Aura OMI observations of regional $\text{SO}_2$ and $\text{NO}_2$ pollution changes from 2005 to 2014

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Abstract

The Ozone Monitoring Instrument (OMI) onboard NASA’s Aura satellite has been providing global observations of the ozone layer and key atmospheric pollutant gases, such as nitrogen dioxide (NO\textsubscript{2}) and sulfur dioxide (SO\textsubscript{2}), since October 2004. The data products from the same instrument provide consistent spatial and temporal coverage and permit the study of anthropogenic and natural emissions on local-to-global scales. In this paper we examine changes in SO\textsubscript{2} and NO\textsubscript{2} over some of the world’s most polluted industrialized regions during the first decade of OMI observations. In terms of regional pollution changes, we see both upward and downward trends, sometimes in opposite directions for NO\textsubscript{2} and SO\textsubscript{2}, for the different study areas. The trends are, for the most part, associated with economic and/or technological changes in energy use, as well as regional regulatory policies. Over the eastern US, both NO\textsubscript{2} and SO\textsubscript{2} levels decreased dramatically from 2005 to 2014, by more than 40 and 80%, respectively, as a result of both technological improvements and stricter regulations of emissions. OMI confirmed large reductions in SO\textsubscript{2} over eastern Europe’s largest coal power plants after installation of flue gas desulfurization devices. The North China Plain has the world’s most severe SO\textsubscript{2} pollution, but a decreasing trend has been observed since 2011, with about a 50% reduction in 2012–2014, due to an economic slowdown and government efforts to restrain emissions from the power and industrial sectors. In contrast, India’s SO\textsubscript{2} and NO\textsubscript{2} levels from coal power plants and smelters are growing at a fast pace, increasing by more than 100 and 50%, respectively, from 2005 to 2014. Several SO\textsubscript{2} hot spots observed over the Persian Gulf are probably related to oil and gas operations and indicate a possible underestimation of emissions from these sources in bottom-up emission inventories. Overall, OMI observations have proved to be very valuable in documenting rapid changes in air quality over different parts of the world during the last decade. The baseline established during the first 10 years of OMI is indispensable for the interpretation of air quality measurements from current and future satellite atmospheric composition missions.
1 Introduction

Sulfur dioxide (SO\(_2\)) and nitrogen dioxide (NO\(_2\)) are reactive, short-lived atmospheric trace gases with both anthropogenic and natural sources. Major sources of NO\(_x\) (NO\(_x\) = NO + NO\(_2\)) include fossil fuel combustion, biomass burning, soil emissions (Vinken et al., 2014b) and lightning (Schumann and Huntrieser, 2007). NO\(_2\) participates in the nitrogen cascade of air–water–soil (EPA, 2011; Galloway et al., 2013), affects atmospheric oxidation rates (Valin et al., 2013), and contributes to surface ozone production (Duncan et al., 2010; Seinfeld and Pandis, 2006). The principal sources of SO\(_2\) are natural volcanic and anthropogenic emissions from burning sulfur-contaminated fossil fuels and the refinement of sulfide ores. Volcanic SO\(_2\) is often injected into the atmosphere at high altitudes above the planetary boundary layer (PBL), while anthropogenic SO\(_2\) emissions are predominantly in or slightly above the PBL. Chemical reactions in the PBL involving SO\(_2\) and NO\(_2\) lead to the production of aerosol oxidation products (sulfate and nitrate aerosols), and tropospheric ozone (Seinfeld and Pandis, 2006). Volatile Organic Compounds (VOCs) oxidize in the presence of NO\(_x\) and sunlight to form ozone (O\(_3\)), a major tropospheric pollutant and greenhouse gas (EPA, 2013), and the oxidation product of NO\(_2\), nitric acid (HNO\(_3\)), reacts with ammonia (NH\(_3\)) to form ammonium nitrate aerosols. SO\(_2\) is oxidized in gas-phase reactions with the hydroxyl radical (OH) or in aqueous-phase reactions with O\(_3\) or hydrogen peroxide (H\(_2\)O\(_2\)) to form sulfate aerosols. The sulfate and nitrate aerosols contribute to fine particulate matter pollution with aerodynamic diameters less than 2.5 µm (PM\(_{2.5}\)), which poses serious health concerns (Lee et al., 2015; Liu et al., 2015), degrades visibility, causes acidification of water and the biosphere with adverse effects on plants and soil, and impacts weather and climate through changes in direct radiative forcing and indirectly modifying cloud formation and optical properties (IPCC Working Group 1 et al., 2013; Twohy, 2005). Consequently, SO\(_2\), NO\(_2\), and their oxidation products, O\(_3\) and PM\(_{2.5}\), are designated Criteria Pollutants (European Commission, 2015; US...
EPA, 2015). Space based characterization of these pollutants enables global consistent monitoring, which is independent from ground-based measuring networks.

The first space-based quantitative data on SO$_2$ mass in volcanic clouds after a major eruption (El Chichon, 1982) was obtained from the six-UV band NASA’s Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) (Krueger, 1983). The TOMS SO$_2$ detection sensitivity was limited by the discrete wavelengths to exceptionally strong anthropogenic emissions, such as those produced by Norilsk smelting plants in Russia or from an accidental combustion of elemental sulfur (S) at the Al-Mishraq State Sulfur Mine Plant in Iraq (Carn et al., 2004; US Department of Veterans Affairs, 2015). Greatly improved sensitivity was demonstrated through detection of SO$_2$ emissions from coal-fired power plants using ESA’s Global Ozone Monitoring Experiment (GOME, 1995–2005) (Burrows et al., 1997; Eisinger and Burrows, 1998) and SCanning Imaging Absorption spectrometer for Atmospheric CHartographY, (SCIAMACHY, 2002–2012) (Bovensmann et al., 1999) hyperspectral UV spectrometers. The first tropospheric NO$_2$ quantification was demonstrated using GOME and SCIAMACHY visible data (Leue et al., 2001; Martin et al., 2002; Richter and Burrows, 2002; Richter et al., 2005). These sensors needed several days to acquire a contiguous global map. The Ozone Monitoring Instrument (OMI) is the first satellite hyperspectral UV/Visible spectrometer with a push broom CCD detector and a wide, 2600-km swath (Levelt et al., 2006b), which enables daily, global contiguous mapping of ozone and other trace gases, including SO$_2$ and NO$_2$ (Levelt et al., 2006a). OMI was launched in July 2004 on NASA’s Aura sun-synchronous afternoon equator crossing polar satellite (Schoeberl et al., 2006) and continues measurements through its 12th year, providing the longest data record currently available. OMI measurements are complemented with two GOME-2 instruments on EUMETSAT’s MetOp-A (2006) and B (2012) operational polar satellites (Richter et al., 2011; Rix et al., 2012; Valks et al., 2011), although with lower spatial resolution and sensitivity to PBL sources (Fioletov et al., 2013). Next generation ESA’s Sentinel series will provide higher spatial resolution and greater sensitivity to SO$_2$ and NO$_2$ sources (Ingmann et al., 2012; Veefkind et al., 2012).
In the PBL, both SO\textsubscript{2} and NO\textsubscript{2} have short lifetimes (< 1 day during the warm season) and are concentrated near their emission sources. This facilitates space-based detection of SO\textsubscript{2} and NO\textsubscript{2} sources and global characterization of their spatiotemporal variability (van der A et al., 2006, 2008; Burrows et al., 1999; Castellanos and Boersma, 2012; Eisinger and Burrows, 1998; Fioletov et al., 2013; de Foy et al., 2009; Hayn et al., 2009; He et al., 2012; Hilboll et al., 2013; Huang et al., 2013; Khokhar et al., 2005; Kim et al., 2009; Krotkov et al., 2008; Martin, 2008a; Martin et al., 2002; Mijling et al., 2009; Richter et al., 2005; Russell et al., 2012; Schneider and Van Der A, 2012; Theys et al., 2015; Valks et al., 2011; Zhou et al., 2009, 2012) and near-surface concentrations (Duncan et al., 2014; Lamsal et al., 2008, 2010, 2015; McLinden et al., 2014). Furthermore, over polluted regions satellite observable SO\textsubscript{2} and NO\textsubscript{2} vertically integrated number density profiles (columns) are highly correlated with underlying emissions, allowing space-based (i.e., “top-down”) inference of spatial and temporal changes in emissions (van der A et al., 2008; Boersma et al., 2008, 2015; Carn et al., 2007; Ding et al., 2015; Duncan et al., 2013; Fioletov et al., 2011, 2015b; de Foy et al., 2014, 2015; Frost et al., 2006; Ghude et al., 2010, 2013; Hayn et al., 2009; He et al., 2012; Kim et al., 2009; Konovalov et al., 2006, 2010; Lamsal et al., 2011; Lee et al., 2011; Li et al., 2010; Lu et al., 2013, 2015; Martin, 2008b; McLinden et al., 2012, 2014; Miyazaki et al., 2012; Napelenok et al., 2008; Reuter et al., 2014; Stavtrakou et al., 2008; Streets et al., 2013; Vinken et al., 2014a, b; Zhang et al., 2007), lifetime (Beirle et al., 2011; Fioletov et al., 2011, 2015b; de Foy et al., 2015; McLinden et al., 2012), physicochemical conversion (Duncan et al., 2010; Valin et al., 2013) and deposition of these species (Nowlan et al., 2014). OMI has been at the forefront of these rapid advances.

Previous OMI studies focused on specific species, emission sources and regions (van der A et al., 2008; Ahmad et al., 2007; Beirle et al., 2011; Boersma et al., 2011, 2015; Castellanos et al., 2014; Ding et al., 2015; Duncan et al., 2013; Fioletov et al., 2015b, 2011; de Foy et al., 2009, 2015; Ghude et al., 2013; Lamsal et al., 2008, 2011, 2015; Lelieveld et al., 2015; Lu et al., 2013; McLinden et al., 2014; Mebust and Cohen, 2014; Mijling and Van Der A, 2012; Mijling et al., 2009; Russell et al., 2012; Valin et al., 2014).
et al., 2013; Vinken et al., 2014a, b; Zhou et al., 2012). While NO$_2$ and SO$_2$ are both dominated by anthropogenic emissions in polluted regions, the origin of their anthropogenic sources differs, as well as the cost and efficacy of their respective emission control techniques. The often different regional trends and abundances of NO$_2$ and SO$_2$ offer valuable insights into energy infrastructures as well as pollution control policies (Li et al., 2010; McLinden et al., 2012). In this paper we examine changes in both SO$_2$ and NO$_2$ over the world’s most polluted regions during the first decade of OMI observations. Section 2 briefly summarizes OMI SO$_2$ and NO$_2$ algorithms and products. Section 3 describes regional SO$_2$ and NO$_2$ changes for the world’s industrial regions with large SO$_2$ emissions from coal burning power plants and industries (Fig. 1). For these regions the paper provides an update to the previously published trend studies and a context for a more detailed analysis of individual sources in a companion paper in this issue (Fioletov et al., 2015a).

2 OMI standard SO$_2$ and NO$_2$ products

OMI is the result of a partnership between NASA and the Dutch and Finnish meteorological institutes and space agencies (Levelt et al., 2006b) and flies on the NASA EOS-Aura satellite (Schoeberl et al., 2006). It measures sunlight backscattered from the Earth over a wide range of Ultraviolet (UV) and visible (Vis) wavelengths to derive abundances of ozone and other trace gases important for air quality and climate. The measurements of SO$_2$ and NO$_2$ are both explicit objectives of the Aura OMI mission (Levelt et al., 2006a) that are aimed at advancing our understanding of the sources and transformation processes of these pollutants and enabling the application of OMI data to inform public policy (Streets et al., 2013). Compared with other satellite UV-Vis instruments, OMI has the highest spatial resolution, least degradation and the longest record, allowing improved space-borne estimation of NO$_2$ and SO$_2$ emissions and studying their temporal behavior (Carn et al., 2007; Castellanos and Boersma, 2012;
Aura has a local equator crossing time of approximately 13:45 in the ascending node, and provides nearly global coverage each day. The OMI detector is a 2-dimensional Charge-Coupled Device (CCD) array. The instrument optics is designed such that the spatial dimension of the detector is oriented across the orbit track, with an 115° field of view, while the other dimension records spectral information. Three separate detectors (Dobber et al., 2006; Levelt et al., 2006b), designated UV-1, UV-2, and Vis, have spectral coverage (full performance) in the ranges of 270–310 nm (spectral resolution, full width at half maximum (FWHM), of 0.63 nm), 310–365 nm (0.45 nm), and 365–500 nm (0.63 nm), respectively. The OMI SO$_2$ product uses spectral measurements between 310.5 and 340 nm in the UV-2 (Li et al., 2013) and the NO$_2$ product uses spectral measurements between 405 and 465 nm in the Vis region (Boersma et al., 2011; Bucsela et al., 2013). The spatial dimension of both detectors is divided into 60 cross-track fields of view (FOV) corresponding to the specific binned CCD detector rows, such that rows 1 and 60 correspond to the western and eastern edges of the swath, respectively. Spectral measurements are made over 2 s exposure intervals. This results in along-track coverage of 13 km and cross-track coverage of 24 km for the near-nadir FOVs (CCD rows about 30). During each orbit, a total of about 1640 exposures are recorded on the sunlit side of the Earth. The width of the swath (2600 km) is such that 14–15 orbits per day are required to observe the entire surface of the Earth, although with increased FOV size at the swath edges. Beginning in 2007, some cross-track positions of the OMI swath were affected by FOV blockage and scattered light, also known as the “row anomaly” (KNMI, 2012). Here we use only unaffected OMI cross track positions (i.e., rows 6–23) throughout the entire mission, also excluding large FOVs at the edge of the swath.
2.1 Retrieval of PBL SO$_2$

OMI original PBL SO$_2$ product employed the band residual difference (BRD) algorithm, which used only 4 discrete wavelengths (Krotkov et al., 2006). The BRD product is sensitive to PBL sources, but has a high noise level (Krotkov et al., 2008) and systematic artifacts that required empirical corrections (Fioletov et al., 2011; Lee et al., 2009). In 2014 we released a new PBL SO$_2$ product, which is retrieved with a new algorithm that employs a principal component analysis (PCA) technique applied to OMI radiances (Li et al., 2013). Using a clear sky Air Mass Factor (AMF) similar to the previous SO$_2$ product, but with the full spectral content between 310.5 and 340 nm, the PCA algorithm reduces retrieval noise by a factor of two (Li et al., 2013). Recently, the Differential Optical Absorption Spectroscopy (DOAS) SO$_2$ algorithm developed for the Sentinel 5 Precursor (TROPOMI) has been applied to the OMI radiances and compared with the operational PCA product (Theys et al., 2015). The two products compare well, which lends confidence in OMI SO$_2$ data. The estimated SO$_2$ noise is similar between PCA and DOAS algorithms, when using similar assumptions for AMF calculation for pollution SO$_2$. However, the DOAS SO$_2$ algorithm requires empirical corrections to remove background bias.

In this study we will use the OMI operational PCA PBL SO$_2$ product, which contains the vertical column density (VCD) in Dobson Units (1 DU = 2.69 × 10$^{16}$ molecules cm$^{-2}$). The product (OMSO2 v1.2.0) is publicly available from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2_v003.shtml). The estimated 1$\sigma$ noise is $\sim$ 0.5 DU over tropical oceanic areas (Li et al., 2013). If we assume that the noise is random and that there are about 100 cloud-free samples per year, the detection limit over low latitudes can be estimated at $\sim$ 0.2 DU for the annual mean (signal-to-noise ratio = 2 : 1 for $\pm 1\sigma$ noise). An important advantage of the PCA algorithm is that the bias over background regions (where SO$_2$ columns are below the OMI detection limit) is sufficiently small (< 0.1 DU) that it requires no empirical background correction, as applied in other
satellite SO$_2$ algorithms (e.g., Fioletov et al., 2013; Theys et al., 2015). The improved data quality, combined with the pixel averaging and oversampling techniques (e.g., de Foy et al., 2009; Beirle et al., 2011; Fioletov et al., 2011, 2013, 2015a, b; Lu et al., 2013; McLinden et al., 2012, 2014), provides greatly enhanced sensitivity to anthropogenic SO$_2$ sources near the surface. It has been demonstrated that US SO$_2$ point sources (e.g., power plants, smelters) with emissions rates as low as $\sim 30$–$40$ ktyr$^{-1}$ can be detected and analyzed using the newest OMI SO$_2$ product (Fioletov et al., 2015b). This limit is substantially lower than that reported (70 ktyr$^{-1}$) for the previous version OMI SO$_2$ data (Fioletov et al., 2011).

### 2.2 Retrieval of tropospheric NO$_2$

There are two algorithms used operationally to determine tropospheric NO$_2$ VCDs: the NASA’s standard product (SP, version 2.1) and the KNMI’s Dutch-OMI-NO$_2$ (DOMINO) algorithm (TM4NO2A, version 2, http://www.temis.nl/airpollution/no2.html) (Boersma et al., 2011). Both products share a common DOAS spectral fitting of laboratory-normalized spectra of NO$_2$, H$_2$O, O$_3$, and Ring spectrum to the OMI-measured sun-normalized spectrum of backscattered radiation in the visible wavelength range of 405–465 nm to calculate NO$_2$ Slant Column Densities (SCDs). The estimated 1$\sigma$ noise is $\sim 10^{15}$ molecules cm$^{-2}$ or $\sim 10\%$ of the measured SCD over polluted regions (Boersma et al., 2011). The SCDs, after subtraction of the stratospheric contribution are converted to tropospheric VCDs by applying AMFs, interpolated from the Look-up-Tables (LUT) with OMI-measured input parameters such as viewing geometry, climatological surface reflectivity, cloud pressure and cloud radiance fraction, assuming a priori NO$_2$ vertical profile shapes. The NASA and KNMI algorithms differ in how they remove the stratospheric contribution and use different a priori tropospheric NO$_2$ profile shapes in the AMF calculation. DOMINO subtracts stratospheric SCD as determined in a data assimilation system, in which the measured SCDs are assimilated with the TM4 chemical transport model (Boersma et al., 2011). The SP estimates stratospheric NO$_2$ di-
rectly from OMI data without using stratospheric chemical transport models. The AMFs are calculated with a priori NO\textsubscript{2} monthly mean vertical profile shapes from the NASA GMI model (Bucsela et al., 2013). Despite the differences, both algorithms produce statistically similar regional trends (see Supplement Fig. S1). Here we use the SP tropospheric NO\textsubscript{2} VCD product version 2.1 publicly available from NASA GES DISC at http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omno2_v003.shtml. Over polluted areas the total errors in OMI tropospheric NO\textsubscript{2} VCDs are typically within 20\% for cloud-free FOVs, as confirmed by validation studies employing in situ and remotely sensed data (Bucsela et al., 2013; Irie et al., 2012; Lamsal et al., 2015; Oetjen et al., 2013).

2.3 Postprocessing of NO\textsubscript{2} and SO\textsubscript{2} data

For this study, level 2 (L2) tropospheric NO\textsubscript{2} and PBL SO\textsubscript{2} VCDs are gridded at different ground resolutions after excluding pixels possibly affected by the (1) row anomaly; (2) snow; (3) transient volcanic SO\textsubscript{2} clouds (Appendix A); (4) cloudy scenes (cloud radiance fraction > 0.5 or > 0.2 for SO\textsubscript{2}). The standard gridded (0.25° × 0.25°) level 3 (L3), filtered, monthly regional mean values are used in time series analyses following Lamsal et al. (2015) (Appendix B). The L3 data are publicly available from NASA GES DISC archive at http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI. We also use L2 (pixel level) data oversampled at higher resolutions (0.01° × 0.01° for NO\textsubscript{2} and 0.02° × 0.02° for SO\textsubscript{2}) to create global and regional maps that highlight point pollution sources. The regional maps are created directly from pre-filtered L2 data by averaging all OMI pixels within 20 km smoothing radius (30 km for SO\textsubscript{2}) for 3–4 year time periods. Unlike previous studies (Lee et al., 2009; Fioletov et al., 2011, 2013; Lu et al., 2013; McLinden et al., 2014), no empirical background correction was applied to the PBL SO\textsubscript{2} data.
3 Regional pollution changes and interpretation

Figure 1 shows SO$_2$ and NO$_2$ multi-year average maps at the beginning of the OMI mission (2005–2007) over the Northern Hemisphere. Regionally, population density (Lamsal et al., 2013), type of power generation and fuel used, economic activity, and regulatory policies determine average levels of air pollution. The SO$_2$ map (Fig. 1a) shows hotspots associated with major coal-fired power plants and industrial activities, such as oil and gas refining and metal smelting. The highest SO$_2$ is found over industrialized and populated regions in eastern China, as the world’s second largest economy relies on sulfur (S) rich coal for $\sim$ 70% of its energy consumption (Klimont et al., 2009; Zhang and Cheng, 2009). Based on bottom-up emission inventories, SO$_2$ emissions from China were the world’s largest, at $\sim$ 33 Tg SO$_2$ in 2005 (Lu et al., 2010, 2011). High S coal-fired power plants are the major contributors to the SO$_2$ over the eastern US (SO$_2$ emissions 14.5 Tg SO$_2$ in 2005 (US EPA, 2014)), eastern Europe and India ($\sim$ 6.7 Tg SO$_2$ (Lu et al., 2011)). SO$_2$ is lower (undetectable) over the western US and western Europe where emissions of SO$_2$ have been relatively small due to small share of coal–fired power plants, the low S content of coal and installation of effective flue gas desulfurization devices capable of capturing more than 95% of SO$_2$ emissions (US EIA, 2010).

Large SO$_2$ column amounts are also observed over the Persian Gulf, due to emissions from the oil and gas industry in the region. Based on a bottom-up SO$_2$ emission inventory, the total SO$_2$ emissions from the Middle East in 2005 were $\sim$ 6 Tg SO$_2$ (Smith et al., 2011b), less than those from India and the US. However, OMI-observed SO$_2$ columns over the Persian Gulf region are significantly larger than over these two regions. This implies that real SO$_2$ emissions from the Middle East (particularly in the Persian Gulf) are significantly underestimated in current bottom-up emission estimates. In addition to anthropogenic SO$_2$, volcanic SO$_2$ is frequently observed over Kamchatka (Russian Federation), Japan, the South Pacific (e.g., Anatahan volcano, Mariana Islands, Mauna Loa, Hawaii), Sicily (Etna), Mexico (Popocatepetel volcano, south of
Mexico city), Central America and Montserrat, West Indies. Although transient volcanic signals were filtered from the PBL SO\textsubscript{2} data (Table A1), the signals from frequently erupting (e.g., Mt. Etna, Popocatepetl) or degassing volcanos remain. Except for Mt. Etna and Mt. Popocatepetl (de Foy et al., 2009), most volcanic sources are located in remote locations and do not contribute to the SO\textsubscript{2} in industrial regions considered here (see OMI daily SO\textsubscript{2} maps for the world’s volcanic regions at http://so2.gsfc.nasa.gov).

The average NO\textsubscript{2} map (Fig. 1b) is correlated with the nighttime lights map (Fig. 1c), used here as a proxy for population density and energy production (Lamsal et al., 2013). For example, the highest NO\textsubscript{2} levels are observed over the world’s most populated and industrialized regions including eastern China, western Europe, and the eastern US, where local NO\textsubscript{2} “hot spots” coincide with large urban agglomerations (Schneider et al., 2015), power plants (Duncan et al., 2013; de Foy et al., 2015) and industrial complexes. NO\textsubscript{2} tropospheric columns over India and the Middle East are significantly less than over China, western Europe and the US. This can be explained by low NO\textsubscript{x} emissions, especially from mobile sources, and, partly, by year-round high temperatures, leading to shorter NO\textsubscript{2} lifetimes (Beirle et al., 2011). For example, Indian NO\textsubscript{x} emissions were relatively low at 5.7 Tg NO\textsubscript{x} in 2005 (Lu and Streets, 2012), whereas those from China and the US were 16.9 Tg NO\textsubscript{x} (Klimont et al., 2009) and 20.4 Tg NO\textsubscript{x} (US EPA, 2014), respectively. Relatively small, but significant areal NO\textsubscript{2} enhancements over west African forest are caused by seasonal biomass burning NO\textsubscript{x} emissions (Mebust and Cohen, 2014).

The differences between the spatial distributions of NO\textsubscript{2} and SO\textsubscript{2} over the large regions indicated as boxes in Fig. 1a and b are related to economic activity, fuel types, combustion technology and different regulatory policies. The most abundant source of SO\textsubscript{2} is Pyrite (mostly FeS\textsubscript{2}) and organic S in lower-grade coal as well as liquid fuel, mostly contained in heterocyclic aromatic compounds in oil, which largely accounts for high SO\textsubscript{2} levels over the Persian Gulf from gas flaring and oil refining. Many developed countries have regulated the S content of fuels and also required catalytic exhaust gas processing, resulting in decreased mobile-source NO\textsubscript{x} and SO\textsubscript{2} emissions in exhaust.
Regulations are also focused on stack emissions of NO\(_x\) and SO\(_x\) (SO\(_x\) = SO\(_2\) + SO\(_3\)) at point sources, such as power plants and smelters. This, in turn, has driven technological changes upstream to meet regulatory requirements. For example, fluidized-bed combustion technology permits burning at lower temperature, producing less NO\(_x\), and the condensed phase chemical capture of S, producing less gaseous SO\(_x\). Chemical Loop Combustion technology uses catalytic oxygenation to oxidize the fuel largely in the absence of N\(_2\), again resulting in greatly reduced NO\(_x\) leaving the combustion chamber. Stack scrubbers (i.e., flue gas desulfurization devices) have been widely deployed in Europe and the US, in particular, for existing plants, to remove SO\(_2\) and other chemicals – notably mercury – from the flue gases, in order to meet regulatory standards. However, these changes have yet to be widely implemented in developing countries.

In addition to emissions, meteorology also plays an important role in regional air pollution, particularly on relatively short time scales (days to months). For midlatitude areas discussed in this study (the eastern US, eastern China, and eastern Europe), the concentrations of SO\(_2\) and NO\(_2\) often exhibit large day-to-day changes. They tend to increase under the relatively stagnant conditions ahead of a cold front and decrease dramatically after the cold front brings precipitation and strong winds into the area (Li et al., 2007). On the interannual time scale, the frequency of cold front passages may be influenced by large-scale circulation patterns such as the position of the Siberian high for eastern China (Jia et al., 2015), leading to interannual changes in SO\(_2\) and NO\(_2\). But meteorology probably plays a lesser role in the longer-term trends that we discuss in this study. For example, given the general trend of weakening surface winds in the Northern Hemisphere (Vautard et al., 2010), one would expect both SO\(_2\) and NO\(_2\) to increase over time in China, with constant emissions. While OMI did initially observe growths in both SO\(_2\) and NO\(_2\) over China (Sect. 3.3), the different trends between the two gases after 2007 imply that different emission control measures may play a more significant role in OMI-observed trends. Similarly, the decreasing pollution levels observed over the eastern US (Sect. 3.1) and eastern Europe (Sect. 3.2) can
only be explained with a reduction in emissions. As for tropical areas such as India, the impact of year-to-year fluctuations in OMI \(\text{SO}_2\) and \(\text{NO}_2\) data caused by meteorological variations is small relative to the observed fast growth in emissions that occurred over areas with newly built power plants and many cities (Sect. 3.4).

With this understanding of the influence of different factors on anthropogenic \(\text{NO}_2\) and \(\text{SO}_2\) columns, we turn, in the remainder of this section, to examining regional decadal trends as seen by OMI measurements. We examine five regions indicated in Fig. 1: the eastern US, eastern Europe and Turkey, eastern China, India and the Middle East that all have \(\text{SO}_2\) and \(\text{NO}_2\) sources detectable by OMI. The regions are in different phases of economic development and environmental regulations. We can therefore compare and contrast the trends in \(\text{SO}_2\) and \(\text{NO}_2\) that have different sources depending on the types of fuels burned, industrial activity and regulations. The \(\text{NO}_2\) and \(\text{SO}_2\) trends from these regions provide insights into underlying economic trends and pollution regulation policies.

### 3.1 Eastern US

Over the eastern US the highest levels of \(\text{SO}_2\) were observed in areas of intense high-S coal combustion for industrial processes and electricity generation, including the Ohio River Valley and SW Pennsylvania (ORV, blue box in Fig. 2). Concentrations are lower (undetectable) over the western US where the local coal is intrinsically lower in S and emissions of \(\text{SO}_2\) have been relatively small (US EIA, 2010). Prior investigations involving OMI have reported a 40% \(\text{SO}_2\) reduction near power plants in the eastern US between 2005 and 2010 (Fioletov et al., 2011). More recent OMI observations (Fig. 2) show that the \(\text{SO}_2\) levels continued to drop after 2010 due to both national (e.g., Clean Air Interstate Rule, CAIR (CAIR, 2009)) and state regulations. Currently, US regional \(\text{SO}_2\) levels are at or below the OMI \(\text{SO}_2\) detection limit of \(\sim 0.1–0.2\) DU. The dramatic decrease over the course of the first 10 years of the OMI mission (Fig. 2) closely matches trends in reported \(\text{SO}_2\) emissions (US EPA, 2014) and sulfate deposition (\(-5\%\text{yr}^{-1}\) decrease over the eastern US from 2000–2010 (Hand et al., 2012;
This striking improvement in SO\(_2\) coincides with implementation of control technology such as flue gas desulfurization (FGD), closure of some of the oldest coal power plants and fuel switching from coal to natural gas. Reductions in SO\(_2\) emissions are required by the 1990 Clean Air Act Amendments (CAAA, 1990) and other regulations. Substantial success has been achieved through market-based cap and trade programs such as the Acid Rain Program (ARP, 2010) and The Clean Air Interstate Rule (CAIR, 2009). These allow electricity producers to pick the most economical emission control methods. The conversion to natural gas with much less fuel S than coal has also contributed to the reduction in SO\(_2\) pollution.

Unlike SO\(_2\), which originates primarily from fuel-bound S, all high-temperature combustion, including internal combustion engines, can generate NO\(_x\). As expected, OMI NO\(_2\) columns peak over major cities and highways as well as over clusters of power plants. Chicago, Atlanta, and the megalopolis from Washington, DC to New York, also called the I-95 corridor (red box in Fig. 2), stand out. At the beginning of the OMI mission in 2005, a broad background of elevated NO\(_2\) was detected over rural areas of the eastern US underlying the hot spots over large metropolitan areas (Fig. 2). Since that time, NO\(_2\) has significantly decreased as a result of emission regulations on power plants and cars (Duncan et al., 2013; Lamsal et al., 2015; Lu et al., 2015; Russell et al., 2012). Decreases in NO\(_2\) are evident in OMI NO\(_2\) data over all major cities, especially over the I-95 corridor (red box in Figs. 2 and S1) (Lu et al., 2015). NO\(_2\) from clusters of power plants has also decreased (e.g., ORV, blue box in Fig. 2). In general, downward trends in OMI NO\(_2\) data near US power plants correlate well with trends in NO\(_x\) emissions from the Continuous Emissions Monitoring System (CEMS) (Duncan et al., 2013) and with surface NO\(_2\) concentrations reported by EPA Air Quality Systems (AQS) (Lamsal et al., 2015; Tong et al., 2015). The NO\(_2\) reductions are due to selective catalytic reduction (SCR) on point sources and three-way catalytic converters on vehicles (Russell et al., 2012).

Figure 3 (upper row) compares year-to-year changes in the SO\(_2\) and NO\(_2\) annual averages over the ORV region (blue box in Fig. 2) with other heavily polluted regions
discussed later. Overall, between 2005 and 2014 the SO\textsubscript{2} drop over ORV was close to 80\%, while NO\textsubscript{2} dropped by 40\%, the largest reductions seen in this study. The magnitude of the relative reduction in NO\textsubscript{2} over the I-95 corridor is similar to that over the ORV (SM: Fig. S1), suggesting similar reduction in NO\textsubscript{x} emissions from power plants (ORV region), cities and mobile sources (I-95 region). Independent analysis of OMI NO\textsubscript{2} data confirmed that NO\textsubscript{x} emissions of 35 major US urban areas decreased by ~50\% from 2004 to 2014 (Lu et al., 2015). We also note the faster decline in NO\textsubscript{2} levels before 2009 because of the installation of NO\textsubscript{x} control devices on power plants and impact of the economic recession in 2007–2009. The annual reduction rate in NO\textsubscript{2} has slowed since 2009 as the US economy has recovered from the recession and the implementation of further pollution controls has slowed. As result of larger SO\textsubscript{2} reductions, the SO\textsubscript{2} / NO\textsubscript{2} column ratio dropped over the ORV region from its maximal values of ~4–5 in 2005 to less than 2 in 2014 and less than 1 over I-95 corridor (SM, Fig. S2). We expect similar change in PM speciation with increasing contribution of nitrate aerosols.

Although both SO\textsubscript{2} and NO\textsubscript{2} are Criteria Pollutants, and there remain jurisdictions in the US in violation of the National Ambient Air Quality Standards (NAAQS) for these primary pollutants, just as important is their role as precursors of key secondary air pollutants such as fine particles and ozone. The greatest numbers of Americans at risk for harmful effects of air pollution are subject to exposure to these secondary pollutants (Lee et al., 2015). Ozone is the Criteria Pollutant most likely to be found in exceedance of the US National Ambient Air Quality Standards (NAAQSs), but controlling NO\textsubscript{x} emissions is more expensive and difficult than controlling SO\textsubscript{2} emissions. By 2014, total US SO\textsubscript{2} emissions fell to about 1/6 of their 1970 peak, but NO\textsubscript{x} emissions only fell substantially after 2000 and are now about 1/2 of their peak in 2000 (http://www.epa.gov/ttnchie1/trends/). Because of these NO\textsubscript{x} reductions, photochemical smog over eastern US has improved significantly over the same time period (Castellanos et al., 2011; Hogrefe et al., 2011; Simon et al., 2015). The total deposition of oxidized N (the combination of wet and dry deposition of species such as NO\textsubscript{2} and
NO$_3^-$) has improved as well (Nowlan et al., 2014) indicating that the efforts to control NO$_x$ emissions have been successful.

### 3.2 Eastern Europe

Europe experienced a $\sim 80\%$ SO$_2$ reduction between 1990 and 2011 (EEA, 2013). Particularly, in western Europe, after significant reduction of SO$_2$ emissions in the 1980s–1990s, the SO$_2$ levels have dropped below the OMI detection limit. There are, however, detectable SO$_2$ sources in eastern Europe (Fig. 4). The spatial distribution of the observed SO$_2$ columns at the beginning of OMI mission is consistent with the spatial pattern of SO$_2$ concentrations derived from the surface monitoring stations for 2005 (Denby et al., 2010). Notable anthropogenic SO$_2$ sources include, for example, the mining and industrial districts in Donbass region in Eastern Ukraine, large coal-fired thermal power plants around the Sea of Marmara and those near Kahramanmaraş in southern Turkey, as well as those near Galabovo in southeastern Bulgaria, Gorj County in southwestern Romania, Belgrade in northern Serbia, and Megalopoli in southern Greece. Most of SO$_2$ hot spots are due to use of local high S lignite (brown) coal for power generation and incomplete SO$_2$ removal from the flue gas. Figure 3 (second row) shows interannual variations in SO$_2$ and NO$_2$ columns over the Maritsa Iztok power complex in Stara Zagora, Bulgaria (see blue box in Fig. 4). Large SO$_2$ reductions ($\sim 50\%$) between 2011 and 2014 are consistent with the installation of desulfurization devices, while NO$_2$ remains approximately constant, suggesting stable electricity production. Another important source of SO$_2$ in the region is the Mt. Etna volcano in Sicily. OMI SO$_2$ retrievals indicate relatively constant SO$_2$ degassing from Mt. Etna during the study period, but considerable decreases in SO$_2$ over Megalopoli, Galabovo, and Gorj County, likely owing to more stringent SO$_2$ controlling measures on power plant emissions in response to mandates by the European Union. SO$_2$ emissions from Turkey, on the other hand, appear to have increased during the same period, particularly over Kahramanmaraş, where new power plants went into service in 2006 (see http://globalenergyobservatory.org/geoid/42972). Increases in SO$_2$ over Serbia may re-
flect growth in energy consumption (mainly coal) as the country’s economy recovers from wars in the 1990s.

Figure 4 (bottom row) also gives the spatial distribution of OMI tropospheric NO$_2$ over eastern Europe, which shows enhanced columns in densely populated and industrial areas. By far the largest NO$_2$ level in eastern Europe was observed over Moscow, Russian Federation (Gorchakov, 2011), followed by industrial regions in south Poland, east Germany and the Czech Republic. High columns are evident over major industrial regions of Wroclaw and large cities, such as Warsaw, Athens, and Budapest. These enhancements correlate well with emissions source distribution. While road traffic is in general the most important NO$_x$ source in Europe (EEA, 2013; Vestreng et al., 2009), in some eastern European countries the power sector is the major contributor (Zyrichidou et al., 2013). New construction and upgrades in capacity of older power plants, as well as emission control measures affect NO$_2$ columns (Castellanos and Boersma, 2012; Zhou et al., 2012). Several studies based on bottom-up emissions and satellite observations have reported substantial decreases in NO$_x$ emissions and NO$_2$ columns in most of the western European countries due to stricter emission regulations (Castellanos and Boersma, 2012; Curier et al., 2014; EEA, 2013; Lamsal et al., 2011; Schneider et al., 2015; Vestreng et al., 2009; Zhou et al., 2012). In contrast, changes in emissions are rather small in eastern Europe (Zyrichidou et al., 2010). An increase in NO$_x$ emissions is reported for those countries where implementation of the European Union (EU) air quality standards is less effective (AQ_Environment_EC, 2015; Vestreng et al., 2009). OMI measurements are consistent with previous studies, suggesting small or insignificant NO$_2$ column trends on a regional level. Changes appear to be country-specific and likely depend on the socio-economic and political situation and legislative abatement measures of the country. The EU air quality standards hold for all EU-countries (including Poland, Hungary, Bulgaria, Croatia, the Baltic States, Slovenia, Slovakia), but not for Serbia, Russia, Ukraine, Belarus, and Turkey. Some countries have asked for time extension to meet certain standards because sev-
eral Member States have particular difficulties in achieving compliance with the criteria for PM and NO$_2$.

### 3.3 Eastern China

The growth of the Chinese economy over the past two decades has been mainly driven by rapid industrialization and urbanization (Huang et al., 2013) and has been accompanied by large increases in both electricity generation (mainly coal-fired power plants) and the number of vehicles on Chinese roads. As evident in Figs. 1a and 5, China has the world’s highest SO$_2$ emissions, particularly over the high S coal-rich heavily industrial areas in Hebei, Henan and Shandong provinces in the North China Plain (NCP, blue box in Fig. 5) and Inner Mongolia (Li et al., 2010; Zhang et al., 2009), the highly populated Sichuan Basin (SB, red box in Fig. 5), the megacity clusters around Shanghai (the Yangtze River Delta, YRD – black box in Fig. 5) and Guangzhou–Hong Kong (the Pearl River Delta, PRD). Similarly, OMI retrievals also reveal much greater NO$_2$ over eastern China than other regions of the world (Fig. 1b), especially over NCP, YRD and PRD (Fig. 5). The NO$_2$ levels are relatively low over SB, but highest over YRD and PRD. The SO$_2$ / NO$_2$ column ratios were 8–10 over SB, 3–5 over NCP and less than 2 over YRD and PRD in 2005 (Fig. S4). The ratios reflect to some extent the level of modernization in the regions. The PRD and YRD have little industry but higher population and car density, therefore greater NO$_2$ relative to SO$_2$.

The overall SO$_2$ loading, although still at a relatively high level, has decreased over the years (Fig. 5). This is more clearly shown in the SO$_2$ time series in Fig. 3, which suggests that the SO$_2$ loading over the NCP peaked in 2007, and has since shown an overall decreasing trend despite relatively large year-to-year variations. The reduction in SO$_2$ during 2008–2010 may be attributed to both the economic recession and emission control measures before the 2008 Beijing Olympic Games (Li et al., 2010; Lu et al., 2011; Mijling et al., 2009; Witte et al., 2009). The temporary rebound in 2011 may reflect a resurgence in the economy due to stimulation by the government. This is followed by a dramatic ~ 50% reduction over the three-year period during 2012–2014.
that may be attributed to both stricter emission reductions targets during the 12th Five-Year Plan (2010–2015) (Tian et al., 2013; Zhao et al., 2013), more widespread use of FGD on coal-fired power plants and industries, as well as a slowdown in the Chinese economy. We confirmed the 2012–2014 SO$_2$ reduction over NCP applying our SO$_2$ retrievals to the measurements from the new Ozone Mapping and Profiler Suite (OMPS) instrument on board NASA-NOAA Suomi National Polar Partnership (SNPP) satellite (Fig. S3). In relative terms the SO$_2$ reduction in 2005–2014 was larger over YRD and SB regions compared to NCP (Fig. S3).

NO$_2$ over NCP, on the other hand, peaked in 2011 after dramatic ~50% increase since 2009 (Fig. 3) and decreased slightly in 2012 and 2013 (Fig. 3). Temporary drop in 2008 can be attributed to strict pollution reduction measures implemented before 2008 Olympic games and economic recession. The reductions were strongest in Beijing, Tianjin and Shijiazhuang regions (Mijling et al., 2009; Witte et al., 2009). The dramatic drop in NO$_2$ in 2014 is likely a result of the slowest economic growth rate for China in nearly 25 years. According to the National Bureau of Statistics, the electricity generation by thermal power plants decreased by several percent in the second half of the year as compared with 2013. Similarly there is also a slowdown in coal-intensive industrial sectors (Guay, 2015) and stricter emission control policies (MEP, 2013). Independent satellite NO$_2$ retrievals with GOME-2A, GOME-2B and OMI also confirm large reduction in NO$_2$ over eastern China between 2013 and 2014 (Richter et al., 2015). Over SB and YRD NO$_2$ columns peaked in 2010 and remained relatively constant afterwards (Fig. S1). As a result of the different trends between SO$_2$ and NO$_2$ the SO$_2$ to NO$_2$ ratios dropped to their lowest values ~2–3, ~1–2 and less than one over SB, NCP and YRD regions, respectively (Fig. S4).

3.4 India

Figure 6 shows multi-year mean OMI SO$_2$ and NO$_2$ maps over India. A number of SO$_2$ and NO$_2$ hot spots are observed, and they match the locations of large coal-fired power plants and major cities (Ghude et al., 2011, 2013). This is because coal-fired
power plants are the dominant SO\(_2\) and NO\(_x\) emission sources in India, and they are often built near large cities where other anthropogenic emissions are also high. Figure 6 also shows that from 2005 to 2014, there was an increase in the OMI-observed SO\(_2\) and NO\(_2\) columns over India, mainly reflecting the fast expansion of the power sector driven by rapid economic growth. Based on an updated unit-based coal-fired power sector database (Lu and Streets, 2012; Lu et al., 2013), the total installed capacity, power generation, and fuel consumption of Indian coal-fired power plants increased dramatically by 126, 91, and 93 \%, respectively, during 2005–2014. The SO\(_2\) emissions from power plants are high, because S in local coal is mostly in organic form and cannot be removed by physical cleaning methods (Lookman and Rubin, 1998).

Unlike the US, Europe, and China, SO\(_2\) and NO\(_x\) emitted from coal-fired power plants are not regulated in India and the installation and operation rates of SO\(_2\) and NO\(_x\) emission control devices are very low. FGD devices for SO\(_2\) were reported to be operating in only three power plants at the beginning of OMI mission (Chikkatur et al., 2007). As for NO\(_x\) emissions, they are also not regulated in India for coal-fired power plants. Although some new plants were reported to be equipped with low-NO\(_x\) burners (LNB), the actual installation rate and performance of these LNB devices are not known. Based on bottom-up emission inventories we estimate that SO\(_2\) and NO\(_x\) emissions from Indian coal-fired power plants increased by 103 and 94 \%, respectively, during 2005–2014 (Lu and Streets, 2012; Lu et al., 2013). As shown in Fig. 3, the growth rates in OMI-observed SO\(_2\) (200 ± 50 \%) and NO\(_2\) (50 ± 20 \%) columns during 2005–2014 were particularly large over the industrial regions in Chhattisgarh and Odisha (blue box in Fig. 6), one of India’s most active areas in terms of building new power plants.

By the end of 2014, the total installed capacity of coal-fired power plants in this region was 28 GW, 85 \% of which (∼24 GW) was installed after 2005, accounting for ∼26 \% of the total newly installed capacity in India. As a result, SO\(_2\) and NO\(_x\) emissions from coal-fired power plants in this region were estimated to increase both by ∼190 \% from 2005 to 2014 (Lu and Streets, 2012; Lu et al., 2013), largely in line with OMI
observations (Fig. 3). India’s total annual SO\textsubscript{2} emissions almost doubled from 6.7 Tg in 2005 to estimated 12 Tg in 2014. In 2014, India has not only surpassed the US to be the world's second largest SO\textsubscript{2} emitting country, but also has reached more than 40 % of the SO\textsubscript{2} emissions of the world’s largest emitter, China.

3.5 Middle East

In the Middle East, abundant oil and gas deposits supply cheap and relatively clean fuels for electricity generation, water desalination, and industries. OMI detects the largest SO\textsubscript{2} emissions over the Persian Gulf. The sources for these emissions are apparently not included in the current global emission inventory such as the 2008 EDGAR-HTAP dataset (e.g., http://edgar.jrc.ec.europa.eu/edgar_album/v42/SO2/TOTALS/v42_SO2_2008_TOT.jpg). Based on the most recent SO\textsubscript{2} emission inventory, the total SO\textsubscript{2} emissions from the Middle East in 2005 were \textasciitilde 6 Tg (Klimont et al., 2013; Smith et al., 2011a), less than those from India and the US. However, OMI observed SO\textsubscript{2} columns over the Gulf region are significantly larger than those over India and US. That suggests that the real SO\textsubscript{2} emissions from the Middle East (particularly in the Persian Gulf) may be several times higher than current bottom-up emission estimates. This is consistent with independent OMI SO\textsubscript{2} retrievals (Theys et al., 2015). Inverse modeling using OMI and SCIAMACHY retrievals also suggests an underestimate of SO\textsubscript{2} emissions from the Persian Gulf (Lee et al., 2011).

In-situ measurements of SO\textsubscript{2} and other pollutants are rarely reported for the region, but available data generally indicate significant SO\textsubscript{2} loading over the Persian Gulf. For example, an aircraft campaign conducted north of the United Arab Emirates during winter 2001 measured SO\textsubscript{2} concentrations of up to 40 ppb (see https://www.rap.ucar.edu/asr2002/i-precip_physics/precip_physics.htm), greater than what has been previously observed over eastern China (Dickerson et al., 2007; He et al., 2012). The largest hotspot observed by the aircraft, near Zirku Island, also appears to be co-located with a hotspot in OMI retrievals. In another study, passive sampling of SO\textsubscript{2} at various locations on Khark Island near the north end of the Gulf during 2003–
2004 reported that the SO$_2$ loading was above the air quality standard (sometimes by several-fold) most of the time (Pourzamani et al., 2012). These high SO$_2$ columns over the Persian Gulf are likely the result of gas flaring activities from offshore oil and natural gas facilities, although shipping emissions and other sources may also contribute to them. Gas flaring is used on offshore oil rigs to dispose of gases such as hydrogen sulfide (H$_2$S) for safety, operational, and economic reasons and can have significant impacts on the local and regional environment in the Middle East.

Middle East cities also show SO$_2$ emissions due to both mobile and stationary sources. Oil-burning boilers may constitute another important source of SO$_2$ in cities or population centers, as implied by the relatively high sulfate ($\sim 10$ µg m$^{-3}$) that is closely associated with oil combustion tracers (e.g., vanadium), according to an aerosol source apportionment study for Kuwait City (Alolayan et al., 2013). The S content in gasoline and diesel is much higher in this region as compared with others such as Europe, which enforces stricter emission control measures (see http://www.unep.org/transport/pcf/PCF/Guides/MiddleEastFuelQuality.pdf). Some of the largest point SO$_2$ sources in the region coincide with smelters or oil refineries, such as the Sarcheshmeh Copper Complex in Kerman Province, Iran, which is the largest copper smelter in the Middle East. Figure 3 (bottom row) show interannual variations in observed SO$_2$ and NO$_2$ columns over Persian Gulf (blue box in Fig. 7). Since 2010 SO$_2$ columns have steadily dropped by $\sim 20\%$, but increased again in 2014 to 2005 levels (but still less than 2010 levels). A recent study (Lelieveld et al., 2015) reported that OMI SO$_2$ over Persian Gulf increased between 2005 and 2010, and then decreased between 2010 and 2014. Their results are based on retrievals using a different algorithm, but are qualitatively consistent with this study.

OMI retrieved regional NO$_2$ levels over Middle East are much smaller than over China (Fig. 6) and the US (Fig. 2). This may also be the result of the short lifetime of NO$_2$ in this hot and photochemically active region (Beirle et al., 2011). NO$_x$ emissions in the region are associated with power generation and mobile sources. Local NO$_2$ enhancements coincide with heavily populated cities that have high car densities, such
as Jerusalem (Israel) and Cairo (Egypt) (Boersma et al., 2009), Tehran (Iran), Kuwait City (Kuwait), Dubai (UAE), Riyadh and Jeddah (Saudi Arabia). In terms of regional trend over the Persian Gulf (blue box in Fig. 7), NO$_2$ columns increased by ~20% between 2005 and 2008, but remained approximately constant afterwards (Fig. 3). For major metropolitan areas in the region, Lelieveld et al. (2015) focused on the reversal of OMI NO$_2$ trends due to recent air quality regulations and domestic and international conflicts in the region. Their results are, for the most part, qualitatively consistent with Fig. 7. For example, their reported decrease of NO$_2$ over Damascus, Syria since 2011 (due to civil war) and increase over Baghdad, Iraq since 2007 are also visible in Fig. 7.

4 Conclusions

The first decade of OMI observations (2005–2014) have yielded profound insights into the spatial distribution and temporal trends in SO$_2$ and NO$_2$ around the world. For regions with detailed bottom-up emissions estimates or continuous emissions monitoring, OMI shows generally good agreement with these independent data sources. OMI-derived trends also agree well with those from available in situ measurements and deposition data. This adds confidence to the use of OMI to track locations, changes, and transport patterns of SO$_2$ and NO$_2$ over areas of the planet lacking local observations. In many regions pollution levels have changed dramatically reflecting underlying changes in SO$_2$ and NO$_x$ emissions (Fig. 8): (1) over the eastern US, both NO$_2$ and SO$_2$ levels decreased dramatically from 2005 to 2014. SO$_2$ concentrations over the Ohio River Valley and western Pennsylvania fell by 80%, consistent with the National Emission Inventory (NEI), which reports a decrease of about 66% for total US emissions. NO$_2$ concentrations over the eastern US fell by more than 40%, also consistent with the NEI trend for emissions from the entire country. The Clean Air Act Amendments and regulations such as CAIR mandated these emissions reductions, and OMI confirmed their efficacy. (2) Over eastern Europe, OMI observed substantial (more than 50%) SO$_2$ decreases in the vicinity of the largest coal-fired power plants, where FGD
was installed during the study period. Over some areas including Turkey and Serbia, local \( \text{SO}_2 \) increased, perhaps because of increased industrial activity. \( \text{NO}_2 \) levels in the vicinity of the largest eastern European power plants in Bulgaria remain constant. (3) Over China, highest \( \text{SO}_2 \) and \( \text{NO}_2 \) levels are observed over the North China Plain, with the highest concentrations in the world. \( \text{SO}_2 \) peaked in 2007, with a secondary peak in 2011, but by 2014 \( \text{SO}_2 \) has fallen to half of the levels seen at the beginning of the OMI record in 2005. Total Chinese electricity production and coal combustion have increased during the same period, and the observed decrease likely has resulted from centralization of industry and power production and the implementation of pollution control devices. \( \text{NO}_2 \) concentrations peaked in 2011, but by 2014 have returned to 2005 levels. (4) Over India, despite relatively low levels as compared with China, both \( \text{SO}_2 \) and \( \text{NO}_2 \) have increased, particularly over the northeast where a large number of newly built coal power plants have doubled \( \text{SO}_2 \) while increasing \( \text{NO}_2 \) by \( \sim 50\% \). This is the fastest increase in pollution concentrations observed by OMI. In 2014 India has surpassed the US to become the world’s second largest \( \text{SO}_2 \) emitting country. (5) Over the Middle East, OMI detected several \( \text{SO}_2 \) hot spots with a broad maximum over the Persian Gulf region. These hotspots are probably related to oil and gas operations but are mostly absent in bottom-up emission inventories, such as EDGAR. High concentrations of \( \text{NO}_2 \) are observed over major cities but less so over oil and gas operations. \( \text{SO}_2 \) shows no discernable trend over the Gulf while \( \text{NO}_2 \) rose from 2005 to 2008 and has since remained largely unchanged.

In summary, this study demonstrates that satellite remote sensing from advanced instruments such as OMI can provide long-term, nearly continuous global monitoring of \( \text{SO}_2 \) and \( \text{NO}_2 \). Where in situ concentration measurements, emission inventories, and deposition monitoring are available, OMI provides complementary measurements to supplement and verify those other data sources. It can also find unreported or underreported major emissions such as over the Persian Gulf. OMI \( \text{SO}_2 \) and \( \text{NO}_2 \) data can also help to further our understanding of the production and impact of secondary pollutants such as tropospheric ozone and particulate matter.
Space-based monitoring plays an increasingly important role in the science of tropospheric chemistry and air quality applications to help mitigate anthropogenic and natural impacts on climate, sensitive ecosystems, and human health. It is essential to continue and maintain overlapping long-term satellite data records. The baseline established during the first 10 years of OMI is invaluable for the interpretation of measurements from future satellite atmospheric chemistry missions. The OMI NO$_2$ and SO$_2$ data sets used in this study will be continued by the TROPOspheric Monitoring Instrument (TROPOMI) (Veefkind et al., 2012), which is planned for launch on ESA’s Sentinel 5 Precursor satellite in 2016. TROPOMI will have a significantly higher signal-to-noise and spatial resolution (7 km × 7 km at nadir) than OMI (13 km × 24 km at nadir); both features are very important for monitoring point pollution sources and trends. TROPOMI is part of the European Sentinel series that will continue the global pollution data record for another 20 years (Ingmann et al., 2012). The space-based capabilities for air quality applications will be further enhanced by the addition of high-ground resolution (at 4 km by 4 km at nadir) hourly observations from the three geostationary satellites over North America (TEMPO, http://tempo.si.edu), over Europe (Sentinel 4 UVN (Ingmann et al., 2012)) and East Asia (GEMS). This constellation will allow for unprecedented observations of the key pollutants in the atmosphere.

Appendix A: Filtering transient volcanic clouds

Days affected by transient volcanic SO$_2$ signals were excluded as follows. Every day the region-wide 99.9-percentile of SO$_2$ VCDs was computed. If it was found to exceed a threshold value (Table A1) then all data from that day were excluded. This was found to perform better than a simple maximum SO$_2$ or NO$_2$ column cut-off as it tended to remove volcanic signals that, while elevated, would not exceed the maximum. A disadvantage of this method is that, while the volcanic contamination would generally only impact a small portion of the region, all data from that day were removed. The SO$_2$ threshold employed varied from 5 to 10 DU (Table A1) and was chosen by examining
the 99.9-percentile time series during known periods of minimal volcanic activity. Different regions were found to be affected differently, a result of their proximity to significant eruptions. For regions that span the northern mid-latitudes such as US, Europe, and China, many of the days occurred in 2008 and 2009 and can be attributed to the eruptions of Kasatochi (Aleutian Islands, Alaska, August 2008, 52° N) and Sarychev (Kuril Islands, eastern Russia, June 2009, 48° N). By contrast, the Nabro eruption (northern Africa, June 2011, 13.37° N) removed the most days over India and Africa whereas the Middle East appeared to be largely unaffected by volcanic emissions.

Appendix B: Timeseries analysis

We use standard Level 3 monthly regional mean SO\(_2\) and NO\(_2\) columns and a regression model discussed in Lamsal et al. (2015) to compare inter-annual timeseries for different regions. The time series of monthly average values (\(\Omega\)) are assumed to be comprised of three additive subcomponents: a seasonal component (\(\alpha\)), a linear trend component (\(\beta\)), and residues or noise (\(R\)) component:

\[
\Omega(t) = \alpha(t) + \beta t + R(t)
\]

where, \(t\) represents time (month). The time dependent seasonal regression coefficient (\(\alpha\)) is given by a constant plus intra-annual sine and cosine harmonic series (Randel and Cobb, 1994):

\[
\alpha(t) = c_0 + \sum_{j=1}^{3} \left( c_{1,j} \sin \left( \frac{2\pi j t}{12} \right) + c_{2,j} \cos \left( \frac{2\pi j t}{12} \right) \right),
\]

where \(c_0, c_{1,j}, \) and \(c_{2,j}\) are constant coefficients. The major portion of the annual cycle is explained by the seasonal variation of the NO\(_x\) and SO\(_2\) lifetime. Other factors, such as monthly variation in source strength, could also affect the annual variation of NO\(_2\) and SO\(_2\) columns, but these contributions especially for NO\(_2\) to the seasonal cycle are
typically smaller especially for polluted areas. The seasonal pattern can evolve with time. We identify and extract seasonal and trend components by exploiting changes in the seasonal pattern (amplitude and phase) for individual years. For each year we fit a regression line using monthly observations from that year itself and 6 observations each from adjacent years. This provides a series of local regression lines that incorporate explicit time dependence. Comparison of local regression lines with high- and low-amplitude regression lines allows identification and isolation of two seasonal terms ($\alpha_1$, $\alpha_2$, where $\alpha = \alpha_1 + \alpha_2$ in Eq. 1) and the linear trend ($\beta$) and residues. Since we are interested in interannual changes, we do not explicitly derive linear trend, but rather calculate changes from 2005 from de-seasonalized NO$_2$ and SO$_2$ columns (Fig. 3).

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Aura OMI observations of regional SO\textsubscript{2} and NO\textsubscript{2} pollution changes

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Vinken, G. C. M., Boersma, K. F., Maasakkers, J. D., Adon, M., and Martin, R. V.: Worldwide biogenic soil NO\textsubscript{x} emissions inferred from OMI NO\textsubscript{2} observations, Atmos. Chem. Phys., 14, 10363–10381, doi:10.5194/acp-14-10363-2014, 2014b.


Table A1. Filtering transient volcanic clouds.

<table>
<thead>
<tr>
<th>Region</th>
<th>Threshold (DU)</th>
<th>Days excluded (2005–2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern US</td>
<td>5</td>
<td>97</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>8</td>
<td>72</td>
</tr>
<tr>
<td>Eastern China</td>
<td>10</td>
<td>71</td>
</tr>
<tr>
<td>India</td>
<td>8</td>
<td>58</td>
</tr>
<tr>
<td>Middle East</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>
Figure 1. OMI-derived maps of PBL SO$_2$ in Dobson Units [DU] (a) and tropospheric NO$_2$ columns in $[10^{15}$ molecules cm$^{-2}$] (b) for 2005–2007 show enhanced pollution levels around major cities and industrial centers, seen also in the “Earth at Night” (city lights) map (c), courtesy of Aura EPO team.
Figure 2. Multiyear average OMI SO$_2$ (top) and tropospheric NO$_2$ (bottom) regional maps over eastern US for 3 periods: 2005–2007, 2008–2010 and 2011–2014. Blue box outlines Ohio River Valley and SW Pennsylvania (ORV) region with largest SO$_2$ emissions from coal-fired power plants. Red box outlines megalopolis from Washington, DC to New York along the I-95 interstate highway (I-95 corridor) with largest NO$_2$ from mobile sources.
Figure 3. Relative changes (compared to 2005) in OMI PBL SO$_2$ columns (left) and tropospheric NO$_2$ columns (right) over 5 world's most polluted regions: (a and b): Ohio River Valley and western Pennsylvania (ORV) in eastern US (ORV – blue box in Fig. 2); (c and d): Maritsa Iztok Power Plants in Bulgaria (blue box in Fig. 4); (e and f): North China Plane (NCP – blue box in Fig. 5); (g and h): NE India (blue box in Fig. 6); (i and j): Persian Gulf (blue box in Fig. 7). Gray circles show de-seasonalized monthly columns (see details in Supplement). Black filled circles show annual means. Vertical bars show standard deviations.
Figure 4. Same as Fig. 2, but for Eastern Europe. The largest SO$_2$ source in the domain is the Etna volcano in Sicily, Italy. The blue box is centered on SO$_2$ polluted area around Maritsa Iztok coal mining region and the largest coal-fired power plant in southeastern Bulgaria.
Figure 5. Similar to Fig. 2 but for eastern China. Blue box outlines North China Plane (NCP) also represented in Fig. 3, red box – Sichuan Basin (SB) and black box represent Yangtze River Delta (YRD). The boxes are also shown in Figs. S1, S3 and S4.
Figure 6. Similar to Fig. 2 but for India. Blue box outlines industrial regions in Chhattisgarh and Odisha, one of India’s most active areas in terms of building new coal-fired power plants. The region is shown in Fig. 3.
Figure 7. Similar to Fig. 2 but for the Middle East. Blue box outlines Persian Gulf region with high SO$_2$ and NO$_2$ levels due to oil and gas operations.
Figure 8. Percent change in OMI annual average columns: SO$_2$ (top) and NO$_2$ (bottom) over the world's most polluted regions.