



Recent large reduction in sulfur dioxide emissions from Chinese power plants observed by the Ozone Monitoring Instrument

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[1] The Ozone Monitoring Instrument (OMI) aboard NASA's Aura satellite observed substantial increases in total column SO₂ and tropospheric column NO₂ from 2005 to 2007, over several areas in northern China where large coal-fired power plants were built during this period. The OMI-observed SO₂/NO₂ ratio is consistent with the SO₂/NO_x emissions estimated from a bottom-up approach. In 2008 over the same areas, OMI detected little change in NO₂, suggesting steady electricity output from the power plants. However, dramatic reductions of SO₂ emissions were observed by OMI at the same time. These reductions confirm the effectiveness of the flue-gas desulfurization (FGD) devices in reducing SO₂ emissions, which likely became operational between 2007 and 2008. This study further demonstrates that the satellite sensors can monitor and characterize anthropogenic emissions from large point sources. **Citation:** Li, C., Q. Zhang, N. A. Krotkov, D. G. Streets, K. He, S.-C. Tsay, and J. F. Gleason (2010), Recent large reduction in sulfur dioxide emissions from Chinese power plants observed by the Ozone Monitoring Instrument, *Geophys. Res. Lett.*, 37, L08807, doi:10.1029/2010GL042594.

1. Introduction

[2] The phenomenal growth of the Chinese economy in the past few decades has been largely driven by expansion in manufacturing industries and fueled by coal, the source of more than 70% of the energy consumed nationwide [National Bureau of Statistics of China, 2008]. By far the largest contributor of anthropogenic SO₂ and NO_x in China, thermal power plants used 50% of the coal production, and emitted an estimated 18 Tg of SO₂ and 9 Tg of NO_x in 2006 [Zhang et al., 2009a]. In light of the impact of coal-fired power plants on local and regional air quality, Ministry of Environmental Protection in China (MEP) [2009] has started implementing stricter emission control measures [e.g., Zhang et al., 2009a; Zhao et al., 2008]. MEP [2009] reported a 9%

reduction of total SO₂ emissions during 2005–2009 through installing flue-gas desulfurization (FGD) devices on power plants and phasing out small power generation units. In contrast, it is estimated that NO_x emissions from power plants may increase by 40% during the same period, due to the relatively poor performance of the commonly used abatement techniques like low-NO_x burners [Zhao et al., 2008].

[3] A number of satellite sensors launched in the last 10–15 years offer powerful tools for studying anthropogenic pollution in the troposphere [e.g., Martin, 2008; Richter et al., 2005; Wang et al., 2007]. Launched in 2004, the Dutch-Finnish built Ozone Monitoring Instrument (OMI) aboard NASA's EOS Aura satellite provides daily global coverage and spatial resolution of 13 km × 24 km at nadir [Levelt et al., 2006]. OMI-retrieved tropospheric NO₂ and SO₂ column amounts have been used to study regional emissions [e.g., Witte et al., 2009], synoptic pollution events [e.g., Krotkov et al., 2008], and large point emission sources [e.g., Carn et al., 2007].

[4] More recently, in the first satellite-based study of individual large point sources in China, Zhang et al. [2009b] identified several coal-fired power plants built between 2005 and 2007 over Inner Mongolia in northern China. They demonstrated that over the areas with the new power plants, the OMI tropospheric NO₂ column amounts in summer 2007 were significantly higher than those in 2005. The OMI-observed increases in NO₂ were found to be well-correlated with the estimated NO_x emission growth based on a bottom-up approach. In this study, we show that OMI also observed substantial changes in SO₂ emissions from these same locations for the period 2005–2008. The purpose of this work is to demonstrate that satellite instruments can be used to monitor the effectiveness of China's SO₂ emission control measures on power plants, by analyzing the OMI observed SO₂/NO₂ ratio, as well as comparing the trends in SO₂ emissions and OMI SO₂ retrievals.

2. Data and Method

[5] The OMI sensor retrieves planetary boundary layer (PBL) SO₂ column amounts from measurements of back-scattered solar UV (BUV) radiation in the wavelength range of 311–315 nm using a Band Residual Difference (BRD) algorithm [Krotkov et al., 2006, 2008]. The retrieved SO₂ slant column density (SCD) (i.e., the effective total column along the mean path of BUV photons) is converted to the total SO₂ vertical column density (VCD) in Dobson Units (1 DU = 2.69 × 10¹⁶ molecules/cm²) using an air mass factor (AMF),

$$\text{total SO}_2\text{VCD} = \frac{SCD}{AMF} \quad (1)$$

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The AMF is a function of SO₂ vertical distribution, satellite viewing geometry, total column ozone, aerosols, and clouds [Krotkov *et al.*, 2008]. A constant AMF of 0.36 is used in the current operational PBL SO₂ product. It is derived by assuming cloud- and aerosol-free conditions, solar zenith angle (SZA) of 30°, surface albedo of 0.05, surface pressure of 1013.25 hPa, summer mid-latitude ozone profile of 325 DU, and SO₂ mostly distributed in the PBL, centered at ~900 hPa. The noise is ~1.5 DU for the instantaneous field of view PBL SO₂ data, but can be greatly reduced through averaging over time and space [Krotkov *et al.*, 2008]. Error may also arise due to the constant AMF employed in the operational product. A recent study [Lee *et al.*, 2009] applying GEOS-Chem simulated SO₂ and aerosol profiles suggests a seasonal average AMF of ~0.5 over China. Validation against aircraft measurements over China [Dickerson *et al.*, 2007; Xue *et al.*, 2010] has shown that the operational OMI PBL SO₂ product can distinguish between clean and polluted conditions [Krotkov *et al.*, 2008].

[6] For this study, we use the PBL SO₂ data from the OMSO₂ L2G product. Daily retrievals, allocated to grid cells of 0.125° × 0.125°, were first filtered to remove data with large solar zenith angle (>70°), or relatively high cloud fraction (OMI retrieved radiative cloud fraction >0.3), or possible contamination due to the OMI row anomaly [Witte *et al.*, 2009], and then averaged to 0.25° × 0.25° resolution. Seasonal mean SO₂ column amounts were then calculated from the daily data, for the summer months (JJA: June, July, and August) during 2005–2008. For our study areas, there are typically 30–50 days with OMI observations for each 0.25° × 0.25° cell in a summer after the data filtering.

[7] The tropospheric NO₂ data utilized in this study are from the 0.25° × 0.25° gridded OMNO₂ L2G product, developed at NASA's Goddard Space Flight Center [Bucsela *et al.*, 2006]. To retrieve NO₂, spectral fitting in the OMI spectral range of 405–465 nm is used to derive the SCD of NO₂, which is then converted to the NO₂ VCD with pre-determined AMF's. The AMF calculations employ climatological NO₂ profiles from the GEOS-Chem model and the Goddard Chemical Transport Model, and account for cloud influence using the OMI cloud product. Over regions with strong emission sources, the retrieval error for the tropospheric NO₂ column mainly comes from the uncertainties in AMF, and is estimated at ~35–60% [Boersma *et al.*, 2004]. For this study, daily NO₂ column amounts were filtered using the same criteria as for the SO₂ data, and averaged into summertime means. The sampling frequency of NO₂ for a single grid cell is similar to that of SO₂.

[8] Using the method similar to that described by Zhang *et al.* [2009b], monthly SO₂ emissions from power plants were estimated with the following equation:

$$E = 2.8 \times U \times T \times F \times C \times S \times R \times (1 - \eta) \times 10^{-6} \quad (2)$$

where E is the SO₂ emissions from a given power generation unit (Mg/month); U is the unit size (generation capacity, MW); T is the annual operation hours; F is the monthly fraction of annual total power generation; C is the coal consumption per unit electricity-supply (gram coal equivalent (gce)/kWh); S is the sulfur content in coal (%); R is the sulfur

release rate during combustion; and η is the sulfur removal efficiency of the FGD devices, if equipped. The uncertainty of the SO₂ emission inventory is about 12% for the whole China [Zhang *et al.*, 2009a], and a recent study suggested ~7% uncertainty in SO₂ emission factors for Chinese power plants [Zhao *et al.*, 2010].

3. Results and Discussion

[9] We focus on three regions in eastern (Figures 1a–1d), central (Figures 1e–1h), and western (Figures 1i–1l) Inner Mongolia. The low population density (~20 people/km²) and relatively limited number of small area sources in these regions make them suitable for studying power plant emissions with satellite data. Figure 1 presents the annual summer (JJA) mean OMI PBL SO₂ column amounts over the three regions from 2005 to 2008 (Figure 1, left to right). Solid circles and triangles in the plot represent areas with and without new power plants becoming operational during 2005–2007, respectively. As shown in Figure 1, substantial increases in SO₂ between 2005 and 2007 are observed by OMI, especially over Shangdu (Figures 1a and 1c), Baotou, and Tuoketuo (Figures 1e and 1g), where new power generation capacity exceeded 2000 MW (Table 1). Shenmu and Huhehaote (Figures 1e and 1g) had relatively smaller growth in power generation capacity, but the OMI-observed column SO₂ also increased over the years. A large increase in OMI SO₂ was observed over Wuhai (Figures 1i and 1k), a city with new power plants and sizable coking and smelting industries. Comparing Figure 1 to Figure 3 of Zhang *et al.* [2009b], which shows the summertime OMI NO₂ over the same three regions, we notice that the increase in SO₂ is more widespread, while the detected growth in NO₂ is more confined to areas near the new power plants. Under mostly cloud-free conditions, SO₂ can have longer atmospheric lifetime, and may be detected over larger areas compared to NO_x from the same sources. It is likely that the industrial SO₂ emissions in these regions also increased from 2005 to 2007. For the urban areas without new power plants (Figure 1, triangles), Zhang *et al.* [2009b] found ~10% increases in OMI NO₂ during 2005–2007. The OMI SO₂ column amounts over these areas, on the other hand, recorded increases of 20–50% during the period (Figure 1), some of which probably reflect growth in the industrial SO₂ sources.

[10] In Figure 2, we present the trends in OMI retrieved SO₂ and NO₂, along with the estimated SO₂ emissions from power plants, over nine selected 1° × 1° areas. The domain size is chosen to include power plants near Zhangjiakou and Datong that are outside of the smaller 0.5° × 0.5° cells. The domains of the nine areas, as well as the changes in OMI SO₂ and NO₂ during 2005–2007 and 2007–2008, are summarized in Table 1. The nine areas can be further grouped into three categories: Baotou, Huhehaote, and Wuhai are industrialized cities with new power plants built between 2005 and 2007; Datong, Shuozhou, and Zhangjiakou are cities without new power plants; and Shangdu, Shenmu, and Tuoketuo are largely rural areas where new power plants came into service during 2005–2007. As already discussed, from 2005 to 2007 the OMI NO₂ changed little but SO₂ increased by ~0.3–0.5 DU over Datong, Shuozhou, and Zhangjiakou. The other six areas with new power plants all show increases in both column NO₂ and SO₂ during this period.

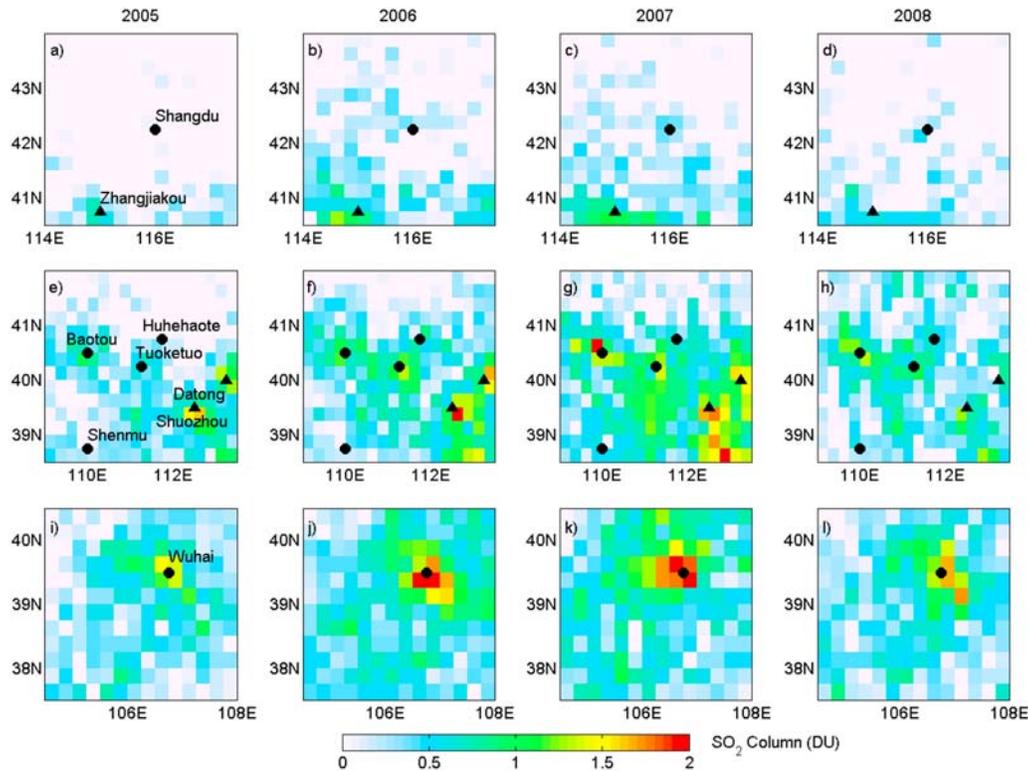


Figure 1. Summertime average OMI SO₂ column amounts over areas in (a–d) eastern, (e–h) central, and (i–l) western Inner Mongolia from 2005 to 2008. Solid circles and triangle represent areas with and without newly built power plants during the period of 2005–2007 (Table 1).

[11] We compare OMI SO₂/NO₂ ratio over areas where pollutants are mainly from power plants (Table 2) to the SO₂ and NO_x emission factors based on the bottom-up approach, to characterize the emissions from those plants. The estimated NO_x emission factors from large Chinese power plants (>100 MW) burning bituminous or lignite (the most common coal types in China) range from 4.05–5.6 kg/t for units equipped with LNB (Low-NO_x Burner) to 6.6–7.4 kg/t for units without LNB [Zhao *et al.*, 2008]. The sulfur content of coals used by power plants in Inner Mongolia varies, mostly within 0.5–2% [Zhao *et al.*, 2008]. Under the assumption that no FGD is employed for SO₂ emission control, the SO₂ emission factor for a power plant depends on the sulfur content of the coal, and can be as low as 9.5 kg/t for 0.5% S coal and as high as 38 kg/t for 2% S coal. The corresponding

SO₂/NO_x emission ratio (mole/mole) would be ~1.4–5.5, largely consistent with *in situ* measurements of a few Chinese power generation units [Zhao *et al.*, 2010]. The OMI SO₂/NO₂ ratio in summer 2007 (Table 2), over areas where power plants dominate NO_x emissions (fraction ≥ 60%), is between 1.6 (Shangdu) and 6.8 (Wuhai). The local coking and smelting industries in Wuhai may contribute a large fraction of SO₂ emissions. Emissions of both NO_x and SO₂ from the three rural areas (Shangdu, Shenmu, and Tuoketuo) are predominantly from power plants, and the 2007 summer OMI SO₂/NO₂ ratios over these areas are 1.6–3.6, close to our estimated emission factors. It should be noted that the satellite SO₂/NO₂ ratio could be biased high compared to the actual emissions. NO₂ is a fraction of NO_x, although the partitioning between NO and NO₂ after emissions should favor NO₂ in the

Table 1. Location of the Nine Areas Marked in Figure 1 and Changes in OMI Column SO₂ and Tropospheric NO₂ During 2005–2007 and 2007–2008

Location	New Capacity (MW)	Change in SO ₂ (DU)		Change in NO ₂ (DU)		
		2005–2007	2007–2008	2005–2007	2007–2008	
Baotou	40–41°N, 109.5–110.5°E	2700	0.29	−0.04	0.057	0.029
Huhehaote	40.25–41.25°N, 111.25–112.25°E	600	0.46	−0.09	0.041	0.012
Wuhai	39–40°N, 106.25–107.25°E	610	0.48	−0.22	0.065	0.0012
Datong	39.5–40.5°N, 112.75–113.75°E	0	0.50	−0.64	0.015	−0.0041
Shuozhou	39–40°N, 112–113°E	0	0.33	−0.49	0.0096	0.00025
Zhangjiakou	40.25–41.25°N, 114.5–115.5°E	0	0.31	−0.23	−0.0065	−0.0059
Shangdu	41.75–42.75°N, 115.5–116.5°E	2400	0.37	−0.10	0.023	0.015
Shenmu	38.25–39.25°N, 109.5–110.5°E	1200	0.33	−0.30	0.049	0.0015
Tuoketuo	39.75–40.75°N, 110.75–111.75°E	2100	0.51	−0.18	0.12	0.0073

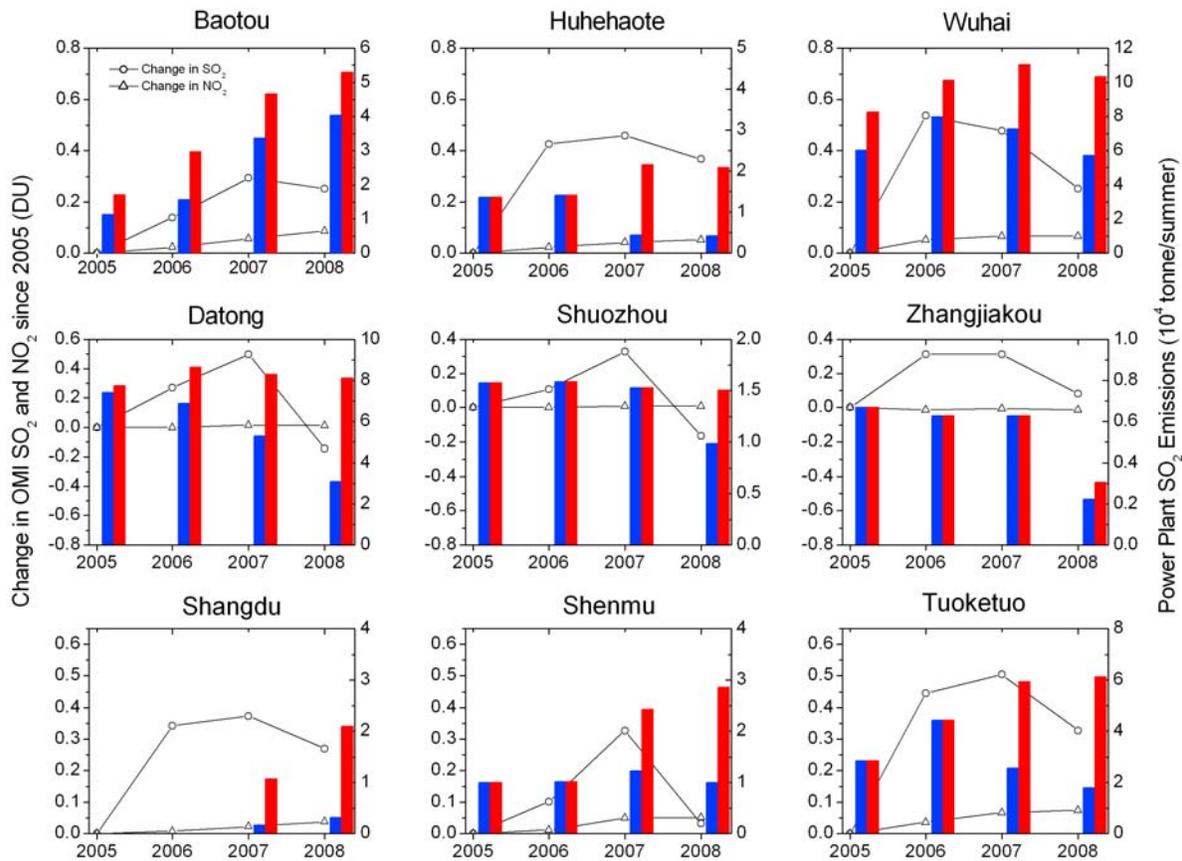


Figure 2. Circles, changes in summertime (JJA) average OMI PBL SO₂ column amounts since 2005 over the nine areas listed in Table 1; triangles, changes in the OMI tropospheric NO₂ column amounts for the same areas; blue bars, the estimated summertime (JJA) SO₂ emissions from the power plants in the same areas assuming full usage of FGD devices (Scenario 1); and red bars, the same as the blue bars but assuming no usage of FGD devices (Scenario 2).

PBL during summer [e.g., *Uno et al.*, 2007]. Also the SO₂ profile assumed in the AMF for the retrieval algorithm (cf. section 2) may result in an overestimate of the SO₂ VCD, due to the terrain height of Inner Mongolia and release height of power plant emissions. Additionally the SO₂/NO_x ratio likely would increase over time after emissions, as NO_x has a shorter chemical lifetime than SO₂. This however may not be a dominant factor for areas with strong sources, as no discernable difference in the OMI SO₂/NO₂ ratio was found between domains of $0.5^\circ \times 0.5^\circ$ and $1^\circ \times 1^\circ$ over the areas in Table 2. Nonetheless, the SO₂ control measures for power plants in this region were likely very limited until summer 2007, as suggested by the comparison here.

[12] Compared to 2007, much lower SO₂ was observed by OMI in summer 2008 over all three regions (Figure 1). The OMI NO₂ product, on the other hand, shows little difference

between the two years (plot not shown). The nine areas (Table 1), on average, see ~ 0.3 DU decrease in OMI SO₂, but less than 0.01 DU change in OMI NO₂. As a result, over areas where NO_x is mainly from power plants (Table 2), the OMI SO₂/NO₂ ratios are 17–84% lower in 2008 than in 2007. Regional reductions in NO₂, SO₂, and CO were also observed from space over the region around Beijing in summer 2008, during the Olympic Games, and have generally been attributed to stringent temporary emission reduction measures [*Witte et al.*, 2009]. Little change in OMI NO₂ over our studied power plants several hundred kilometers away from Beijing implies that the working load of these power plants probably remained about the same between 2007 and 2008. And the OMI-observed decreases in SO₂ in 2008 are likely the outcome of more widespread installation and operation of FGD units in these power plants.

Table 2. Ratio of Summer Average OMI PBL SO₂ to OMI Tropospheric NO₂ Over the Areas Where Power Plants Emitted > 60% of NO_x in 2007

	Baotou	Wuhai	Datong	Shuozhou	Shangdu	Shenmu	Tuoketuo
2007	4.0	6.8	4.5	4.9	1.6	3.0	3.6
2008	3.3	5.6	2.0	2.6	0.3	1.2	2.8
Relative % change 2007–2008	-17	-17	-56	-46	-84	-60	-23
Fraction of NO _x emissions by power plants in 2007	0.70	0.94	0.62	0.80	0.98	0.97	0.96

[13] The estimated SO₂ emissions from power plants given in Figure 2 are based on two scenarios: Scenario 1 (Figure 2, blue bars) assumes full operation of all the installed FGD units, while in Scenario 2 (Figure 2, red bars) no FGD devices are in use. For most of the nine areas, a combination of the two emission scenarios is required to match the estimated emissions with OMI observations. For example over Baotou, it is likely that there was very limited FGD usage during 2005–2007 (Scenario 2), and the decrease in OMI SO₂ during 2007–2008 was due to operation of FGD (Scenario 1). In Huhehaote the FGD was probably not in use in 2007, as suggested by the similar OMI SO₂ levels between 2006 and 2007; the decline in OMI SO₂ from 2007 to 2008 is likely caused by the start of FGD run. Sharp drops in OMI SO₂ over Wuhai, Datong, and Shuozhou also likely reflect the dramatic increase in FGD usage from 2007 to 2008. Zhangjiakou has relatively small power plant emissions. Part of the reduction in OMI SO₂ is probably attributable to the closure of small power plants in this area near Beijing during the Olympic Games. For rural areas (Shangdu, Shenmu, and Tuoketuo), the emissions may follow Scenario 2 (no FGD) more closely during 2005–2007, but are better represented by Scenario 1 in 2008. The new power plants in Shangdu and Shenmu may be in test run before officially coming into service in 2006, and their emissions during that period are not reflected in the estimates. Overall, the comparison between the OMI SO₂ trend and the two emission scenarios suggests a dramatic rise in the utilization of FGD devices from 2007 to 2008. A similar comparison for 0.5° × 0.5° grid cells encompassing the same nine locations yielded consistent results.

[14] It is necessary to discuss some other factors that may have led to the apparent drop in the OMI SO₂/NO₂ ratio during 2007–2008. One possibility is that change in meteorology between the two years might have a larger influence on SO₂ lifetime than on NO₂ lifetime. But the meteorological records from several stations in Inner Mongolia do not show any change (e.g., precipitation, wind, temperature) consistent across all the areas that would explain the reduction in OMI SO₂. The increase in OMI SO₂ from 2005 to 2007, despite the interannual meteorological variability, also suggests that the trend in emissions should be the more important factor. Another possibility is that change in clouds, aerosols, total column ozone, and surface albedo between 2007 and 2008 might have affected SO₂ retrievals more than NO₂ retrievals. However this does not appear to be the case in our study: the effects of clouds are likely small as we focus on mostly cloud-free conditions; OMI SO₂ retrieval is insensitive to surface albedo; the interannual variability in the OMI total column ozone is too small to explain the large decrease in SO₂; and similar to meteorology, MODIS aerosol optical depth does not demonstrate a consistent trend over all study areas.

[15] In conclusion, we show that the OMI satellite sensor can detect both SO₂ and NO₂ emissions from large point sources in northern China, where significant increases in both gases were observed from 2005 to 2007, over areas with newly established power plants. The OMI SO₂/NO₂ ratio is close to the estimated emission factors for coal-fired power plants based on a bottom-up approach. Between 2007 and 2008, OMI detected little change in NO₂ but dramatic decline in SO₂ over the same areas. While the almost constant NO₂ levels between the two years imply steady electricity generation from the power plants, the large reduction in SO₂ con-

firms the effectiveness of the FGD units, which likely became operational between 2007 and 2008. This study demonstrates that the OMI data are capable of verifying the effectiveness of China's SO₂ emission control measures on power plants. Further improvement in instruments and algorithms may make satellite sensors even more powerful tools in air quality evaluation and management.

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