Reductions in NO\textsubscript{2} concentrations in Seoul, South Korea detected from space and ground-based monitors prior to and during the COVID-19 pandemic

Seunghwan Seo\textsuperscript{1}, Si-Wan Kim\textsuperscript{2,4*}, Kyoung-Min Kim\textsuperscript{1}, Lok N Lamsal\textsuperscript{3,5} and Hyungah Jin\textsuperscript{1}

1 Department of Atmospheric Sciences, Yonsei University, Seoul, Republic of Korea
2 Irreversible Climate Change Research Center, Yonsei University, Seoul, Republic of Korea
3 Goddard Earth Sciences Technology and Research, Universities Space Research Association, Columbia, MD, United States of America
4 Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, United States of America
5 Global Environment Research Division, Climate and Air Quality Research Department, National Institute of Environmental Research, Incheon, Republic of Korea

* Author to whom any correspondence should be addressed.

E-mail: siwan.kim@yonsei.ac.kr

Keywords: NO\textsubscript{2}, Seoul, South Korea, OMI, trend, COVID-19

Supplementary material for this article is available online

Abstract

Nitrogen oxides detected in urban regions are primarily emitted by transportation methods and are crucial precursors for air pollutants and climate forcers such as ozone and fine particulate matter. We investigate the trends of nitrogen dioxide (NO\textsubscript{2}) obtained from a satellite instrument and surface monitors over the megacity, Seoul, South Korea, from 2005 to 2019. Both satellite Ozone Monitoring Instrument NO\textsubscript{2} and surface \textit{in situ} concentrations decreased by up to 30\% between 2015 and 2019 while significant trends were not observed between 2005 and 2015. Further analysis shows the continual reduction of NO\textsubscript{2} concentrations prior to and during the COVID-19 pandemic in 2020. This study highlights the efficacy of South Korean pollution control policies targeting vehicular emissions. However, this study also found inconsistencies between trends observed in the official bottom-up emission inventory and data collected from space and surface sites. Further research will be urgently needed to understand the causes for the discrepancies.

1. Introduction

Nitrogen oxides (NO\textsubscript{x} as sum of NO and NO\textsubscript{2}) in the low atmosphere are released primarily through fossil fuel combustions (Crutzen 1979, Ryerson \textit{et al} 2001, Harley \textit{et al} 2005, van Vuuren \textit{et al} 2011, McDonald \textit{et al} 2012) and can also be emitted through other modes of anthropogenic activities such as agriculture (Matson \textit{et al} 1998, Almaraz \textit{et al} 2018). NO\textsubscript{x} plays a central role in atmospheric chemistry and air quality, particularly in population-dense urban areas with heavy road traffic. NO\textsubscript{x} along with carbon monoxide (CO) and volatile organic compounds (VOC) is the main precursor of tropospheric ozone (O\textsubscript{3}) (Haagen-Smit 1952, Crutzen 1979, Jacob 1999, Ryerson \textit{et al} 2001, Marr and Harley 2002, Jacobson 2005, Pollack \textit{et al} 2013, Kim \textit{et al} 2016). Furthermore, NO\textsubscript{x} can react with OH radical or other cations to form secondary organic/inorganic aerosols (e.g., organic nitrate, ammonium nitrate) (Park \textit{et al} 2004, Ayres \textit{et al} 2015, Seinfeld and Pandis 2016). Therefore, NO\textsubscript{x} is an essential precursor for both O\textsubscript{3} and particulate matter (PM). Enhanced concentrations of both O\textsubscript{3} and PM are currently major environmental and public health issues in Seoul, South Korea. For example, a recent tropospheric ozone assessment report showed that ozone levels were increasing in South Korea between 2000 and 2014 (Gaudel \textit{et al} 2018). High PM concentrations and severe haze with enhanced nitrates were observed in South Korea (Lee \textit{et al} 2017, Jordan \textit{et al} 2020). Therefore, it is imperative to understand NO\textsubscript{x} concentration trends in order to establish mitigation strategies and regulatory policies for O\textsubscript{3} and PM. There have been several studies concerning air quality in Seoul due to the extensive use of diesel engine passenger cars and trucks in...
South Korea (Souri et al. 2017, Goldberg et al. 2019, Souri et al. 2020). However, recent studies do not provide a consistent characterization of NOx emission estimations in the Seoul metropolitan area (Goldberg et al. 2019, Kim et al. 2020). An accurate understanding of the atmospheric composition in Seoul will be beneficial in improving our overall understanding of emissions and atmospheric chemistry over continental Asia and the subsequent consequences of long-range transport and pollution sources.

Seoul, the capital of South Korea, currently has a population of around 10 million people living in the urban core—an area of 605 km² (http://data.si.re.kr/node/337). 40% of the national population resides in Seoul and the surrounding Gyeonggi-do region with a combined population of 22 million people over an 10,800 km² area (http://stat gg.go.kr/statgg/tblInfo/mainStats.html).

Fuel sale statistics in Seoul indicated that the volume of diesel fuel sold was almost equal to that of gasoline fuel in 2010 (https://data.seoul.go.kr/dataList/datasetView.do?infId=10789&srvType=S&serviceKind=2; table 1). In the Gyeonggi region, the volume of diesel fuel sold exceeded that of gasoline (table 1). In addition to the high-degree of anthropogenic activity, the greater use of diesel fuel for passenger cars in these regions can further contribute to NOx emissions and local air quality (see McDonald et al. 2012 for detailed emission factors for motor vehicles).

In this study, we analyze the satellite-observed tropospheric NO2 columns from 2005 to 2019 to derive the trends and enhancement levels of NO2 in Seoul. Ground level air quality monitoring data are additionally utilized to confirm the satellite trends of NO2. Furthermore, to understand the effect of government response to the coronavirus disease 2019 (COVID-19) on NOx emission trends, monthly averaged values of NO2 concentrations for 2019–2020 are compared with climatology covering 2005–2018. Finally, we analyze the NOx emission trends provided by the Korean Ministry of Environment’s National Pollutants Emission Service (NAPES) official bottom-up emission inventory and compare the trends with results from this study.

2. Data and methods

2.1. Surface observations

Korean Ministry of Environment (MOE) have provided real-time ground-based air quality observation data of nitrogen dioxide (NO2), carbon monoxide (CO), and ozone (O3) via the Airkorea website (https://www.airkorea.or.kr). We use hourly data from all stations in a domain of 126.5°E–127.3°E, 37.2°N–37.8°N, covering the Seoul metropolitan area. As of 2020, there are 132 stations in this domain. The Seoul Metropolitan Area (SMA) defined in this study is shown in figure 1 (green box).

2.2. Satellite data

The Ozone Monitoring Instrument (OMI) is one of instruments onboard the EOS-Aura satellite. The satellite was launched into a sun-synchronous orbit in 2004 (Bucsela et al. 2006, Levelt et al. 2006, Boersma et al. 2011, Levelt et al. 2018), with a low-Earth (705 km) orbit and an Equator overpass time of approximately 13:45 local standard time (LST). The Differential Optical Absorption Spectroscopy (DOAS) technique is used to obtain NO2 slant column densities (SCDs) from the OMI spectra. Next, air mass factors (AMF) are calculated for each ground pixels to convert SCDs to vertical column densities (VCDs) following the equation below:

\[ \text{VCD} = \frac{\text{SCD}}{\text{AMF}} \]  \hspace{1cm} (1)

AMF is derived as a function of atmospheric scattering, vertical shape factor, and optical properties such as solar zenith angle, satellite viewing angle, and surface albedo (Palmer et al. 2001). The final step is the separation of stratospheric and tropospheric components. Details on the NO2 algorithm and data assessment can be found in Lamsal et al. 2021). In this study, we utilize Version 4.0 daily OMI level 3 tropospheric VCD data available from

| NOx emission [kton/yr]/[ton/km²] | Total | Diesel | Gasoline | LNG |
|---------------------------------|-------|--------|----------|-----|
| South Korea                     | 1140.6/11.4 | 505.8/5.0 | 323.9/3.2 | 110.1/1.1 |
| (100.0%)                        | (44.3%)   | (28.4%)  | (9.6%)   |
| Seoul                           | 75.5/124.8 | 40.8/67.4 | 7.1/11.7 | 17.3/28.6 |
| (100.0%)                        | (54.1%)   | (9.4%)   | (23.0%)  |
| Incheon                        | 54.2/51.0 | 19.7/18.5 | 1.8/1.7 | 13.5/12.7 |
| (100.0%)                        | (36.5%)   | (3.4%)   | (25.0%)  |
| Gyeonggi                        | 179.4/17.6 | 119.1/11.7 | 7.5/0.7 | 24.0/2.4 |
| (100.0%)                        | (66.4%)   | (4.2%)   | (13.4%)  |
the NASA Aura validation data center (AVDC) website (https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L3/OMNO2d_HR/OMNO2d_HRD) with a spatial resolution of 0.1° × 0.1°. These data are created by including good quality clear-sky observations with effective cloud fraction < 0.3.

2.3. The bottom-up NOx emission inventory

We acquired the bottom-up NOx emissions data over the Seoul, Incheon, and Gyeonggi region from National Air Pollutants Emission Service (NAPES) on the National Center for Fine Dust Information website (https://airemiss.nier.go.kr/mbshome/mbs/airemiss/index.do). To estimate air pollutant emissions, NAPES utilizes the Clean Air Policy Support System (CAPSS), based on Air Pollutants Emission Inventory generated by the Ministry of Environment, South Korea.

3. Results

3.1. Spatial distribution of NO2 columns over SMA from 2005 to 2019

First, the spatial distributions of tropospheric NO2 column observations (OMI L3 data) over a domain including SMA and their changes with time are investigated. In figure 2, the left panel shows the spatial distributions for the photochemistry-enhanced season (May—October, hereafter the O3 season) while the right panel shows distributions for November—April (hereafter the non-O3 season), the season in which photochemistry is less active. For the O3 season, the impact of local emissions is dominant while large-scale transport tends to be more important for the non-O3 season when the chemical lifetime of NOx is longer. The main sink process of NOx is an oxidation to HNO3, which takes place mainly in a gas-phase reaction of NO2 with OH during daytime. The OH concentration is higher in the O3 season than in the non-O3 season. Therefore, NOx chemical lifetime in the O3 season is shorter than that in the non-O3 season. During winter, a hydrolysis of N2O5 in aerosols increases and is getting an important sink for NOx (Martin et al 2003, Lamsal et al 2010, Lamsal et al 2014, Laughner and Cohen 2019, Shah et al 2020). Shah et al (2020) reported the NOx chemical lifetime of 6 h during summer and 21 h during winter in China in 2017. Figures 2(a) and (b) illustrate the NO2 column values averaged from 2005 to 2014 while figures 2(c) and (d) show averages from 2015 to 2019. Differences between the two periods are shown in figures 2(e) and (f). For the O3 season, the center of the NO2 plumes is observed over SMA. The NO2 column averaged over SMA is 13.30 ± 1.51 × 1015 molecules cm−2 for 2005–2014 (figure 2(a)), and 10.11 ± 1.81 × 1015 molecules cm−2 for 2015–2019 (figure 2(c)); it decreased by 3.19 × 1015 molecules cm−2 between the two periods (figure 2(e)). For the non-O3 season, the center of plume is located in the southeastern region of Seoul probably due to stronger westerly, while the observed concentrations are higher than those of the O3 season due to the enhanced chemical lifetime of NOx during the non-O3 season. NOx decreased between the two periods in Seoul and its southeast region, where strong plumes were observed. However, in other areas, there were negligible changes in NO2 columns during the non-O3 season. Uncertainties in the satellite NO2 retrieval increase in winter compared to summer due to a possibility of snow in the ground, accumulation of NO2 near the surface (meaning decreased satellite sensitivity), and increased aerosol loadings (Richter and Burrows 2002, Boersma et al 2004). Year-to-year variations in averaged spatial distributions of tropospheric NO2 columns over SMA from 2005 to 2019 are also
3.2. Trends of satellite NO2 columns and surface NO2 concentrations over SMA from 2005 to 2019

Because the OMI sensor may degrade with time, it is useful to compare the results derived from OMI data with the in situ observations. Figure 3 exhibits the trends of NO2 concentrations averaged over the SMA box limits (shown as a green box in figure 1) observed by surface monitors and OMI from 2005 to 2019. NO2 concentrations measured at the surface did not show consistent trends between 2005 and 2015, but decrease after 2015. The trends of surface NO2 concentration for both the O3 season and non-O3 season are similar. After 2015, there is a measured NO2 reduction rate of $-5.3\% \text{yr}^{-1}$ during the morning commute time (7–9 LST) and of $-6.8\% \text{yr}^{-1}$ during the OMI overpass time (12–14 LST) for the O3 season (figure 3(a)). For the non-O3 season, surface NO2 concentrations decrease with a rate of $-2.6\% \text{yr}^{-1}$ during the morning commute time and $-3.9\% \text{yr}^{-1}$ during the OMI overpass time (figure 3(b)). The NO2 reductions rates for the O3 season are greater than the reduction rates observed in the non-O3 season. Similarly, the OMI tropospheric NO2 columns significantly decreased after 2015 ($-7.0\% \text{yr}^{-1}$) compared to 2005–2014 when the NO2 columns decreased at a rate of $-2.0\% \text{yr}^{-1}$ for the O3 season (figure 3(c)). The OMI NO2 columns decline at a rate of $-3.0\% \text{yr}^{-1}$ after 2015 for the non-O3 season (figure 3(d)). The satellite NO2 column reduction rate during the non-O3 season is less than half the rate during the O3 season. In the Supplementary Material, there is a similar figure that includes both O3 and non-O3 seasons. Monthly mean satellite NO2 columns are well correlated with monthly mean surface NO2 concentrations (correlation coefficient ranging from 0.78 to 0.81) (see the Supplementary Material).
In this section, the declining trends in satellite NO$_2$ column in recent years is similar to the trends in the in situ surface observations. It confirms utility of space-based NO$_2$ observations in deriving trends of NO$_2$ abundances and NO$_x$ emissions (see also Richter et al 2005, Kim et al 2006, Kim et al 2009, Russell et al 2010, Kim et al 2011, Hilboll et al 2013, Lamsal et al 2015, Duncan et al 2016, Kim et al 2020a).

### 3.3. Impact of COVID-19 on NO$_2$ abundances

The initial outbreak of coronavirus disease 2019 (COVID-19) was first identified in November 2019 according to World Health Organization (WHO 2020). In addition to more than 1 million deaths attributed to COVID-19, the pandemic has also caused global economic and social disruption (Leggett 2020) (~2.5 million deaths as of March 1, 2021, according to WHO website, [https://covid19.who.int/](https://covid19.who.int/)). The first COVID-19 case in South Korea was identified in Daegu on 18 February, 2020. During this time the Korean government enforced social distancing protocol and various degrees of closures, which may have affected volumes of road-traffic due to remote-work/virtual-learning and constrained commercial and industrial activities and travels. To understand the effects of COVID-19 on surface and tropospheric NO$_2$ concentrations, monthly climatology from 2005–2018 and the monthly averages from July 2019–May 2020 are compared in figure 4. Figure 4(a) shows values from the OMI L3 data, while figures 4(b) and (c) present the surface-observed concentrations for 07–09 LST and 12–14 LST, respectively. Both satellite and surface observational data indicate that the NO$_2$ concentrations from July 2019 to January 2020, preceding the COVID-19 outbreak in South Korea, are persistently lower than the climatological values by 6%–8%, suggesting that reductions of NO$_x$ occurred independently of the COVID-19 pandemic. NO$_2$ concentrations at surface strikingly decreased during the COVID-19 pandemic in South Korea (after February 2020) by up to ~50% compared to the climatology, which is observed even in the morning commute time as well as the OMI overpass time around noon. The satellite data measured a smaller degree of NO$_2$ reduction. The NO$_2$ concentrations over SMA have remained at lower levels than climatological values after May 2020 (not shown).
In China, NO$_2$ concentrations were substantially decreased during the initial lock-down period (24 January–February), but were recovered to climatological levels in early April towards the end of the mandated lock-down period (Bauwens et al 2020). In contrast, Seoul measured NO$_2$ concentrations consistently much lower than the climatology from 23 February to even May 2020 - with extended periods of social distancing having huge impacts on improving air quality. However, it is also important to note that NO$_2$ concentrations were lower than the climatological values prior to December 2019, before the COVID-19 outbreak in South Korea. From our observations, we speculate that the reduction of NO$_x$ emission and NO$_2$ levels over SMA is due to pollution.
controls. MOE has established and implemented several policies: tightening emission standards for diesel vehicles, liquidating decrepit diesel cars, and supporting attachment of diesel particulate filter. It is noteworthy that fuel consumptions in Seoul slightly decreased from 2016 to 2018 and increased from 2018 to 2019 to the level in 2017, and those in Incheon, and Gyeonggi were almost steady or slightly increased from 2016 to 2019 (Supplementary Material). However, NO2 abundances decreased for this period.

3.4. Comparison of trends of observed NO2 concentrations and NOx emissions over SMA
Finally, NOx emission trends in the bottom-up emission inventories for Seoul, estimated by NAPES are compared with observed NO2 concentration trends over SMA (figure 5). The two data are normalized by their respective values in 2005. The emission inventory indicates that large reductions in the NOx emissions (total or on-road) between 2005 and 2011 occur with a declining rate of $-8 \sim -7\%$ yr$^{-1}$, while observed NO2 concentrations are steady during the same period. Both the observations and emission inventory show negligible changes between 2011 and 2015. After 2015, the observed concentrations show declining trends as discussed above. In contrast, the emission inventory indicates increases in NOx emissions after 2015. Thus, there is a clear discrepancy between the observed trends and the bottom-up estimations, which will need further investigation. Basic elements in the bottom-up inventory such as source speciation, activity, and emission factors will need to be critically evaluated for consistent trend estimations. Future studies adopting top-down approach that utilize the data from satellites such as OMI, TROPOMI, and GEMS (Kim et al 2020b) would be beneficial for improving the emission inventory.

4. Conclusions
The Seoul metropolitan area has the highest population density in South Korea. The air quality in this region is determined by a complex interaction of local emissions and foreign transportation (Jordan et al 2020). It is a prerequisite to quantify local emissions and their change to understand accurate source-receptor relationship in this region. NOx plays a crucial role in chemistry of O3 and PM. Thus, in this study, we focus on detecting NO2 abundances and their changes with time in SMA.

OMI tropospheric NO2 columns and surface NO2 concentrations over SMA were analyzed mainly from 2005 to 2019. The trends derived from surface monitoring sites are quite similar to those from OMI. The changes in NO2 concentrations between 2005 and 2015 were negligible, while significant decreases were observed after 2015—in both surface and satellite observations. For the non-ozone season, reductions were detected, but are less significant than those of ozone season. While several factors such as long chemical lifetime due to weakened photochemical reactions (Lee et al 2013) and enhanced long-range transportation (Jeong et al 2011), and blocking via high pressure system (Yun and Yoo 2019) act on NO2 concentrations during the non-ozone season, local emissions have a dominant effect on air qualities in SMA during the ozone season. For this reason, we speculate that the local NO2 emissions over the SMA region have decreased due to pollution controls led by Korean government. Meanwhile, NOx emission inventories estimated by NAPES do not agree with the recent decreasing trends of NO2 concentrations, which requires further investigation on the bottom-up
emission estimates as well as the top-down emission development utilizing environmental satellite retrievals and intensive measurement data sets based on aircrafts and surface monitors.

Despite the progress made by effective environmental policy and regulation, Seoul still has NO2 concentrations almost double that of other megacities such as Los Angeles in the United States. Surface monitored NO2 concentration in SMA and the Los Angeles Basin are 32 ppb and 15 ppb, respectively in 2016. OMI tropospheric NO2 columns in SMA and the Los Angeles Basin are $15.6 \times 10^{15}$ molec. cm$^{-2}$ and $7.7 \times 10^{15}$ molec. cm$^{-2}$, respectively for the same year. Thus, a continual effort must be made to reduce the NO2 pollution in Seoul as striking decreases of the NO2 concentration demonstrated during the COVID-19 pandemic. Preventive measures Korean government applied during the pandemic were important in protecting public health from the disease and from poor air quality. In the future, regional chemical transport modeling will be conducted to quantify the effect of Korean and Chinese NOx emission trends on NO2, O3, and PM concentrations in Seoul and the surrounding regions.

Acknowledgments

This work was supported by ‘Development of Climate and Atmospheric Environmental Applications’ project, funded by Electronics and Communications Research Institute which is a subproject of ‘Development of Geostationary Meteorological Satellite Ground Segment (NMSC-2019-01)’ program funded by National Meteorological Satellite Center of Korea Meteorological Administration. This subject is supported by Korea Ministry of Environment (MOE) as ‘Public Technology Program based on Environmental Policy (2017000160001)’. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1A2C2014131). S.-W. Kim also acknowledges support from NRF-2018R1A5A1024958. We acknowledge the free use of tropospheric OMI NO2 column data.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Seunghwan Seo @ https://orcid.org/0000-0001-7175-3366  
Si-Wan Kim @ https://orcid.org/0000-0002-7889-189X

References

Almaraz M, Bai E, Wang C, Trousdell J, Conley S, Falooana I and Houlton B Z 2018 Agriculture is a major source of NOx pollution in California Science Advances 4 no. 1, eaao3477

Ayres R B et al 2015 Organic nitrate aerosol formation via NO3 + biogenic volatile organic compounds in the southeastern United States Atmos. Chem. Phys. 15 13377–92

Bauwens M et al 2020 Impact of coronavirus outbreak on NO2 pollution assessed using TROPOMI and OMI observations Geophys. Res. Lett. 47 e2020GL087978

Boersma K F, Eides H J and Brinkman E J 2004 Error analysis for tropospheric NO2 retrieval from space J. Geophys. Res. 109 D04311

Boersma K F et al 2011 An improved retrieval of tropospheric NO2 columns from the ozone monitoring instrument Atmos. Meas. Tech. 4 1905–28

Bucsela E J, Gelarier E A, Wenig M O, Gleason J F, Veefkind P, Boersma F and Brinkman E J 2006 Algorithm for NO2 vertical column retrieval from the ozone monitoring instrument IEEE T. Geoscience and Remote Sensing 44 1245–58

Crutzen P J 1979 The role of NO and NO2 in the chemistry of the troposphere and stratosphere Annu. Rev. Earth Planet. Sci. 7 443–72

Duncan B N, Lamsal L N, Thompson A M, Yoshida Y, Lu Z, Streets D G, Hurwitz M M and Pickering K E 2016 A space-based, high-resolution view of notable changes in urban NOx pollution around the world (2005–2014) J. Geophys. Res. Atmos. 121 976–96

Gaudel A et al 2018 Tropospheric ozone assessment report: present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation Elem. Sci. Anth. 6 39

Goldberg D L et al 2019 A top-down assessment using OMI NO2 suggests an underestimate in the NOx emissions inventory in Seoul, South Korea, during KORUS-AQ Atmos. Chem. Phys. 19 2019

Haagen-Smit A J 1952 Chemistry and physiology of Los Angeles smog Ind. Eng. Chem. 44 1342–6

Harley R A, Marr I C, Lehner J K and Giddings S N 2005 Changes in motor vehicle emissions on diurnal to decadal time scales and effects on atmospheric composition Environ. Technol. 39 5356–62

Hilboll A, Richter A and Burrows J P 2013 Long-term changes of tropospheric NO2 over megacities derived from multiple satellite instruments Atmos. Chem. Phys. 13 4145–69

Jacob D 1999 Introduction to Atmospheric Chemistry (Princeton, NJ: Princeton University Press) 199–219

Jacobsen M Z 2005 Fundamentals of Atmospheric Modeling 2nd edn (New York: Cambridge University Press)

Jeong U, Kim J, Lee H, Jung J, Kim Y J, Song C H and Koo J-H 2011 Estimation of the contributions of long range transported aerosol in East Asia to carbonaceous aerosol and PM concentrations in Seoul, Korea using highly time resolved measurements: a PSCF model approach, J. Environ. Monit. 2011 1905
Jordan C E et al 2020 Investigation of factors controlling PM$_{2.5}$ variability across the South Korean Peninsula during KORUS-AQ Ecol. Sci. Anth. 8 28
Kim H C, Kim S, Lee S-H, Kim B-U and Lee P 2020a Fine-scale columnar and surface NO$_2$ concentrations over South Korea: comparison of surface monitors, TROPOMI, CMAQ and CAPS$^3$ inventory, Atmosphere 11 101
Kim J et al 2020b New era of air quality monitoring from space: geostationary environment monitoring spectrometer (GEMS) Bull. Amer. Meteor. Soc 101 E1–22
Kim S-W et al 2006 Satellite-observed U.S. power plant NO$_2$ emission reductions and their impact on air quality Geophys. Res. Lett. 33 122812
Kim S-W, Heckel A, Frost G J, Richter A, Gleason J, Burrows J P, McKeen S, Hsie E-Y, Grainer C and Trainer M 2009 NO$_2$ columns in the western United States observed from space and simulated by a regional chemistry model and their implications for NO$_2$ emissions J. Geophys. Res. 114 D11101
Kim S-W et al 2011 Evaluations of NO$_2$ and highly reactive VOC emission inventories in Texas and their implications for ozone plume simulations during the Texas Air Quality Study 2006, Atmos. Chem. Phys. 11 13161–86
Kim S-W et al 2016 Modeling the weekly cycle of NO$_x$ and CO emissions and their impacts on O$_3$ in the Los Angeles-South Coast Air Basin during the CalNex 2010 field campaign J. Geophys. Res. Atmos. 121 1340–60
Lamsal L N, Martin R V, van Donkelaar A, Celarier E A, Buscela E J, Boersma K F, Dijksoen M, Lue C and Wang Y 2010 Indirect validation of tropospheric nitrogen dioxide retrieved from the OMI satellite instrument: Insight into the seasonal variation of nitrogen oxides at northern midlatitudes, J. Geophys. Res. 115, D05302
Lamsal L N et al 2014 Evaluation of OMI operational standard NO$_2$ column retrievals using in situ and surface-based NO$_2$ observations Atmos. Chem. Phys. 14 11587–609
Lamsal L N, Duncan B N, Yoshida Y, Krotkov N A, Pickering K E, Streets D G and Lu Z 2015 U.S. NO$_2$ trends 2003–2013: EPA Air Quality System (AQS) data versus improved observations from the Ozone Monitoring Instrument (OMI) Atmos. Environ. 110 130–43
Lamsal L N et al 2021 Ozone Monitoring Instrument (OMI) Aura nitrogen dioxide standard product version 4.0 with improved surface and cloud treatments Atmos. Meas. Tech. 14 455–479
Laughner J L and Cohen R C 2019 Direct observation of changing NO$_2$ lifetime in North American cities Science 366 723–7
Leggett T 2020 Coronavirus: global growth ‘could halve if outbreak intensifies’ BBC Retrieved (https://bbc.com/news/business-51700935)
Lee H-J, Kim S-W, Broio J, Cooper O R, Frost G J, Kim C-H, Park R J, Trainer M and Woo J-H 2013 Transport of NO$_x$ in East Asia identified by satellite and in situ measurements and Lagrangian particle dispersion model simulations J. Geophys. Res. Atmos. 119 2574–96
Lee H-M, Park R J, Henze D K, Lee S, Shim C, Shin H-J, moon K-J and Woo J-H 2017 PM$_{2.5}$ source attribution for Seoul in May from 2009 to 2013 using GEOS-Chem and its adjunct model Environ. Pollut. 221 377–84
Levett P F, van den Oord G H J, Dobber M R, Mälkki A, Visser H, de Vries J, Stammes P, Lundell J O V and Saari H 2006 The ozone monitoring instrument IEEE T. Geoscience and Remote Sensing 44 1093–101
Levett P F et al 2018 The ozone monitoring instrument: overview of 14 years in space Atmos. Chem. Phys. 18 2018
Marr L C and Harley R A 2012 Modeling the effect of weekday-weekend differences in motor vehicle emissions on photochemical air pollution in central California Environ. Sci. Technol. 36 4099–106
Martin R V, Jacob D J, Chance K, Kurosu T P, Palmer P I and Evans M J J 2003 Global inventory of nitrogen oxide emissions constrained by space-based observations of NO$_2$ columns J. Geophys. Res. 108 4557
Matson P A, Naylor R K and Ortiz-Monasterio I 1998 Integration of environmental, agronomic, and economic aspects of fertilizer management Science 280 112–5
McDonald B C, Dallmann T R, Martin E W and Harley R A 2012 Long-term trends in nitrogen oxide emissions from motor vehicles at national, state, and air basin scales J. Geophys. Res. Atmos. 117 D00V18
Palmer P I, Jacob D J, Chance K, Martin R V, Spurr R J D, Kurosu T P, Bey I, Yantosca R, Fiore A and Li Q 2001 Air mass factor formulation for spectroscopic measurements from satellites: application to formaldehyde retrievals from the Gloval Ozone Monitoring Experiment J. Geophys. Res. 106 14539–50
Park R J, Jacob D J, Field B D, Yantosca R M and Chin M 2004 Natural and transboundary pollution influences on sulfate-nitrate-ammonium aerosols in the United States: Implications for policy, J. Geophys. Res. 109 D15204
Pollack H B, Ryerson T B, Trainer M, Neuman J A, Roberts J M and Parrish D D 2013 Trends in ozone, its precursors, and related secondary oxidation products in Los Angeles, California: a synthesis of measurements from 1960 to 2010 J. Geophys. Res. Atmos. 118 5893–911
Richter A and Burrows J P 2002 Tropospheric NO$_2$ from GOME measurements J. Geophys. Res. 107 923–39
Richter A, Burrows J P, Nu’u H B, Granier C and Nieuwet M 2005 Increase in tropospheric nitrogen dioxide over China observed from space and simulated by a regional chemistry model and their implications for NO$_x$ emissions Atmos. Chem. Phys. 5 1757–67
Ryerson T B et al 2001 Observations of ozone formation in power plant plumes and implications for ozone control strategies Science 292 719–23
Seinfeld J H and Pandis S N 2016 Atmospheric Chemistry and Physics: from air Pollution to Climate Change 3rd edn (Hoboken, NJ: Wiley-Interscience) 1120 pp
Shah V, Jacob D J, Li K, Sillvern R F, Zhai S, Liu M, Lin J and Zhang Q 2020 Effect of changing NOx lifetime on the seasonality and long-term trends of satellite-observed tropospheric columns over China Atmos. Chem. Phys. 20 1483–95
Souri A H, Choi Y, Jeon W, Woo J-H, Zhang Q and Kurokawa J-I 2017 Remote sensing evidence of decadal changes in major tropospheric ozone precursors over East Asia J. Geophys. Res. Atmos. 122 2474–92
Souri A H et al 2020 An inversion of NO$_2$ and non-methane volatile organic compound (NMVOC) emissions using satellite observations during the KORUS-AQ campaign and implications for surface ozone over East Asia Atmos. Chem. Phys. 20 8537–54
van Vuuren D P, Bouwman L F, Smith S J and Dentener F 2011 Global projections for anthropogenic reactive nitrogen emissions to the atmosphere: an assessment of scenarios in the scientific literature Curr. Opin. Environ. Sustain. 3 359–69
World Health Organization 2020 Coronavirus disease (COVID-19) pandemic Available from (https://who.int/emergencies/diseases/novel-coronavirus-2019)
Yun S-G and Yoo C 2019 The effects of spring and winter blocking on PM$_{10}$ Concentration in Korea Atmosphere 10 410