



Daily monitoring of Ecuadorian volcanic degassing from space

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ARTICLE INFO

Article history:

Received 1 December 2006

Accepted 31 January 2008

Available online 4 March 2008

Keywords:

OMI
sulfur dioxide
volcanic degassing
Ecuador

ABSTRACT

We present daily measurements of sulfur dioxide (SO₂) emissions from active volcanoes in Ecuador and southern Colombia between September 2004 and September 2006, derived from the Ozone Monitoring Instrument (OMI) on NASA's EOS/Aura satellite. OMI is an ultraviolet/visible spectrometer with an unprecedented combination of spatial and spectral resolution, and global coverage, that permits daily measurements of passive volcanic degassing from space. We use non-interactive processing methods to automatically extract daily SO₂ burdens and information on SO₂ sources from the OMI datastream. Maps of monthly average SO₂ vertical columns retrieved by OMI over Ecuador and S. Colombia are also used to illustrate variations in regional SO₂ loading and to pinpoint sources. The dense concentration of active volcanoes in Ecuador provides a stringent test of OMI's ability to distinguish SO₂ from multiple emitting sources. Our analysis reveals that Tungurahua, Reventador and Galeras were responsible for the bulk of the SO₂ emissions in the region in the timeframe of our study, with no significant SO₂ discharge detected from Sangay. At Galeras and Reventador, we conclude that OMI can detect variations in SO₂ release related to cycles of conduit sealing and degassing, which are a critical factor in hazard assessment. The OMI SO₂ data for Reventador are the most extensive sequence of degassing measurements available for this remote volcano, which dominated regional SO₂ production in June–August 2005. At Tungurahua, the OMI measurements span the waning stage of one eruptive cycle and the beginning of another, and we observe increasing SO₂ burdens in the months prior to explosive eruptions of the volcano in July and August 2006. Cumulative SO₂ loadings measured by OMI yield a total of ~1.16 Tg SO₂ emitted by volcanoes on mainland Ecuador/S. Colombia between September 2004 and September 2006; as much as 95% of this SO₂ may originate from non-eruptive degassing. Approximate apportionment of the total SO₂ loading indicates that ~40% originated from Tungurahua, with ~30% supplied by both Reventador and Galeras. These measurements of volcanic SO₂ degassing in Ecuador confirm OMI's potential as an effective, economical and risk-free tool for daily monitoring of SO₂ emissions from hazardous volcanoes.

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1. Introduction

Ecuador can claim to have experienced the most dramatic recent upsurge in volcanic unrest of any nation burdened by active volcanism. Little more than a decade saw significant eruptions from Guagua Pichincha in 1998–99 (Smithsonian Institution, 1999), the reactivation of Tungurahua in 1999 (Ruiz et al., 2006), one of Ecuador's largest historical eruptions at Reventador in 2002 (Hall et al., 2004), in addition to renewed activity at Galeras (Colombia), close to Ecuador's northern border, beginning in 1988 (Williams et al., 1990a). Several other Ecuadorian volcanoes are potentially active or require regular surveillance: Sangay has been continuously active since 1628 (Monzier et al., 1999), and little more than a century ago Cotopaxi was persistently active whilst Tungurahua was dormant (Whymper, 1892). This dense concentration of hazardous volcanoes presents challenges for ground-based monitoring

efforts, exacerbated by Ecuador's topography, which features several glaciated volcanic summits situated at altitudes of ~6 km.

Satellite remote sensing offers obvious attractions as a means of monitoring Ecuador's volcanoes, including a synoptic perspective unhindered by the sparse road network that constrains ground-based measurements. Progress has been made in measuring several of the classic indicators of volcanic unrest (e.g., gas emissions, deformation, thermal anomalies) from space with sufficient precision and temporal resolution to permit timely detection of perturbations in a volcanic system. Examples include near real-time thermal infrared (IR) imaging of volcanoes by IR sensors on geostationary and polar-orbiting satellites (e.g., Harris et al., 2000; Wright et al., 2004), and operational tracking of volcanic ash clouds for aviation hazard mitigation (e.g., Tupper et al., 2004). Until recently however, satellite measurements of volcanic sulfur dioxide (SO₂) emissions, a key yardstick at many restless volcanoes, were limited to large eruptions, with ground-based or airborne measurements fulfilling most routine SO₂ monitoring requirements. Furthermore, most space-based SO₂ measurements to date have been post-eruption, and hence of limited use

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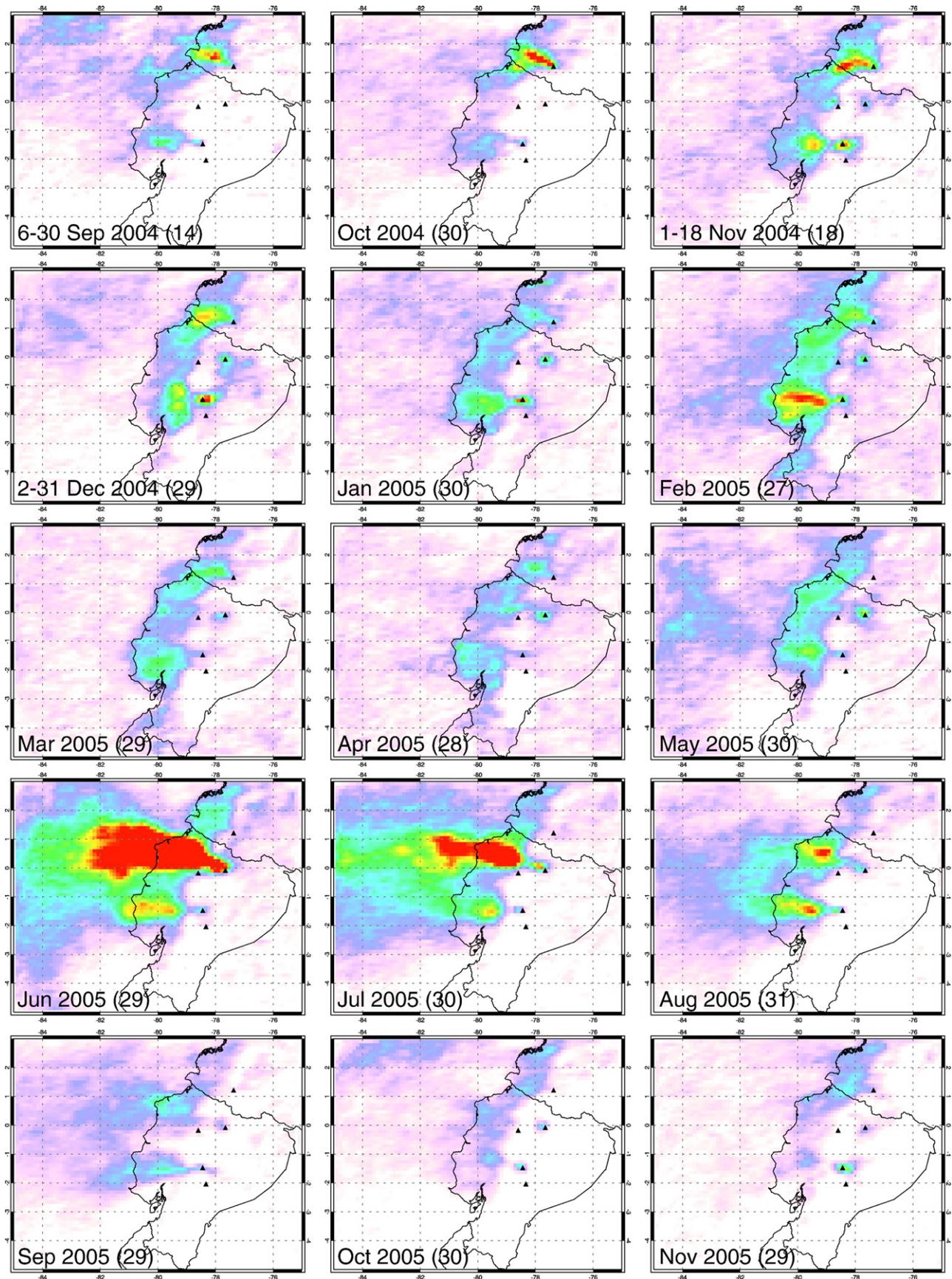


Fig. 1. Maps of monthly average SO₂ column amounts measured by OMI over Ecuador and S. Colombia, September 2004–September 2006. All maps use the same color scale. The volcanoes marked on the maps are, from north to south: Galeras, Reventador, Guagua Pichincha, Tungurahua and Sangay. Unless specified, date ranges (indicated on each map) span the entire month; the number of daily measurements used to calculate each average is given in parentheses after the date.

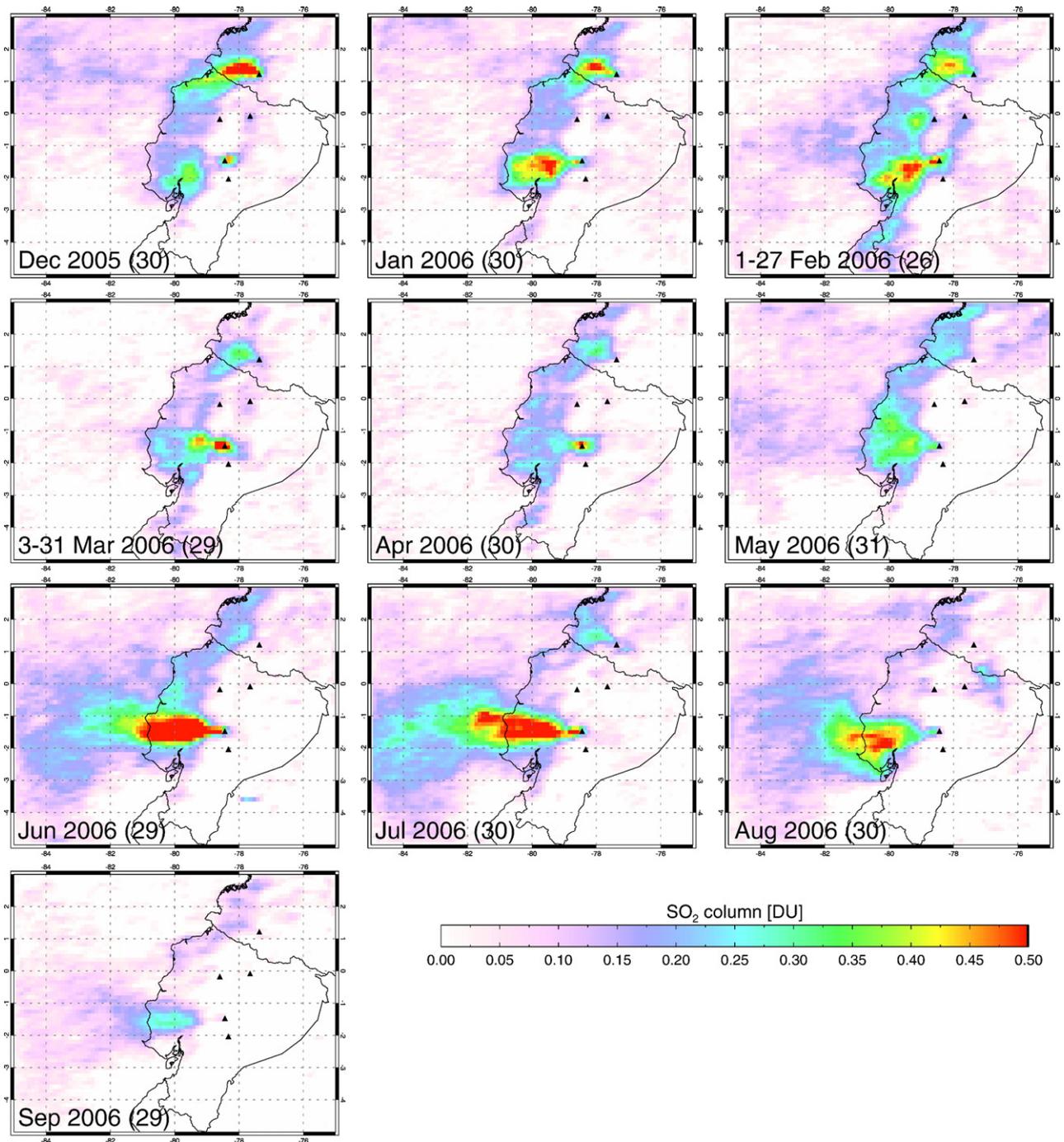


Fig. 1 (continued).

for volcanic hazard mitigation. Here we introduce a significant advance offered by the Ozone Monitoring Instrument (OMI), an ultraviolet/visible (UV/VIS) sensor launched in July 2004 on NASA's Earth Observing System (EOS) Aura satellite. OMI has an unprecedented combination of footprint size, spectral resolution and swath width that permits daily, contiguous global mapping of SO_2 at all altitudes from the planetary boundary layer (PBL) to the stratosphere. Due to these unique characteristics, OMI has achieved the first daily, space-based measurements of passive volcanic degassing.

The purpose of this paper is twofold. Using OMI SO_2 data collected over Ecuador and southern Colombia (Galeras volcano) from September 2004–September 2006, we demonstrate that valuable information on trends in, and sources of, volcanic SO_2 emissions can be extracted from largely automated processing of daily OMI data. Galeras is in-

cluded in the analysis as its SO_2 emissions frequently drift over northern Ecuador. We also derive an estimate of the total SO_2 burden in the volcanic emissions, with the main aim being determination of the ratio of passive (i.e., non-eruptive) to explosive degassing from the OMI measurements. Previous attempts to ascertain this ratio, which has ramifications for estimates of global volcanic SO_2 emission rates, for a period of volcanic activity have required concurrent ground-based and satellite data (e.g., Bluth et al., 1994).

2. Monitoring of volcanic SO_2 in the northern Andes

Volcanoes of the Andean Northern Volcanic Zone with reported degassing data are characterized by elevated sulfur emissions. Nevado del Ruiz (Colombia) released ~ 0.75 Tg of SO_2 during its 1985 eruption

(Volcanic Explosivity Index [VEI] 3; Krueger et al., 1990), and the similarity between this SO₂ yield and that of the much larger 1980 Mount St Helens eruption (VEI 5; 0.8 Tg SO₂) attests to its sulfur-rich nature. Ruiz subsequently sustained SO₂ fluxes of ~10³–10⁴ tons day⁻¹ (t d⁻¹) until at least the early 1990s (Williams et al., 1990b; Smithsonian Institution, 1991). Following reactivation in 1988, Galeras (Colombia) initially discharged 3000–5000 t d⁻¹ or more of SO₂, where after fluxes declined to ~300 t d⁻¹ by 1995 (Zapata et al., 1997). In Ecuador, Reventador's explosive eruption on 3 November 2002 produced ~0.1 Tg of SO₂, and in the ensuing ~4 weeks vigorous degassing, detected from space by the Total Ozone Mapping Spectrometer (TOMS), emitted a further ~0.22 Tg (Dalton, 2005; S.A. Carn, unpublished data). Tungurahua awoke in August 1999 following ~80 years of repose, and until early 2000 produced high SO₂ fluxes that occasionally exceeded 10⁴ t d⁻¹ (Arellano et al., 2008-this issue). Between 2001 and early 2005 the volcano exhibited four roughly year-long eruptive cycles, defined by Ruiz et al. (2006) on the basis of explosion frequency, which were characterized by fluctuating SO₂ emissions averaging ~1500 t d⁻¹ (Arellano et al., 2008-this issue). All of these volcanoes have released the vast majority of their volatiles via non-eruptive or passive degassing.

Most of the SO₂ data summarized above are derived from intermittent ground-based or airborne COSPEC or differential optical absorption spectroscopy (DOAS) measurements, with TOMS satellite data supplying total SO₂ estimates for the large Ruiz and Reventador eruptions, and a few of the larger explosions of Tungurahua (Carn et al., 2003). There is also an extensive TOMS database of SO₂ emissions from eruptions in the Ecuadorian territory of the Galápagos Islands from 1979–2005, which will be reported elsewhere (Head et al., manuscript in preparation). Neither TOMS nor other more sensitive satellite instruments such as the Global Ozone Monitoring Experiment (GOME) and the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), which have also measured volcanic SO₂ emissions over Ecuador (Afe et al., 2004; Khokhar et al., 2005), are capable of providing daily observations of tropospheric SO₂ plumes generated by passive degassing. At the time of writing the only Ecuadorian volcano subject to frequent ground-based gas monitoring is Tungurahua, which has a UV spectrometer network deployed on its flanks for static scanning measurements of SO₂ emissions (Arellano et al., 2008-this issue).

3. The Ozone Monitoring Instrument

OMI is a UV/VIS (270–500 nm) nadir solar backscatter spectrometer in polar orbit on Aura with a local afternoon equatorial overpass at 13:45 (Levelt et al., 2005a). The instrument provides daily, contiguous global mapping of ozone, SO₂ and other trace gases (NO₂, BrO, HCHO) with a nadir spatial resolution of 13×24 km (Levelt et al., 2005b). OMI's UV-2 channel (306–380 nm), which is used for SO₂ retrievals, has an average spectral resolution of 0.45 nm (Levelt et al., 2005a). The combination of full UV-2 coverage at high spectral resolution and small footprint size permits SO₂ retrievals with unprecedented sensitivity for a space-based instrument.

Several different retrieval schemes can be used to derive SO₂ column amounts from OMI radiances. Here, we use the Band Residual Difference (BRD) algorithm described by Krotkov et al. (2006). The BRD technique uses calibrated residuals at SO₂ absorption band centers in the 310–315 nm wavelength range, produced by the operational OMI ozone algorithm, to generate a total column SO₂ measurement. While not optimal, the BRD retrieval produces a two orders of magnitude improvement in the minimum detectable amount of SO₂ relative to TOMS (detection limits for a SO₂ cloud comprised of 5 adjacent pixels containing more than 5 noise standard deviations, are ~50 and ~7000 t for OMI and TOMS, respectively), permitting daily measurements of passive volcanic degassing (Krotkov et al., 2006; Carn et al., 2007). At the time of writing, OMI BRD SO₂ columns have not been validated, but

comparisons between SO₂ burdens derived from BRD retrievals, TOMS SO₂ data (which have been validated), and IR satellite SO₂ retrievals (e.g., Atmospheric Infrared Sounder [AIRS]) for several volcanic eruption clouds have shown agreement to within ~20% (S.A. Carn, unpublished data).

Accurate retrieval of vertical SO₂ columns requires knowledge of the SO₂ vertical profile, which governs the air mass factor (AMF) used to convert slant SO₂ columns (SC) to vertical columns (VC=SC/AMF). This information is seldom available at the time of measurement, so our initial approach for OMI SO₂ retrievals has been to generate three SO₂ column amounts for three generalized SO₂ profiles: SO₂ distributed evenly in the PBL (below ~3 km altitude AMSL), and SO₂ layers (Gaussian, with 1 km standard deviation) centered at 5 km and 15 km altitude AMSL. These cases are intended to represent typical SO₂ vertical distributions for low altitude volcanic degassing or anthropogenic pollution, volcanic degassing in the free troposphere, and high-altitude eruption clouds, respectively. Given the high elevation of the Ecuadorian and Colombian volcanoes (the mean altitude of Galeras, Reventador, Tungurahua and Sangay is ~4.5 km), we use the 5 km case in this analysis. Volcanic plumes will typically rise above vent altitude, but since the exact plume altitude is rarely known, this is a necessary assumption. Underestimating the altitude of the SO₂ will usually result in an overestimate of the SO₂ amount, and vice versa.

No attempt has been made here to account for the effects of aerosol (ash and sulfate) on UV SO₂ retrievals, which can be significant (Krotkov et al., 1997). This is a goal of future work, but for this analysis of predominantly non-eruptive, ash-poor plumes we assume that associated errors will be considerably less than the maximum 30% error on TOMS SO₂ retrievals of ash-laden explosive eruption clouds (Krueger et al., 1995). Krotkov et al. (2006) and Carn et al. (2007) discuss other potential sources of error in the OMI SO₂ measurements. Current information on OMI SO₂ algorithms and publicly released datasets is provided at <http://so2.umbc.edu/omi>.

4. OMI data analysis

Our OMI analysis software generates daily maps of SO₂ vertical column densities (VCDs) for any region of the globe, and can also calculate cumulative or average SO₂ maps for any time period (e.g., Fig. 1). The average maps in Fig. 1 show the geographic region selected for our analysis of Ecuador and S. Colombia. Readers interested in daily SO₂ maps, not presented here due to space limitations, are requested to contact the authors.

The main goal of this work is to extract volcanological data, such as SO₂ cloud mass and the likely source of observed SO₂ emissions, from the daily OMI observations with a minimum of analyst input or manual image analysis. Interactive, offline calculation of daily SO₂ cloud tonnages, the approach adopted with TOMS data, is impractical with OMI as the SO₂ cloud detection rate is much higher. We have therefore tested three techniques to derive SO₂ burdens non-interactively from subsets of OMI data over pre-defined regions i.e., to isolate the volcanic SO₂ signal from omnipresent background noise resulting from cumulative measurement, modeling, and calibration errors. These are briefly described below.

The Fixed Threshold (FT) method is the simplest burden derivation procedure, using only the volcanic region as input. A constant threshold SO₂ VCD (in Dobson Units [DU]) value (T) is assigned, and the reported SO₂ burden is the total SO₂ mass retrieved in all OMI pixels within the region that contain $\geq T$ DU of SO₂. For the analysis presented here, $T=0.6$ DU (equivalent to ~5–30 t of SO₂ depending on the location of the pixel in the OMI swath) was used in calculations using the FT method. This is approximately equal to noise at the 3 σ level observed in BRD volcanic SO₂ retrievals in SO₂-free regions (Krotkov et al., 2006).

The Normalized Cloud-mass (NC) technique requires selection of two (or more) nominally SO₂-free background regions with fixed

dimensions adjacent to the volcanic region (chosen so as to avoid other potential sources of SO₂). Total SO₂ burdens are calculated for each data subset, then the background SO₂ burdens are normalized to the area of the volcanic region, averaged, and the result is subtracted from the total SO₂ mass measured in the volcanic region. This is the approach used historically for derivation of SO₂ cloud tonnages from TOMS data (Krueger et al., 1995).

Finally, the Statistical Threshold (ST) method also utilizes two nominally SO₂-free, fixed background regions close to the selected volcanic region. Using the mean (\bar{x}_n) and standard deviation (σ_n) of SO₂ VCDs retrieved on each day in background region n , a threshold value (T) equal to $\frac{1}{2}((\bar{x}_1 + 3\sigma_1) + (\bar{x}_2 + 3\sigma_2))$ is calculated. The SO₂ burden reported for the volcanic region is then the total SO₂ mass retrieved in all OMI pixels enclosed by the region that contain $\geq T$ DU of SO₂.

The ST method intrinsically accounts for any daily variations in retrieval noise and/or bias, and is assumed to provide the most robust indication of whether SO₂ is present in statistically significant

amounts. However, this method probably underestimates the total mass of SO₂ present, since pixels containing low SO₂ amounts in the peripheral regions of volcanic clouds may be excluded from the mass calculation. In assessing total volcanic SO₂ emissions for this study, we therefore use the ST results to identify the existence of volcanic SO₂ in the scene, but take the largest corresponding SO₂ burden returned by any method (ST, FT or NC) as the total SO₂ amount present on that day.

We also attempt to identify the source of the strongest SO₂ emissions observed on each day (Fig. 2), exploiting OMI's good spatial resolution. The source is defined here as the closest active volcano to the center coordinates of the OMI pixel containing the maximum retrieved SO₂ VCD. Volcanoes located more than 50 km from the SO₂ maximum are excluded, based on the observation that the minimum distance separating the region's active volcanoes is ~100 km. Estimates of SO₂ advection during the ~24 h of transport between consecutive OMI overpasses yield distances that greatly exceed that

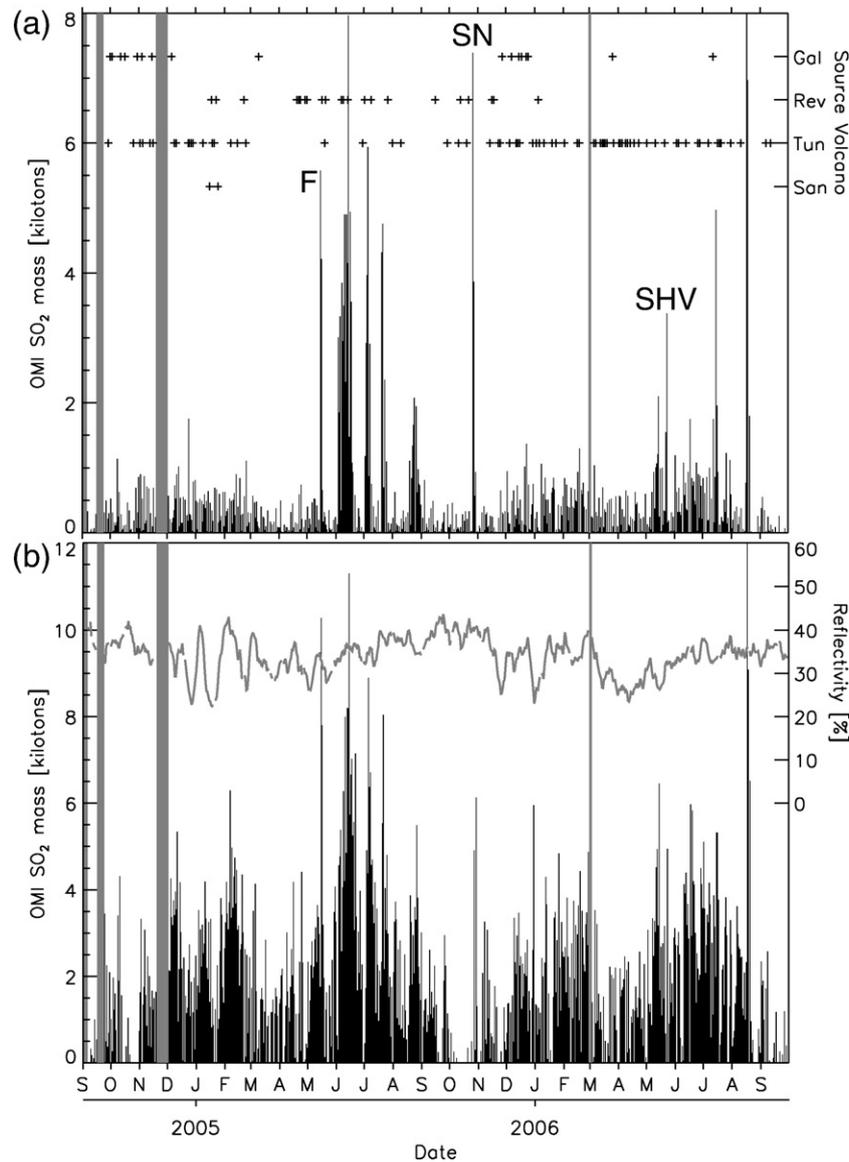


Fig. 2. Daily SO₂ burdens (kilotons; black bars) measured by OMI over Ecuador and S. Colombia, September 2004–September 2006. The geographic region used to derive burdens is represented by the maps in Fig. 1. OMI data gaps of >1 day are denoted by vertical gray bars. Note variable scale on the ordinate. (a) SO₂ burdens calculated using the FT method (see text for description of methods). Crosses show the results of automated identification of the source of the strongest SO₂ emissions on each day (Gal: Galeras; Rev: Reventador; Tun: Tungurahua; San: Sangay). SO₂ burdens over Ecuador impacted by three eruptions outside the region are indicated (F: Fernandina; SN: Sierra Negra; SHV: Soufriere Hills, Montserrat); (b) SO₂ burdens calculated using the NC method. The background regions used were: 5°–10°S, 75°–85°W (northern Peru) and 5°–10°N, 85°–95°W (E. Pacific Ocean). The gray curve shows average UV reflectivity at 331 nm for the volcanic region, smoothed using a 7-day moving average, which is provided as a proxy for the fraction of the scene that is cloud-covered (higher reflectivity implying greater cloud coverage). Note that SO₂ burdens calculated using the ST method are not shown here, but results are very similar to (a).

Table 1
Significant eruptions in Ecuador and the Galápagos Islands since September 2004

Volcano	Date	Duration ^a	Plume altitude (km) ^a	SO ₂ production (kt)
Fernandina	13 May 2005	3 days?	9	80
Sierra Negra	22 Oct 2005	8 days	>15 ^b	2000 ^c
Tungurahua	14 Jul 2006	1 day	15–16	12
Tungurahua	16 Aug 2006	7 hours	15–16	35

^a Data sources: Smithsonian Institution (2005a,f, 2006d).

^b Refers to the initial eruption column; most subsequent emissions were at ~3–5 km altitude.

^c Preliminary estimate using the procedure described by Krueger et al. (1996) to account for residual SO₂ during effusive eruptions.

between adjacent volcanoes, rendering the source ambiguous (e.g., typical wind speeds of 5–15 knots reported by the Washington Volcanic Ash Advisory Center [VAAC; <http://www.ssd.noaa.gov/VAAC/>] imply ~220–670 km of transport in 24 hours). Hence the source identification process used here is typically only valid for contiguous SO₂ plumes physically connected to a source characterized by a diurnally stable emission rate, and not for detached, drifting SO₂ clouds. For the same reasons, when two or more volcanoes are degassing simultaneously we do not attempt to allocate fractions of the total measured SO₂ burden to specific sources, although this can sometimes be done interactively and may also be possible non-interactively with more sophisticated image analysis techniques.

Most of the SO₂ detected by OMI over Ecuador and S. Colombia during the study period (6 September 2004–30 September 2006) was the product of non-eruptive degassing. However, two larger eruptions of Tungurahua in July and August 2006 discharged SO₂ clouds that extended beyond the limits of the geographic region shown in Fig. 1 and these were analyzed offline (Table 1). In addition, two of the largest eruptions in Ecuadorian territory during this period occurred at Fernandina and Sierra Negra (Galápagos Islands) in May and October 2005, respectively. Total SO₂ production for these eruptions, which emitted more SO₂ than any single eruption in mainland

Ecuador in 2004–2006, is given here for completeness (Table 1), but detailed analysis of these events will be reported elsewhere.

5. Results and discussion

Monthly average OMI SO₂ maps for Ecuador and S. Colombia are shown in Fig. 1. These depict relative levels of degassing at the region's volcanoes during each month. Time-series plots of OMI SO₂ burdens over the region generated using the FT and ST methods described above are shown in Fig. 2, in which the source volcano identified during data processing is also indicated. The source(s) of SO₂ emissions charted in Fig. 2 can also be deduced by cross-referencing with the appropriate map in Fig. 1. Note the spikes in SO₂ burden associated with drifting SO₂ clouds from eruptions of Fernandina, Sierra Negra and Soufriere Hills, Montserrat, when in transit over Ecuador (Fig. 2). The similar magnitude of SO₂ burdens calculated using the FT and ST methods (Figs. 2a, 3) indicates that our choice of 0.6 DU as a fixed noise threshold was reasonable in this case.

We stress that the SO₂ amounts measured by OMI and displayed in Fig. 2 are burdens and not fluxes. The entire region demarcated in Fig. 1 is sensed by OMI in ~2 min during a single orbit, and in these cases the SO₂ measured during an OMI overpass can be considered an 'instantaneous' SO₂ burden. The temporal information required to convert this to a flux (e.g., the duration of an emission event responsible for a known mass of SO₂) is usually lacking. If the region straddles two OMI orbits, then one orbital period (~90 min) elapses between measurements during the first, easternmost, orbit and the next, but even in these cases the same SO₂ cloud is never measured twice daily at equatorial latitudes. A rigorous analysis of the expected relationship between OMI-derived SO₂ burdens and coincident SO₂ flux measurements requires additional data (e.g., accurate plume altitudes, daily meteorological data, a model to simulate conversion of SO₂ to sulfate and wet/dry deposition in a tropospheric volcanic plume). However, based on several comparisons between OMI SO₂ data and contemporaneous SO₂ emission rates at other volcanoes (S.A. Carn, unpublished data), we believe that OMI-derived SO₂ burdens are a good proxy for SO₂ fluxes at the source, with optimal correspondence in

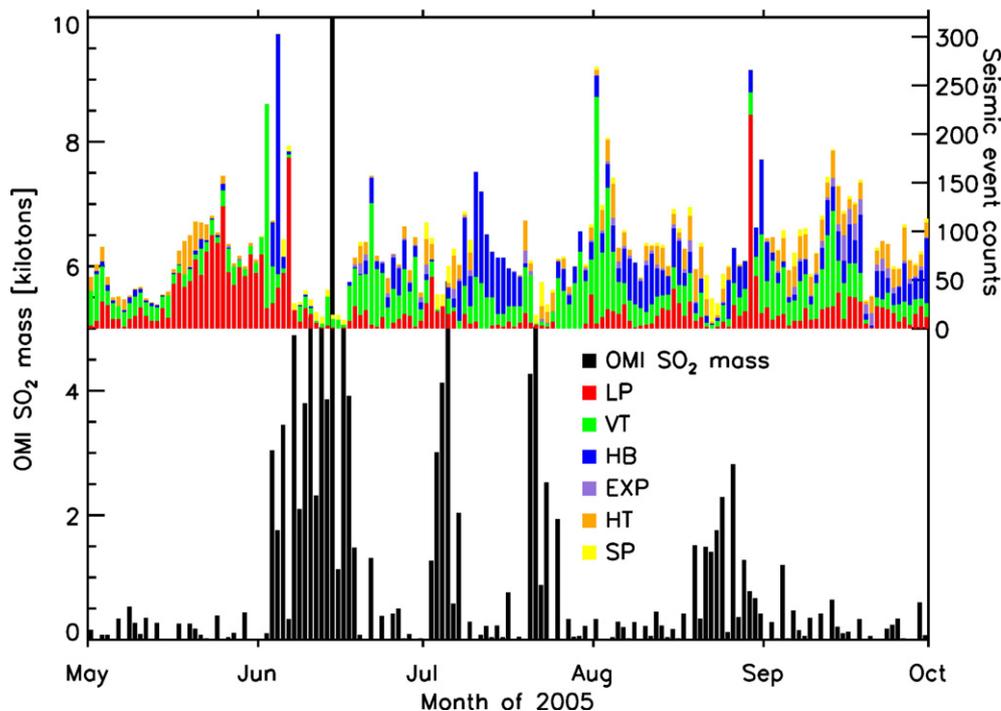


Fig. 3. OMI SO₂ burdens calculated using the ST method (lower panel) and seismic event counts for Reventador (upper panel; courtesy IG-EPN) for May–September 2005. Seismic events shown are long-period (LP), volcano-tectonic (VT), hybrid (HB), explosion signals (EXP), harmonic tremor (HT) and spasmodic tremor (SP).

magnitude expected for plumes above the PBL in cloud-free conditions where the SO₂ lifetime is close to 1 day.

In the following summary we discuss the patterns of SO₂ degassing revealed by the OMI measurements (Figs. 1, 2) separately for each of the four volcanoes responsible for the emissions: Galeras, Reventador, Tungurahua and Sangay. Clearly, our decision to attribute the observed SO₂ emissions to these volcanoes is influenced by external knowledge and is not solely based on the satellite data; for example, SO₂ originating from Galeras and Reventador was frequently observed over Guagua Pichincha, but in the absence of reports of substantive activity at this volcano we eliminated it from our list of potential sources. As with all volcanological data, the OMI SO₂ measurements are best interpreted in conjunction with other available monitoring parameters. However, we also emphasize that, with the exception of Tungurahua, all the volcanoes discussed below were monitored infrequently with ground-based COSPEC or DOAS in 2004–2006, and hence the OMI measurements provide new, and in some cases the only, constraints on SO₂ emissions.

5.1. Galeras

Activity at Galeras was relatively low from 1994 until June 2004, but increased in July–August 2004 when a series of explosive events occurred (Smithsonian Institution, 2005e). Based on seismic tremor, September through November 2004 saw continuous gas and ash emissions from Galeras (Smithsonian Institution, 2005e), and this is confirmed by clear SO₂ plume signals in corresponding OMI monthly averages (Fig. 1), and by its selection as the predominant SO₂ source at this time (Fig. 2). An explosive eruption of Galeras on 21 November 2004 coincided with an OMI data gap from 18 November–2 December (Fig. 2; note that such lengthy data gaps are highly unusual and only occurred early in the Aura mission due to instrument testing). OMI measurements indicate reduced degassing from late 2004 into 2005 (Fig. 1), consistent with available reports (Smithsonian Institution, 2005e). However, we reiterate that OMI provides the most extensive and consistent record of SO₂ emissions from Galeras in 2004–2006, as COSPEC and/or DOAS data were typically collected no more than once or twice a week (e.g., see reports of activity at Galeras, available from the Instituto Colombiano de Geología y Minería [INGEOMINAS] at <http://intranet.ingeo Minas.gov.co/pasto/>).

Long-period seismicity, indicative of pressurized fluid flow, triggered evacuations around Galeras in mid-November 2005, and a small explosive eruption occurred on 24 November (Smithsonian Institution, 2006a). Inspection of daily SO₂ maps reveals that OMI began measuring increased SO₂ emissions from Galeras on 25 November; this is also apparent from the source selection and a clear increase in SO₂ burdens over the region at this time (Fig. 2a), and is presumably linked to open-system degassing following the vent-clearing explosion on 24 November. Elevated SO₂ emissions continued through February 2006 (reported SO₂ fluxes ranged from 200–1500 t d⁻¹ in early 2006; Smithsonian Institution, 2006a), shown by high average SO₂ VCDs west of Galeras in this period (Fig. 1).

By April–May 2006, growth of a lava dome in Galeras' crater (Smithsonian Institution, 2006c) had evidently curbed the SO₂ emissions (Figs. 1, 2). Further evacuations and small explosive eruptions followed on 12 July (Smithsonian Institution, 2006c). Significantly, although OMI detected a small SO₂ cloud produced by the 12 July event (Galeras was picked as the strongest SO₂ source on that day; Fig. 2a), we observe no elevated SO₂ emissions from Galeras in the ensuing ~2 months (Fig. 1), in contrast to the period following the July–August 2004 and November 2005 eruptions. A preliminary inference is that either the source of the July 2006 explosions was shallower, perhaps triggered by crystallization of magma in the lava dome, and as such did not release volatiles from deeper in the system, or that the volatile reservoir at depth had been depleted by prior degassing.

In summary, we conclude that OMI measurements are able to track cycles of degassing and conduit sealing at Galeras. Monitoring cyclic degassing, sealing, pressurization (manifested by long-period seismicity) and explosive eruptions is a critical aspect of hazard assessment at the volcano (Stix et al., 1993; Fischer et al., 1994). Incorporating daily OMI SO₂ data into existing monitoring strategies would therefore provide some useful additional constraints on the status of the volcano and also on models of degassing and explosive eruptions at Galeras (e.g., Stix et al., 1993, 1997).

5.2. Reventador

Reventador is a remote, poorly monitored volcano and OMI measurements of its SO₂ emissions permit unique insights into its activity in 2004–2006. The initial appearance of a SO₂ signal at Reventador in November 2004 (Fig. 1) correlates with renewed lava effusion (the first since 2002) and a dramatic increase in seismicity in early November, followed by visual confirmation of significant degassing on November 10 (Smithsonian Institution, 2004). The subsequent ~6 months saw little significant detectable change in emissions (Fig. 1); inspection of daily OMI data shows sporadic SO₂ plumes from Reventador in this period, though given the volcano's location on the tropical eastern flank of the Cordillera Real it is possible that cloud cover (which would reduce the SO₂ VCD measured by OMI if located above the SO₂) and/or wet deposition of SO₂ masked more persistent degassing.

OMI detected a major increase in measurable SO₂ output from Reventador in June 2005 (Figs. 1, 2, 3), and four distinct phases of elevated emissions were evident before the end of August 2005 (3–16 June, 2–7 July, 20–25 July and 17–30 August; Figs. 2, 3). During this period, SO₂ plumes frequently extended large distances from Reventador out across the Pacific Ocean (a vapor/ash plume caused light ashfall in Quito on 8 June; Smithsonian Institution, 2005b), hence the volcano was seldom picked as the strongest SO₂ source (Fig. 2) since the locations of SO₂ VCD maxima exceeded the 50 km distance threshold. Strombolian fountaining was reported at Reventador on 11–12 June (Smithsonian Institution, 2005b), when SO₂ emissions were elevated (Figs. 2, 3), but this had been supplanted by Vulcanian activity during observations on 16–19 June (Smithsonian Institution, 2005b), when SO₂ discharge had declined (Figs. 2, 3). This is consistent with plugging of the conduit, reduced degassing, and increased explosive activity at the end of the 3–16 June phase of gas release. We surmise that before the resumption of significant SO₂ degassing on 2 July the conduit plug had been sufficiently weakened by explosive activity to permit higher gas fluxes, or that explosions had begun to tap deeper, more SO₂-rich magma. Similar processes may explain the subsequent SO₂ degassing cycles observed by OMI, since Strombolian and Vulcanian activity, the former generating voluminous gas plumes, was reported intermittently at Reventador in July and August 2005 (Smithsonian Institution, 2005d). Measured SO₂ emissions declined substantially in September 2005 (Fig. 1), although explosive activity continued (Smithsonian Institution, 2005d).

Hence, as at Galeras, OMI SO₂ measurements reveal cycles of degassing at Reventador that likely relate to periodic conduit sealing. We note that the SO₂ burdens measured by OMI in June–August 2005 (Fig. 2) exhibit a striking anti-correlation with contemporaneous seismic event counts (Fig. 3), with SO₂ emission peaks occurring during periods of relative seismic quiescence, particularly with respect to hybrid earthquakes. This unique observation, impossible without the OMI measurements, suggests that seismic events indicative of pressurization were less frequent when SO₂ emissions were elevated, as might be expected for a volcano fluctuating between open- and closed-system degassing.

5.3. Tungurahua

Tungurahua produced the most persistent emissions in the region from September 2004–September 2006, evident from the high

incidence of source selection (Fig. 2a) and confirmed by inspection of daily OMI images. Tungurahua's gas emissions are typically the result of multiple small explosive, jetting and chugging events (Ruiz et al., 2006), which produce emissions that merge to form a continuous tropospheric gas plume. The beginning of our study period captured the latter half of Tungurahua's 2004–2005 eruptive cycle, which peaked in July 2004 and waned early in 2005 (Johnson et al., 2005; Ruiz et al., 2006). This waning cycle appears to be reflected in the OMI SO₂ measurements by a reduction in SO₂ burdens beginning in March 2005 (Fig. 2a). Low volcanic and seismic activity was reported at Tungurahua from February until mid-July 2005 (Smithsonian Institution, 2005c), although SO₂ emissions continued (Figs. 1, 2c), possibly supplied by low-energy degassing of remnant shallow magma (Arellano et al., 2008-this issue). Overall, 2005 was deemed the quietest year at Tungurahua since reactivation in 1999, prompting thoughts of a possible cessation of unrest (Smithsonian Institution, 2006d).

However, a new eruptive cycle was heralded by increased SO₂ output in December 2005 (Figs. 1, 2), coincident with seismic events that suggested a new injection of magma (Smithsonian Institution, 2006d; Arellano et al., 2008-this issue). A further escalation in seismic activity (long-period earthquake swarms and harmonic tremor) occurred in late March 2006, but without any significant detectable response in SO₂ emissions at the surface (Fig. 2), consistent with the deep location of seismic hypocenters (Smithsonian Institution, 2006d). OMI detected increased SO₂ discharge from Tungurahua beginning around 9 May (also evident in ground-based SO₂ flux data; Fig. 4), by which time hypocenter depths had shallowed and explosion signals had begun to dominate the seismic record (Smithsonian Institution, 2006d). Reduced SO₂ emissions were measured at the end of May, but they recovered to elevated levels in June and July (Figs. 1, 4), culminating in an explosive eruption on 14 July (Table 1). At the time this eruption was Tungurahua's largest of 1999–2006, but it was later surpassed in magnitude by the 16 August 2006 eruption (Fig. 2; Table 1). We observe generally increasing SO₂ burdens in the ~1.5 months prior to the 14 July event (Fig. 4). On 16 August, the OMI overpass at ~1930UT, ~4.5 hours before the eruption onset, revealed a significant SO₂ plume extending from Tungurahua, which may have marked the inception of activity that escalated into an eruption later that day. The paroxysmal SO₂ cloud (~35 kt; Table 1) was measured by OMI on the following day as it drifted away from Tungurahua.

We have made some preliminary comparisons between the OMI SO₂ data and SO₂ fluxes measured at Tungurahua (Fig. 4). Detailed intercomparison of the datasets would entail accounting for specific measurement conditions on each day, and is beyond the scope of this paper. We note that both techniques measured peaks in SO₂ emission in mid-May, early June and late July 2006 (Fig. 4), disregarding the peaks in OMI SO₂ burden corresponding to the explosive eruptions on 14 July and 16 August which were not measured from the ground. At other times, such as the period between the 14 July and 16 August eruptions when SO₂ fluxes were generally elevated, there is some disparity (Fig. 4). There are several possible reasons for this mismatch between ground-based and satellite measurements, including increased masking of the SO₂ plume by overlying clouds, higher wind speeds (leading to more rapid dispersion of SO₂ after emission), lower plume altitude (impacting the AMF used for OMI SO₂ retrievals), or a change in degassing style. For example, we might expect better agreement between the two datasets during continuous, steady-state degassing than during periods of pulsatory emissions. In the latter case the timing of the satellite overpass relative to emission pulses becomes important, and biases in ground-based data are also possible if transient bursts of high SO₂ flux are captured by the measurements. In some respects the ground-based and satellite measurements are complementary, with ideal conditions for one technique less favorable for the other, hence OMI data analysis could enhance monitoring of Tungurahua's activity. Additional monitoring strategies are desirable as it has been shown that seismic and acoustic signals may not scale with eruption intensity at the volcano (Johnson et al., 2005).

5.4. Sangay

The value of daily OMI observations is perhaps most apparent in the case of Sangay, Ecuador's most remote and poorly monitored volcano, whose eruptions are a potential aviation hazard. Based on OMI measurements, SO₂ emissions from Sangay appeared negligible in 2004–2006. Although it is difficult to unambiguously distinguish between Tungurahua and Sangay as the origin of drifting SO₂ clouds in southern Ecuador, we assume that Tungurahua would be the more likely source. Sangay was selected as the source of observed SO₂ emissions on only 2 days: 16 and 25 January 2005, but we have no correlative observations to verify this activity since there is currently no ground-based SO₂ monitoring at this remote volcano. Ash clouds

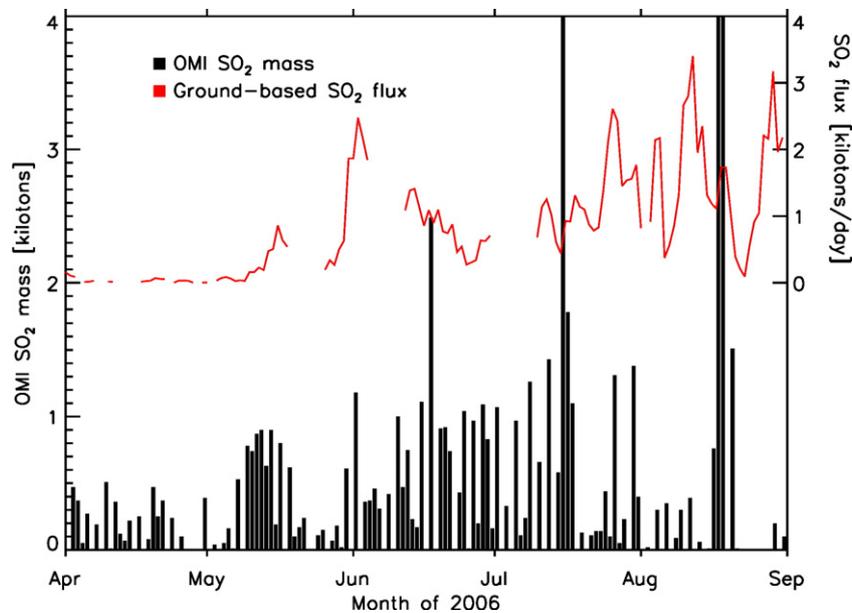


Fig. 4. Preliminary comparison between OMI SO₂ burdens calculated using the ST method and SO₂ fluxes measured at Tungurahua using ground-based DOAS (Arellano et al., 2008-this issue) for April–August 2006. The DOAS data have been smoothed using a 3-day moving average.

and IR hot spots were detected at Sangay by the Washington VAAC in December 2004 and October 2005 (<http://www.ssd.noaa.gov/VAAC/messages.html>), so it is apparent that the frequent explosive activity noted by observers of the volcano for centuries (Smithsonian Institution, 1996; Monzier et al., 1999) continues, but the activity may be predominantly phreatic, producing little SO₂. Furthermore, reports suggest that explosions have become smaller and less frequent since the 1970s, and only weak steaming was observed at the summit in January 2006 (Smithsonian Institution, 2006b). The detection of short-lived, intermittent explosive eruption clouds by polar-orbiting satellites depends strongly on the timing of the eruption relative to the satellite overpass, but we believe that frequent monitoring with OMI would identify any significant future increase in SO₂ emissions from Sangay.

6. Total SO₂ burdens in 2004–2006

Using the technique described in section 4, we calculate a cumulative SO₂ loading of ~1.16 Tg measured by OMI over Ecuador and S. Colombia between September 2004 and September 2006. This includes the Tungurahua eruptions listed in Table 1, but excludes SO₂ associated with drifting SO₂ clouds from distant volcanoes (Fig. 2). Including the very productive Galápagos eruptions (Table 1) raises the total SO₂ loading to ~3.24 Tg. Several factors are unaccounted for in this analysis: meteorological cloud located above the SO₂ (which would reduce the SO₂ VCD measured by OMI; average scene reflectivity is provided in Fig. 2b as a proxy for cloud cover), aerosol effects (assumed to introduce errors of <<30%) and AMF changes due to variable SO₂ altitude. The latter are the subject to ongoing modeling efforts but accurate assessment is precluded in this case by inadequate knowledge of actual SO₂ plume altitudes. To demonstrate the effect (which is non-linear with altitude), modeling of a mid-latitude case indicates that lowering the assumed SO₂ altitude from 5 to 3 km reduces the AMF, and increases the retrieved SO₂ VCD, by ~50%.

Using average SO₂ VCDs measured by OMI over the entire study period (not shown), we can roughly apportion percentages of the total SO₂ loading (excluding the Galápagos eruptions) to the three volcanoes responsible for the bulk of the emissions (Sangay is excluded). This entails subjectively pairing regions of elevated SO₂ VCDs with source volcanoes, and hence is imprecise, but the highly stable easterly wind pattern over Ecuador (Fig. 1) favors this approach. The apportionment indicates that 42% of the total SO₂ loading originated from Tungurahua, with 32% from Reventador and 26% from Galeras. Since the SO₂ yield from major explosive eruptions is known (the two Tungurahua eruptions in 2006; Table 1), we estimate that as much as 95% or more of the total SO₂ loading was produced by non-eruptive degassing, although whether large fractions of emissions from Reventador and Tungurahua qualify as passive is arguable. We note that this result concurs with earlier work by Berresheim and Jaeschke (1983), who concluded that ~90% of global volcanic SO₂ emissions originated from passive degassing. As stated earlier, further work is needed to decipher the relationship between OMI-derived instantaneous SO₂ burdens and SO₂ emission rates.

7. Summary

We have demonstrated that daily OMI SO₂ measurements are able to detect important trends in degassing, such as cycles of conduit sealing and open-vent discharge, at hazardous volcanoes in Ecuador and S. Colombia. These data are freely available and therefore constitute an economical and effective new resource for risk-free volcano monitoring in such regions. Our data processing techniques permit automated calculation of daily SO₂ burdens, and the spatial resolution of OMI permits identification of the major SO₂ source when appropriate geometric constraints are applied. The dense concentration of active volcanoes in Ecuador provides a stringent test of these

procedures. Future priorities are to validate the OMI SO₂ columns, and to establish the relationship between OMI-derived SO₂ burdens and SO₂ emission rates at the source, in order to construct baseline degassing databases for volcanoes with minimal ground-based monitoring. We also hope to develop image processing methods to extract SO₂ burdens for discrete clouds, and integrate improved cloud, AMF and aerosol corrections into the measurements.

The daily OMI SO₂ measurements are a rich data source, which we have not attempted to interpret in great detail here. Clearly, the measurements are best interpreted in concert with other parameters. In addition to ground-based gas measurements and seismic data, we speculate that fusion of other satellite data (e.g., thermal IR; Harris et al., 2000; Wright et al., 2004) with the OMI measurements might be particularly fruitful.

Acknowledgements

We acknowledge NASA funding of OMI SO₂ product development and analysis (award nos. NNS06AA05G, NNG06GJ02G, and NNG06GI00G). Liliana Troncoso (IG-EPN, Quito) contributed the Reventador seismic data, and G. Bluth and T. Fischer provided meticulous reviews that significantly improved the paper. Data used in this paper were produced by NASA in collaboration with the Royal Dutch Meteorological Institute (KNMI) in the Netherlands. The OMI project is managed by the Netherlands Agency for Aerospace Programs (NIVR) and KNMI.

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