Volcanic eruption detection by the Total Ozone Mapping Spectrometer (TOMS) instruments: a 22-year record of sulfur dioxide and ash emissions

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Abstract: Since their first deployment in November 1978, the Total Ozone Mapping Spectrometer (TOMS) instruments have provided a robust and near-continuous record of sulfur dioxide (SO_2) and ash emissions from active volcanoes worldwide. Data from the four TOMS satellites that have flown to date have been incorporated into a TOMS volcanic emissions database that presently covers 22 years of SO_2 and ash emissions, representing the longest satellite-derived record of volcanic activity in existence. At the time of writing, this database comprises 194 eruptive events and 100 eruptions from 60 volcanoes, resulting in 666 days of volcanic cloud observations. Regular eruptions of Nyamuragira (DR Congo) since 1978, accompanied by copious SO_2 production, have contributed approximately 20% of the days on which clouds were observed. The latest SO_2 retrieval results from Earth Probe (EP) TOMS document a period (1996-2001) lacking large explosive eruptions, and also dominated by SO_2 emission from 4 eruptions of Nyamuragira. EP TOMS has detected the SO_2 and ash produced during 39 eruptive events from 15 volcanoes to date, with volcanic clouds observed on 128 days. Data from EP TOMS have recently begun to degrade, and its erstwhile successor (QuikTOMS) failed to achieve orbit in 2001. New SO_2 algorithms are currently being developed for the Ozone Monitoring Instrument (OMI), which will continue the TOMS record of UV remote sensing of volcanic emissions from 2004.

Volcanic eruptions vary greatly in style, duration and vigour, but all subaerial eruptions involve the emplacement of material, typically including water vapour and other gases, silicate ash, and aerosols, into the atmosphere above the eruption vent. The detection, analysis and tracking of the ensuing volcanic clouds and plumes is crucial for effective mitigation of volcanic hazards such as airborne ash (e.g. Casadevall 1994), understanding of magmatic degassing processes (e.g. Scaillet et al. 1998; Wallace 2001) and quantifying effects of volcanic emissions on the Earth's atmosphere-climate system (e.g. McCormick et al. 1995). Satellite remote sensing has made an indispensable contribution to volcanic cloud studies over the past few decades, by providing regular, synoptic views of gas and ash clouds, and quantitative information on their composition, as they are erupted and dispersed over areas that may range from hundreds to millions of square kilometres (e.g. Oppenheimer 1998a).

One of the first space borne instruments to provide quantitative data on the mass and spatial distribution of two important volcanic cloud components (sulfur dioxide [SO_2] and volcanic ash) was the Total Ozone Mapping Spectrometer (TOMS), which was first deployed on the Nimbus-7 satellite in 1978 (Heath et al. 1975). TOMS was developed to produce daily global maps of the spatial variation of column ozone amounts in the Earth's atmosphere using absorption bands in the ultraviolet (UV) spectral region from 300 to 340 nm (Krueger 1984). However, SO_2 and ozone have similar molecular structures and hence SO_2 also has absorption bands in the UV region exploited by TOMS. When present in significant amounts, as in volcanic eruption clouds, SO_2 produces an 'apparent' ozone signal in the TOMS data which can be converted into a quantitative measurement of column SO_2 amounts (see Krueger et al. (1995) for a detailed description of the TOMS SO_2 algorithm). UV wavelengths measured by TOMS can also be used to locate and quantify the mass of UV-absorbing aerosols (e.g. silicate ash, desert dust, smoke from biomass burning) in the atmosphere and can also detect non-absorbing aerosols such as sulfate (Seftor et al. 1997; Torres et al. 1998). The TOMS Aerosol Index (AI) data can be used to derive ash masses in drifting volcanic clouds (Krotkov et al. 1997, 1999).

Although not the most abundant volcanic gas (water vapour [H_2O], carbon dioxide [CO_2] and occasionally hydrogen chloride [HCl] are produced in greater amounts; e.g. Delmelle & Stix 2000) SO_2 is one of the most important species since SO_2 clouds in the atmosphere are ultimately converted into sulfuric acid or sulfate aerosol, which can have significant radiative effects especially if present in the stratosphere (e.g. Andres & Kasgnoc 1998). Stratospheric sulfate aerosol layers scatter incident solar radiation and absorb emitted terrestrial radiation, warming the upper atmosphere whilst cooling the lower atmosphere, and also promote heterogeneous chemical reactions that deplete the Earth's protective ozone layer (Prather 1992). Of all volcanic gases, SO_2 is also the principal species that is not subject to interference by other large sources or high background concentrations, making it an obvious target for remote sensing. Models predict background SO_2 values of less than 0.5 Dobson Units (DU; 1 DU = 2.687×10^{16} molecules.cm^{-2} = 10 ppm-m) over much of the globe with less than 3 DU over polluted regions of the Northern Hemisphere (Chin et al. 2000). In contrast, SO_2 column amounts in volcanic clouds can range from 30 to 1000 DU, with the maximum amounts observed in the centres of large, very fresh eruption clouds (Figure 1).

The ability of TOMS to map SO_2 in addition to ozone was not realized until 1982, when the SO_2-rich clouds produced by the eruption of the Mexican volcano El Chichón were serendipitously detected in TOMS Ozone data (Krueger 1983). In 1984, during real-time processing of TOMS data for the Mauna Loa eruption in Hawaii, SO_2 clouds were discovered emerging from the volcanic Isla Fernandina (Galápagos Islands), and later verified as the result of an effusive eruption, marking the first instance of an eruption 'early warning' using TOMS. These discoveries initiated two decades of SO_2 algorithm development and research into volcanic emissions using TOMS data, resulting in significant contributions to our understanding of volcanic degassing, volcanic hazards, and the impact of volcanic eruptions on the Earth's atmosphere (see Krueger et al. (2000) for a review).

Nimbus-7 TOMS operated for almost 15 years (Table 1) and its lifetime spanned a period of heightened volcanic activity that included the major explosive eruptions of Mt St Helens (USA) in 1980, El Chichón in 1982 and most notably Pinatubo (Philippines) in 1991 (Figure 1; Bluth et al. 1992). Data collected by Nimbus-7 TOMS allowed the first quantitative assessments of the contribution to the atmospheric sulfur budget from individual volcanic eruptions (Krueger et al. 1990; Bluth et al. 1992, 1994, 1995; Schnetzler et al. 1994; Constantine et al. 2000) and from long-term explosive volcanism (Bluth et al. 1993, 1997; Pyle et al. 1996). Meteor-3 TOMS flew in tandem with Nimbus-7 until the latter failed in 1993, then, following the end of the Meteor-3 mission in December 1994, there was a gap of approximately 19 months before the Earth Probe satellite recommenced the TOMS program in July 1996 (Table 1). A fourth TOMS was launched on the Japanese ADEOS satellite in September 1996, but unfortunately the satellite failed prematurely the following year. Earth Probe (EP) TOMS had initially been flown in a low orbit (500 km, producing a nadir footprint of 24×24 km; Table 1) to provide increased sensitivity, at the expense of gaps between successive orbits in equatorial latitudes, whilst ADEOS TOMS (in a higher orbit at ~800 km) provided global coverage. However, following the demise of ADEOS, EP's orbit was raised (to 739 km, producing a nadir footprint of 39×39 km; Table 1) with its remaining fuel in order to maximise the coverage of the one remaining TOMS satellite. EP TOMS is still operational at the time of writing (January 2002), although its orbit is not sufficiently high to provide contiguous daily coverage in equatorial latitudes (between ~30°N and ~30°S). A fifth TOMS launch was attempted in September 2001, but the QuikTOMS satellite which had been due to replace the aging EP TOMS regrettably failed to achieve orbit.

In this paper we present the latest results of our ongoing analysis of the TOMS database covering 22 years of volcanic emissions. ‘New’ eruptive events, i.e. events listed in the available historic records of volcanism (e.g. Simkin & Siebert 1994) but previously absent from the TOMS database, are regularly discovered as the data archive is analysed in more detail, thus no list can be regarded as definitive. There may also be eruptions or volcanic clouds that remain undetected or observed by other means that could yet emerge from the daily TOMS record, though this would involve detailed analysis of each day’s data for each active volcano since 1978. Furthermore, ongoing development and updating of the TOMS algorithms also produces some variability in retrieved volcanic cloud characteristics depending on the algorithm version that is employed. Most previously published work by the TOMS volcanic emissions group has utilised version 6 data from Nimbus-7 TOMS, whereas the algorithms currently in use with EP TOMS data are the version 7 production algorithm (also referred to as the sulfur dioxide index or SOI; McPeters et al. 1998) and a more accurate iterative SO_2 retrieval scheme developed within our group (Krueger et al. 1995). Our long-term goal is to reprocess all the Nimbus-7 TOMS data using the updated algorithms, to produce a fully consistent dataset of volcanic SO_2 emissions. The TOMS database is thus in a perpetual state of flux, but with the recent loss of QuikTOMS and the ongoing degradation of EP TOMS, it is an appropriate time to summarize the results of the TOMS era and to look ahead to the future of UV remote sensing.

Our aim in this paper is to document the *status quo* of the TOMS volcanic emissions database and provide a general overview of the record to date, and also to focus in more detail on recent results from EP TOMS since its launch in 1996. A subsidiary aim is to refute any notion that TOMS detects only the large, stratospheric volcanic clouds such as those produced by the eruption of Pinatubo in 1991 (Figure 1; Bluth et al. 1992). Although uniquely able to image these huge clouds, TOMS is also able to provide useful quantitative information on the SO_2 and ash released by smaller eruptive events (typically assigned a Volcanic Explosivity Index (VEI) of 3; Newhall & Self 1982) that occur far more frequently, and thus is an important source of data for volcanic emissions research and hazard assessments and for airborne hazard mitigation in particular.

We also look ahead to the next generation of UV remote sensing instruments and consider the potential capabilities of the Ozone Monitoring Instrument (OMI), due to be launched on the EOS/Aura satellite in 2004, with regard to volcanic emissions. OMI and other UV instruments such as SCIAMACHY (to be launched on ENVISAT in 2002) will offer many improvements over TOMS and will build on the 22-year heritage of the TOMS instruments that is discussed in this paper.

The TOMS volcanic emissions database

Overview

The TOMS volcanic emissions database is an archive of eruption data amassed by current and previous members of our group over the lifetime of the TOMS instruments. It is by no means an exhaustive list of all the volcanic eruptions that have occurred in this period, as such lists have been exhaustively compiled elsewhere (e.g. Simkin & Siebert 1994), but an inventory of all eruptions that produced sufficient SO_2 and/or ash to be detected in TOMS imagery and that have been located in the dataset (TOMS images and an eruption inventory can be viewed on the TOMS volcanic emissions website; http://skye.gsfc.nasa.gov).

TOMS detection limits

TOMS detection limits have varied over time as the 4 satellites that have carried a TOMS instrument to date have been flown at different altitudes, producing different footprint areas (Table 1). Smaller footprint areas result in increased sensitivity, such that smaller amounts of SO_2/ash can be detected, and lower instrument noise levels mean that less SO_2/ash is required to produce a recognizable signal above background noise.

Detection limits in Table 1 are computed for a representative volcanic SO_2 cloud signal of 5 anomalous TOMS nadir pixels, each at 5ó above the background. Such a signal observed close to a volcano near the time of a known eruption would be easily identifiable as a volcanic cloud, although in practice smaller signals may also be classified as volcanic in origin. This is largely dependent on the data analyst and the noise level of the data in the area of interest, thus the limits in Table 1 are given as a guide to the size of signal that would be unambiguously identified as volcanic for each of the TOMS satellites, in nadir-view data. The TOMS footprint increases in size considerably towards the edges of each swath (e.g. McPeters et al. 1998), increasing the detection limit of the sensor. The EP TOMS footprint increases in area by a factor of 6 from nadir to the swath edges, with a commensurate increase in the detection limit. A more detailed study of TOMS SO_2 retrieval accuracy and error analysis was carried out by Krueger et al. (1995).

Detection limits for ash clouds are more difficult to quantify, since ash mass retrievals are not routinely performed using TOMS data. TOMS AI data are mainly used for the detection and tracking of ash and aerosols (e.g. Seftor et al. 1997), although quantitative information on ash/aerosol properties can be retrieved (Krotkov et al. 1997, 1999). The TOMS AI is dimensionless quantity, for which meteorological (water) clouds yield approximately zero, and ash clouds yield increasingly positive values. The densest ash clouds produce AI values of 10 or higher, with a noise level of ~0.2 AI units for Nimbus-7 TOMS (Krotkov et al. 1999).

Timing is also a factor that impacts the likelihood of TOMS detection of an eruption. In mid-latitudes TOMS overpasses occur once per day, typically around local noon, whilst at higher latitudes the successive TOMS orbits converge and increase the frequency of coverage. TOMS does not function at night, being a UV sensor that measures backscattered solar radiance. Thus a mid-latitude eruptive event occurring just after the daily TOMS overpass will be missed, unless it is of sufficient magnitude to produce a cloud that persists for at least 24 hours. Similarly, a small eruption occurring just a few hours before the TOMS overpass may be missed if the resulting cloud disperses quickly. These issues are mainly applicable to smaller events, many of which are missed by TOMS simply due to unfortunate timing.

Description of the database

We have categorized the current TOMS volcanic emissions database in a number of ways to illustrate the distribution of TOMS-detected eruptions by satellite, volcano, geographic location, volcano type and tectonic setting (Tables 1-6). In these tables we use ‘events’ to indicate discrete eruptive episodes that are clearly separable in time from preceding or subsequent episodes, whilst ‘eruptions’ are classified according to Simkin & Siebert (1994) for pre-1994 eruptions and in a similar fashion for post-1994 eruptions. Thus a single (usually explosive) eruption may comprise many discrete events (e.g. the 1982-83 eruption of Galunggung, Java; Bluth et al. 1994), whereas effusive eruptions, which typically involve continuous activity for a period of days or weeks precluding separation of individual events, may be classified as a single event/eruption. We use this distinction to convey a sense of the number of individual volcanic clouds detected by TOMS, particularly for prolonged eruptions that may actually involve multiple significant SO_2 and/or ash emissions. 'Days tracked' gives a sense of the longevity of effusive eruptions, being simply a count of the number of days on which volcanic clouds were observed, and of the lifetime of explosively released volcanic clouds as SO_2 is scavenged or converted to sulfate aerosol and ash sediments out.

Tables 2-6 integrate data from each of the 4 TOMS satellites that have operated to date (Table 1). As mentioned above, TOMS data from the different satellites have been processed using different versions of the retrieval algorithms, and hence SO_2 tonnages are not given in these tables since the pre-EP TOMS data have not yet been fully processed using the updated algorithms. Hence combining SO_2 data from Nimbus-7/Meteor-3 and EP/ADEOS TOMS is not currently valid. In time we expect to reprocess the entire dataset to achieve internal consistency. Much of the version 6 SO_2 data from Nimbus-7 volcanic cloud studies has been published elsewhere (e.g. Bluth et al. 1993, 1997). EP TOMS SO_2 data since 1996 are presented in a later section of this paper.

Using the criteria defined above, the 1978-2001 TOMS database currently comprises 194 eruptive events and 100 eruptions from 60 volcanoes, producing a total of 666 days of volcanic cloud observations. Figure 2 charts the yearly totals of these parameters through the TOMS era to date. The 194 events can be further broken down into 139 (~72%) involving detectable SO_2 emission and 55 (~28%) lacking detectable SO_2 that were detected in TOMS AI data by virtue of ash emission only. Of the 194 events, 147 (~76%) are associated with predominantly explosive eruptions and 47 (~24%) with eruptions of a predominantly effusive nature (NB: slow effusion of viscous, silicic magma as in lava dome eruptions is not regarded as effusive in this case). This reflects the generally higher altitudes reached by explosively released volcanic clouds, which renders them more conducive to detection by TOMS; explosive eruption clouds are more likely to penetrate meteorological cloud decks that hinder detection of lower level clouds, and to reach sufficient altitudes above the mean penetration level of UV light to produce high signal to noise ratios. In terms of VEI, using Simkin & Siebert's (1994) compilation of VEI data for eruptions between 1978 and 1993 indicates that TOMS instruments have detected 100% of eruptions of VEI 4 or above (consisting of 1 VEI=6, 3 VEI=5 and 10 VEI=4 eruptions) and ~60% of eruptions (or eruptive events) with a VEI of 3. Of the eruptions listed with VEIs of 2, 1 and 0 from 1978-1993, TOMS detected 3.8%, 1.4% and 2.6% respectively. Although these eruptions are classed as being of low explosivity (typically effusive eruptions), the few eruptions in this class that TOMS detects probably involve sufficient thermal energy (perhaps from fire fountaining activity) to loft large amounts of SO_2 to the upper troposphere (Stothers et al. 1986).

Volcanoes with TOMS-detected eruptions

Table 1 lists the 60 volcanoes responsible for the 100 eruptions detected by TOMS since 1978. A list of eruption dates (not given here) and many volcanic cloud images can be viewed on our group website (http://skye.gsfc.nasa.gov). The geographic distribution of these volcanoes exhibits a significant bias towards the northern hemisphere, with 36 (60%) situated north of the equator and 24 (40%) to the south (Wolf volcano in the Galápagos Islands, listed with a latitude of 0° [Table 2], is in fact marginally in the southern hemisphere). Their distribution is furthermore biased towards tropical latitudes, with 37 (~62%) situated between the Tropics of Cancer and Capricorn and 29 (~48%) between 15°N and 15°S. Only 3 volcanoes (5%) lie further than 30°S whereas 19 (~32%) lie further than 30°N, of which 15 (25%) are at latitudes of 50°N or more (volcanoes in the Kuriles, Kamchatka, Aleutians, Alaska and Iceland). The extremes of the distribution are occupied by Heard Island (in the southern Indian Ocean) and Krafla (Iceland).

Although volcanoes in high northern latitudes already comprise a significant proportion of the list, their contribution to the TOMS database would probably be greater were it not for the under representation of eruptions in this region in the boreal winter months. High latitude volcanoes suffer from insufficient UV levels during the winter (and thus a shorter TOMS detection ‘window’) and persistent cloud cover may also be a problem. Furthermore, if eruption clouds from these volcanoes drift further north beyond the light terminator (the boundary between day and night) then they will also elude detection. High ozone levels at these latitudes may also obscure lower level SO_2, though stratospheric plumes should still be detected. On the other hand, the decrease in the altitude of the tropopause from the equator (~17 km) to the poles (~11 km) may enhance detection in some circumstances, and the convergence of TOMS orbits towards the poles produces more frequent images at high latitudes.

Ranked in order of number of events, the list is dominated by the Indonesian volcanoes Galunggung, Rinjani, Colo and Soputan, with 59 events (~30% of the total) between them. With the exception of Rinjani, which was active in 1994, this is largely due to a remarkably active period of the early 1980s in Indonesia (mainly 1982-83) when Galunggung, Colo and Soputan experienced multiple explosive eruptions, producing ash and SO_2 clouds that severely disrupted air traffic over Southeast Asia (Tootell 1985; Gourgaud et al. 1985), at a time when smoke from forest fires in Kalimantan was also creating large aerosol clouds over the region. Nyamuragira (Democratic Republic of Congo) has erupted every 1-2 years on average since 1978 giving a total of 12 eruptions (also classified as 12 events due to the continuous nature of most

Nyamuragira eruptions), each involving production of copious SO_2 without any significant amounts of ash. The remainder of the volcanoes with at least 5 eruptive events in the database (Soufriere Hills, Redoubt, Mt St Helens, Popocatépetl and Bezymianny) have all experienced, or are currently undergoing, dome-forming eruptions. This type of eruption is notorious for producing intermittent and often unpredictable explosive activity (e.g. Christiansen & Peterson 1981; Newhall & Melson 1983; Miller & Chouet 1994), as gas pressures within a growing lava dome periodically exceed the strength of the magma, precipitating explosive disruption of the dome (Sparks 1997). These volcanoes have thus produced multiple events in the TOMS database, although many have only 1 listed eruption (Table 1).

In terms of days tracked, the dataset is clearly dominated by Nyamuragira which currently has 127 days (19% of the total) of observed clouds (Table 1). This is a result of Nyamuragira's frequent, long-lived eruptions, each of which have involved, on average, 10-11 days of continuous SO_2 emission. It does not imply that the SO_2 clouds produced by Nyamuragira have long atmospheric residence times, since much of this SO_2 remains in the troposphere and is typically only tracked by TOMS for a maximum of 2-3 days before dispersing, although a small proportion of SO_2 from Nyamuragira may reach the stratosphere during its larger eruptions (e.g. Krueger et al. 1996). The high totals for Galunggung and Rinjani are also due to frequent eruptive events rather than long cloud lifetimes, and eruptions involving continuous emission of SO_2 or ash for several days or weeks contribute to high totals for Krafla, Cerro Azul (Galápagos Islands) and Lonquimay (Chile). Conversely, the high totals for Pinatubo and El Chichón, and to a lesser extent Mt Spurr and Cerro Hudson, are due to the production of single, large, stratospheric SO_2 clouds that were tracked by TOMS for many days as the slow conversion to sulfate aerosol proceeded (Krueger 1983; Bluth et al. 1992, 1995).

Regions with TOMS detected eruptions

Tables 3 and 4 divide the database into regions, following the classification of Simkin & Siebert (1994). South America heads the list of regions when ranked by number of volcanoes with TOMS-detected eruptions (10, or ~17% of the total), due largely to the inclusion of the 5 Galápagos Island volcanoes that erupted between 1978 and 2001. These volcanoes also contribute significantly to the 116 days of volcanic cloud observations recorded for South America (Table 4). Indonesia comes a close second in terms of volcanoes with detected eruptions (9, or ~15% of the total), whereas it dominates the list of events (65, or ~34% of the total) due to the activity of Galunggung (Java), Colo (Sulawesi), Soputan (Sulawesi) and Rinjani (Lesser Sunda Islands) during the TOMS era. Volcanoes of the Alaskan peninsula and SW Alaska have also produced a significant number of eruptive events (16, or ~8% of the total) over the 22 year period, principally during the 1989-90 eruption of Redoubt (Miller & Chouet 1994) and the 1992 eruptions of Mt Spurr (Bluth et al. 1995). Nyamuragira's contribution gives Africa the highest total of days tracked from only 2 volcanoes (Table 4), although South America (predominantly the Galápagos Islands, Cerro Hudson and Lonquimay which between them produced 85% of South America's total) and Indonesia have comparable totals. Despite the large contribution of the 1991 Pinatubo and 1982 El Chichón eruptions to the respective total days tracked for the Philippines and Mexico, the data in Table 4 underline the prevalence of frequent explosive activity (e.g., Galunggung 1982-83) and long-duration effusive eruptions (Nyamuragira, Galápagos Islands) in the TOMS database, and highlights Africa (i.e. Nyamuragira) as the site of most persistent volcanic cloud emission (in this case consisting entirely of SO_2 emissions; Table 2) in the 1978-2001 period.

Only 3 of the 19 regions in Simkin & Siebert (1994) have no listed eruption in the TOMS database for 1978-2001 (Table 4). The Atlantic Ocean and Antarctica regions have relatively few active volcanoes and have not seen significant recorded eruptions in this period (Simkin & Siebert 1994), and in any case much of the Antarctic suffers from insufficient UV light levels for much of the year. New Zealand is covered adequately by TOMS, but the most significant eruption of recent times in this region, that of Ruapehu in September 1995 (GVN 1995) unfortunately fell in the 19-month gap between Meteor-3 and EP TOMS. This eruption would almost certainly have been detected had there been a TOMS satellite operating at the time. Ruapehu also erupted in June-July 1996, producing a substantial plume on July 16, 1996 (GVN 1996a) just one day before the activation of EP TOMS.

Volcano types with TOMS-detected eruptions

Expressing the TOMS database in terms of volcano type (following Simkin & Siebert (1994)) reveals the expected predominance of stratovolcanoes as the source of over 80% of the eruptive events and 66% of the eruptions detected by TOMS (Table 5). Shield volcanoes, such as Nyamuragira and the Galápagos Island volcanoes, have produced over 30% of the total days tracked from only 13% of contributing volcanoes, reflecting the long durations of eruptions from this volcano type. Lava domes and calderas only achieve significant total days tracked due to the inclusion of El Chichón and Krafla, respectively, in these categories (Table 2). Note that in this case eruptions from volcanoes classed as calderas (Krafla and Banda Api [Indonesia]) certainly do not imply caldera-forming eruptions. In fact these data are somewhat misleading in that a significant proportion of eruptions in the database have involved lava dome-forming eruptions of volcanoes classed as stratovolcanoes rather than lava domes. If the data from all dome-forming eruptions are collated irrespective of volcano type, the result is 48 eruptive events, 21 eruptions and 104 days tracked from 14 volcanoes, representing ~25%, 21%, ~16% and ~23% of the respective totals. This comprises dome-forming eruptions of Augustine (Alaska), Bezymianny (Kamchatka), El Chichón, Langila (Papua New Guinea), Lascar (Chile), Makian (Indonesia), Mayon (Philippines), Merapi (Indonesia), Mt St Helens (USA), Popocatépetl (Mexico), Redoubt, Shiveluch (Kamchatka), Soufriere Hills and Soufriere St Vincent (West Indies), several of which are ongoing at the time of writing. The TOMS record demonstrates the hazardous nature of this type of volcanism, which can produce a series of significant SO_2 and ash clouds over a protracted period and threaten aircraft operations (e.g. Casadevall 1994).

Tectonic settings with TOMS-detected eruptions

The final database summary considers the tectonic setting of the eruptions that constitute the current TOMS database (Table 6). Subduction zone volcanoes, which produce volatile-rich magmas and are thus most prone to explosive eruptions, represent ~82% of the total number of volcanoes in the database and are responsible for ~85% of recorded events, 71% of recorded eruptions and ~65% of the total days tracked. However, the significant contribution from effusive volcanism in hotspot and rift settings is once more in evidence, with the former responsible for 35% of the total days tracked from 18% of listed volcanoes. Although only ~15% of TOMS-detected erupted events are accountable to hotspot-related volcanism, the latter accounts for ~22% of events involving SO_2 production (Table 2), reflecting the relatively high sulfur content of the basaltic magma erupted in this setting (Wallace & Carmichael 1992).

Although the most prolific contributor to the TOMS database since 1978, Nyamuragira, is in central Africa, it is clear from Table 6 that the Pacific Rim and Indonesia experience by far the greatest frequency of major eruptive activity of any region of the globe. This is not surprising, as most of the world's subaerial volcanoes are situated in these regions (Simkin and Siebert 1994). The 22-year TOMS database is only a snapshot of geological time, but as the longest satellite-derived record of volcanic emissions it demonstrates the need for continuous surveillance of the Pacific region using space-borne instruments, to enable rapid detection, location and tracking of volcanic clouds as they impinge on aircraft flight paths. Near real-time 24-hour surveillance could be achieved using combined UV and IR sensors on a geostationary platform situated over the Pacific, though such a mission has yet to be approved.

Results from Earth Probe TOMS (1996-2001)

EP TOMS was launched in mid-1996 in a low earth orbit, providing increased sensitivity to target gases and aerosols due to a reduced footprint area (Table 1). The improved sensitivity of EP TOMS was exploited for validation experiments, wherein ground-based correlation spectrometry (COSPEC) was used to measure passive SO_2 emissions from Popocatépetl concurrently with EP TOMS operating in a special 'stare mode' (fixed scan position) over the volcano (Schaefer et al. 1997). However, increased sensitivity came at the expense of gaps between adjacent EP TOMS pixels and between successive orbit tracks (McPeters et al. 1998), and thus an increased probability of missing smaller or more fleeting volcanic eruptions. Consequently, although the EP TOMS detection limit for volcanic clouds (prior to September 1997) was up to 11 times smaller than previous TOMS instruments (Table 1), the non-contiguous coverage of EP TOMS meant that some events would be missed and that larger volcanic cloud signals would be truncated if they intersected a data gap.

The EP TOMS orbit has since been raised (Table 1), although gaps still exist between pixels (towards the centre of each swath) and between orbits (in equatorial latitudes). Despite these caveats, the ability of EP TOMS to detect smaller eruptive events enhances its utility as a hazard mitigation tool. The coarse spatial resolution (Table 1) means that information on the location of SO_2 or ash is relatively imprecise, but the data can warn of the presence of volcanic clouds. In fact, the EP TOMS spatial resolution is probably good enough for adequate location for the purposes of airborne ash warnings.

The EP TOMS database

The current inventory of eruptions and eruptive events detected by EP TOMS to date is presented in chronological order in Table 7. Note that these data were incorporated into the analysis of the entire TOMS database discussed above and presented in Tables 2-6. As for the complete 1978-2001 TOMS database, the list in Table 7 is provisional and is regularly being updated, though all the major events recorded until the end of 2001 are listed. An eruption of Nyiragongo (DR Congo) that was detected by EP TOMS in January 2002 (NASA Earth Observatory Newsroom 2002) is thus excluded from the list. Results from ADEOS TOMS are also excluded; although ADEOS provided contiguous coverage in tandem with EP TOMS, the satellite failed prematurely after ~9 months of operation. ADEOS TOMS only detected 4 eruptive events during its short life (Table 1), although 1 of these, an eruption of Langila (Papua New Guinea) in February 1997, was missed by EP TOMS due to data gaps. Contiguous data from ADEOS TOMS were also used to supplement EP TOMS during the 1996 eruption of Nyamuragira (Table 7), which was affected by data gaps in EP TOMS data.

Two dates are given for each eruption in Table 7; the actual eruption date as given in available sources, and the date of first detection by EP TOMS. These dates are often coincident, signifying an eruption that occurred before the TOMS overpass on that particular day. Where the TOMS detection date trails the recorded eruption date by a day or more, this may signify an eruption that occurred after the daily TOMS overpass, an eruption that fell in an EP TOMS data gap on preceding day, or an eruption that did not produce sufficient SO_2 and/or ash in its early phase to exceed the TOMS detection limits. To date, there are no recorded occurrences of detection of precursory activity (i.e. the TOMS detection date preceding the recorded eruption date) by EP TOMS, or any other TOMS instrument.

The latest EP TOMS SO_2 retrieval results are also given for each eruption in Table 7. Retrievals presented in this paper have been generated using an iterative four-band matrix inversion method detailed in Krueger et al. (1995). We typically quote an error of 30% on these retrievals, though for a fuller discussion of the errors involved the reader is referred to Krueger et al. (1995). Generating the SO_2 tonnages listed in Table 7 is a two-step process. First, a retrieval is performed using 4 bands of TOMS data for a subset of the image containing the volcanic cloud under scrutiny. To then derive the SO_2 tonnage contained in the cloud, an empirical background correction is applied by subtracting the SO_2 tonnage contained in background regions adjacent to the volcanic cloud from the SO_2 tonnage contained in a box surrounding the cloud. Background boxes are chosen to be of similar size to the box containing the volcanic cloud, and areas are normalized to the area of the cloud box (see Krueger et al. (1995) for a detailed description). To account for the small gaps between adjacent EP TOMS pixels, the data are interpolated onto a regular, contiguous grid (typically 0.5°×0.5°) before the tonnage calculation procedure. The above method has been complicated recently (since 2001) by the appearance of a cross-track bias in EP TOMS data (see below), which results in a variation of background SO_2 with scan position across each TOMS swath. We are attempting to compensate for this by selecting the band combination that produces the lowest retrieval noise, and by applying offsets to individual bands before performing the retrieval.

It should be noted that retrieved SO_2 does not equate to total SO_2 production in the majority of cases. This applies especially to effusive eruptions involving continuous emission (and coincident removal) of SO_2 (e.g. at Nyamuragira; Figure 3), where it is necessary to account for SO_2 remaining from the previous day along with any new SO_2 produced in the interim (Krueger et al. 1996). The procedure is complicated for EP TOMS data due to the data gaps that often bisect large clouds; an interpolation method must then be used to estimate the amount of 'missing' SO_2. We are currently investigating ways to produce estimates of total SO_2 production by continuously emitting volcanoes using the daily satellite 'snapshots' from polar orbiting platforms such as TOMS, and hence the SO_2 data in Table 7 will be revised as these techniques are refined. Explosively released eruption clouds can be corrected for SO_2 removal between the time of eruption and the time of the TOMS overpass, if more than one day's worth of data are available (and no data gaps intervene) and if a constant SO_2 removal rate (integrating SO_2 removal through conversion to sulfate and dry/wet deposition processes) can be assumed, by back extrapolation of the TOMS-derived tonnages to the time of eruption to estimate the erupted mass. However, many of the explosive events listed in Table 7 were relatively short-lived and were only tracked by TOMS for a single day, precluding the aforementioned approach. The technique is also not applicable when the eruption plume is still being fed at the time of the first TOMS overpass.

A significant feature of the EP TOMS era to date has been the lack of major explosive eruptions, with the most significant emissions in Table 7 being produced by predominantly effusive events. Two of the most significant explosive eruptions of the last 5 years occurred at Shishaldin on April 19, 1999 and at Hekla on February 26, 2000 (an effusive eruption which involved an initial explosive phase; Figure 4; GVN 2000b); independent data suggests that both of these eruptions produced a small stratospheric aerosol signal (Rizi et al. 2000; GVN 2000b) and this seems likely considering the high northern latitudes of these volcanoes (Table 7).

The total retrieved SO_2 in Table 7 amounts to ~3.9 Megatons (Mt), of which ~3.1 Mt (~79%) was produced during eruptions of primarily effusive or non-explosive nature (not including lava dome eruptions) and ~2.8 Mt (~72%) was emitted by Nyamuragira alone, which has erupted 4 times since 1996 (e.g. Figure 3). Of a total of ~134 days of EP TOMS volcanic cloud observations, Nyamuragira is responsible for 62 days or ~46% of the total, and this figure may increase as the eruptions are examined in more detail. It is interesting to note that Bluth et al. (1993) found that non-explosive volcanism contributes around 70% of the total annual volcanogenic SO_2 flux to the atmosphere, based on Nimbus-7 TOMS data for 1978-1993, a period that saw several very large explosive eruptions. If an estimate of the annual flux of SO_2 from passive volcanic degassing (e.g. 9 Mt; Stoiber et al. 1987) is added to our EP TOMS results for 1996-2001, the contribution of non-explosive volcanism amounts to ~98% of the total. This is clearly an artefact of the lack of Pinatubo or El Chichón scale events since 1996, but there is also a semantic difference as Bluth et al. (1993) include effusive eruptions such as those of Mauna Loa (Hawaii) in 1984, Krafla in 1984, Sierra Negra in 1979 and several Nyamuragira eruptions in their total explosive flux.

Also included in Table 7 are several volcanic clouds which were close to EP TOMS detection limits, but which still produced an identifiable signal in the data. Such signals are typically noticed in TOMS Ozone data as small regions of abnormally high ozone, which can be attributed to SO_2 if other potential causes of high ozone can be disregarded. Low level SO_2 plumes can occasionally be seen in Ozone data (e.g. Manam 1997, Etna 2001; Figure 5) when they are absent from SOI images; this is a useful tool for locating weaker clouds and quantitative estimates of the implied SO_2 mass can also be derived. This is achieved by first isolating the volcanic signal by subtracting an average background ozone value, and then using the ratio of the absorption cross-sections of ozone and SO_2 to calculate an effective amount of SO_2 that would produce the observed signal in TOMS Ozone data. This is performed for each anomalous pixel, then the results are summed to produce an estimate of the total SO_2 mass.

Eruption case studies

Nyamuragira

Eruptions of Nyamuragira dominate the short-term EP TOMS record (Table 7; Figure 3) as they do the whole 1978-2001 TOMS database, both in terms of number of days of observed clouds and total SO_2 tonnage (2.8 Mt between 1996 and 2001). Although the latter is only an estimate at present, Nyamuragira’s total is at least an order of magnitude greater than that of any other volcano, and it may even exceed Pinatubo as the largest volcanic SO_2 source of the last 22 years in the TOMS record. Nyamuragira (and neighbouring Nyiragongo) is difficult to monitor in the field, due partly to its frequent eruptions of extensive lava flows (GVN 1996b, 1998c, 2000a, 2001b) but mainly due to persistent regional instability in the eastern DR Congo since the 1994

Rwandan civil war, and badly funded monitoring resources (Oppenheimer 1998b). Thus the TOMS satellite record provides an extremely valuable dataset documenting the SO_2 emissions from this exceptional volcano (Figure 3).

The size of the Nyamuragira dataset derived from the 22 years of TOMS data is too large to permit a detailed analysis in this paper; such analyses are ongoing and will be documented in due course. No detailed analysis of the sulfur contents of Nyamuragira lavas has been published to date (though S-bearing pyrrhotites have been found in the groundmass of some lavas; Aoki et al. 1985), but we speculate that the voluminous SO_2 emissions from the volcano are somehow related to the unique characteristics of the erupted lavas. Both Nyamuragira and nearby Nyiragongo erupt highly potassic (K_2O rich) lavas (Aoki et al. 1985) which have very low viscosities due to their low silica contents (Hayashi et al. 1992). This low viscosity results in exceedingly high lava flow rates, such as those recorded during the devastating 1977 eruption of Nyiragongo (Tazieff 1977). Low viscosity lavas may also promote highly efficient separation of magma and gas as magma batches rise to the surface during eruptions, allowing large gas clouds to develop. Furthermore, studies of earthquakes beneath Nyamuragira indicate that the erupted magma may originate from a storage region at considerable depth (between 4 and 7 km; Aoki et al. 1985), suggesting that there is little inter-eruptive degassing that would deplete the available SO_2 reservoir.

Another characteristic of the EP TOMS data for Nyamuragira is the frequent occurrence of negative AI values associated with the volcanic clouds, which indicates the presence of sulfate aerosol (Table 7). This suggests efficient removal of emitted SO_2 through conversion to sulfate in the moist tropical atmosphere of central Africa.

Popocatépetl

EP TOMS has detected at least 5 eruptive events from Popocatépetl since the volcano awoke from dormancy in December 1994 (Table 7), in a period which has seen the volcano record exceptionally high passive SO_2 degassing rates (up to 9-13 kt/day; Delgado-Granados et al. 2001). These high SO_2 fluxes were exploited in a TOMS validation campaign in collaboration with COSPEC operators (Schaefer et al. 1997). Popocatépetl's high altitude summit (~5400 m) means that degassed SO_2 is released well above the boundary layer, making it an ideal target for validation campaigns as the rate of SO_2 removal is lower and the high altitude is more conducive to detection of emissions by TOMS.

Since 1994, Popocatépetl has undergone phases of lava dome growth and destruction in its summit crater (GVN 1997c, 1998e, 2000e, 2001g; Delgado-Granados et al. 2001). A large explosion on June 30, 1997 partially destroyed a pre-existing lava dome but unfortunately coincided with a data gap in EP TOMS data and followed the failure of ADEOS TOMS by one day. A new dome subsequently began to extrude on July 4, 1997 (GVN 1998a), one day after an SO_2 plume from Popocatépetl (containing no detectable ash) was detected by EP TOMS (Table 7). We believe that the EP TOMS SO_2 signal on July 3 may represent vigorous gas venting associated with the emplacement of this new dome.

Most if not all of the other instances when emissions from Popocatépetl have been detected by EP TOMS coincide with phases of dome growth. The highest dome growth rates recorded at Popocatépetl since 1994 occurred in mid-December 2000, when magma extrusion rates of ~180-200 m^3/s were inferred and exceptionally high SO_2 fluxes (up to 100 kt/day) were measured (GVN 2000e). The largest TOMS-detected SO_2 emission from Popocatépetl in our dataset (26 kt) coincided with these other geophysical maxima on December 19, 2000 (Table 7).

GVN (2000e) states that seismic tremor amplitude at Popocatépetl in mid-December 2000 was the highest observed since the volcano began erupting in 1994, with amplitudes on June 30, 1997 the next highest. Although the event on June 30, 1997 was unfortunately missed by EP and ADEOS TOMS, the presence of a measurable SO_2 plume 3 days later on July 3, 1997 suggests that the June 30 event would have produced a sizeable signal. If so, then it may be possible to positively correlate tremor amplitudes (and hence dome growth rates) with the satellite-derived SO_2 flux, which would provide a valuable alternative means of monitoring the volcano (and others like it) and, potentially, assessing the volatile content of the magma supplying the lava domes.

Soufriere Hills, Montserrat

The Soufriere Hills volcano (SHV) on Montserrat (West Indies) is currently undergoing an andesitic dome-forming eruption that began in July 1995 (Young et al. 1998). The most vigorous phase of the eruption to date occurred in 1997, which is reflected in the incidence of EP TOMS-detected events (Table 7). Beginning in August 1997 and continuing in September-October 1997, SHV produced a series of powerful vulcanian explosions that lofted ash to altitudes of up to ~15 km (Druitt et al. 2002). EP TOMS succeeded in detecting only 4 of a total of 88 eruption clouds (Table 7), with the timing of the explosions relative to the TOMS overpass being the most critical factor; many explosions occurred in the evening or early morning, and thus the ash produced had dispersed before TOMS flew over. An interesting observation made by EP TOMS is that only one of the 4 explosions (on October 19, 1997) produced measurable SO_2, albeit a very small signal (Table 7). This was towards the end of the vulcanian explosion sequence (Druitt et al. 2002), signifying a possible impending change in the eruptive conditions. Another possible explanation is that SO_2 may have been efficiently scavenged in the ash-rich clouds (Rose 1977), impeding its detection by TOMS.

The largest SO_2 masses in the SHV volcanic clouds detected by EP TOMS to date have been measured in clouds arising from large dome collapse events during periods of active lava dome growth, e.g. December 26, 1997 and July 29, 2001 (Table 7). However, between March 1998 and November 1999 no lava dome growth was recorded at SHV, yet dome collapses still occurred periodically (Norton et al. 2002). Two of these events were detected by EP TOMS, including one that produced significant SO_2 (July 20, 1999; Table 7). This indicates that high gas pressures within the quiescent dome may have influenced the timing of this particular dome collapse, but more generally it highlights the fact that even 'quiescent' domes can produce substantial gas/ash clouds and that they require constant surveillance to mitigate associated hazards.

Volcanic clouds produced by SHV are typically small, and pose problems for detection even for sensors with higher spatial resolution than EP TOMS such as GOES (Rose & Mayberry 2000). Our EP TOMS data demonstrate that, although detection of these small clouds occurs less frequently, important quantitative information on the compositions of these clouds can still be obtained.

Tungurahua

Tungurahua is a similar case to Popocatépetl, being a volcano at high altitude (~5000 m) that, in its current phase of unrest, has been erupting sporadically for several years (since 1999, with the first explosive activity recorded on October 5; GVN 1999c). It is situated near the equator (Table 7) and so is susceptible to EP TOMS data gaps which may intersect the volcano on 2 of every 3 days. The first recorded detection of a Tungurahua eruptive event by EP TOMS that has been discovered in the database to date occurred on October 17, 1999 (Table 7). This coincided with increased activity and the raising of the alert level to orange for the first time, along with evacuations on Oct 16 (GVN 1999c). The November 16, 1999 event registered by EP TOMS (Table 7) corresponded with a further increase in volcanic activity at Tungurahua; specifically an increase in number of daily explosions which probably increased the likelihood of detection by TOMS (GVN 1999c). There may be many more cases of detection of events from Tungurahua, since the entire database for the volcano has yet to be examined day-by-day. The present dataset indicates that EP TOMS succeeds in detecting eruptive events associated with significant changes in activity at the volcano.

Miyake-jima

Nyamuragira notwithstanding, Miyake-jima has the highest retrieved SO_2 mass (270 kt) of the remaining volcanoes in the EP TOMS dataset (Table 7). This volcanic island south of Tokyo experienced a large phreatic eruption from the Mount Oyama vent on August 18, 2000, following several months of increasing unrest (GVN 2000c). The eruption produced a volcanic cloud containing ~23 kt of SO_2 and significant ash, and may have produced a small stratospheric aerosol signal over southern Japan (GVN 2000c). Shortly after this explosive event, the volcano entered into an extended phase of voluminous passive SO_2 release, peaking on December 7, 2000 when SO_2 fluxes (measured by COSPEC) of ~230 kt/day were recorded, which may be the highest passive SO_2 flux measured at any volcano to date (K. Kazahaya, pers. comm. 2001). The entire EP TOMS dataset for Miyake-jima has yet to be checked, but currently 14 days of volcanic cloud observations have been made at the volcano, spanning the period from the August

18 explosion until September 14, 2000. This presumably represents the most vigorous period of degassing, when plumes were reaching sufficient altitudes to be detected easily by EP TOMS. With the exception of the August 18 cloud, no ash has been detected by EP TOMS in Miyake-jima emissions, and to date no further SO_2 emissions from the volcano (after September 14, 2000) have been found in TOMS data, including the period around December 7, 2000 when the maximum SO_2 flux was measured using ground-based techniques.

Etna

Etna is known for its persistent summit degassing that has been maintained for many years (e.g. Allard 1997), but SO_2 emissions from Etna have only rarely been detected by TOMS. Recent analysis of notable eruptive events in Etna's past (such as the September 1980 eruptions) which were detected in TOMS data suggest that there may be several more such events as yet undiscovered in the database. To verify this will require more detailed analysis of the daily TOMS images.

Etna's most recent eruption, and one of its most spectacular of recent times, occurred in July-August 2001 when lava flows descended the southern flanks of the volcano and a new cinder cone was constructed (INGV, 2001). Despite the impressive eruptive plumes produced by the volcano during July 2001, EP TOMS only detected weak signals associated with this eruption. These signals appeared in EP TOMS Ozone data (indicative of SO_2 emissions close to TOMS detection limits) on 3 (or possibly 4) days in late July (July 25, 27, 28 [possibly] & 31), and consisted of small plumes extending from Etna towards the SE (e.g. Figure 5), except on July 31 when the signal was NE of Etna over mainland Italy. The first detection on July 25 corresponded with increasing magmatic activity and rates of growth at the Piano del Lago cone that was created during the 2001 eruption. The period from July 27-31 was perhaps the most vigorous phase of the eruption, after which activity began to diminish until the eruption ceased on August 10 (INGV 2001). Thus, as is often the case, EP TOMS succeeded in detecting the emissions associated with the most vigorous phase of a relatively non-explosive eruption.

We have attempted to derive quantitative estimates of the SO_2 masses that were implied by the observed EP TOMS Ozone signals. This assumes that the apparent increase in ozone over the volcano is entirely due to SO_2, which masquerades as ozone due to similar absorption bands of the two gases in the UV. Biomass burning is another potential source of tropospheric ozone, but we discount this as a source of the signal due to the relatively unvegetated slopes of Etna, and we assume no short-wavelength local variations in stratospheric and upper tropospheric ozone due to other causes. Using the procedure briefly outlined above, we arrive at estimated SO_2 masses of ~1.8 kt and ~2.7 kt on July 25 and 27, respectively. These are rather modest values, but may represent a small amount of SO_2 reaching higher altitudes than the bulk of the emissions from the eruption, with the latter ‘lost’ in the background TOMS signal.

The future of EP TOMS

EP TOMS, in its fifth year of operation, continues to function at the time of writing (January 2002) and is still able to detect volcanic clouds, as evidenced by the January 2002 eruption of Nyiragongo (NASA Earth Observatory Newsroom 2002). However, the instrument has developed technical problems since 2000, which are likely to impact its long-term future. A major degradation in the throughput of EP TOMS has been noticed since late 2000, with more than 70% of the original transmission lost to date. Unless the rate of change decreases, EP TOMS data will have little value after the end of 2002. The instrument has also has developed a serious cross-track spectral bias that results in shifts of the retrieved background SO_2 of 10 - 20 DU over most latitudes. This offset increases the uncertainty of our eruption tonnage estimates.

Furthermore, the planned successor to EP TOMS failed to achieve orbit in September 2001 (Table 1). It is believed that the launch rocket released the QuikTOMS satellite at a lower altitude and velocity than intended and that it did not achieve a stable orbit for this reason. The failure of QuikTOMS to achieve orbit has cast doubt on the plan to continue measuring volcanic emissions without interruption until the next generation of UV sensor is launched, and has expedited the need to prolong the life of the aging EP TOMS. Recently it seems that the rate of degradation of EP TOMS may have slowed, which may allow its life to be prolonged until the launch of OMI in 2004.

UV remote sensing of volcanic emissions in the post-TOMS era

The next few years will see the launch of instruments with the capabilities to build on and enhance the extensive heritage of the TOMS satellites with regard to volcanic emissions monitoring (Table 8). Most important of these will be OMI, which will be launched on EOS Aura in 2004 to serve its primary purpose of continuing the global ozone mapping mission begun by the TOMS instruments. Our group is currently involved with the development of SO_2 retrieval algorithms for OMI, based on experience gained over the 22-year TOMS era. A long OMI mission could extend the volcanic record until the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Ozone Mapping and Profiler Suite (OMPS) instruments operationally measure volcanic eruptions starting in 2009 (Table 8).

OMI will offer several improvements over TOMS which will greatly reduce the detection limits of the instrument (Table 9), including a smaller footprint area, measurement of multiple wavelengths (740 compared to 6 on TOMS) and reduced radiometric noise levels. Footprint area is unimportant when the cloud is larger than the footprint, but sub-pixel clouds produce absorption equivalent to the average amount of SO_2 distributed across the full pixel. This effect limits the minimum SO_2 mass that can be detected. Thus, decreasing the footprint area allows detection of smaller eruption clouds. OMI will have 1/5th the footprint area of EP TOMS (Table 8), and will also offer a special 13 x 13km mode for occasional use, which will permit detection and tracking of even smaller SO_2 clouds and, potentially, passive degassing signals (Table 9). Parallel wavelength sampling with OMI will produce a greater signal:noise than the serial sampling TOMS, and OMI will measure many more wavelengths. In principle, these two factors can produce a lower noise level in OMI SO_2 retrievals. The potential capabilities of multiple wavelength UV sensors such as OMI have been demonstrated by retrievals using data from the Global Ozone Monitoring Experiment (GOME) on ERS-2 (Table 8). With an SO_2 noise standard deviation of 0.4 DU, Eisinger & Burrows (1998) obtained the first detection of industrial SO_2 from space. We are also evaluating the possibilities of the forthcoming Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY; Table 8) for use in remote sensing of volcanic emissions.

Although procedures to quantitatively retrieve SO_2 from infrared (IR) satellite data, such as that collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Spaceborne Thermal Emission Spectrometer (ASTER), both on the EOS/Terra platform (Table 8), are being developed (e.g. Realmuto et al. 1997; Realmuto 2000), they have yet to achieve the sensitivity of UV techniques. These IR methods exploit SO_2 absorption bands at 7.3 and 8.7 ìm but suffer from problems due to competing water vapour absorption in the same wavelength region, and the background emissivity must also be characterized, although they do offer higher spatial resolution than UV sensors (Table 8). Unlike UV methods, IR techniques fail if the target is opaque, as for very fresh eruption clouds. However, IR sensors offer the potential of SO_2 detection by day and night (UV instruments only work by day), and so a combination of UV and IR instruments is necessary to enable detection of volcanic clouds under all possible conditions.

Summary

During approximately 5300 days of operation between 1978 and 1993, Nimbus-7 TOMS detected volcanic clouds on 467 days, or 1 cloud every 11-12 days on average. EP TOMS operated for around 1600 days between its launch in 1996 and the end of 2001, detecting volcanic clouds on 128 days; an average of 1 cloud every 12-13 days. The vast majority of SO_2 and ash clouds originate from volcanoes of the Pacific Rim and Indonesia, though the African volcano Nyamuragira (along with Nyiragongo) is clearly a target that requires constant surveillance. Although the Nimbus-7 TOMS era saw a higher incidence of major explosive eruptions (Bluth et al. 1993, 1997), the EP TOMS results to date suggest that, even during relatively quiescent periods, a more sensitive instrument will detect volcanic events at a similar frequency by capturing eruptions of smaller size. Such eruptions can be as hazardous to aircraft as much larger events, making detection and tracking of small volcanic clouds crucial for effective hazard mitigation. The success of EP TOMS in detecting smaller events bodes well for the next generation of higher resolution UV instruments such as OMI, though the best scenario for future volcanic cloud remote sensing would be the concurrent operation of UV and IR sensors, ideally from geostationary platforms, thus enabling detection of volcanic emissions within minutes of eruption by day and night.

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Table 1. *TOMS missions 1978-2001*

Satellite	Activation/ Ending dates	Nadir footprint (km)	SO_2 detection limit (tons)*	Eruptive events detected†	Days tracked‡
Nimbus-7	November 1, 1978 May 6, 1993	50	10700 (1ó = 6 DU)	132	467
Meteor-3	August 22, 1991 December 24, 1994	62	16460 (1ó = 6 DU)	29	76
Earth Probe	July 17, 1996 Operating, Jan 2002	24 (Launch – Sept 97) 39 (Nov 97 – present)	1440 (1ó = 3.5 DU) 3800 (1ó = 3.5 DU)	39	128
ADEOS	September 11, 1996 June 30, 1997	42	3780 (1ó = 3 DU)	4	21
QuikTOMS	Failed at launch, September 21, 2001	42	-	-	-

* Computed for a cluster of 5 nadir pixels at 5ó; DU = Dobson Units or Milli Atm cm.
† Gives the total number of eruptive events detected by each TOMS mission.
‡ Gives the total number of days of TOMS volcanic cloud observations for each mission.

Table 2. *TOMS volcanic emissions database (1978-2001) organized by volcano*

Volcano*	Latitude	Type†	Events‡ (%)	SO_2 events§	No SO_2 events‖	Eruptions¶	Days tracked[1] (%)
Alaid	50.9°N	St	2 (1.0)	2	0	1	14 (2.1)
Ambrym	16.3°S	St	2 (1.0)	2	0	2	7 (1.1)
Augustine	59.4°N	LD	1 (0.5)	1	0	1	1 (0.2)
Banda Api	4.5°S	C	1 (0.5)	1	0	1	3 (0.5)
Bezymianny	56.0°N	St	5 (2.6)	2	3	5	6 (0.9)
Bulusan	12.8°N	St	1 (0.5)	0	1	1	1 (0.2)
Cameroon	4.2°N	St	2 (1.0)	2	0	2	5 (0.8)
Canlaon	10.4°N	St	1 (0.5)	1	0	1	1 (0.2)
Cerro Azul	16.3°S	Sh	2 (1.0)	2	0	2	23 (3.5)
Cerro Hudson	45.9°S	St	3 (1.6)	3	0	1	20 (3.0)
Cerro Negro	12.5°N	CC	1 (0.5)	0	1	1	6 (0.9)
Chikurachki	50.3°N	St	2 (1.0)	2	0	1	5 (0.8)
Cleveland	52.8°N	St	3 (1.6)	1	2	3	3 (0.5)
Colo (Una Una)	0.2°S	St	10 (5.2)	2	8	1	14 (2.1)
El Chichón	17.4°N	LD	2 (1.0)	2	0	1	33 (5.0)
Etna	37.7°N	Sh	3 (1.6)	3	0	2	6 (0.9)
Fernandina	0.4°S	Sh	3 (1.6)	3	0	3	13 (2.0)
Galunggung	7.3°S	St	24 (12.4)	24	0	1	33 (5.0)
Heard	53.1°S	St	1 (0.52)	1	0	1	1 (0.2)
Hekla	64.0°N	St	2 (1.0)	2	0	2	5 (0.8)
Karkar	4.6°S	St	2 (1.0)	2	0	1	5 (0.8)
Kelut	7.9°S	St	1 (0.5)	1	0	1	2 (0.3)
Kliuchevskoi	56.1°N	St	3 (1.6)	3	0	2	6 (0.9)
Krafla	65.7°N	C	3 (1.6)	3	0	3	23 (3.5)
Langila	5.5°S	CV	1 (0.5)	1	0	1	1 (0.2)
Lascar	23.3°S	St	1 (0.5)	1	0	1	7 (1.1)
Lonquimay	38.4°S	St	1 (0.5)	0	1	1	21 (3.2)
Lopevi	16.5°S	St	1 (0.5)	1	0	1	1 (0.2)
Makian	0.3°N	St	1 (0.5)	1	0	1	7 (1.1)
Makushin	53.9°N	St	1 (0.5)	1	0	1	1 (0.2)
Manam	4.1°S	St	2 (1.0)	2	0	2	3 (0.5)
Marchena	0.3°N	Sh	1 (0.5)	1	0	1	3 (0.5)
Mauna Loa	19.5°N	Sh	1 (0.5)	1	0	1	15 (2.3)
Mayon	13.3°N	St	1 (0.5)	1	0	1	4 (0.6)
Merapi	7.5°S	St	2 (1.0)	0	2	2	2 (0.3)
Miyakejima	34.1°N	St	1 (0.5)	1	0	1	14 (2.1)
Mt St Helens	46.2°N	St	6 (3.1)	3	3	1	12 (1.8)
Nevado del Ruiz	4.9°N	St	3 (1.6)	3	0	1	7 (1.1)
Nyamuragira	1.4°S	Sh	12 (6.2)	12	0	12	127 (19.1)
Oshima	34.7°N	St	1 (0.5)	1	0	1	1 (0.2)
Pacaya	14.4°N	CV	1 (0.5)	0	1	1	2 (0.3)
Pagan	18.1°N	St	1 (0.5)	1	0	1	2 (0.3)
Pavlof	55.4°N	St	4 (2.1)	2	2	3	6 (0.9)
Pinatubo	15.1°N	St	3 (1.6)	3	0	1	60 (9.0)
Popocatépetl	19.0°N	St	5 (2.6)	5	0	1	6 (0.9)
Rabaul	4.3°S	PS	1 (0.5)	1	0	1	5 (0.8)
Redoubt	60.5°N	St	8 (4.1)	2	6	1	9 (1.4)
Rinjani	8.4°S	St	17 (8.8)	7	10	1	23 (3.5)
Sangeang Api	8.2°S	CV	1 (0.5)	0	1	1	1 (0.2)
Shishaldin	54.8°N	St	1 (0.5)	1	0	1	3 (0.5)
Shiveluch	56.7°N	St	3 (1.6)	0	3	3	4 (0.6)
Sierra Negra	0.8°S	Sh	1 (0.5)	1	0	1	7 (1.1)
Soputan	1.1°S	St	8 (4.1)	5	3	5	15 (2.3)
Soufriere Hills	16.7°N	St	10 (5.2)	4	6	1	10 (1.5)
Soufriere St Vincent	13.3°N	St	2 (1.0)	1	1	1	2 (0.3)
Spurr	61.3°N	St	3 (1.6)	3	0	1	21 (3.2)
Tungurahua	1.5°S	St	3 (1.6)	3	0	1	3 (0.5)
Ulawun	5.1°S	St	4 (2.1)	4	0	4	12 (1.8)
Westdahl	54.5°N	St	1 (0.5)	0	1	1	1 (0.2)
Wolf	0°	Sh	1 (0.5)	1	0	1	12 (1.8)

* Volcanoes in italics indicate the weakest volcanic cloud signals (typically 1-2 anomalous pixels slightly above noise levels in the region of the volcano on dates of known eruptive events).
† Follows the classification of Simkin and Siebert (1994). C: Caldera; CC: Cinder cone(s); CV: Complex volcano; LD: Lava dome(s); PS: Pyroclastic shield; Sh: Shield volcano; St: Stratovolcano.
‡ Gives the number of eruptive events detected by TOMS for each volcano. Percentage of the total (194) given in parentheses.
§ Gives the number of eruptive events producing detectable SO_2 for each volcano. These events may have produced SO_2 only, or SO_2 and ash.
|| Gives the number of eruptive events producing only detectable ash (in TOMS AI data) for each volcano (i.e. no detectable SO_2).
¶ Gives the number of eruptions detected by TOMS for each volcano. The total number of eruptions detected is 100 so percentages are not given.
1. Gives the total number of days of TOMS volcanic cloud observations for each volcano. Percentage of the total (666) given in parentheses.

Table 3. *TOMS volcanic emissions database (1978-2001) organized by volcano region*

Region*	Subregion*	Volcanoes† (%)	Events‡ (%)	Eruptions§	Days tracked‖ (%)
01	Italy	1 (1.7)	3 (1.6)	2	6 (0.90)
02	Africa – W & N	1 (1.7)	2 (1.0)	2	5 (0.75)
	Africa – Kenya to Zaire	1 (1.7)	12 (6.2)	12	127 (19)
03	Indian Ocean	1 (1.7)	1 (0.52)	1	1 (0.15)
05	Vanuatu & S	2 (3.3)	3 (1.6)	3	8 (1.2)
	Offshore New Guinea & Admiralty Is.	2 (3.3)	4 (2.1)	3	8 (1.2)
	New Britain	3 (5.0)	6 (3.1)	6	18 (2.7)
06	Sulawesi	2 (3.3)	18 (9.3)	6	29 (4.4)
	Lesser Sunda Islands	2 (3.3)	18 (9.3)	2	24 (3.6)
	Java	3 (5.0)	27 (14)	4	37 (5.6)
	Halmahera	1 (1.7)	1 (0.52)	1	7 (1.1)
	Banda Sea	1 (1.7)	1 (0.52)	1	3 (0.45)
07	Philippines - N	3 (5.0)	5 (2.6)	3	65 (9.8)
	Philippines - Central	1 (1.7)	1 (0.52)	1	1 (0.15)
08	Mariana Islands	1 (1.7)	1 (0.52)	1	2 (0.30)
	Izu & Volcano Islands	2 (3.3)	2 (1.0)	2	15 (2.3)
09		2 (3.3)	4 (2.1)	2	19 (2.9)
10		3 (5.0)	11 (5.7)	10	16 (2.4)
11	Aleutian Islands	4 (6.7)	6 (3.1)	6	8 (1.2)
	Alaska – Peninsula & SW	4 (6.7)	16 (8.3)	6	37 (5.6)
12	USA – W Coast States	1 (1.7)	6 (3.1)	1	12 (1.8)
13	Hawaii	1 (1.7)	1 (0.52)	1	15 (2.3)
14	Nicaragua	1 (1.7)	1 (0.52)	1	6 (0.9)
	Mexico – S	1 (1.7)	2 (1.0)	1	33 (5.0)
	Mexico – Central Belt & Durango	1 (1.7)	5 (2.6)	1	6 (0.9)
	Guatemala	1 (1.7)	1 (0.52)	1	2 (0.30)
15	Galápagos Islands	5 (8.3)	8 (4.1)	8	58 (8.7)
	Ecuador	1 (1.7)	3 (1.6)	1	3 (0.45)
	Colombia	1 (1.7)	3 (1.6)	1	7 (1.1)
	Chile – S & Argentina	1 (1.7)	3 (1.6)	1	20 (3.0)
	Chile – N, Bolivia & Argentina	1 (1.7)	1 (0.52)	1	7 (1.1)
	Chile – C & Argentina	1 (1.7)	1 (0.52)	1	21 (3.2)
16		2 (3.3)	12 (6.2)	2	12 (1.8)
17	Iceland – S	1 (1.7)	2 (1.0)	2	5 (0.8)
	Iceland – NE	1 (1.7)	3 (1.6)	3	23 (3.5)

* Numbered volcano regions (and named subregions within each region) correspond to those in Simkin and Siebert (1994): 01: Europe to Caucasus, 02: Africa & Red Sea. 03: Mid-East & Indian Ocean, 05: Melanesia & Australia, 06: Indonesia & Andaman Islands, 07: Philippines & SE Asia, 08: Japan, Taiwan & Marianas, 09: Kuriles, 10: Kamchatka, 11: Alaska, 12: Canada & Western USA, 13: Hawaii & Pacific Ocean, 14: Mexico & Central America, 15: South America, 16: West Indies, 17: Iceland & Arctic Ocean.

† Gives the number of volcanoes in each region/subregion responsible for eruptions detected by TOMS. Percentage of the total (60) given in parentheses.
‡ Gives the number of eruptive events in each region/subregion detected by TOMS. Percentage of the total (194) given in parentheses.
§ Gives the number of eruptions in each region/subregion detected by TOMS. The total number of eruptions detected is 100 so percentages are not given.
|| Gives the total number of days of TOMS volcanic cloud observations for each region/subregion. Percentage of the total (666) given in parentheses.

Table 4. *Summary of regional TOMS volcanic emissions observations (1978-2001)*

Region*	Volcanoes† (%)	Events‡ (%)	Eruptions§	Days tracked‖ (%)
01 Europe to Caucasus	1 (1.7)	3 (1.6)	2	6 (0.90)
02 Africa & Red Sea	2 (3.3)	14 (7.2)	14	132 (20)
03 Mid-East & Indian Ocean	1 (1.7)	1 (0.52)	1	1 (0.15)
04 New Zealand to Fiji	0	0	0	0
05 Melanesia & Australia	7 (12)	13 (6.7)	12	34 (5.1)
06 Indonesia & Andaman Islands	9 (15)	65 (34)	14	100 (15)
07 Philippines & SE Asia	4 (6.7)	6 (3.1)	4	66 (10)
08 Japan, Taiwan & Marianas	3 (5.0)	3 (1.6)	3	17 (2.6)
09 Kuriles	2 (3.3)	4 (2.1)	2	19 (2.9)
10 Kamchatka	3 (5.0)	11 (5.7)	10	16 (2.4)
11 Alaska	8 (13)	22 (11)	12	45 (6.8)
12 Canada & Western USA	1 (1.7)	6 (3.1)	1	12 (1.8)
13 Hawaii & Pacific Ocean	1 (1.7)	1 (0.52)	1	15 (2.3)
14 Mexico & Central America	4 (6.7)	9 (4.6)	4	47 (7.1)
15 South America	10 (17)	19 (9.8)	13	116 (17)
16 West Indies	2 (3.3)	12 (6.2)	2	12 (1.8)
17 Iceland & Arctic Ocean	2 (3.3)	5 (2.6)	5	28 (4.2)
18 Atlantic Ocean	0	0	0	0
19 Antarctica & S Sandwich Islands	0	0	0	0

* Numbered volcano regions correspond to those in Simkin and Siebert (1994).
† Gives the number of volcanoes in each region responsible for eruptions detected by TOMS. Percentage of the total (60) given in parentheses.
‡ Gives the number of eruptive events in each region detected by TOMS. Percentage of the total (194) given in parentheses.
§ Gives the number of eruptions in each region detected by TOMS. The total number of eruptions detected is 100 so percentages are not given.
‖ Gives the total number of days of TOMS volcanic cloud observations for each region. Percentage of the total (666) given in parentheses.

Table 5. *TOMS volcanic emissions database (1978-2001) organized by volcano type*

Volcano type*	Volcanoes† (%)	Events‡ (%)	Eruptions§	Days tracked‖ (%)
Stratovolcano	43 (72)	158 (81)	66	385 (58)
Shield	8 (13)	24 (12)	23	206 (31)
Lava domes	2 (3.3)	3 (1.5)	2	34 (5.1)
Caldera	2 (3.3)	4 (2.1)	4	26 (3.9)
Complx volc	3 (5)	3 (1.6)	3	4 (0.6)
Cinder cones	1 (1.7)	1 (0.52)	1	6 (0.9)
Pyroclastic shield	1 (1.7)	1 (0.52)	1	5 (0.75)

* Volcano classification corresponds to that in Simkin and Siebert (1994).
† Gives the number of volcanoes of each type responsible for eruptions detected by TOMS. Percentage of the total (60) given in parentheses.
‡ Gives the number of eruptive events detected by TOMS for each volcano type. Percentage of the total (194) given in parentheses.
§ Gives the number of eruptions detected by TOMS for each volcano type. The total number of eruptions detected is 100 so percentages are not given.
‖ Gives the total number of days of TOMS volcanic cloud observations for each volcano type. Percentage of the total (666) given in parentheses.

Table 6. *TOMS volcanic emissions database (1978-2001) organized by tectonic setting*

Tectonic setting*	Volcanoes† (%)	Events‡ (%)	Eruptions§	Days tracked‖ (%)
Subduction zones	49 (82)	165 (85)	71	432 (65)
Hotspots	11 (18)	29 (15)	29	234 (35)
Rifts	4 (6.7)	19 (9.8)	19	160 (24)
Pacific Rim (including Indonesia)	46 (77)	150 (77)	67	414 (62)
Pacific Rim (excluding Indonesia)	37 (62)	85 (44)	53	314 (47)
Atlantic Region	4 (6.7)	17 (8.8)	7	40 (6.0)
Pacific Region	52 (87)	159 (82)	76	487 (73)

* *Hotspots* covers Hawaii, Iceland, Galápagos Islands, DR Congo, Cameroon and the Indian Ocean; *Rifts* covers Iceland, DR Congo and Cameroon; *Atlantic Region* covers Iceland and the West Indies; *Pacific Region* covers the Pacific Rim (including Indonesia) plus Hawaii and the Galápagos Islands.

† Gives the number of volcanoes in each tectonic setting responsible for eruptions detected by TOMS. Percentage of the total (60) given in parentheses.

‡ Gives the number of eruptive events detected by TOMS for each tectonic setting. Percentage of the total (194) given in parentheses.

§ Gives the number of eruptions detected by TOMS for each tectonic setting. The total number of eruptions detected is 100 so percentages are not given.

‖ Gives the total number of days of TOMS volcanic cloud observations for each tectonic setting. Percentage of the total (666) given in parentheses.

Table 7. *Volcanic eruptions detected by the Earth Probe TOMS, 1996-2001*

Volcano (Region)	Latitude	Eruption date*	EP TOMS first detection date	Days tracked	Retrieved SO_2 (kt)†	Aerosol Index‡
Nyamuragira (DR Congo)	1.41ºS	Dec 1, 1996	Dec 2, 1996	~14	~500	negative
Manam (Papua New Guinea)§||	4.1ºS	Feb 9, 1997	Feb 9, 1997	1	low	-
Bezymianny (Kamchatka)§	55.98ºN	May 9, 1997	May 9, 1997	2-3	0	1.9
Popocatépetl (Mexico)§	19.02ºN	June 30, 1997	Jul 3, 1997	1	7	-
Soufriere Hills (Montserrat)§	16.72ºN	Aug 8, 1997	Aug 8, 1997	1	0	2.3
Soufriere Hills§	16.72ºN	Sep 27, 1997	Sep 27, 1997	1	0	2.3
Soufriere Hills§	16.72ºN	Oct 18, 1997	Oct 18, 1997	1	0	2.0
Soufriere Hills§	16.72ºN	Oct 19, 1997	Oct 19, 1997	1	low	2.4
Soufriere Hills§	16.72ºN	Dec 26, 1997	Dec 26, 1997	1	31¶	5.2
Soufriere Hills§	16.72ºN	Jul 3, 1998	Jul 3, 1998	1	2	-
Cerro Azul (Galápagos Is)	0.9ºS	Sep 15, 1998	Sep 16, 1998	~14	250	negative
Manam‡	4.1ºS	Oct 5, 1998	Oct 5, 1998	1	17	-
Nyamuragira	1.41ºS	Oct 17, 1998	Oct 18, 1998	~14	~1000	negative
Popocatépetl§	19.02ºN	Nov 25, 1998	Nov 25, 1998	1	10	-
Mt Cameroon (Cameroon)	4.20ºN	Mar 28, 1999	Mar 30, 1999	4	45	-
Shishaldin (Aleutian Islands)	54.75ºN	Apr 19, 1999	Apr 19, 1999	3	63	8.7
Soufriere Hills§	16.72ºN	Jul 20, 1999	Jul 20, 1999	1	16	2.6
Tungurahua (Ecuador)§	1.47ºS	Oct 17, 1999	Oct 17, 1999	1	0	2.0
Tungurahua§	1.47ºS	Nov 16, 1999	Nov 16, 1999	1	6	3.7
Nyamuragira	1.41ºS	Jan 27, 2000	Jan 29, 2000	~12	~300	-
Hekla (Iceland)	63.98ºN	Feb 26, 2000	Feb 27, 2000	3	180	negative
Miyake-jima (Japan)	34.08ºN	Aug 18, 2000	Aug 18, 2000	14	270	4.9
Ulawun (Papua New Guinea)	5.05ºS	Sep 28, 2000	Sep 29, 2000	3	37	8.7
Popocatépetl§	19.02ºN	Dec 15, 2000	Dec 15, 2000	1	23	-
Popocatépetl§	19.02ºN	Dec 18-19, 2000	Dec 19, 2000	2	26	2.3
Nyamuragira	1.41ºS	Feb 6, 2001	Feb 6, 2001	~22	962	negative
Cleveland (Aleutian Islands)	52.82ºN	Feb 19, 2001	Feb 19, 2001	1	6	4.6
Cleveland	52.82ºN	Mar 11, 2001	Mar 11, 2001	1	low	3.9
Cleveland	52.82ºN	Mar 19, 2001	Mar 20, 2001	1	0	2.1
Popocatépetl§	19.02ºN	Apr 28-29, 2001	Apr 29, 2001	1	4	1.7
Ulawun	5.05ºS	Apr 30, 2001	Apr 30, 2001	2	30¶	-
Shiveluch (Kamchatka)§	56.65ºN	May 22, 2001	May 22, 2001	1	0	2.8
Etna (Italy)||	37.73ºN	Jul 17, 2001	July 25, 2001	3	low	-
Soufriere Hills§	16.72ºN	Jul 29, 2001	Jul 30, 2001	1	33	-
Tungurahua§	1.47ºS	Aug 5, 2001	Aug 6, 2001	1	32	1.6

* Data sources: GVN (1996b, 1997a, b, c, 1998b, c, d, e, 1999a, b, c, 2000a, b, c, d, e, 2001a, b, c, d, e, f, g); Montserrat Volcano Observatory (MVO) unpublished data; Etna reports (http://www.ct.ingv.it/etna2001/main.htm).
† Gives current best estimate of the SO_2 mass detected by TOMS. *Low* denotes possible signals in SOI or Ozone data that are close to detection limits.
‡ Volcanic ash returns a positive Aerosol Index (AI) value; AI increases with increasing ash cloud optical depth and ash cloud altitude (e.g. Krotkov et al. 1999). Negative AI indicates the presence

of non UV-absorbing aerosols such as sulfate (Seftor et al. 1997). The maximum observed AI is given for each eruption that produced aerosols detected by TOMS, unless negative.
§ Denotes volcanoes displaying intermittent eruptive activity over a number of years. In this case, *Eruption date* refers to the date of the eruptive event considered most likely to have produced the cloud detected by TOMS, and not the date when unrest began.
|| Denotes eruptions that were detected in EP TOMS Ozone data only.
¶ Denotes SO_2 clouds truncated at the edge of a TOMS swath; hence these are minimum estimates of total SO_2 production.

Table 8. *Current and future instruments capable of mapping SO_2 clouds*

Instrument	Satellite	Data coverage dates	Spectral type	Features
GOME I	ERS-2	April 1995 - present	UV	960 km swath; not contiguous daily global coverage, 40×320 km ground resolution
EP TOMS	Earth Probe	July 1996 – present	UV	Contiguous daily global coverage, 39×39 km ground resolution
MODIS	EOS Terra, Aqua	Feb 2001 - present	IR	2330 km swath; contiguous global coverage every 1-2 days, 1 km ground resolution (IR)
ASTER	EOS Terra	Feb 2001 - present	IR	60 km swath; selective data acquisition, 90 m ground resolution (TIR)
SCIAMACHY	ENVISAT-1	March 2002 -	UV	960 km swath; not contiguous daily global coverage; 25×240 km ground resolution
OMI	EOS Aura	2004 -	UV	Contiguous daily global coverage; 13×24 km ground resolution
GOME II	EUMETSAT MetOp 1, 2, 3	2005 - 2020	UV	see GOME I
ODUS	GCOM-A1	2007 -	UV	non-sun-synchronous orbit; 2020 km ground resolution
OMPS	NPOESS	2008 - 2020	UV	Contiguous daily global coverage, 50x50 km ground resolution

Table 9. *Detection limit (3s above background) of passive SO_2 flux from a 5000m volcano for OMI and EP TOMS (after Nov 1997) nadir pixels*

Instrument	Minimum detectable SO_2 flux, tons/day		
	Plume velocity 1 m/s	Plume velocity 5 m/s	Plume velocity 10 m/s
EP TOMS (1s = 3.5 DU)	1010	5050	10100
OMI (plume traverses 13 km pixel width; 1s = 0.2 DU)	36	180	360
OMI (plume traverses 25 km length of pixel; 1s = 0.2 DU)	19	95	190
COSPEC	10	52	104
Typical volcano	100 – 5000	100 - 5000	100 – 5000

Figure captions

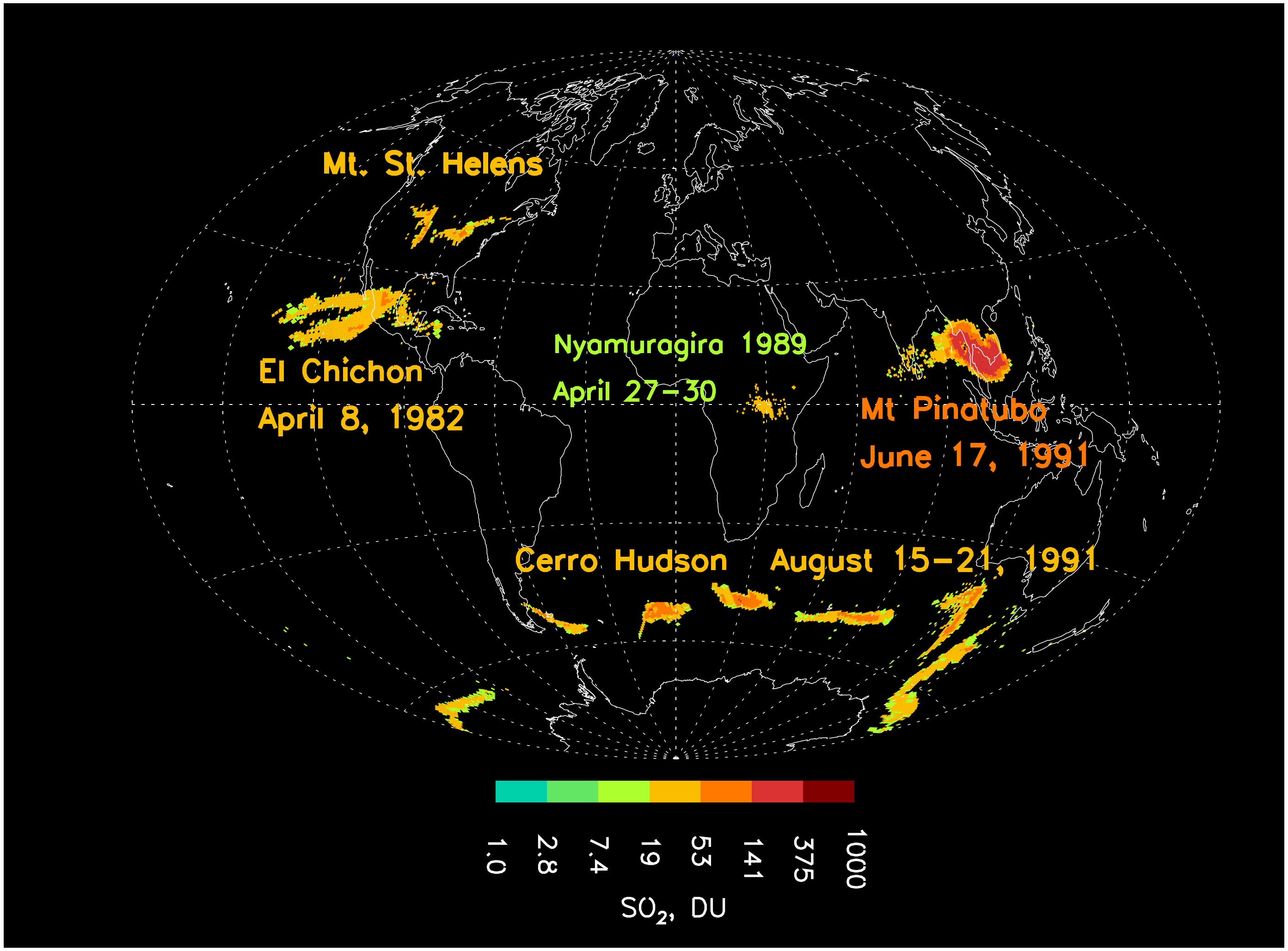
Fig. 1. Composite map of several large volcanic SO_2 eruption clouds measured by Nimbus-7 TOMS between 1978 and 1993 (Krueger et al. 2000). The volcanic clouds shown were produced by eruptions of Mt St Helens (USA; May 18, 1980), El Chichón (Mexico; April 4-5, 1982), Nyamuragira (DR Congo; April 24, 1989), Pinatubo (Philippines; June 15, 1991) & Cerro Hudson (Chile; August 15, 1991). Scale is in Dobson Units (DU).

Fig. 2. Plot showing the number of: volcanoes with TOMS-detected eruptions, TOMS-detected eruptive events, TOMS-detected eruptions, and days of TOMS volcanic cloud observations for each year between 1978 and 2001. A data gap between Meteor-3 TOMS and EP TOMS intervened in 1995.

Fig. 3. SO_2 clouds from recent eruptions of Nyamuragira, DR Congo (*triangle*) observed by EP TOMS. (a) February 6, 2001; (b) October 19, 1998. The data have been interpolated onto a 0.2°×0.2º grid to eliminate gaps between TOMS pixels. Note that the scale differs between plots.

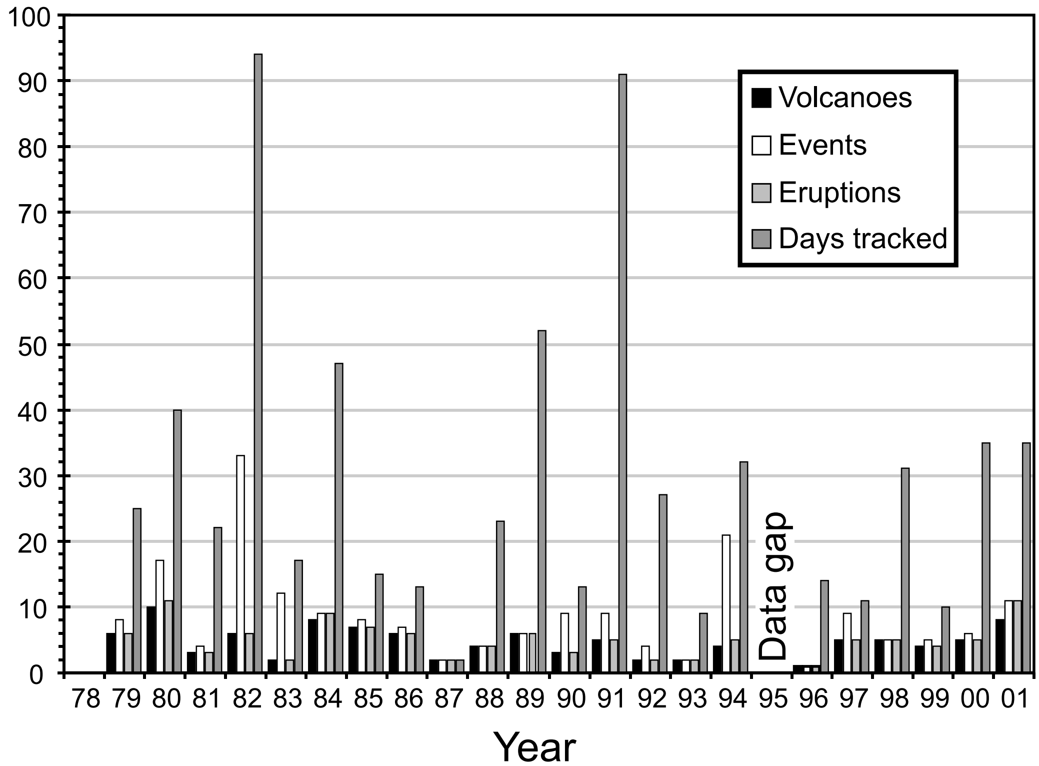
Fig. 4. SO_2 cloud from the February 26, 2000 eruption of Hekla, Iceland (*triangle*) as measured by EP TOMS on February 27. The data have been interpolated onto a 0.2°×0.2º grid to eliminate gaps between TOMS pixels. The cloud, which was wrapped around a rotating weather system, contained an estimated SO_2 mass of ~180 kt at this time. Note the problem of relatively high background SO_2 in the region of the cloud, and the data are cut off by the light terminator at the top of the image.

Fig. 5. Plot of EP TOMS Ozone data over Mount Etna, Sicily (*triangle*) on July 27, 2001. Note the relatively high ozone values over mainland Europe and the ozone 'plume' emerging from Etna, a result of SO_2 absorption. We estimate that this plume contained around 3 kt of SO_2.



Mt. St. Helens
El Chichon
April 8, 1982
Nyamuragira 1989
April 27-30
Mt Pinatubo
June 17, 1991
Cerro Hudson
August 15-21, 1991
1.0
2.8
7.4
19
53
141
375
1000
SO2, DU

Figure 1



100
90
80
70
60
50
40
30
20
10
0
Volcanoes
Events
Eruptions
Days tracked
Data gap
78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01
Year

Figure 2

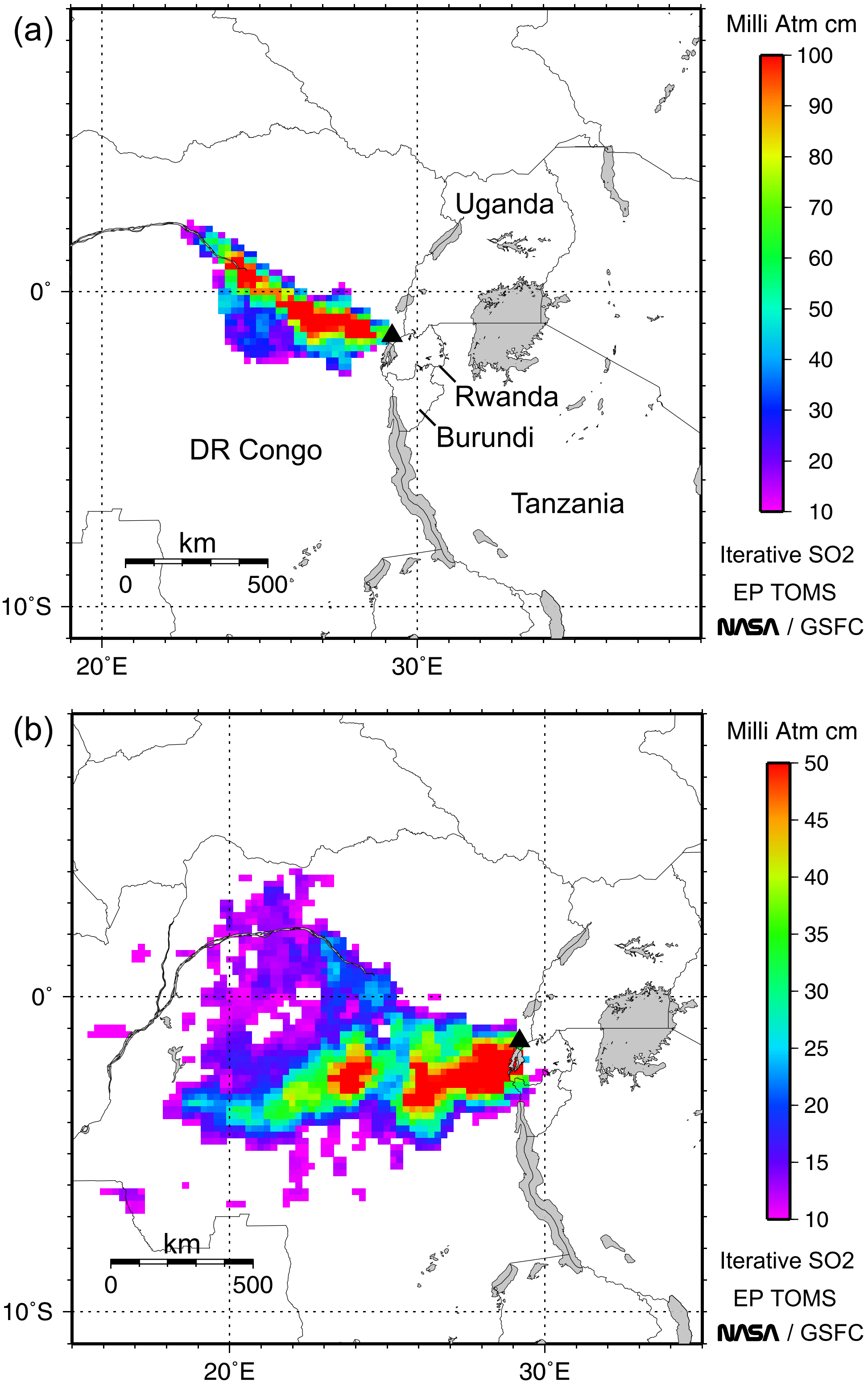

(a)
Milli Atm cm
100
90
80
70
60
50
40
30
20
10
Uganda
Rwanda
Burundi
DR Congo
Tanzania
km
0
500
0˚
10˚S
20˚E
30˚E
Iterative SO2
EP TOMS
NASA / GSFC
(b)
Milli Atm cm
50
45
40
35
30
25
20
15
10
km
0
500
0˚
10˚S
20˚E
30˚E
Iterative SO2
EP TOMS
NASA / GSFC

Figure 3

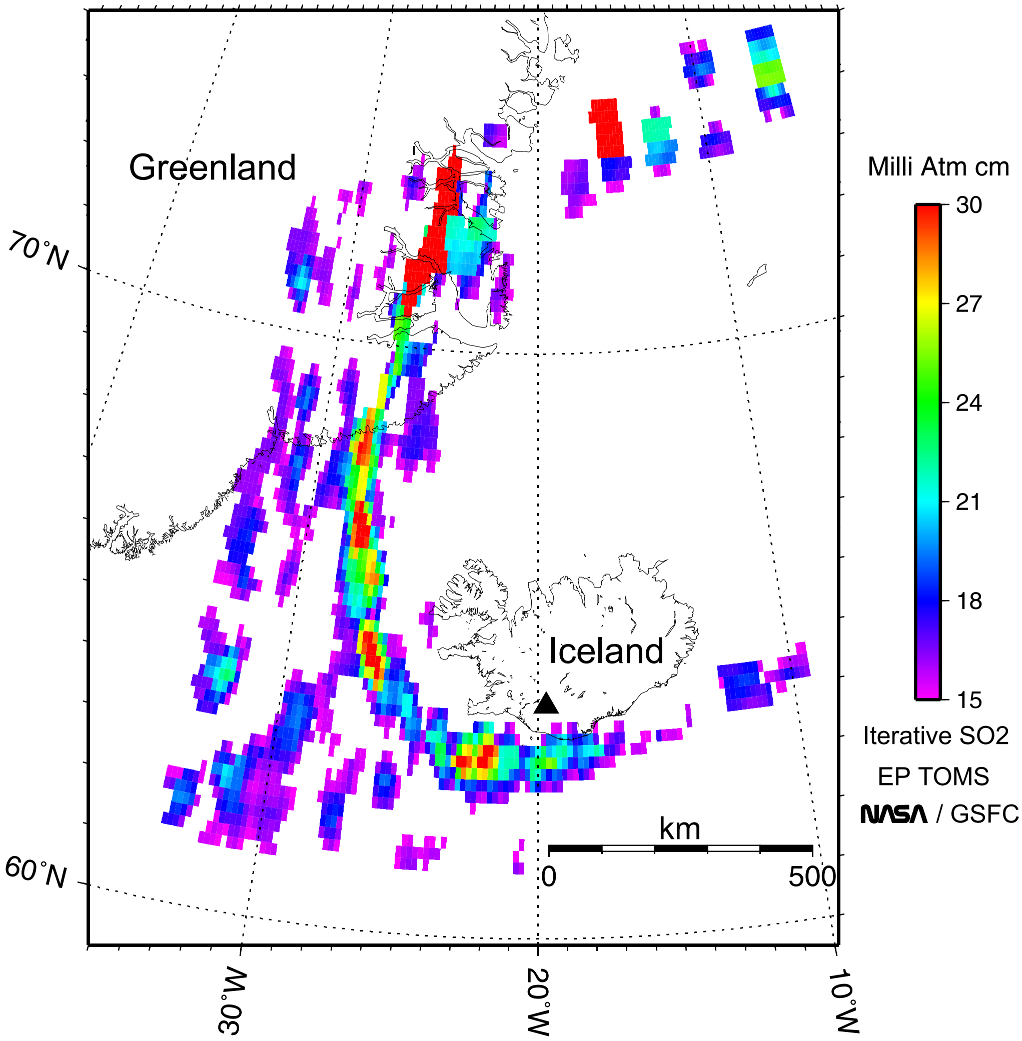

Greenland
70°N
60°N
Iceland
km
0
500
30°W
20°W
10°W
Milli Atm cm
30
27
24
21
18
15
Iterative SO2
EP TOMS
NASA / GSFC

Figure 4

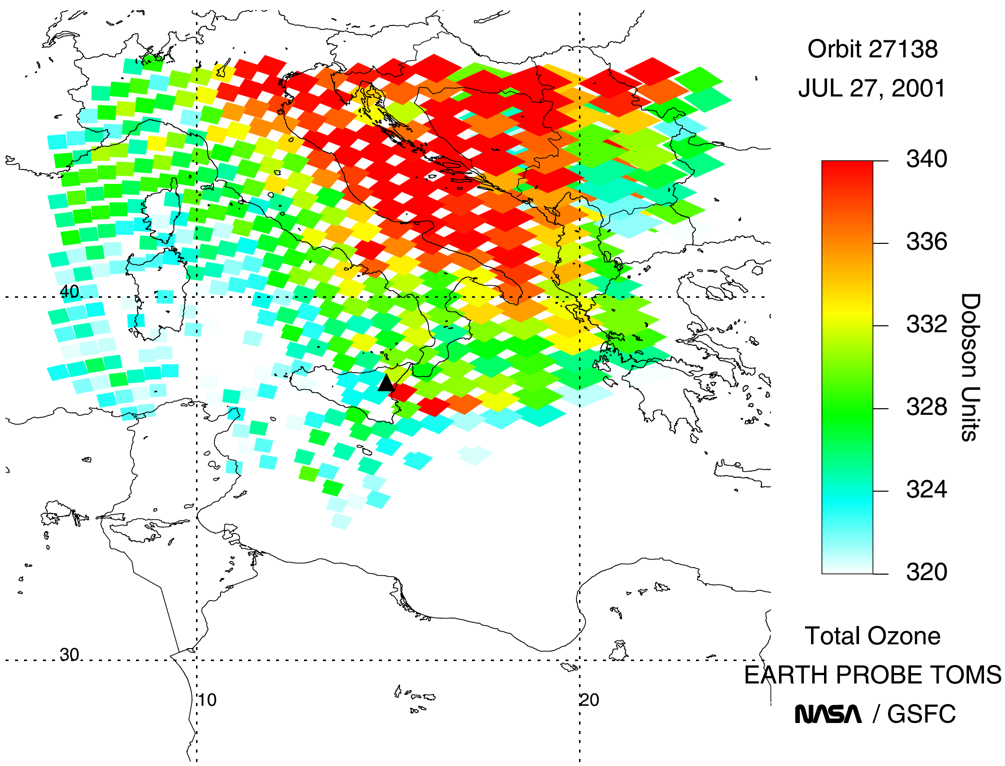

Orbit 27138
JUL 27, 2001
340
336
332
328
324
320
Dobson Units
40
30
10
20
Total Ozone
EARTH PROBE TOMS
NASA / GSFC

Figure 5