SO$_2$ columns over China: Temporal and spatial variations using OMI and GOME-2 observations

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Abstract. Enhancements of SO$_2$ column amounts due to anthropogenic emission sources over China were shown in this paper by using OMI and GOME-2 observations. The temporal and spatial variations of SO$_2$ columns over China were analyzed for the time period 2005-2010. Beijing and Chongqing showed a high concentration in the SO$_2$ columns, attributable to the use of coal for power generation in China and the characteristic of terrain and meteorology. The reduction of SO$_2$ columns over Beijing and surrounding provinces in 2008 was observed by OMI, which confirms the effectiveness of strict controls on pollutant emissions and motor vehicle traffic before and during 2008 Olympic and Paralympic Games. The SO$_2$ columns over China from GOME-2 (0.2-0.5 DU) were lower than those from OMI (0.6-1 DU), but both showed a decrease in SO$_2$ columns over northern China since 2008 (except an increase in OMI SO$_2$ in 2010).

1. Introduction
As a pollution gas, sulfur dioxide(SO$_2$) has a significant impact on the urban environment and global climate. Satellite remote sensing technology has been widely used in quantitatively assessing volcanic SO$_2$ emissions since the N7-TOMS has the first sighting of El Chichón SO$_2$ in 1982$^{[1]}$. The launching of the Ozone Monitoring Instrument (OMI) $^{[2-3]}$ and Global Ozone Monitoring Experiment-2 (GOME-2)$^{[4-6]}$ sensors improved the detection accuracy for SO$_2$ columns.

The inversion algorithms for determining SO$_2$ vertical column density (VCD) in ultraviolet channels mainly include Differential Optical Absorption Spectroscopy (DOAS)$^{[7]}$, Linear Fit (LF) algorithm$^{[8]}$, and Band Residual Difference algorithm (BRD)$^{[9]}$. BRD and DOAS algorithms have been widely used to detect the anthropogenic low SO$_2$ emission$^{[10-13]}$. Enhancements of SO$_2$ columns due to anthropogenic emissions over China were shown in this paper by using OMI and GOME-2 observations.

2. Satellite observations
Jointly developed by the Netherlands and Finland, the OMI sensor aboard the NASA EOS/Aura platform was launched on 15 July 2004, which is in a sun-synchronous ascending polar orbit with 1:45 pm local equator crossing time. With high SO$_2$ detection sensitivity and daily global coverage, OMI
not only detects high SO$_2$ emissions of volcanic eruptions but also monitors anthropogenic SO$_2$ emissions$[3]$. Planetary Boundary Layer (PBL) SO$_2$ column, derived using the BRD algorithm, was used in this paper study regional emissions over China. OMI observations were affected by the row anomaly since 2008, and consequently affect the level 2 SO$_2$ product. Therefore, in this paper we use the level 3 SO$_2$ product (OMSO2e), which is averaged global gridded products and screened for bad data points from level 2 SO$_2$ product.

The GOME-2 on board of the MetOp-A satellite was launched into a sun synchronous polar orbit at 800 km altitude in October 2006, and crossed the equator at 09:30 local time. GOME-2 measures both the earth radiance reflected by the Earth’s atmosphere and the direct Sun light, covering the wavelength region of 240–790nm at moderate spectral resolution of 0.2–0.4 nm. With a pixel size of 80×40km$^2$ (240×40km$^2$ for the backscan), global coverage can be achieved within 1.5 days. However, the GOME-2 observations are affected by the optical degradation since 2009$[14]$. Degradation effects are mainly visible for BrO, SO$_2$ and HCHO, i.e. for the trace gases that are retrieved from spectral measurements in the UV wavelength region. Therefore, for correction of GOME-2 in-orbit instrument degradation, the retrieved SO$_2$ columns were subtracted by the background SO$_2$ columns from the ocean area (155-175°E, 20-40°N) in this study.

3. Results and discussions

3.1. OMI SO$_2$ over China

In this paper, we focus on six typical regions in China, region 1 (Xinjiang, Tibet, Qinghai), region 2 (Hebei, Shandong, Shanxi), region 3 (Pearl River Delta), region 4 (Sichuan, Chongqing), region 5 (Beijing) and region 6 (Anhui, Jiangsu, Shanghai, Zhejiang), as shown in Figure 1 (red line areas). By calculating the monthly and annual average of OMI Level 3 SO$_2$ PBL data, the temporal and spatial variations of SO$_2$ columns from October 2004 to December 2010 was analyzed.

Figure 1. Six typical regions over China (red line areas)

Figure 2 presents the monthly average OMI SO$_2$ PBL columns over the six regions, and figure 3 shows the annual average OMI SO$_2$ PBL columns from 2005 to 2010. As shown in Figure 2, the SO$_2$ column has a periodic change within a year, generally peaks in winter, and minimizes in summer. This is mainly a result of anthropogenic activities (like coal heating) in winter, and the temperature dependence of the rate constant for the SO$_2$ (g) to sulfate conversion. The average SO$_2$ conversion rate is 7.55% hr$^{-1}$ in winter, but 16.77% hr$^{-1}$ in summer$[15–17]$. Region 1 (Xinjiang, Tibet, Qinghai) has the lowest SO$_2$ columns. Northern and eastern China (Hebei, Shandong, Shanxi), which has the high population density and large area emissions, shows high SO$_2$ columns which increased from 2005 to 2007 and decreased since 2008 (Figure 3). Figure 3 also shows that the annual SO$_2$ columns over Beijing substantially decreased since 2006, which confirms the effectiveness of strict controls on pollutant emissions and motor vehicle traffic before and during 2008 Olympic and Paralympic Games.
Because of subtropical monsoon climate of Guangzhou, rainy season largely reduces SO$_2$ concentration in Pearl River Delta. Therefore, the annual mean SO$_2$ columns over Pearl River Delta are lower than those over region 2, 4, 5 and 6. Chongqing shows a high concentration in SO$_2$ columns, mainly attributable to the use of coal for power generation and the characteristic of terrain and meteorology.

In Figure 4, the spatial distributions of annual mean SO$_2$ columns over China from 2005 to 2010 are presented. As seen in Figure 4, the high SO$_2$ columns are generally in Hebei, Shanxi, Shandong, Chongqing, Guangzhou and Shanghai provinces. The Pearl River Delta had a low SO$_2$ column during the 2010, which was related with the linkage air quality guarantee measures before and during the 2010 Asian Games.

**Figure 2.** OMI SO$_2$ monthly average from October 2004 to December 2010

**Figure 3.** OMI SO$_2$ annual average from 2004 to 2010
3.2. **GOME-2 SO$_2$ over China**

GOME-2 is also widely used to monitor anthropogenic low SO$_2$ emission in the PBL layer, which has detrimental health and acidifying effects. SO$_2$ columns from GOME-2 have a similar spatio-temporal changes over the six regions with OMI (Figures 5, 6 and 7). Western China (Xinjiang, Tibet, Qinghai) has the lowest SO$_2$ columns, while northern and eastern China (Hebei, Shandong, Shanxi) has the highest. However, the values of SO$_2$ columns from GOME-2 are lower than those from OMI. The annual mean GOME-2 SO$_2$ columns over northern China are between 0.2-0.5 DU, while the corresponding OMI SO$_2$ columns are between 0.6-1 DU. In addition, the OMI observed that annual mean SO$_2$ columns of Beijing have a large increase in 2010, but annual mean GOME-2 SO$_2$ columns over Beijing decreased in 2010.

![Figure 4](image-url)  
**Figure 4.** Spatial distribution of annual mean OMI SO$_2$ columns over China. (a)2005; (b)2006; (c)2007; (d)2008; (e)2009; (f)2010.

![Figure 5](image-url)  
**Figure 5.** GOME-2 SO$_2$ monthly average from January 2007 to December 2010
4. Conclusions
In this paper, we present the SO$_2$ columns over China by using OMI and GOME-2 observations. Results show that Beijing and Chongqing had a high SO$_2$ columns, attributable to the use of coal for power generation in China and the characteristic of terrain and meteorology. The reduction of SO$_2$ columns over Beijing and surrounding provinces in 2008 was observed by OMI, which confirms the effectiveness of strict controls on pollutant emissions and motor vehicle traffic before and during 2008 Olympic and Paralympic Games. The Pearl River Delta had a low SO$_2$ column during the 2010, which was related with the linkage air quality guarantee measures before the 2010 Asian Games.
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