–1738. https://doi.org/10.5194/acp-4-1461-2004

Bae, C., Kim, B.-U., Kim, H. C., Yoo, C., & Kim, S. (2020). Long-Range Transport Influence on Key Chemical Components of PM2.5 in the Seoul Metropolitan Area, South Korea, during the Years 2012–2016. *Atmosphere*, *11*(1), Article 1. https://doi.org/10.3390/atmos11010048

Brewer, J. F., Jacob, D. J., Jathar, S. H., He, Y., Akherati, A., Zhai, S., Jo, D. S., Hodzic, A., Nault, B. A., Campuzano-Jost, P., Jimenez, J. L., Park, R. J., Oak, Y. J., & Liao, H. (2023). A Scheme for

Representing Aromatic Secondary Organic Aerosols in Chemical Transport Models: Application to Source Attribution of Organic Aerosols Over South Korea During the KORUS-AQ Campaign. *Journal of Geophysical Research: Atmospheres*, *128*(8), e2022JD037257. https://doi.org/10.1029/2022JD037257

Choi, W., Ho, C.-H., Heo, J.-W., Kim, K.-Y., Kim, S.-W., & Kim, J. (2022). Recent Air Quality Deterioration on Weekends in Seoul, South Korea: A Focus on External Contribution. *Asia-Pacific Journal of Atmospheric Sciences*. https://doi.org/10.1007/s13143-022-00287-0

Colombi, N. K., Jacob, D. J., Yang, L. H., Zhai, S., Shah, V., Grange, S. K., Yantosca, R. M., Kim, S., & Liao, H. (2023). Why is ozone in South Korea and the Seoul metropolitan area so high and increasing? *Atmospheric Chemistry and Physics*, *23*(7), 4031–4044. https://doi.org/10.5194/acp-23-4031-2023

Dang, R., Jacob, D. J., Zhai, S., Coheur, P., Clarisse, L., Van Damme, M., Pendergrass, D. C., Choi, J., Park, J., Liu, Z., & Liao, H. (2023). Diagnosing the Sensitivity of Particulate Nitrate to Precursor Emissions Using Satellite Observations of Ammonia and Nitrogen Dioxide. *Geophysical Research Letters*, *50*(24), e2023GL105761. https://doi.org/10.1029/2023GL105761

Dang, R., Jacob, D. J., Zhai, S., Yang, L. H., Pendergrass, D. C., Coheur, P., Clarisse, L., Van Damme, M., Choi, J., Park, J., Liu, Z., Xie, P., & Liao, H. (2024). A Satellite-Based Indicator for Diagnosing Particulate Nitrate Sensitivity to Precursor Emissions: Application to East Asia, Europe, and North America. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.4c08082

Farmer, D. K., Matsunaga, A., Docherty, K. S., Surratt, J. D., Seinfeld, J. H., Ziemann, P. J., & Jimenez, J. L. (2010). Response of an aerosol mass spectrometer to organonitrates and organosulfates and implications for atmospheric chemistry. *Proceedings of the National Academy of Sciences*, *107*(15), 6670–6675. https://doi.org/10.1073/pnas.0912340107

Fisher, J. A., Jacob, D. J., Travis, K. R., Kim, P. S., Marais, E. A., Chan Miller, C., Yu, K., Zhu, L., Yantosca, R. M., Sulprizio, M. P., Mao, J., Wennberg, P. O., Crounse, J. D., Teng, A. P., Nguyen, T. B., St. Clair, J. M., Cohen, R. C., Romer, P., Nault, B. A., … Mikoviny, T. (2016). Organic nitrate chemistry and its implications for nitrogen budgets in an isoprene- and monoterpene-rich atmosphere: Constraints from aircraft ($SEAC^4RS$) and ground-based (SOAS) observations in the Southeast US. *Atmospheric Chemistry and Physics*, *16*(9), 5969–5991. https://doi.org/10.5194/acp-16-5969-2016

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., … Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hu, H., Wang, H., Lu, K., Wang, J., Zheng, Z., Xu, X., Zhai, T., Chen, X., Lu, X., Fu, W., Li, X., Zeng, L., Hu, M., Zhang, Y., & Fan, S. (2023). Variation and trend of nitrate radical reactivity towards volatile organic compounds in Beijing, China. *Atmospheric Chemistry and Physics*, *23*(14), 8211–8223. https://doi.org/10.5194/acp-23-8211-2023

Jeong, J. I., Park, R. J., Song, C.-K., Yeh, S.-W., & Woo, J.-H. (2024). Quantitative analysis of winter PM2.5 reduction in South Korea, 2019/20 to 2021/22: Contributions of meteorology and emissions. *Science of The Total Environment*, *907*, 168179. https://doi.org/10.1016/j.scitotenv.2023.168179

Kiendler-Scharr, A., Mensah, A. A., Friese, E., Topping, D., Nemitz, E., Prevot, A. S. H., Äijälä, M., Allan, J., Canonaco, F., Canagaratna, M., Carbone, S., Crippa, M., Dall Osto, M., Day, D. A., De Carlo, P., Di Marco, C. F., Elbern, H., Eriksson, A., Freney, E., … Wu, H.-C. (2016). Ubiquity of organic nitrates from nighttime chemistry in the European submicron aerosol. *Geophysical Research Letters*, *43*(14), 7735–7744. https://doi.org/10.1002/2016GL069239

Kim, B.-U., Bae, C., Kim, H. C., Kim, E., & Kim, S. (2017). Spatially and chemically resolved source apportionment analysis: Case study of high particulate matter event. *Atmospheric Environment*, *162*, 55–70. https://doi.org/10.1016/j.atmosenv.2017.05.006

Kim, E., Jeong, S., Kang, Y.-H., Myung, M., & Kim, S. (2025). Influence of top-down adjusted upwind emissions on PM2.5 concentrations: The case of long-range transport in South Korea. *Environmental Pollution*, *368*, 125799. https://doi.org/10.1016/j.envpol.2025.125799

Kim, H., Zhang, Q., Bae, G.-N., Kim, J. Y., & Lee, S. B. (2017). Sources and atmospheric processing of winter aerosols in Seoul, Korea: Insights from real-time measurements using a high-resolution aerosol mass spectrometer. *Atmospheric Chemistry and Physics*, *17*(3), 2009–2033. https://doi.org/10.5194/acp-17-2009-2017

Kim, N. R., & Lee, H. J. (2024). Ambient PM2.5 exposure and rapid population aging: A double threat to public health in the Republic of Korea. *Environmental Research*, *252*, 119032. https://doi.org/10.1016/j.envres.2024.119032

Kim, Y., Yi, S.-M., & Heo, J. (2020). Fifteen-year trends in carbon species and PM2.5 in Seoul, South Korea (2003–2017). *Chemosphere*, *261*, 127750. https://doi.org/10.1016/j.chemosphere.2020.127750

Koo, J.-H., Kim, J., Lee, Y. G., Park, S. S., Lee, S., Chong, H., Cho, Y., Kim, J., Choi, K., & Lee, T. (2020). The implication of the air quality pattern in South Korea after the COVID-19 outbreak. *Scientific Reports*, *10*(1), 22462. https://doi.org/10.1038/s41598-020-80429-4

Kumar, N., Park, R. J., Jeong, J. I., Woo, J.-H., Kim, Y., Johnson, J., Yarwood, G., Kang, S., Chun, S., & Knipping, E. (2021). Contributions of international sources to PM2.5 in South Korea. *Atmospheric Environment*, *261*, 118542. https://doi.org/10.1016/j.atmosenv.2021.118542

Kwon, S., Hu, Q., Seo, J., Park, S., Moon, J., Kim, J., Park, S., Park, Y., & Kim, H. (2025). Characterization of particulate matter at Mt. Gwanak (at 632 m) and vertical mixing impacts on haze in Seoul during winter. *Science of The Total Environment*, *958*, 178106. https://doi.org/10.1016/j.scitotenv.2024.178106

Lee, H.-M., Kim, N. K., Ahn, J., Park, S.-M., Lee, J. Y., & Kim, Y. P. (2024). When and why PM2.5 is high in Seoul, South Korea: Interpreting long-term (2015–2021) ground observations using machine learning and a chemical transport model. *Science of The Total Environment*, *920*, 170822. https://doi.org/10.1016/j.scitotenv.2024.170822

Leung, D. M., Tai, A. P. K., Mickley, L. J., Moch, J. M., van Donkelaar, A., Shen, L., & Martin, R. V. (2018). Synoptic meteorological modes of variability for fine particulate matter (PM2.5) air quality in major metropolitan regions of China. *Atmos. Chem. Phys.*, *18*(9), 6733–6748. https://doi.org/10.5194/acp-18-6733-2018

Lim, S., Lee, M., Savarino, J., & Laj, P. (2022). Oxidation pathways and emission sources of atmospheric particulate nitrate in Seoul: Based on δ^{15}N and Δ^{17}O measurements. *Atmospheric Chemistry and Physics*, *22*(8), 5099–5115. https://doi.org/10.5194/acp-22-5099-2022

Lim, Y.-H., Oh, J., Han, C., Bae, H.-J., Kim, S., Jang, Y., Ha, E., & Hong, Y.-C. (2020). Long-term exposure to moderate fine particulate matter concentrations and cause-specific mortality in an ageing society. *International Journal of Epidemiology*, *49*(6), 1792–1801. https://doi.org/10.1093/ije/dyaa146

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021

Ng, N. L., Brown, S. S., Archibald, A. T., Atlas, E., Cohen, R. C., Crowley, J. N., Day, D. A., Donahue, N. M., Fry, J. L., Fuchs, H., Griffin, R. J., Guzman, M. I., Herrmann, H., Hodzic, A., Iinuma, Y., Jimenez, J. L., Kiendler-Scharr, A., Lee, B. H., Luecken, D. J., … Zaveri, R. A. (2017). Nitrate radicals and biogenic volatile organic compounds: Oxidation, mechanisms, and organic aerosol. *Atmospheric Chemistry and Physics*, *17*(3), 2103–2162. https://doi.org/10.5194/acp-17-2103-2017

NIER. (2022). *Annual report of air quality in Korea 2022*. https://www.airkorea.or.kr/web/detailViewDown?pMENU_NO=125

Oak, Y. J., Jacob, D. J., Pendergrass, D. C., Dang, R., Colombi, N. K., Chong, H., Lee, S., Kuk, S. K., & Kim, J. (2024). Air quality trends and regimes in South Korea inferred from 2015–2023 surface and satellite observations. *EGUsphere*, 1–35. https://doi.org/10.5194/egusphere-2024-3485

Oak, Y. J., Jacob, D. J., Pendergrass, D. C., Dang, R., Colombi, N. K., Chong, H., Lee, S., Kuk, S. K., & Kim, J. (2025). Air quality trends and regimes in South Korea inferred from 2015–2023 surface and satellite observations. *Atmospheric Chemistry and Physics*, *25*(5), 3233–3252. https://doi.org/10.5194/acp-25-3233-2025

Oh, J., Lim, Y.-H., Han, C., Lee, D.-W., Myung, J., Hong, Y.-C., Kim, S., & Bae, H.-J. (2024). Mortality Burden Due to Short-term Exposure to Fine Particulate Matter in Korea. *Journal of Preventive Medicine and Public Health*, *57*(2), 185–196. https://doi.org/10.3961/jpmph.23.514

Park, J., Kim, H., Kim, Y., Heo, J., Kim, S.-W., Jeon, K., Yi, S.-M., & Hopke, P. K. (2022). Source apportionment of PM2.5 in Seoul, South Korea and Beijing, China using dispersion normalized PMF. *Science of The Total Environment*, *833*, 155056. https://doi.org/10.1016/j.scitotenv.2022.155056

Park, T., Singh, R., Ban, J., Kim, K., Park, G., Kang, S., Choi, S., Song, J., Yu, D.-G., Bae, M.-S., Ahn, J., Jung, H.-J., Lim, Y.-J., Kim, H. W., Hwang, T. K., Choi, Y. J., Kim, S.-Y., Kim, H. S., Chang, Y. W., … Lee, T. (2023). Seasonal and regional variations of atmospheric ammonia across the South Korean Peninsula. *Asian Journal of Atmospheric Environment*, *17*(1), 1–11. https://doi.org/10.1007/s44273-023-00008-7

Pendergrass, D. C., Jacob, D. J., Oak, Y. J., Lee, J., Kim, M., Kim, J., Lee, S., Zhai, S., Irie, H., & Liao, H. (2025). A continuous 2011-2022 record of fine particulate matter (PM2.5) in East Asia at daily 2-km resolution from geostationary satellite observations: Population exposure and long-term trends. *Atmospheric Environment*, 121068. https://doi.org/10.1016/j.atmosenv.2025.121068

Pendergrass, D. C., Shen, L., Jacob, D. J., & Mickley, L. J. (2019). Predicting the Impact of Climate Change on Severe Wintertime Particulate Pollution Events in Beijing Using Extreme Value Theory. *Geophysical Research Letters*, *46*(3), 1824–1830. https://doi.org/10.1029/2018GL080102

Pendergrass, D. C., Zhai, S., Kim, J., Koo, J.-H., Lee, S., Bae, M., Kim, S., Liao, H., & Jacob, D. J. (2022). Continuous mapping of fine particulate matter ($PM_{2.5}$) air quality in East Asia at daily 6 × 6 km^2 resolution by application of a random forest algorithm to 2011–2019 GOCI geostationary satellite data. *Atmospheric Measurement Techniques*, *15*(4), 1075–1091. https://doi.org/10.5194/amt-15-1075-2022

Shah, V., Jacob, D. J., Li, K., Silvern, R. F., Zhai, S., Liu, M., Lin, J., & Zhang, Q. (2020). Effect of changing NO_x lifetime on the seasonality and long-term trends of satellite-observed tropospheric NO_2 columns over China. *Atmospheric Chemistry and Physics*, *20*(3), 1483–1495. https://doi.org/10.5194/acp-20-1483-2020

Shen, L., Mickley, L. J., & Murray, L. T. (2017). Influence of 2000–2050 climate change on particulate matter in the United States: Results from a new statistical model. *Atmospheric Chemistry and Physics*, *17*(6), 4355–4367. https://doi.org/10.5194/acp-17-4355-2017

Tai, A. P. K., Mickley, L. J., & Jacob, D. J. (2010). Correlations between fine particulate matter (PM2.5) and meteorological variables in the United States: Implications for the sensitivity of PM2.5 to climate change. *Atmospheric Environment*, *44*(32), 3976–3984. https://doi.org/10.1016/j.atmosenv.2010.06.060

Wang, H., Lu, K., Chen, S., Li, X., Zeng, L., Hu, M., & Zhang, Y. (2021). Characterizing nitrate radical budget trends in Beijing during 2013–2019. *Science of The Total Environment*, *795*, 148869. https://doi.org/10.1016/j.scitotenv.2021.148869

Wang, H., Wang, H., Lu, X., Lu, K., Zhang, L., Tham, Y. J., Shi, Z., Aikin, K., Fan, S., Brown, S. S., & Zhang, Y. (2023). Increased night-time oxidation over China despite widespread decrease across the globe. *Nature Geoscience*, *16*(3), 217–223. https://doi.org/10.1038/s41561-022-01122-x

Wang, Y., Duan, X., & Wang, L. (2019). Spatial-Temporal Evolution of PM2.5 Concentration and its Socioeconomic Influence Factors in Chinese Cities in 2014–2017. *International Journal of Environmental Research and Public Health*, *16*(6), Article 6. https://doi.org/10.3390/ijerph16060985

Wang, Y., Xi, S., Zhao, F., Huey, L. G., & Zhu, T. (2023). Decreasing Production and Potential Urban Explosion of Nighttime Nitrate Radicals amid Emission Reduction Efforts. *Environmental Science & Technology*, *57*(50), 21306–21312. https://doi.org/10.1021/acs.est.3c09259

Zhai, S., Jacob, D. J., Pendergrass, D. C., Colombi, N. K., Shah, V., Yang, L. H., Zhang, Q., Wang, S., Kim, H., Sun, Y., Choi, J.-S., Park, J.-S., Luo, G., Yu, F., Woo, J.-H., Kim, Y., Dibb, J. E., Lee, T., Han, J.-S., … Liao, H. (2023). Coarse particulate matter air quality in East Asia: Implications for fine particulate nitrate. *Atmospheric Chemistry and Physics*, *23*(7), 4271–4281. https://doi.org/10.5194/acp-23-4271-2023

Zhai, S., Jacob, D. J., Wang, X., Shen, L., Li, K., Zhang, Y., Gui, K., Zhao, T., & Liao, H. (2019). Fine particulate matter ($PM_{2.5}$) trends in China, 2013–2018: Separating contributions from

anthropogenic emissions and meteorology. *Atmospheric Chemistry and Physics*, *19*(16), 11031–11041. https://doi.org/10.5194/acp-19-11031-2019
Zhang, Z., Lu, B., Liu, C., Meng, X., Jiang, J., Herrmann, H., Chen, J., & Li, X. (2024). Nitrate pollution deterioration in winter driven by surface ozone increase. *Npj Climate and Atmospheric Science*, *7*(1), 1–9. https://doi.org/10.1038/s41612-024-00667-5
Zhao, D., Chen, H., Sun, X., & Shi, Z. (2018). Spatio-temporal Variation of PM2.5 Pollution and its Relationship with Meteorology among Five Megacities in China. *Aerosol and Air Quality Research*, *18*(9), 2318–2331. https://doi.org/10.4209/aaqr.2017.09.0351