Comparing satellite and ground-based observations of paroxysmal degassing events at Etna volcano, Italy

Céline L. Mandon
Michigan Technological University

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COMPARING SATELLITE AND GROUND-BASED OBSERVATIONS OF PAROXYSMAL DEGASSING EVENTS AT ETNA VOLCANO, ITALY

By

Céline L. Mandon

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

(Geology)

MICHIGAN TECHNOLOGICAL UNIVERSITY

2012

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This thesis, “Comparing Satellite and Ground-based Observations of Paroxysmal Degassing Events at Etna Volcano, Italy,” is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN GEOLOGY.

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Date
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Abstract

Mount Etna, Italy, is one of the most active volcanoes in the world, and is also regarded as one of the strongest volcanic sources of sulfur dioxide ($SO_2$) emissions to the atmosphere. Since October 2004, an automated ultraviolet (UV) spectrometer network (FLAME) has provided ground-based $SO_2$ measurements with high temporal resolution, providing an opportunity to validate satellite $SO_2$ measurements at Etna. The Ozone Monitoring Instrument (OMI) on the NASA Aura satellite, which makes global daily measurements of trace gases in the atmosphere, was used to compare $SO_2$ amount released by the volcano during paroxysmal lava-fountaining events from 2004 to present. We present the first comparison between $SO_2$ emission rates and $SO_2$ burdens obtained by the OMI transect technique and OMI Normalized Cloud-Mass (NCM) technique and the ground-based FLAME Mini-DOAS measurements. In spite of a good data set from the FLAME network, finding coincident OMI and FLAME measurements proved challenging and only one paroxysmal event provided a good validation for OMI. Another goal of this work was to assess the efficacy of the FLAME network in capturing paroxysmal $SO_2$ emissions from Etna, given that the FLAME network is only operational during daylight hours and some paroxysms occur at night. OMI measurements are advantageous since $SO_2$ emissions from nighttime paroxysms can often be quantified on the following day, providing improved constraints on Etna’s $SO_2$ budget.
1. Introduction

Sulfur dioxide (SO$_2$) is an atmospheric trace gas emitted by natural sources such as volcanic eruptions, oxidation of oceanic dimethyl sulphide (DMS) (Berresheim et al. 1995) and anthropogenic sources from the industry. It is dangerous for human health (Ware et al. 1986; Katsouyanni et al. 1997; Hansell and Oppenheimer 2004) and causes acid rain (Likens and Bormann 1974). The lifetime of SO$_2$ in the lower troposphere is approximately one day at this latitude, where after which it begins to be deposited or oxidized to sulfate (Stevenson et al. 2003). Sulfate aerosol, which has a long lifetime in the stratosphere, reflects incoming solar radiation, causing the cooling of the atmosphere below it (Charlson et al. 1992).

SO$_2$ is typically the third most abundant volcanic gas species after H$_2$O and CO$_2$, so the amount released into the atmosphere during an eruption can be significant and have impacts on climate and environment on both local and regional scales. Monitoring volcanic SO$_2$ is also very important for volcanologists as it reflects the activity of a volcano. Indeed, changes in SO$_2$ emission rates show variations within volcanic systems, and such changes can be precursors of an eruption (Casadevall et al. 1981; Caltabiano et al. 1994; Young et al. 1998; Watson et al. 2000; Sutton et al. 2001).

Ash emissions are often coupled with gas emissions during an eruption, which means that ash might be also emitted in the atmosphere. Ash particles, coupled with sulfate aerosol, are known to be a significant hazard to aviation, as the 2010 Eyjafjallajökull eruption demonstrated, and remote sensing of SO$_2$ provides an effective means of tracking drifting volcanic clouds.

Remote sensing of atmospheric SO$_2$ is possible due to the low background concentration of the specie in the atmosphere and its strong absorption features in the ultraviolet (UV) region of the electromagnetic spectrum. The first satellite sensor used to measured volcanic SO$_2$ emissions was the Total Ozone Mapping Spectrometer (TOMS),
after the observation of the 1982 El Chichon eruption cloud (Krueger 1983). Technology has been recently improved, leading to satellites with better spectral and spatial resolutions, such as the Global Ozone Monitoring Equipment (GOME and GOME-2) and the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY).

The spatial and temporal resolutions of the Ozone Monitoring Instrument (OMI) are the best currently available for space-based measurement of volcanic SO$_2$ emissions in the UV. OMI is a UV/visible sensor launched in July 2004 on the Earth Observing System Aura satellite by NASA. Validation of its trace gas measurements is critical to ensure high-quality SO$_2$ data. Validation of SO$_2$ measurements in volcanic clouds is more difficult than for anthropogenic sources, mostly because volcanic eruptions are unpredictable and plume trajectories can be uncertain, and also because of the heterogeneity within the cloud itself. Although some successful validation has been achieved, (Spinei et al. 2010; Carn and Lopez 2011a), ongoing validation is still required, especially for volcanoes with different eruptive styles.

Validation efforts typically require comparison of satellite data and ground-based remote measurements, derived from instruments such as the correlation spectrometer (COSPEC), used for volcanic SO$_2$ fluxes measurement since the early 1970s (Newcomb and Millán 1970; Moffat and Millán 1971; Stoiber and Jepsen 1973) or more recently Differential Optical Absorption Spectroscopy (DOAS) SO$_2$ measurements (Noxon 1975; Platt 1994; Platt and Stutz 2008). Because of the unpredictable and hazardous character of volcanic eruptions, ground-based measurements are not always easy. Furthermore, scientists have to be ready to quickly deploy the equipment in places that may not be easily accessible.

Mount Etna, Italy, is known for its globally significant SO$_2$ release into the atmosphere (Caltabiano et al. 1994; Allard 1997). As well as continuous passive degassing, explosive eruptions generate plumes with a high content of SO$_2$. A scanning UV spectrometer network, FLAME (FLux Automatic MEasurements),
permits automatic measurement of SO$_2$ fluxes with high time resolution (~6 min), with data available since October 2004 (Burton et al. 2004; Salerno et al. 2009a).

The aim of this study is to compare OMI SO$_2$ data with ground-based data from the FLAME network for some paroxysmal events of Mount Etna, and to improve constraints on Etna’s SO$_2$ emissions by quantification of paroxysmal SO$_2$ discharge.
2. Geological settings

Mount Etna, located on the eastern coast of Sicily (Italy), is a composite stratovolcano 3330 m-high and 0.5 Ma old (Gillot et al. 1994; Corsaro and Cristofolini 1997; Schiano et al. 2001). It is only 30 kilometers from Catania, the second biggest city in Sicily and although the activity is rarely explosive, particle and ash emissions in the atmosphere regularly lead to the closure of the International Airport Fontanarossa.

2.1 Tectonic and Geology

Mount Etna is surrounded by three different geological units: 1) The Calabro-Peloritan unit to the east, which is part of the Alpine-Appenninic orogenic belt; 2) the northern part of the African plate to the south, called the Hyblean Plateau; 3) and to the west, the Appennine-Maghrebian chain. A major fault trending SSE-NNW, the Tindari-Letojanni-Malta fault, crosses this area (Figure 2.1). This is the most likely source for the strongest earthquakes in the area, while the NE-SW fault system in the Hyblean Plateau is active, but with events with weaker magnitudes (Azzaro R. and Barbano M.S. 2000).
2.2 Volcanic activity

Mount Etna is the most active volcano in Europe and one of the world’s strongest sources of SO$_2$ emissions (Caltabiano et al. 1994; Allard 1997) derived from continuous degassing of volatile-rich alkaline basalts (Métrich and Clocchiatti 1989; Métrich 1993) at the summit craters: Voragine, Bocca Nuova, South-East and North-East (Figure 2.2). The activity is mainly effusive, with paroxysmal events characterized by strong strombolian explosions that can evolve into pulsating or continuous lava-fountains. However, some sub-plinian and plinian eruptions have been identified in Etna’s historic record (Guest et al. 1984; Chester et al. 1987; Coltelli et al. 1995, 1998).
Some of the paroxysmal events that occurred in the last twelve years were studied in order to have a better knowledge of the mechanisms that drive basaltic lava-fountain episodes. There are two physical models to explain this type of activity: 1) the Collapsing Foam (CF) model (Jaupart and Vergniolle 1988, 1989; Vergniolle and Jaupart 1990) that implies the collapse of a foam layer at the top of a shallow magma chamber which causes bubble coalescence and an annular flow that ascend the conduit and feed the lava fountain (previous gas-magma separation); 2) the Rise Speed Dependent (RSD) model (Parfitt 2004) that implies increase of the magma ascent rate, rapid exsolution of volatiles and bubble coalescence during the magma ascent in the conduit (syneruptive degassing).

The 2000 southeast crater lava fountains were the most studied and all the results agree for the foam collapse model with the top of the shallow magma reservoir at 1.5-1.8 km (Allard et al. 2005; Spilliaert et al. 2006; Andronico and Corsaro 2011). More recently, some other lava-fountain events have been explained by this model: the 10 May 2008 eruption (Bonaccorso et al. 2011a), the 11-13 January 2011 eruption, (Calvari et al. 2011), and the 10 April 2011 eruption (Bonaccorso et al. 2011b).

The average flux of \( \text{SO}_2 \) supplied by passive degassing varies with time depending on the type of activity: 4000-5500 tons per day from 1975 to 1999 (Allard 1997; Bruno et al. 2001), around 1000 tons per day in 2002 (McGonigle et al. 2003) and around 3500 tons per day during the period 2005-2008 (Salerno et al. 2009b). The \( \text{SO}_2 \) flux can reach 10000-15000 tons per day during vigorous strombolian activity and more than 20000 tons per day during continuous lava fountaining (Allard 1997).
The cavity on the east flank of the SEC is the New South-East Crater, formed since the beginning of the 2011 activity. Courtesy of Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Italy.

The origin of the volcanism in this area is still not well understood, mostly because it is located near the subduction of the African plate under the European plate and also above the mantle-plume beneath Sicily. Different theories exist: 1) volcanism related to a backarc marginal basin (Barberi et al. 1974); 2) the rollback motion of the Ionian slab associated with decompression melting of upper mantle material (Gvirtzman and Nur 1999); 3) the rise of a mantle plume from the 670 km discontinuity (Marone et al. 2004; Montelli et al. 2006; Cadoux et al. 2007) or 4) from the deep mantle (Schiano et al. 2001). However, geochemical studies of magma show evidences of a transition from a predominant mantle-plume source to subduction related basalts (Tanguy et al. 1997; Gvirtzman and Nur 1999; Schiano et al. 2001,
Clocchiatti et al. 2004) probably due to the southward migration of the Ionian slab leading to the juxtaposition with the mantle plume beneath Sicily (Schiano et al. 2001). Because the activity of a subduction related volcano can be more explosive than one in a hotspot setting, monitoring and study of Mount Etna’s activity is crucial.

2.3 Eruptive history

Mount Etna started to form around 0.5 Ma. Some lahar and tephra deposits give evidence of explosive activity at different periods throughout the volcano’s history. The oldest is a tephra deposit estimated to be 150-100 ka old (Condomines et al. 1982; Coltelli et al. 2000) followed by evidence of plinian, sub-plinian and strombolian activity until the 15 ka Ellittico caldera formation (Kieffer 1973, 1985; Duncan 1976; Romano and Guest 1979; Guest et al. 1984; Chester et al. 1987; Coltelli 1994, 2000). Some strong eruptions occurred in historic time, including the 122 BC plinian eruption (Coltelli et al. 1998) and the 1669 eruption which killed 15 000 people (Corsaro et al. 1996; Ciuccarelli 2001, 2004; Branca and Del Carlo 2004).

Mount Etna exhibited low activity after the 2001 and 2002-2003 eruptions until 2006. Table 2.1 is a summary of all the paroxysmal events from 2004 to present.

Some big eruptions occurred in 2007 and 2008 after which the activity calmed down. January 2011 was the beginning of a new eruptive cycle, which is still going on. This new eruptive cycle began with the January 12th eruption. Twenty-five paroxysms had occurred since that time, with the last one on April 24th, 2012. The episodes lasted from ~1h30 to ~14h30 and were separated by quiescent intervals ranging from 5 days to 58 days. The paroxysms are characterized by strong strombolian activity and lava fountains.
Table 2.1

Paroxysmal events at Mount Etna from 2004 to present. SEC: South-East crater. Sources: Istituto Nazionale di Geofisica e Vulcanologia (http://www.ct.ingv.it/), Smithsonian and USGS (http://www.volcano.si.edu/world/volcano.cfm?vnum=0101-06=&volpage=weekly). The SO$_2$ mass emitted was estimated using the Normalized Cloud-Mass technique from the OMIplot software.

<table>
<thead>
<tr>
<th>Date</th>
<th>Onset time</th>
<th>Duration</th>
<th>Area of activity</th>
<th>Description of activity</th>
<th>Lava flow length</th>
<th>Plume height &amp; Ash erupted</th>
<th>SO$_2$ mass emitted (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/09/04</td>
<td>10:30</td>
<td>1 day</td>
<td>Radial fissure eruption Base of SEC</td>
<td>Effusive eruption</td>
<td>2.5 km</td>
<td>4 * 10$^7$ m$^3$</td>
<td></td>
</tr>
<tr>
<td>16/12/05</td>
<td></td>
<td></td>
<td>Central vent eruption Bocca Nuova</td>
<td>Explosive eruption strombolian activity, ash plume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22/12/05</td>
<td></td>
<td></td>
<td>Central vent eruption Bocca Nuova</td>
<td>Explosive eruption strombolian activity, ash plume drifted E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Eruption 14/07 to 14/12/06</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total volume produced : 1.8 ± 0.3 * 10$^7$ m$^3$</td>
</tr>
<tr>
<td>14/07/06</td>
<td>23:30</td>
<td>10 days</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, small ash falls, lava flow</td>
<td>3 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31/08/06</td>
<td></td>
<td>16 days</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava flows, lapilli and bombs, ash plume on 10/09</td>
<td>3 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22/09/06</td>
<td>afternoon</td>
<td>5 days</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava flows</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03/10/06</td>
<td>Late afternoon</td>
<td>3 days</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava flows</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/10/06</td>
<td>Evening</td>
<td>1 day</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava flows</td>
<td>2 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Onset time</td>
<td>Duration</td>
<td>Area of activity</td>
<td>Description of activity</td>
<td>Lava flow length</td>
<td>Plume height &amp; Ash erupted</td>
<td>SO2 mass emitted (t)</td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>----------</td>
<td>------------------</td>
<td>--------------------------------------------------------------</td>
<td>------------------</td>
<td>---------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>20/10/06</td>
<td>06:00</td>
<td>~ 14 hours</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava flows</td>
<td>&lt; 1 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23/10/06</td>
<td>07:00</td>
<td>10h50</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, pulsating lava fountain, ash plume at 17:00 drifted ESE</td>
<td>2.5 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>05/11/06</td>
<td>20:04</td>
<td>~ 9 hours</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava flows, ash plume</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>16/11/06</td>
<td>05:07</td>
<td>10h30</td>
<td>Central vent eruption SEC Radial fissure eruption SSE and SE flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flow, ash plume drifted ENE then NE, rock falls and avalanches</td>
<td>3 km</td>
<td>4 km 7*10^6 kg</td>
<td>1450</td>
</tr>
<tr>
<td>21/11/06</td>
<td>12:00</td>
<td>9h</td>
<td>Central vent eruption SEC Radial fissure eruption SSE and SE flank of SEC</td>
<td>Explosive eruption strombolian activity, lava fountain 300m high at 19:00, ash plume at 15:00, lava flow</td>
<td>4.8 km 10^6 kg</td>
<td>7810</td>
<td></td>
</tr>
<tr>
<td>24/11/06</td>
<td>02:19</td>
<td>13h10</td>
<td>Central vent eruption SEC Radial fissure eruption SSE flank of SEC</td>
<td>Explosive eruption strombolian activity, ash plume drifted SE, lava flows</td>
<td>5.3 km 10^6 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30/11/06</td>
<td>16:00</td>
<td>7h</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava fountain, ash plume, lava flow</td>
<td>4.7 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11/04/07</td>
<td>03:00</td>
<td>5h</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava fountain, ash plume drifted E, 2 lava flows</td>
<td>3 km and &lt; 1 km</td>
<td>5 km</td>
<td>5480</td>
</tr>
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</table>
Table 2.1, continued

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<thead>
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<th>Date</th>
<th>Onset time</th>
<th>Duration</th>
<th>Area of activity</th>
<th>Description of activity</th>
<th>Lava flow length</th>
<th>Plume height &amp; Ash erupted</th>
<th>SO2 mass emitted (t)</th>
</tr>
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<tr>
<td>29/04/07</td>
<td>15:00</td>
<td>9h</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, lava fountain, ash plume, lava flows</td>
<td>6 km</td>
<td></td>
<td>3860</td>
</tr>
<tr>
<td>04/09/07</td>
<td>16:00</td>
<td>13h</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, continuous lava fountain 400-600m high, lava flows, ash plume drifted E</td>
<td>4.6 km</td>
<td>4.2 km 3.9-4.9*10^5 m^3</td>
<td>12120</td>
</tr>
<tr>
<td>23/11/07</td>
<td>20:20</td>
<td>8h</td>
<td>Central vent eruption SEC and Bocca Nuova</td>
<td>Explosive eruption strombolian activity, continuous lava fountain 600m high, lava flows, ash plume drifted NE</td>
<td>4.2 km</td>
<td>6.5 km</td>
<td>14730</td>
</tr>
<tr>
<td>10/05/08</td>
<td>14:00</td>
<td>4h</td>
<td>Central vent eruption SEC</td>
<td>Explosive eruption strombolian activity, ash plume drifted N, lava flows</td>
<td>6.4 km 4.5*10^6 m^3</td>
<td>6.4 km</td>
<td>18300</td>
</tr>
<tr>
<td>13/05/08</td>
<td>11:15</td>
<td>6h45</td>
<td>Radial fissure eruption E base of NEC, E flank and base of SEC</td>
<td>Explosive eruption strombolian activity, ash plume drifted NNE, continuous lava fountain 100-150 m high for few hours, lava flows</td>
<td>6 km</td>
<td>4.6-5.3 km</td>
<td>26500</td>
</tr>
<tr>
<td>14/05/08</td>
<td></td>
<td></td>
<td>Radial fissure eruption E base of NEC, E flank and base of SEC</td>
<td>Explosive eruption strombolian activity, ash plume drifted NE then S, lava fountain 100 m high, lava flows</td>
<td>5 km</td>
<td>4.5 km</td>
<td>1970</td>
</tr>
<tr>
<td>15/05/08</td>
<td></td>
<td></td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, ash plume drifted SE from 02:50 to 14:17, lava flows</td>
<td>6 km</td>
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Table 2.1, continued

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<th>Area of activity</th>
<th>Description of activity</th>
<th>Lava flow length</th>
<th>Plume height &amp; Ash erupted</th>
<th>SO2 mass emitted (t)</th>
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<td>17/05/08</td>
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<td></td>
<td>Radial fissure eruption E base of NEC, E flank and base of SEC</td>
<td>Explosive eruption strombolian activity, lava flows, ash plume drifted N</td>
<td></td>
<td>max 4 km</td>
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<tr>
<td>11/07/08</td>
<td>morning</td>
<td>1 day</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flow</td>
<td></td>
<td></td>
<td>2</td>
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<tr>
<td>25/08/10</td>
<td>15:09</td>
<td>20 min</td>
<td>Central vent eruption Bocca Nuova</td>
<td>Explosive eruption strombolian activity, ash plume drifted E</td>
<td></td>
<td>4.3 km</td>
<td>2</td>
</tr>
<tr>
<td>12/01/11</td>
<td>21:10</td>
<td>3h40</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flows, ash plume drifted SSW, continuous lava-fountain 800 m high</td>
<td>4.3 km</td>
<td>7.3 km</td>
<td>2</td>
</tr>
<tr>
<td>18/02/11</td>
<td>04:30</td>
<td>8h50</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flow, ash emission, pulsating lava fountain</td>
<td></td>
<td>8 km</td>
<td>2600</td>
</tr>
<tr>
<td>10/04/11</td>
<td>10:00</td>
<td>6h</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, lava fountain 300 m high, gas and ash plume drifted SE, lava flows</td>
<td>2.5 km</td>
<td>5.3 km</td>
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<td>12/05/11</td>
<td>03:20</td>
<td>2h50</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, lava fountain 300 m high, ash plume drifted SSE, lava flow</td>
<td></td>
<td>5.3 - 6.3 km</td>
<td>5.3</td>
</tr>
<tr>
<td>Date</td>
<td>Onset time</td>
<td>Duration</td>
<td>Area of activity</td>
<td>Description of activity</td>
<td>Lava flow length</td>
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<tr>
<td>09/07/11</td>
<td>13:15</td>
<td>4h25</td>
<td>Radial fissure eruption E flank of SEC</td>
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<td>19/07/11</td>
<td>02:00</td>
<td>3h</td>
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<td>Explosive eruption strombolian activity, lava flows, lava fountain 250 m high, ash and gas plume drifted E</td>
<td>5 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25/07/11</td>
<td>04:00</td>
<td>4h</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flows, pulsating lava fountain 350 m high, ash and gas plume drifted E</td>
<td>7 km</td>
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<td>30/07/11</td>
<td>10:00</td>
<td>14h30</td>
<td>Radial fissure eruption E flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flows, continuous lava fountain 450-500 m high, ash and gas plume drifted E</td>
<td>3 km</td>
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<td>05/08/11</td>
<td>22:30</td>
<td>3h45</td>
<td>Central vent eruption New SEC Radial fissure E flank of the old SEC</td>
<td>Explosive eruption strombolian activity, lava flows, lava fountain 500m high, ash plume drifted SE</td>
<td>10.7 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/08/11</td>
<td>09:00</td>
<td>4h</td>
<td>Central vent eruption New SEC</td>
<td>Explosive eruption strombolian activity, pulsating lava fountain 100 m high, lava flows, ash plume</td>
<td>3.7 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/08/11</td>
<td>04:55</td>
<td>5h</td>
<td>Central vent eruption New SEC</td>
<td>Explosive eruption strombolian activity, ash and gas plume drifted SW, continuous lava fountain, lava flows, avalanches</td>
<td>9 km</td>
<td></td>
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<td>Date</td>
<td>Onset time</td>
<td>Duration</td>
<td>Area of activity</td>
<td>Description of activity</td>
<td>Lava flow length</td>
<td>Plume height &amp; Ash erupted</td>
<td>SO2 mass emitted (t)</td>
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<td>29/08/11</td>
<td>05:46</td>
<td>4h</td>
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<td>Radial fissure eruption SE flank of SEC</td>
<td>100 m high, ash plume drifted SSE</td>
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<td>08/09/11</td>
<td>08:30</td>
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<td>Explosive eruption strombolian activity, lava flow, pulsating lava fountain, ash plume</td>
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<td>10 km</td>
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<td>Radial fissure eruption SE and N flank of SEC</td>
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<td>28/09/11</td>
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<td>Central vent eruption New SEC</td>
<td>Explosive eruption strombolian activity, lava flows, continuous lava fountain</td>
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<td>10.5 km</td>
<td>3710</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>800 m high, ash plume drifted SW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08/10/11</td>
<td>13:00</td>
<td>4h45</td>
<td>Central vent eruption New SEC</td>
<td>Explosive eruption strombolian activity, lava flows, continuous lava fountain, ash and gas plume drifted E</td>
<td></td>
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<td>Radial fissure eruption SE and N flank of SEC</td>
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<td></td>
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<td>3h35</td>
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<td></td>
<td>5.5 km</td>
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<td>300 m high, ash plume drifted E</td>
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</tr>
<tr>
<td>15/11/11</td>
<td>10:20</td>
<td>4h30</td>
<td>Central vent eruption New SEC</td>
<td>Explosive eruption strombolian activity, lava flows, lava fountain</td>
<td></td>
<td>&lt; 4 km</td>
<td>10.5 km</td>
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<td></td>
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<td>800 m high, ash drifted SE</td>
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<td>Duration</td>
<td>Area of activity</td>
<td>Description of activity</td>
<td>Lava flow length</td>
<td>Plume height &amp; Ash erupted</td>
<td>SO2 mass emitted (t)</td>
</tr>
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</tr>
<tr>
<td>05/01/12</td>
<td>03:45</td>
<td>4h15</td>
<td>Central vent eruption New SEC, Radial fissure eruption SE and N flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flows, continuous lava fountain 150 m high, ash and gas plume drifted SSW, small lahar, pyroclastic flow and phreatomagmatism</td>
<td>2 km</td>
<td>9 km</td>
<td>6520</td>
</tr>
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<td>09/02/12</td>
<td>00:00</td>
<td>11h</td>
<td>Central vent eruption New SEC</td>
<td>Explosive eruption, strombolian activity, lava flows, continuous lava fountain 500 m high, ash plume drifted W</td>
<td>&lt; 3 km</td>
<td>9.3 km</td>
<td>1110</td>
</tr>
<tr>
<td>04/03/12</td>
<td>05:30</td>
<td>5h</td>
<td>Central vent eruption New SEC, Radial fissure eruption SW and N flank of SEC</td>
<td>Explosive eruption strombolian activity, lava flows, continuous lava fountain, ash plume drifted NE, pyroclastic flows, lahar, phreatic explosion</td>
<td>3.5 km</td>
<td>7.5 km</td>
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<tr>
<td>18/03/12</td>
<td>08:00</td>
<td>3h10</td>
<td>Central vent eruption New SEC, Radial fissure eruption N flank of SEC</td>
<td>Explosive eruption strombolian activity, lava fountain, lava flows, avalanches, ash plume drifted E, lahar, pyroclastic flow, phreatic explosion</td>
<td>4 km</td>
<td>7.5 km</td>
<td>6770</td>
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<tr>
<td>01/04/12</td>
<td>03:30</td>
<td>3h10</td>
<td>Central vent eruption New SEC, Radial fissure eruption SE flank of SEC</td>
<td>Explosive eruption strombolian activity, lava fountain, lava flows, gas and ash plume drifted SE, pyroclastic flows, phreatic explosion</td>
<td>&lt; 4km</td>
<td>10.5 km</td>
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<td>Description of activity</td>
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<td>Plume height &amp; Ash erupted</td>
<td>SO2 mass emitted (t)</td>
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<td>14:16</td>
<td>3h45</td>
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<td>6.3 km</td>
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<td>1h30</td>
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<td>Explosive eruption strombolian activity, lava fountain, lava flows, gas and ash plume drifted E</td>
<td></td>
<td>5.5 km</td>
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</tbody>
</table>
3. OMI

3.1 The Ozone Monitoring Instrument

OMI is a Dutch-Finnish polar-orbiting hyperspectral ultraviolet-visible (270-500 nm) spectrometer launched in July 15, 2004 on the Earth Observing System Aura satellite by the NASA. It provides daily, global contiguous mapping of ozone and trace gases including SO$_2$, NO$_2$, BrO, HCOH, and OCIO. The two-dimensional charge couple device (CCD) detectors that measure backscattered radiances permit acquisition of spectral and spatial information at the same time. It has a 2600 km swath, spatial resolution of 13×24 km at nadir and a local afternoon equatorial crossing time at 13:45 which make it one of the best satellite sensors for SO$_2$ measurements launched to date (Levelt et al. 2006).

SO$_2$ is detected using its well-characterized differential absorption structure in the UV wavelength region, which must be separated from that due to stratospheric ozone in the same region. The OMI channel used to detect SO$_2$ is UV-2, from 310 nm to 365 nm, with a spectral resolution of 0.45 nm (Levelt et al. 2006). It also provides measurements of gas traces column amounts, aerosol index (AI), UV reflectivity, cloud top pressure and cloud fraction.

Since June 2007, an anomaly has been observed in the OMI data, called the row anomaly, affecting different cross-track scenes. Radiances measured within the row anomaly are not useable for trace gas retrievals, leading to stripes without data in each OMI swath. This row anomaly data gap prevented measurement of the Etna plume for some eruptions in 2011 and 2012, precluding calculation of the SO$_2$ mass in the volcanic cloud (http://so2.gsfc.nasa.gov/Documentation/OMSO2Readme_V111_0818.htm).
3.2 OMI data analysis

The operational OMI SO$_2$ data products (OMSO2) are free to download from the NASA GES DISC website (http://mirador.gsfc.nasa.gov/cgi-bin/mirador/collectionlist.pl?keyword=omso2). We used the OMIPlot software (Carn 2011b) to analyze them, which is written in Interactive Data Language (IDL). Several different algorithms have been used for retrieval of SO$_2$ from OMI measurements: the Band Residual Difference (BRD) algorithm (Krotkov et al. 2006), the Linear Fit (LF) algorithm (Yang et al. 2007), the Iterative Spectral Fitting (ITF) (Yang et al. 2009), and the Extended Iterative Spectral Fitting (EITF) (Yang et al. 2010). The LF algorithm is used for operational SO$_2$ retrievals, provided in the public available OMSO2 dataset.

We used the LF algorithm data in this study, which permits generation of daily maps of SO$_2$ vertical column densities (VCD) (http://so2.gsfc.nasa.gov) by converting the satellite slant column densities (SCD) using an air mass factor (AMF). The LF algorithm uses 10 OMI wavelengths that correlate with local maximum and minimum absorption of SO$_2$ (Yang et al. 2007). By making assumptions about the vertical distribution of SO$_2$, it provides three estimates of the SO$_2$ VCD in Dobson Units (1 DU = 2.69 × 10$^{16}$ molecules/cm$^2$): the Lower Tropospheric SO$_2$ column (TRL), which corresponds to a center of mass altitude (CMA) of 2.5 km; the Middle Tropospheric SO$_2$ column (TRM), which corresponds to a CMA of 7.5 km; and the Upper Tropospheric and Lower Stratospheric SO$_2$ column (STL), which corresponds to a CMA of 17 km. The LF algorithm generates SO$_2$ VCD for these three a-priori SO$_2$ vertical distributions, which are then analyzed manually with the OMIPlot software. The BRD algorithm is also used operationally to generate SO$_2$ VCDs assuming a CMA of 0.9 km, for SO$_2$ confined to the Planetary Boundary Layer (PBL).

Plume height was either provided by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Catania, which monitors Mount Etna, or estimated with the READY system and the HYSPLIT trajectory model (http://www.ready.noaa.gov).
http://ready.arl.noaa.gov/HYSPLIT.php ). Figure 3.1 is an example of the HYSPLIT trajectory model for the August 29th, 2011 paroxysm. Because the plume was covered by the row anomaly on that day, we used the OMI picture of the day after to calculate the SO\textsubscript{2} mass. The plume location is known with the OMI picture, at the overpass time. We then find the right plume height, the one which has a trajectory that passes above Mount Etna. The model also permits to compare the onset time of eruption. Moreover, we can see in this case that the plume height varies a lot as it is drifted away from the vent.

Once we had the plume height, we interpolated the OMI-derived SO\textsubscript{2} VCDs for the four CMAs to the actual reported or estimated plume altitude.

![Figure 3.1: Figure from the HYSPLIT trajectory model on August 30\textsuperscript{th}, 2011.](image)
We used the Transects technique to calculate SO$_2$ fluxes and the Normalized Cloud-mass technique (NCM) for SO$_2$ mass calculation from OMI SO$_2$ data. These techniques are described below.

### 3.2.1. SO$_2$ Transect technique

The SO$_2$ transect technique is used for calculation of SO$_2$ fluxes in the plume from the daily OMI images. The technique is essentially the same as the technique commonly used to derive SO$_2$ emission rates from ground-based measurements of SO$_2$ column amounts in volcanic plumes (e.g. Stoiber et al. 1983). For satellite data validation during the Etna paroxysmal eruptions it is only useful for specific conditions: the eruption has to have happened a short time before the OMI image acquisition in order to have plume transects geometry and meteorological conditions similar to those of the ground-based measurements.

Transects are drawn perpendicular to the observed plume direction and the software calculates automatically the plume width and average SO$_2$ column in the plume cross-section. The flux is then calculated based on a wind speed entered by the user. Fluxes are obtained in metric tons per day (t/d) for the different SO$_2$ CMAs (PBL, TRL, TRM and STL).

### 3.2.2. Normalized Cloud-mass (NCM) technique

This technique consists of selecting a box in the daily OMI SO$_2$ image that contains the volcanic plume, in order to calculate the uncorrected SO$_2$ mass. Because of the OMI SO$_2$ background noise, another box is also selected, with a similar size and
meteorological conditions to the plume box (if possible), but free of volcanic SO₂. The NCM technique calculates the SO₂ mass of the two boxes and then subtracts the background SO₂ mass to have the corrected SO₂ mass of the volcanic plume, using the following equation:

\[
\text{SO}_2_{\text{Cloud Mass}} = \text{SO}_2_{\text{Cloud}} - ((\text{Area}_{BG}/\text{Area}_{\text{Cloud}}) \times \text{SO}_2_{BG \text{ Mass}})
\]

Where \(\text{SO}_2_{\text{Cloud Mass}}\) is the SO₂ mass in the volcanic plume after correction; \(\text{SO}_2_{\text{Cloud}}\) is the uncorrected SO₂ mass in the plume; \(\text{Area}_{\text{Cloud}}\) is the area of the box containing the volcanic plume; \(\text{Area}_{BG}\) is the area of the background box and \(\text{SO}_2_{BG \text{ Mass}}\) the SO₂ mass (retrieval noise) in the background box. Masses are obtained in tons (t).

The NCM technique was used to estimate the SO₂ mass emitted reported in Table 2.1. For some recent eruptions, the row anomaly previously mentioned affects the OMI data coverage of the Etna plume, preventing the SO₂ mass calculation. However, if the SO₂ plume persists in the atmosphere for a few days, we were able to measure the SO₂ mass on a subsequent day.

### 3.2.3 Error calculation

There are different error sources for the SO₂ flux and mass calculation.

The main error sources for the flux calculation are the wind speed and the plume height. The distance measurement between the vent and the transect in the Transect technique is another error source, but minor compare to the other ones. The presence of clouds and ash are also minor errors. We estimated an error of ± 30% for SO₂ flux.

The main error source for the mass calculation is the plume height. The presence of clouds and ash are also minor errors. We estimated an error of ± 20% for the SO₂ mass.
4. Ground-based measurements

4.1 FLAME Network

The FLAME network is an automatic scanning array designed, built and installed at Etna in October 2004 by the INGV. It was composed of 5 UV scanning spectrometers (mini-DOAS) until 2009. Since 2010, 4 more stations have been added to the network to increase the probability of detecting and tracking the plume, and improve monitoring of Etna’s SO₂ emissions (Figure 4.1). Data from the spectrometers are used to measure the SO₂ flux automatically and in real time (Burton et al. 2004).

Figure 4.1: Location of the 9 UV spectrometer stations of the FLAME network. Courtesy of Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Italy.
A filter for visible light (HOYA U330) receives the diffuse sky radiation. It is then reflected into a telescope with a 8 mrad instrumental field-of-view (FOV) by a 45° plane mirror. Fiber optic cables (1000 µm) focus the beams and connect the telescope to an Ocean Optics S2000 spectrometer. This spectrometer has a spectral resolution of 0.6-0.9 nm (full width at half maximum) and a wavelength range of 295-375 nm. The instrument scans the sky from 12° to 168° in a vertical plane in around 6 minutes, generating 105 spectra per scan (104 spectra with angular spacing of 1.5° and a dark-spectrum) (McGonigle et al. 2003; Salerno et al. 2009a, 2009b). The data acquisition period depends on the season, with almost 9 hours typical during the summer.

4.2 Mini-DOAS Data Analysis

Column amounts (CA) are retrieved automatically on site using a DOAS-type retrieval based on the Rodgers (1976, 2000) optimal estimation algorithm. Spectra are first processed with a low-pass filter in order to suppress the noise, and then transformed into optical depth. CA are calculated from the optical depth and transmitted to the INGV Observatory in Catania by FreeWave radio modem (Salerno et al. 2009a, 2009b).

Fluxes are calculated in Catania following the technique described by Stoiber et al. (1983). CAs permit calculation of SO₂ column cross-sections, which are then multiplied by the plume-transport speed. The wind speed at plume height is estimated using the LAMI model (Limited Area Model Italy) from the European Center for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/) (Salerno et al. 2009b).

The INGV Observatory of Catania provided the ground-based data.
4.3 Error calculation

The uncertainty for the SO$_2$ flux calculation was estimated by Salerno et al. (2009b) as -22%, +30%. The Matlab code we used for the SO$_2$ mass calculation didn’t change this error as we just integrated the fluxes to calculate the mass.
5. Results and comparison

5.1. OMI Results

5.1.1. Transects Technique

The cloud fraction image provided by OMIplot permits an assessment of the presence or absence of significant meteorological cloud at the volcanic plume location (Figure 5.1). Depending on the relative position of clouds and the volcanic plume, the SO$_2$ mass calculated may be overestimated (if the SO$_2$ is above the clouds) or underestimated (if the cloud is obscuring part or all the SO$_2$ plume). Furthermore, they can modify the rate of SO$_2$ depletion via aqueous phase reactions, leading to an underestimation of SO$_2$ if the volcanic plume is entrained into cloud (Jaeschke et al. 1982). Therefore, cloud coverage is an important parameter to take into account.

The OMI-derived cloud fraction is available for any single pixel and the OMSO2 data product also provides a cloud top pressure. It is then possible to calculate the estimated height of the cloud and compare it with the (known or estimated) volcanic plume height. We used the U.S. Standard Atmosphere, 1976 published by the U.S. Government Printing Office, Washington, D.C. (http://www.pdas.com/m1.html) to estimate the cloud height.

Visible images from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite are also useful to assess cloud coverage as the sensor is in the A-train satellite constellation with Aura and overpasses the area a few minutes before OMI (http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=aeronet&subset%20=ETNA) (Figure 5.2).
Figure 5.1: Cloud fraction image on 05/14/08.
Figure 5.2: Aqua MODIS image above Sicily on 05/14/08. The blue circle is the Etna location.

Figures 5.1 and 5.2 show a good agreement in cloud locations. The volcanic plume is also visible on the Aqua image, drifted South-East by the wind.

The INGV provided the wind speed at the location of the ground-based stations. As it can easily vary as the plume drifts away, we used the READY Hysplit model to have another value of it. The Archived Meteorology data provides an estimation of the wind speed depending on the location and altitude (http://ready.arl.noaa.gov/READYamet.php). The READY Trajectory model was also used to compare the results. It gives us the onset and end times of the eruption. These combined with the plume length calculated with OMIplot, allow us to have another
estimation of the wind speed. The most true value was used to calculate the flux, depending on the location of the transect.

The plume height can be found for some eruptions in the INGV reports of activity (http://www.ct.ingv.it/index.php?option=com_docman&Itemid=344&lang=it). However, this is the height at the vent, and as the plume drifts away, the altitude might change. We used the READY Trajectory model to have another estimation of the height at the plume location.

Wind speed and plume height are two important parameters as they are used in the flux calculation. When these two data sets are more accurate, the approximation for flux is more accurate.

The OMIplot distance calculation technique was used to calculate the distance between each transects and the vent. Using the wind speed data, we were then able to calculate the corresponding time range of the flux emission.

Figures 5.3 to 5.6 show the transect images of the days used for the comparison.

We didn’t calculate flux too close from the volcano. Indeed, because of the large OMI pixel size, the plume needs to have dispersed enough to cover a sufficient fraction of it, and avoid an underestimation of SO$_2$. 
Figure 5.3: OMI picture with transects used to calculate the SO$_2$ fluxes for the 11/16/06 paroxysmal event.
Figure 5.4: OMI picture with transects used to calculate the SO$_2$ fluxes for the 05/14/08 paroxysmal event.
Figure 5.5: OMI picture with transects used to calculate the SO$_2$ fluxes for the 04/10/11 paroxysmal event.
Figure 5.6: OMI picture with transects used to calculate the SO$_2$ fluxes for the 08/12/11 paroxysmal event.
5.1.2. Cloud-Normalized Mass Technique

The CNM technique was used to calculate the SO$_2$ mass. As described before, we chose two different boxes, one with the volcanic plume and one for the background (figures 5.7 to 5.10).

Figure 5.7: OMI image with the boxes used for the SO$_2$ mass calculation on 11/16/06 paroxysmal event.
Figure 5.8: OMI image with the boxes used for the SO$_2$ mass calculation on 05/14/08 paroxysmal event.
Figure 5.9: OMI image with the boxes used for the $SO_2$ mass calculation on 04/10/11 paroxysmal event.

The grey bands in Figure 13 are the row anomaly. We can see that it cuts a part of the volcanic plume, which means there is no data for this part. It is, in this case, really important to take it into account for the $SO_2$ flux and mass calculation.
Figure 5.10: OMI image with the boxes used for the SO$_2$ mass calculation on 08/12/11 paroxysmal event.
The July 9th, 2011 eruption occurred in the afternoon, after the OMI overpass above Mount Etna. We calculated the SO$_2$ mass of the volcanic plume using the image of July 10th, so that almost 24 hours after the emission (Figure 5.11). We see on the picture that the end of the plume is cut by the row anomaly. However, we were able to estimate with HYSPLIT that a very short part of the plume is cut by the anomaly. The SO$_2$ mass calculated is then very close to the real one. This technique allows us to compare data for events which occur during the afternoon. However, because of the lapse time, an underestimation of SO$_2$ is most likely due to its oxidation into sulfate aerosols.

Figure 5.11: OMI image with the boxes used for the SO$_2$ mass calculation on 07/09/11 paroxysmal event.
5.2. Ground-based results

The \( \text{SO}_2 \) fluxes were provided by the INGV of Catania with the wind speed at the station location. For each flux calculated with OMIplot, we had the corresponding time of emission. Because the distance between the transects and the vent and the wind speed values are not hundred percent accurate, we calculated an average of the DOAS fluxes for the comparison, ± 10 minutes of the flux emission time. We also reported the maximum and minimum fluxes during this time lapse in our comparison.

We estimated the \( \text{SO}_2 \) mass erupted for each paroxysmal event with a Matlab code. \( \text{SO}_2 \) fluxes from the beginning of the eruption until its end were integrated in order to have the \( \text{SO}_2 \) mass erupted during this time lapse.

5.3. Comparison

The conditions were adequate for comparisons of both flux and mass between the OMI and FLAME measurements for four paroxysmal events during the period 2004 to present. Because of its occurrence in the afternoon, only the mass comparison was possible for a fifth eruption.

5.3.1. November 16\(^{th}\), 2006

The November 16\(^{th}\), 2006 eruption occurred between 04:07 and 14:00 GMT. As the FLAME network only measures during daytime, there is no ground-based data for the beginning of the event. The first measure was at 07:39, so we compared the data from this time to the OMI overpass time, at 13:27. The data for this day are presented in Table 5.1 and plotted in Figure 5.12.
Considering the plume height at 4 km, we used the TRL and TRM values to calculate the SO$_2$ fluxes and total SO$_2$ masses.

The conditions for this day were quite favorable, with an almost constant wind-speed, between 4.67 m/s and 6.18 m/s, and a cloud-free background. However, the satellite was not near nadir, so had larger pixel dimensions.

Table 5.1
SO$_2$ fluxes in t/d obtained by OMI transects and Mini-DOAS on 11/16/06.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Distance from the vent (km)</th>
<th>OMI</th>
<th>DOAS Average</th>
<th>DOAS Maximum</th>
<th>DOAS Minimum</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>3064.44</td>
<td>5419.38</td>
<td>5824.05</td>
<td>5208.65</td>
<td>43.45</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>3922.84</td>
<td>6951.55</td>
<td>7615.45</td>
<td>6381.28</td>
<td>43.57</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>4915.37</td>
<td>8079.29</td>
<td>8254.72</td>
<td>7820.51</td>
<td>39.16</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>5421.08</td>
<td>11080.97</td>
<td>11157.76</td>
<td>11002.05</td>
<td>51.08</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
<td>5427.74</td>
<td>10032.57</td>
<td>10231.55</td>
<td>9843.55</td>
<td>45.90</td>
</tr>
<tr>
<td>6</td>
<td>92</td>
<td>5528.00</td>
<td>8270.64</td>
<td>9293.61</td>
<td>7472.14</td>
<td>33.16</td>
</tr>
</tbody>
</table>
**Figure 5.12**: SO₂ fluxes obtained by OMI transects, blue line, compared to SO₂ fluxes obtained by Mini-DOAS, red line, on 11/16/06. The DOAS value is the average flux of the 20 minutes around the OMI flux emission time.

The two curves in Figure 5.12 show a same trend, an increase of SO₂ fluxes with the distance from the vent. However, the results show a disagreement, with the best OMI estimation 33% smaller for transect 6. Various errors could account for this difference.
The first cause must be an error ranging between 5% and 20% for the Mini-DOAS measurements (Edmonds et al, 2003), depending on the SO\textsubscript{2} concentration of the plume and the background noise, and varying during the day. Furthermore, clouds may have been present earlier in the morning, leading to erroneous values of Mini-DOAS fluxes. However, the underestimation is around 40% for all the results, which rules out those errors, more or less important depending on the time. The wind speed and/or the plume height estimations are then the most likely errors.

Table 5.2 presents the total SO\textsubscript{2} masses calculated with both techniques. In opposition to the fluxes, the OMI value is 64% larger than the DOAS one. This could be explained by the fact that the eruption starts at 04:07 GMT and DOAS measurements at 07:39. The OMI picture takes into account the SO\textsubscript{2} erupted from the beginning of the eruption whereas the Mini-DOAS starts measuring more than three hours later. We estimated the fluxes from 04:07 until 07:39 for Mini-DOAS and obtained a SO\textsubscript{2} mass closer than the OMI mass.

Table 5.2

<table>
<thead>
<tr>
<th>OMI</th>
<th>DOAS</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1452.40 ± 290.48</td>
<td>887.23 -195.19, +266.17</td>
<td>63.70</td>
</tr>
<tr>
<td>1452.40 ± 290.48</td>
<td>1090.90 -240.00, +327.27</td>
<td>33.14</td>
</tr>
</tbody>
</table>

Total SO\textsubscript{2} mass in tons obtained by OMI CNM technique and Mini-DOAS on 11/16/06. The second row is with the SO\textsubscript{2} flux estimation for DOAS.
5.3.2. May 14th, 2008

We compared the SO$_2$ fluxes from the beginning of the DOAS measurements, at 05:47 GMT until the OMI overpass at 12:24. As said before, some clouds were present above Sicily around noon. However, the cloud fraction is very low, 0.84% for transect 1 and 0.25% for transect 2. The cloud altitude estimated with the U.S. Standard Atmosphere, 1976, is 4-5 km and 5-6 km respectively. The plume height at the vent is 4 km, which means that the volcanic plume is either mixed or under the clouds, which could lead to an underestimation of SO$_2$. As there is no cloud above the Ionian Sea, the other transects are not affected by this possible error.

The wind speed given by the INGV was almost constant at the vent, ranging between 6 m/s and 7 m/s and the satellite near nadir. The wind speed obtained with the READY Trajectory model was however a bit lower, around 5.5 m/s.

The plume height varies, around 4 km at the vent and 5 km at its end.

Table 5.3
SO$_2$ fluxes in t/d obtained by OMI transects and Mini-DOAS on 05/14/08.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Distance from the vent (km)</th>
<th>OMI</th>
<th>DOAS Average</th>
<th>DOAS Maximum</th>
<th>DOAS Minimum</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>14135.33</td>
<td>7430.87</td>
<td>7698.69</td>
<td>7161.89</td>
<td>90.22</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>9791.38</td>
<td>10819.58</td>
<td>11888.16</td>
<td>10140.34</td>
<td>9.50</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>5977.24</td>
<td>11278.95</td>
<td>11831.39</td>
<td>10726.50</td>
<td>47.01</td>
</tr>
<tr>
<td>4</td>
<td>58</td>
<td>4478.01</td>
<td>12119.31</td>
<td>13174.50</td>
<td>11064.12</td>
<td>63.05</td>
</tr>
<tr>
<td>5</td>
<td>86</td>
<td>3028.77</td>
<td>15030.79</td>
<td>15910.99</td>
<td>14150.59</td>
<td>79.85</td>
</tr>
<tr>
<td>6</td>
<td>106</td>
<td>3095.05</td>
<td>11723.60</td>
<td>12853.04</td>
<td>10502.62</td>
<td>73.60</td>
</tr>
<tr>
<td>7</td>
<td>119</td>
<td>2187.77</td>
<td>5139.90</td>
<td>5553.04</td>
<td>4724.16</td>
<td>57.44</td>
</tr>
<tr>
<td>8</td>
<td>145</td>
<td>2013.07</td>
<td>4075.89</td>
<td>4826.28</td>
<td>2813.78</td>
<td>50.61</td>
</tr>
</tbody>
</table>
The error difference is very high for all the transects except the second and OMI fluxes are always smaller than DOAS fluxes except for the first transect (Table 5.3). As showed in Figure 5.13, OMI fluxes decrease when DOAS fluxes tend to increase. This gap could be explained by an erroneous wind speed. The strongest fluxes occurred later for OMI than for DOAS. As there is no information about the onset time of the eruption, we were just able to estimate it with the READY Trajectory model, around 05:00 GMT.

The total SO$_2$ mass is almost the same for both techniques (Table 5.4). The DOAS measurement began at 05:47, less than an hour after the estimated onset of the eruption. Furthermore, fluxes are generally weak at the beginning of an eruption and tend to have a normal distribution. As a result, the SO$_2$ mass from DOAS must be a little bit higher, then closer than the OMI one.

The good agreement between SO$_2$ masses reinforces the fact that the gap between the strongest fluxes may be due to an erroneous wind speed. If the masses are in the same range, fluxes should not be that different.
Figure 5.13: SO₂ fluxes obtained by OMI transects, blue line, compared to SO₂ fluxes obtained by Mini-DOAS, red line, on 05/14/08. The DOAS value is the average flux of the 20 minutes around the OMI flux emission time.

Table 5.4
Total SO₂ mass in tons obtained by OMI CNM technique and Mini-DOAS on 05/14/08.

<table>
<thead>
<tr>
<th>OMI</th>
<th>DOAS</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1754.00 ± 350.80</td>
<td>1637.00 -360.14, +491.10</td>
<td>7.15</td>
</tr>
</tbody>
</table>
5.3.3. April 10\textsuperscript{th}, 2011

We compared the SO\textsubscript{2} fluxes from the beginning of the DOAS measurements, at 07:19 GMT until the OMI overpass at 12:42. A part of the volcanic cloud is cut by the ROW anomaly for that day. Comparing the image with the anomaly (Figure 5.14) and the one with the estimated plume (Figure 5.15) allows us to assume that around half of the plume is covered by the anomaly. Furthermore, the shape of transects obtained by the CNM technique reinforces this hypothesis. Figure 5.16 shows the transect 6. We found with the distance calculation tool from OMIplot, that the plume width is around 80 km at this location. We see in the figure that the plume is cut at the highest SO\textsubscript{2} amount, and around 43 km from the west edge, which is almost half of its width.
Figure 5.14: OMI picture with the ROW anomaly on 04/10/11.
Figure 5.15: OMI picture without the ROW anomaly on 04/10/11.
Figure 5.16: Plume transect for transect 6 on 04/10/11.

The conditions were favorable, with a cloud-free background. The wind speed at the vent varies from 6.7 to 8.3 m/s. However, the wind speed estimated with READY is a little bit higher, around 9 m/s, which is also closer to the one calculated with the plume length and duration of the emission. We used this value of 9 m/s for the OMI flux calculation. The plume height given by the INGV is 5.3 km, which is consistent with the one estimated by the trajectory model.
### Table 5.5

SO$_2$ fluxes in t/d obtained by OMI transects and Mini-DOAS on 04/10/11.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Distance from the vent (km)</th>
<th>OMI</th>
<th>OMI*2</th>
<th>DOAS Average</th>
<th>DOAS Maximum</th>
<th>DOAS Minimum</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>4191.88</td>
<td>8383.76</td>
<td>8582.96</td>
<td>10084.82</td>
<td>6958.71</td>
<td>2.32</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
<td>6430.93</td>
<td>12861.86</td>
<td>12479.15</td>
<td>14604.33</td>
<td>10277.14</td>
<td>3.07</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>5739.70</td>
<td>11479.41</td>
<td>14009.73</td>
<td>15382.56</td>
<td>11524.14</td>
<td>18.06</td>
</tr>
<tr>
<td>4</td>
<td>49</td>
<td>5167.10</td>
<td>10334.19</td>
<td>14521.67</td>
<td>15482.66</td>
<td>13667.55</td>
<td>28.84</td>
</tr>
<tr>
<td>5</td>
<td>57</td>
<td>3807.19</td>
<td>7614.37</td>
<td>11026.48</td>
<td>13156.89</td>
<td>9266.87</td>
<td>30.94</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
<td>3407.86</td>
<td>6815.71</td>
<td>9104.01</td>
<td>9676.80</td>
<td>8222.14</td>
<td>25.14</td>
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<tr>
<td>7</td>
<td>107</td>
<td>1392.21</td>
<td>2784.42</td>
<td>1961.28</td>
<td>2013.64</td>
<td>1726.33</td>
<td>41.97</td>
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<td>8</td>
<td>112</td>
<td>1195.76</td>
<td>2391.52</td>
<td>2004.15</td>
<td>2365.79</td>
<td>1726.33</td>
<td>19.33</td>
</tr>
<tr>
<td>9</td>
<td>117</td>
<td>964.39</td>
<td>1928.78</td>
<td>2237.18</td>
<td>2625.11</td>
<td>1979.47</td>
<td>13.79</td>
</tr>
<tr>
<td>10</td>
<td>122</td>
<td>669.29</td>
<td>1338.58</td>
<td>1919.11</td>
<td>2095.48</td>
<td>1834.42</td>
<td>30.25</td>
</tr>
</tbody>
</table>

Assuming that half of the plume is covered by the row anomaly, we multiplied the OMI data by two before comparing. As showed in Table 5.5, the best agreement is for transects 1 and 2, with a low percent difference, 2.32 and 3.07 respectively. Transects 3, 8 and 9 also show a decent agreement, with percent difference inferior to 20. Furthermore, the two curves on Figure 5.17 have the same trend and OMI fluxes on the range of DOAS fluxes for transects 1, 2, 3, 9 and 10.

The SO$_2$ masses are also really close (Table 5.6), with only 2.95 percent difference, calculated from 08:00 GMT, beginning of the event, until 12:43, overpass of the satellite.
Figure 5.17: SO$_2$ fluxes obtained by OMI transects, blue line, compared to SO$_2$ fluxes obtained by Mini-DOAS, red line, on 04/10/11. The DOAS value is the average flux of the 20 minutes around the OMI flux emission time.
Table 5.6
Total SO$_2$ mass in tons obtained by OMI CNM technique and Mini-DOAS on 04/10/11.

<table>
<thead>
<tr>
<th></th>
<th>OMI</th>
<th>OMI * 2</th>
<th>DOAS</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>768.80</td>
<td>1493.60 ± 307.52</td>
<td>1537.60 - 328.59, +448.08</td>
<td>2.95</td>
</tr>
</tbody>
</table>

5.3.4. August 12$^{th}$, 2011

The paroxysmal event on August 12$^{th}$, 2011 occurred between 07:00 and 11:30 GMT, during daytime and before the OMI overpass, with a cloud-free background and a plume height around 3.7 km. These conditions are favorable for the comparison. However, the satellite is not near nadir, and the average wind speed at the vent is very different from the one at the plume location, 4.9 m/s and ~8 m/s respectively. There is then a big difference between the wind speeds used to calculate DOAS and OMI fluxes.

The results presented in Table 5.7 and plotted in Figure 5.18 show a big difference between the fluxes, with OMI estimation being ~ 300% larger, and until 1058% larger for transect 6. Transect 1 is the only one under 100% larger. The trend is the same for the mass comparison, with 502 percent difference (Table 5.8).
Table 5.7

SO$_2$ fluxes in t/d obtained by OMI transects and Mini-DOAS on 08/12/11.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Distance from the vent (km)</th>
<th>OMI</th>
<th>DOAS Average</th>
<th>DOAS Maximum</th>
<th>DOAS Minimum</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36</td>
<td>2818.26</td>
<td>1536.11</td>
<td>2225.88</td>
<td>1052.76</td>
<td>83.47</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>8103.45</td>
<td>1920.91</td>
<td>3427.85</td>
<td>1321.31</td>
<td>321.85</td>
</tr>
<tr>
<td>3</td>
<td>69</td>
<td>18365.24</td>
<td>3591.23</td>
<td>5010.16</td>
<td>2045.37</td>
<td>411.39</td>
</tr>
<tr>
<td>4</td>
<td>94</td>
<td>14948.17</td>
<td>3483.89</td>
<td>3810.79</td>
<td>2987.05</td>
<td>329.07</td>
</tr>
<tr>
<td>5</td>
<td>114</td>
<td>18434.54</td>
<td>5388.92</td>
<td>6372.85</td>
<td>4734.96</td>
<td>242.08</td>
</tr>
<tr>
<td>6</td>
<td>136</td>
<td>17189.70</td>
<td>1484.21</td>
<td>2778.73</td>
<td>826.50</td>
<td>1058.17</td>
</tr>
</tbody>
</table>

As showed in Figure 5.18, OMI fluxes are, except for transect 1, never in the range of DOAS fluxes. This eruption is characterized by pulsating lava fountains 100m high for two hours and strong strombolian activity at the beginning and end of the event. If we compare with the DOAS data of the other eruptions, fluxes are usually between 6000 t/d and 14000 t/d during fountaining activity while they are between 2000 t/d and 5000 t/d on that day. We can assume that the DOAS data were underestimated. Indeed, accuracy of fluxes depends on the geometry of the plume and constancy of the plume transport direction. Their variation can lead to under or overestimation from -22% to +36% (Salerno et al. 2009b). The plume also might have been at the spatial limit of the scanner-network, with only part of it on the field of view.

The OMI picture (Figure 5.10) shows a plume drifted toward two main directions, east and south-east, which highlights a variation of the plume transport direction with time. The geometry of cloud could then be affected, resulting in erroneous fluxes. As said before, wind speed estimated with READY is much higher than the one given by the INGV. A wrong wind speed and/or plume height also may account for the discrepancy.
On the other hand, we measured fluxes by drawing transects in the OMI picture, with a plume that has not the same shape as near the vent when DOAS fluxes are measured. The volcanic cloud is dispersed by the variation of wind direction and an overestimation of SO$_2$ by OMI is likely.

**Figure 5.18:** SO$_2$ fluxes obtained by OMI transects, blue line, compared to SO$_2$ fluxes obtained by Mini-DOAS, red line, on 08/12/11. The DOAS value is the average flux of the 20 minutes around the OMI flux emission time.
Table 5.8
Total SO$_2$ mass in tons obtained by OMI CNM technique and Mini-DOAS on 08/12/11.

<table>
<thead>
<tr>
<th></th>
<th>OMI</th>
<th>DOAS</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3367.60 ± 673.52</td>
<td>559.86 -123.17, +167.96</td>
<td>501.51</td>
</tr>
</tbody>
</table>

5.3.5. July 9$^{th}$, 2011

The July 9$^{th}$, 2011 eruption occurred from 12:15 to 16:40 GMT according to the INGV report, with a plume height of 6.8 km and a cloud-free background.

As the eruption occurred after the OMI overpass on July 9$^{th}$, we had to process the image of the following day. It was then not possible to make a flux comparison.

We assumed that the OMI SO$_2$ mass takes into account SO$_2$ emission from 12:15 to 16:40. DOAS measurements stop at 16:21, while fluxes are still high, ~ 5700 t/d. We calculated the DOAS SO$_2$ mass assuming the fluxes from 16:21 until 17:00 (Figure 5.19). The result shows a better agreement with OMI, even if the percent difference is still 35.57 (Table 5.9).
Figure 5.19: DOAS flux versus time graph on 07/09/11. The red line is the assumed trend of the curve when DOAS measurement stops.

Table 5.9
Total SO$_2$ mass in tons obtained by OMI CNM technique and Mini-DOAS on 07/09/11. The second line shows the SO$_2$ mass calculated with DOAS data until 17:00.

<table>
<thead>
<tr>
<th></th>
<th>OMI</th>
<th>DOAS</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1747.56 ± 349.51</td>
<td>1224 - 269.28, +367.20</td>
<td>42.77</td>
<td></td>
</tr>
<tr>
<td>1747.56 ± 349.51</td>
<td>1289 - 283.58, +386.70</td>
<td>35.57</td>
<td></td>
</tr>
</tbody>
</table>
6. Conclusion

This kind of comparison between satellite and ground-based sensors is always tricky as it requires finding overlapping ground-satellite days. In the case of Mount Etna, it was really challenging as the OMI satellite has an overpass time around 12:45. Only the events that occurred in the morning were comparable, as the FLAME network, having UV-spectrometers using sun radiation, does not measure during nighttime. The afternoon eruptions could be compared if the volcanic plume was still visible the day after, with a likely SO$_2$ underestimation due to chemical reactions in the atmosphere.

Although Mount Etna is a very active volcano, especially since the beginning of 2011, it was difficult to find good data for both sensors. Furthermore, the degassing rate is not big enough to be detected by the OMI satellite, so only the paroxysmal events were used for the comparison. Out of eleven days of Mini-DOAS data, only five of them were comparable with the OMI data.

The row anomaly present in the northern hemisphere since June 2007 was another difficulty as it often appears to be above the volcano, preventing the use of OMI data.

Otherwise, there were only five ground-based stations until 2010, located south, south-east and east of Mount Etna. As a result, measurements were not possible when the plume was drifted in other directions. The improvement of the FLAME network after 2010 helped to cover a bigger area, with stations all around the volcano. However, the plume is still sometimes at the spatial limit or outside of the scanner network, and measurements are not possible when there is a cloud cover above the volcano. Furthermore, we began the comparison after all the paroxysmal events occurred. Wind speed and plume height could have been better estimated if the project was known at that time.
The comparison was in good agreement only for April 10\textsuperscript{th}, 2011 event, with both SO\textsubscript{2} flux and mass in the same range. Results of May 14\textsuperscript{th}, 2008 highlight the importance of accurate wind speed data. The flux comparison shows a discrepancy between both sensors whereas the mass comparison, which does not require transport rate for its calculation, has a good agreement. Plume height is also important, as the November 16\textsuperscript{th}, 2006 event shows it. Fluxes have the same trend but values with different magnitudes. After the emission, the plume is drifted away by winds of which speed and altitude may vary with time.

The plume transport direction is another important parameter to take into account as the geometry of the plume affects the flux calculation for the Mini-DOAS. The ground-based results of August 12\textsuperscript{th}, 2011 eruption are likely underestimated because of a variation in the plume transport direction during the event.

Further research should be conducted with better wind speed and plume height measurements for paroxysmal events occurring in the morning. Those parameters and their variations with time and space should be better constrained and included in OMIplot to have more accurate results. More data are required to continue this comparison, make a validation of OMI volcanic SO\textsubscript{2} retrievals and improve the next generation of this kind of space-based sensors. Moreover, different techniques than the transects one should be used to estimate the flux with OMIplot in order to have several results which do not take into account the same parameters for the calculation, and especially wind speed and plume height. A better knowledge of SO\textsubscript{2} lifetime with the atmospheric conditions above Mount Etna would also permit to compare the eruptions that occur in the afternoon with more accuracy.
7. References


Smithsonian/USGS – Global Volcanism Program [Internet]:
http://www.volcano.si.edu/world/volcano.cfm?vnum=0101-06=&volpage=weekly


8. Appendix

A: Copyright for Figure 2.2 (Personal communication through e-mail)

Giuseppe Salerno giuseppe.salerno@ct.ingv.it

Dear Celine,

I know, it's not easy to find overlapped ground-satellite days, maybe just few case studies it's a good start, why the results retrieved from the compared days are not good?

Flame: right now the UV scanning network consists of nine scanners all stations have the same technology (attached fig). no probime, about the INGV map, state the appropiate reference (e.g., courtesy of Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Italy)

If you have a skype account we can make a plan to have a chat, though it's not easy due to the time zone, anway we can try it.

all the best
Giuseppe

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website: www.ingv.it; www.ct.ingv.it

23 avril
Hey Giuseppe,

As you noticed I used the GoogleEarth map with the FLAME stations location in my thesis. The problem is that I would need GoogleEarth's permission to use it. I found one of your map of the network in your paper: Three-years of SO2 flux measurements of Mt. Etna using an automated UV scanner array: Comparison with conventional traverses and uncertainties in flux retrieval. I added the 4 new stations on it. I now need your permission to use it in my thesis. I attach it so you can see the changes I made.

Hope you are enjoying your summer.

Celine

hello Celine, nice to hear from you,

the picture is fine, you got the permission.

Please remember that flame data has been provided just for the thesis, since these data results from a team work any official report, article and/or presentation at conferences, should involve my team as co-author.

Please if you need other help do not hesitate to contact me.
all the best

Giuseppe
Hello,

I'm student at Michigan Technological University in the USA and I made my master's thesis on SO2 fluxes at Mount Etna, in collaboration with Giuseppe Salerno from the INGV.

I would like to use in my thesis a figure from one of your paper: Seismicity, seismotectonics and crustal velocity structure of the Messina Strait (Italy), figure 1a, the simplified tectonic map.

I modified it a little bit but I still need your permission to publish it in my thesis.

Waiting for your answer,

Best regards.

Céline Mandon

Luciano Scarfi  scarfi@ct.ingv.it  19 aout

Hello Céline,

I'm sorry for the late reply but I'm on holidays. If you cite the source I have nothing against it.

Bye

Luciano Scarfi