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Journal of Volcanology and Geothermal Research 63 (1994) 243–256

Journal of volcanology
and geothermal research

Evaluation of sulfur dioxide emissions from explosive volcanism: the 1982–1983 eruptions of Galunggung, Java, Indonesia

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Received 5 June 1993; accepted 9 March 1994

Abstract

Galunggung volcano, Java, awoke from a 63-year quiescence in April 1982, and erupted sporadically through January 1983. During its most violent period from April to October, the Cikasasah Volcano Observatory reported 32 large and 56 moderate to small eruptions. From April 5 through September 19 the Total Ozone Mapping Spectrometer (TOMS), carried on NASA's Nimbus-7 satellite, detected and measured 24 different sulfur dioxide clouds; an estimated 1730 kilotons (kt) of SO_2 were outgassed by these explosive eruptions. The trajectories, and rapid dispersion rates, of the SO_2 clouds were consistent with injection altitudes below the tropopause. An additional 300 kt of SO_2 were estimated to have come from 64 smaller explosive eruptions, based on the detection limit of the TOMS instrument.

For the first time, an extended period of volcanic activity was monitored by remote sensing techniques which enabled observations of both the entire SO_2 clouds produced by large explosive eruptions (using TOMS), and the relatively lower levels of SO_2 emissions during non-explosive outgassing (using the Correlation Spectrometer, or COSPEC). Based on COSPEC measurements from August 1982 to January 1983, and on the relationship between explosive and non-explosive degassing, approximately 400 kt of SO_2 were emitted during non-explosive activity. The total sulfur dioxide outgassed from Galunggung volcano from April 1982 to January 1983 is calculated to be 2500 kt (±30%) from both explosive and non-explosive activity. While Galunggung added large quantities of sulfur dioxide to the atmosphere, its sporadic emissions occurred in relatively small events distributed over several months, and reached relatively low altitudes, and are unlikely to have significantly affected aerosol loading of the stratosphere in 1982 by volcanic activity.

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SSDI 0377-0273(94)00024-B

1. Introduction

Large explosive eruptions such as that of El Chichón (VEI 4–5; VEI is the Volcanic Explosivity Index initiated by Newhall and Self, 1982) and Mount Pinatubo (VEI 6) appear to have emitted much more gaseous sulfur than can be easily explained by straightforward analyses and inventory of erupted magma (Luhr, 1991; Westrich and Gerlach, 1992). Such discrepancies have led to a renewed interest in assessing the total sulfur budget of volcanic eruptions. Volcanoes emit sulfur dioxide during both explosive eruptive events and during periods of non-explosive eruptive activity. In short-lived, powerful eruptions, such as those of Pinatubo in June 1991, the explosive emission of SO_2 is usually much greater than the non-explosive contribution. In contrast, non-explosive eruptions such as exhibited by Mauna Loa (typical eruption VEI 0) and Mount Etna (typical eruption VEI 1–2) outgas essentially all their sulfur non-explosively. To accurately assess the total sulfur budget for moderate strength volcanic activity (VEI 2–4), exhibited by Galunggung in 1982, it is important to simultaneously monitor both explosive and non-explosive outgassing of sulfur dioxide.

Concurrent explosive and non-explosive emissions, however, preclude the use of a single technique to measure SO_2 production given the current technology. Large SO_2 clouds need to be captured in their full spatial extent, regardless of associated water vapor and co-emitted tephra. The Total Ozone Mapping Spectrometer (TOMS) satellite instrument has proven to be an effective tool for observing the entire SO_2 clouds from large, explosive eruptions (Krueger, 1983; Bluth et al., 1993). The single daily overpass of the Nimbus-7 (1978–1993) or Meteor-3 (1991–present) satellites provides a consistent means of monitoring the Earth for large volcanic events. However, the TOMS instrument does not have the sensitivity to detect and measure low emission levels. The detection limit is approximately 5–10 kt per SO_2 cloud but this is highly dependent on the time between eruption and TOMS observation, scan angle and light level, regional weather conditions, and operating efficiency of the TOMS instrument.

Low-level, diffuse emissions require an instrument with much higher spatial and temporal resolution than TOMS. Ground-based or airborne instruments such as the Correlation Spectrometer (COSPEC) can measure outgassing from small eruptions, and daily low-level emissions (on the order of tons/day; Casadevall et al., 1981). But the COSPEC is used on relatively few eruptions because it must be transported to the eruption site. For many eruptions, joint use of the two instruments could give a more complete analysis of outgassed sulfur than either used independently.

Previous attempts to combine the two techniques met with only limited success, due primarily to the vastly different sensitivities. TOMS detected large amounts of emitted SO_2 during the first several days of the 1984 eruption of Mauna Loa, but individual eruption clouds were difficult to quantify (Walter et al., 1993). In this same period, the high rates of SO_2 outgassing saturated the COSPEC signal and measurements gave minimum values (Casadevall et al., 1984). At Redoubt volcano, Alaska, TOMS detected and tracked only a single SO_2 cloud for two days following the December 14–15, 1989 eruptions and a single cloud for one day following the March 9, 1990 eruption (Schnetzler et al., 1994). The COSPEC method was used to monitor daily outgassing beginning March 20, 1990 (Casadevall et al., 1990). Earlier use of COSPEC was hampered by darkness and low sun angle, and later by poor weather. Because of Redoubt's high latitude, operation of the TOMS instrument was similarly hampered by low light levels.

After nearly 63 years of dormancy, Galunggung volcano, Java (108°04′E, 7°15′S) began erupting on April 5, 1982 and continued intermittently through January 1983. The volcano and eruption chronology are described in detail by Katili and Sudradjat (1984). From the start of activity through September 1982, Galunggung erupted violently (VEI 2–4) at least 88 times. Eruption column altitudes from individual Vulcanian eruptions ranged from 8 to 21 km. From late September 1982 through January 1983, the energy of eruptions diminished and the eruption style changed from Vulcanian to Strombolian (Katili and Sudradjat, 1984). The eruptions forced 62,000 people to evacuate their homes, and caused at least 37 deaths (Smithsonian Institution/SEAN, 1989). The aim of this work is to combine the unique capabilities of different remote sensing techniques in order to more fully evaluate the sulfur dioxide degassing during the 10-month period of Galunggung's eruptive activity.

2. Methods

The TOMS instrument on board NASA's Nimbus-7 satellite was in operation from late 1978 to 1993. The satellite is in a sun-synchronous orbit around the Earth, making a complete observation of the Earth every day in 13.7 orbits (Krueger, 1983). Each orbit is comprised of a series of 2800-km-wide scans of 35 pixels each, with pixel resolution ranging from 50 km at the orbit center to about 200 km at the orbit edges. Each scan is completed in 8 seconds, thus the data comprising the complete Galunggung SO_2 clouds were collected within a few minutes, essentially giving a snapshot view of the eruption clouds. TOMS measures the reflected sunlight off the Earth's surface in six ultraviolet wavelengths. From this information, both total column ozone and sulfur dioxide are calculated, based on the decrease in reflected light due to absorption and scattering by these gases (Krueger, 1983). The uncertainty in TOMS measurements is inherently difficult to estimate, because there are very few opportunities to compare data with other techniques. Such an opportunity arose recently, when the SO_2 cloud emitted from the September 17, 1992 eruption of Mount Spurr, Alaska drifted over an operating Brewer spectrometer in Toronto, Ontario, during a TOMS overpass. Sulfur dioxide measurements of the two instruments agreed to within 20% (unpublished data); this is consistent with the cloud tonnage error estimate of ±30% of Krueger et al. (1990) which we use here.

Two sources of information were helpful in pinpointing major events and potentially large SO_2 clouds from the Galunggung eruptions: the reports of the Cikasasah Volcano Observatory, located 6 km from the active crater on the southeastern flank of the volcano, and the ash-cloud monitoring of the Geostationary Meteorological Satellite (GMS). The Cikasasah Observatory reported the relative magnitude and timing of eruptions (Katili and Sudradjat, 1984). Knowledge of eruption timing is vital, especially for less-powerful events, because the single daily overpass of Nimbus-7 means an eruption cloud might not enter the TOMS view for up to 24 hours. Small clouds may disperse within this 24-hour period and thus completely avoid detection; also, estimates of emitted SO_2 are based on the dispersion rate (calculated from TOMS measurements) of SO_2 clouds, so the time between eruption and observation must be known. The GMS is located at 140°E latitude over the equator (approximately 30°E of the volcano), providing visible and infrared images every 30 minutes to 4 hours, and has the ability to discern and track volcanic ash clouds based on their characteristic reflection of sunlight (Sawada, 1987).

The basic principles and techniques of the COSPEC instrument are described in Stoiber and Jepsen (1973); uncertainties in the method of detecting SO_2 loadings, described by Casadevall et al. (1981), normally range from ±10 to 50% depending mainly on weather conditions and availability of multiple measurements. The COSPEC is operated by aiming it through a sulfur-dioxide-bearing cloud, and measuring the modulation of incoming solar ultraviolet light in the characteristic spectral bands of sulfur dioxide. The instrument can be used to traverse an individual cloud by a moveable platform, either car or plane, or may be placed in a fixed location and scan transects across the emitted cloud. An airborne reconnaissance technique was originally attempted at Galunggung but was discontinued because the majority of SO_2 plumes remained below the rim of the newly formed crater

(Katili and Sudradjat, 1984). The fixed platform technique, with the instrument based at the Cikasasah Observatory, was used for all the successful measurements of the Galunggung eruptions (Badruddin, 1986). Measurement periods averaged about 30 minutes in length with typically one data collection period per day, usually during the morning.

3. Results

TOMS data for the 24 detected eruption clouds during the period from April to September 1982 are summarized in Table 1. During this time the Cikasasah Observatory reported approximately 32 "large" eruptions and 56 "medium", "small", or "mild" eruptions (some of these eruptions could be considered continuations of previous activity). TOMS detected SO_2 clouds from 23 of the 32 large eruptions between April 5 and September 19, and from one mild eruption on April 21. Most of the SO_2 clouds detected by the TOMS instrument were short lived and were observed on only a single day. After September 19, 1982, no additional Galunggung eruption clouds were detected by TOMS, although explosive activity continued until February 1983.

The emitted SO_2 values reported in Table 1 are calculated from TOMS measured tonnages. Measured tonnages are minimum values because of the sulfur dioxide loss rate due to physical dispersion and chemical conversion of the cloud during the time between eruption and satellite observation. This loss rate is highly dependent on cloud altitude. If the erupted SO_2 remains below the tropopause (in this region, approximately 16 km) there is more rapid oxidation, conversion to sulfuric acid and rainout than in the drier, relatively less reactive conditions in the stratosphere. With large stratospheric clouds this is a relatively minor correction because the amount lost at cloud boundaries is small relative to the mass of the SO_2 cloud (e.g., the Pinatubo SO_2 cloud mass decreased by less than 10% per day during the first week of observation; Bluth et al., 1992). In contrast, SO_2 tonnages of small, tropospheric sulfur dioxide clouds with a high perimeter to mass ratio are more affected by physical and chemical processes. Evidence from ground observations, comparisons of cloud movements with wind data, and satellite measurements indicated that the Galunggung SO_2 clouds were largely, if not completely, below the tropopause.

For Galunggung clouds observed on only one day (which were all clouds with masses smaller than 100 kt) we assumed a 50% loss of sulfur dioxide to detection per 24-hour period. This linear correction is an average based on Nimbus-7 TOMS observations of other tropospheric eruptions. For clouds that survived for longer than one day, the SO_2 tonnages were extrapolated to the time of eruption using the measured values. The emitted SO_2 value reported for the June 24 eruption was derived from TOMS measurements on and after the second day because data from some scans through the SO_2 cloud were not recovered during the first day of observation. The total SO_2 emitted from Galunggung using TOMS data in Table 1 is therefore estimated at 1730 kt.

Information on the Galunggung ash clouds from GMS data are presented in Table 2 (data from Sawada, 1987). Only GMS data for eruptions corresponding to TOMS-observed eruptions are included. From April to September GMS observed thirteen eruptions which were not found by TOMS; conversely, TOMS detected six eruptions which GMS did not observe. The earlier explosive eruptions from April to July produced relatively greater amounts of sulfur dioxide (in both area and mass) than the less powerful eruptions in August and September; in contrast, the emitted ash cloud areas as seen by GMS showed no signs of a systematic decrease with eruption strength until late September.

The TOMS SO_2 cloud images for the June 24 and July 13 eruptions are shown in Fig. 1. These images display rather dramatically the extent of the SO_2 clouds after the explosive activity, and the rapid dispersion of the clouds so that only a few days later they were no longer detectable. The July 14 TOMS image (Fig. 1d) shows two SO_2 clouds, one to the west and another stretching to the southwest. There are several peaks within the

Table 1
SO_2 cloud characteristics from TOMS observations of the 1982 Galunggung

Eruption dates (GMT)[a]	Dates observed (GMT)	Distance tracked[b] (km)	Cloud area (10^3 km^2)	Emitted SO_2 (kt)
April				
4–5 (21:00–00:40)	5 (04:41)	100 NE	10	10
8 (14:08–14:30)	9 (04:11)	600 WSW	50	85
21 (01:00–07:19)	21 (04:25)	over volcano	150	25
	22 (04:44)	over, E–W	160	
24 (21:55–22:12)	25 (03:56)	over, N–S	100	100
	26 (04:14)	500 ESE	110	
May				
5 (18:00–18:59)	6 (03:50)	over, N–S	160	100
	7 (04:10)	500 ENE	135	
17 (13:50–14:21)	18 (04:04)	1000 SE	85	100
17 (22:20–22:47)	18 (04:04)	200 SE	60	45
18 (15:23–16:00)	19 (04:23)	700 ESE	75	45
June				
3 (03:14–21:55)	4 (04:08)	800 WSW	475	220
	5 (06:08)	1700 WSW	400	
	6 (06:26)	2800 WSW	240	
24 (11:50–20:54)	25 (05:23)	600 W, SW	440	430
	26 (05:41)	800 WSW	775	
	27 (06:00)	1600 W	460	
July				
13 (04:40–16:15)	14 (04:18)	500 W, 400 SSE	N/A	
	15 (04:37)	200 NW–SE	835	355[c]
	16 (04:55)	200 NW–SE	715	
15 (10:48–12:00)	16 (04:55)	500 SE	95	45
15–16 (23:00–07:00)	16 (05:46)	200 ENE	75	20
16–17 (23:10–06:00)	17 (05:12)	400 SW	200	20
August				
15 (22:14–23:14)	16 (05:48)	400 WSW	15	10
25–26 (20:17–00:26)	26 (05:25)	300 W	35	15
27 (15:21–19:20)	28 (04:18)	100 SW	35	20
29 (03:19–06:45)	29 (04:37)	over, SW	75	10
30–31 (20:53–00:55)	31 (05:13)	200 W	35	15
September				
1–2 (21:05–01:08)	2 (04:07)	200 WSW	50	15
4 (02:04–05:35)	4 (04:44)	over volcano	85	10
14 (19:04–21:49)	15 (04:39)	over, SW	35	10
16 (08:25–17:04)	17 (05:15)	over, SW	50	10
18 (16:18–19:04)	19 (04:09)	over volcano	50	15

[a] From Cikasasah Volcano Observatory (Katili and Sudradjat, 1984). Local time is GMT +7 hours.

[b] Distance calculated from the volcano to the cloud center.

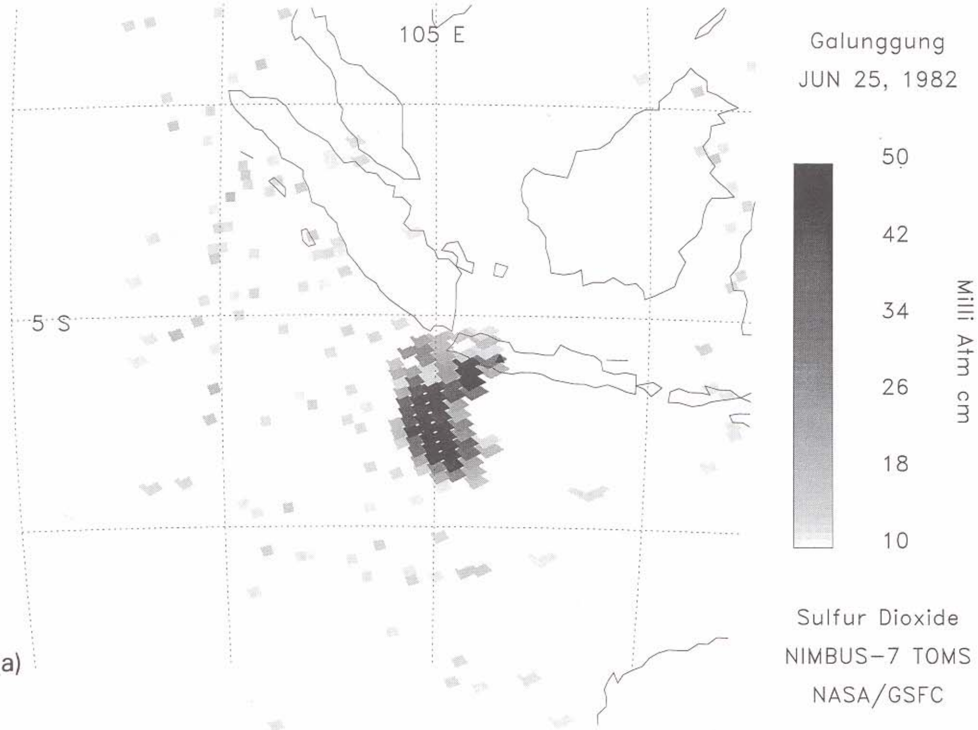
[c] Emission estimate made from second day of TOMS observation due to data losses.

Table 2
GMS observation of the 1982 Galunggung ash clouds corresponding to TOMS SO_2 observations (data from Sawada, 1987)

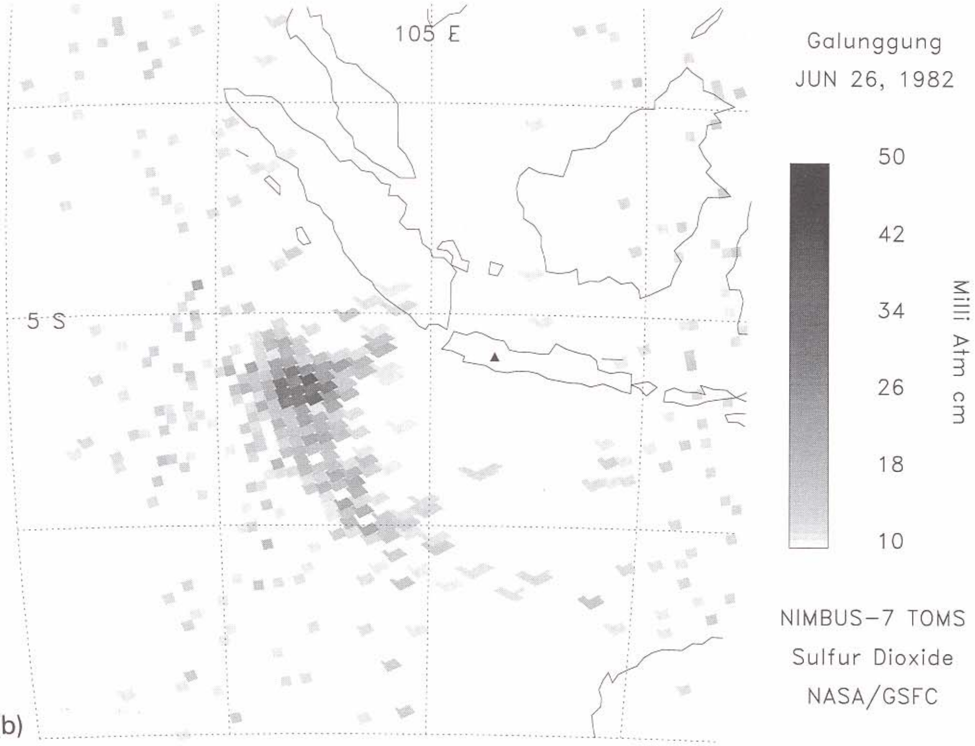
Eruption dates[a]	Dates observed (GMT)	Distance tracked[b] (km)	Maximum area (10^3 km^2)	Altitude[c] (km)
April				
4–5	5 (00:00–09:00)	100 N, NE	34	15.0
8	not observed			
21	not observed			
24	24–25 (22:30–00:00)	over volcano	13.5	17.8
May				
5	5–6(21:00–12:00)	over, NE, SW	190	16.2
17	17–18 (16:00–06:00)	400 SE	64	16.2
17	18–19 (00:00–00:00)	2000 SE	190	15.5
18	18–19 (09:00–03:00)	2000 SE	120	16.2
18	18–19 (16:00–12:00)	1500 SE, E	370	16.2
June				
3	not observed			
24	24–26 (16:00–03:00)	300 WSW	370	14.2
July				
13	13–14 (16:00–12:00)	200 E, SE	72	16.2
14	14–15 (00:00–06:00)	200 S	31	14.4
14	14–15 (06:00–06:00)	400 SE	88	15.0
15–16	15–16 (12:00–09:00)	400 SE	130	15.0
16–17	not observed			
August				
15	16 (00:00–16:00)	500 S, SW	250	13.5
25–26	25–26 (22:00–16:00)	200 WNW	75	N/A
27	27–28 (16:00–10:30)	100 WSW	275	10.2
29	29–30 (06:00–12:00)	500 SSW	150	N/A
30–31	30–31 (22:30–16:00)	300 SW	180	N/A
September				
2	2 (00:00–16:00)	500 SW	180	13.6
4	not observed			
14	not observed			
16	16 (16:00–22:30)	100 SW	30	N/A
18	18 (18:00–22:30)	100 SW	30	N/A

[a] Eruptions as reported in Table 1.
[b] Distance calculated from the volcano to the cloud center.
[c] Maximum cloud heights calculated using air-temperature profiles based on radiosonde data, and cloud-top temperatures inferred from GMS infrared photos.

Fig. 1. TOMS images for the two largest, June 24 and July 13, Galunggung eruptions in 1982. ▲ = the location of Galunggung volcano on the island of Java; gridlines are at 10° intervals. Disasters were twice narrowly averted when commercial aircraft encountered ash clouds from these eruptions. Both ash and gas clouds occupied the major air route from Southeast Asia to Australia, but dispersed after a few days. Data are shown in actual pixel dimensions from the TOMS instrument. (a) June 25, 05:23 GMT. (b) June 26, 05:41 GMT. (c) June 27, 06:00 GMT. (d) July 14, 04:18 GMT. Data were not recovered during a few scans near the southern tip of the cloud. (e) July 15, 04:37 GMT. (f) July 16, 04:55 GMT.


105 E
5 S
Galunggung
JUN 25, 1982
50
42
34
26
18
10
Milli Atm cm
Sulfur Dioxide
NIMBUS-7 TOMS
NASA/GSFC

(a)


105 E
5 S
Galunggung
JUN 26, 1982
50
42
34
26
18
10
Milli Atm cm
NIMBUS-7 TOMS
Sulfur Dioxide
NASA/GSFC

(b)

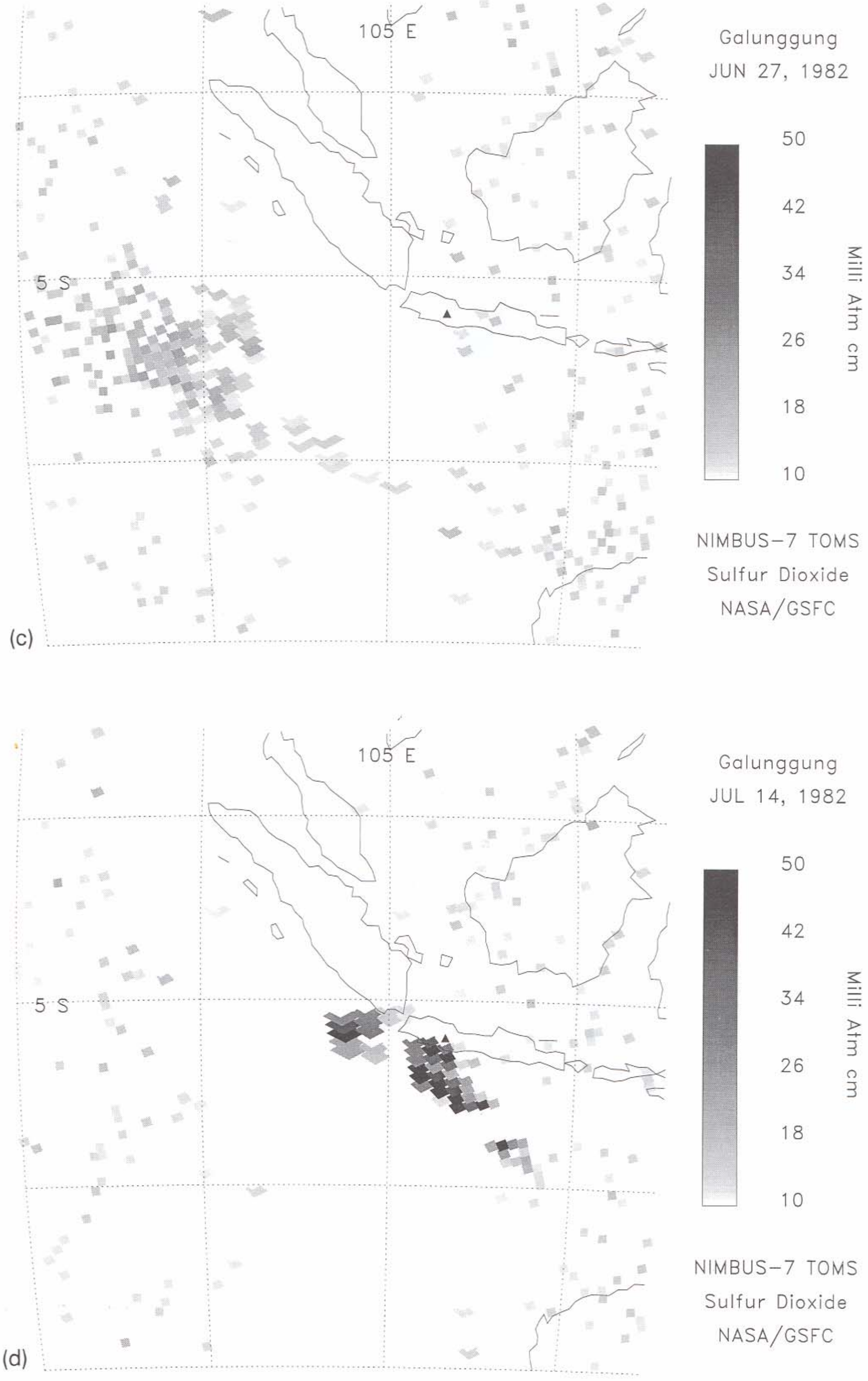


Fig. 1 (continued).

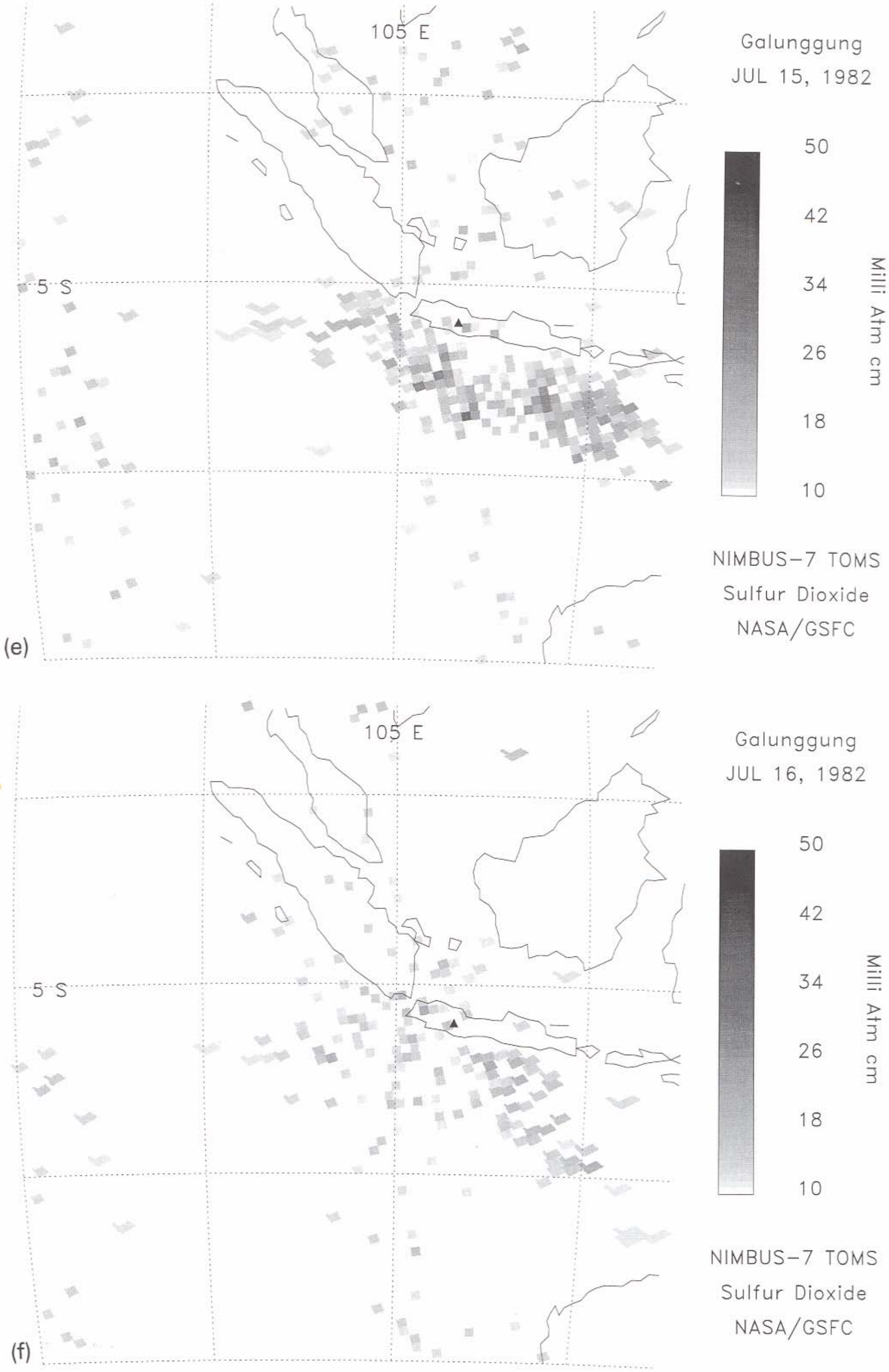


Fig. 1 (continued).

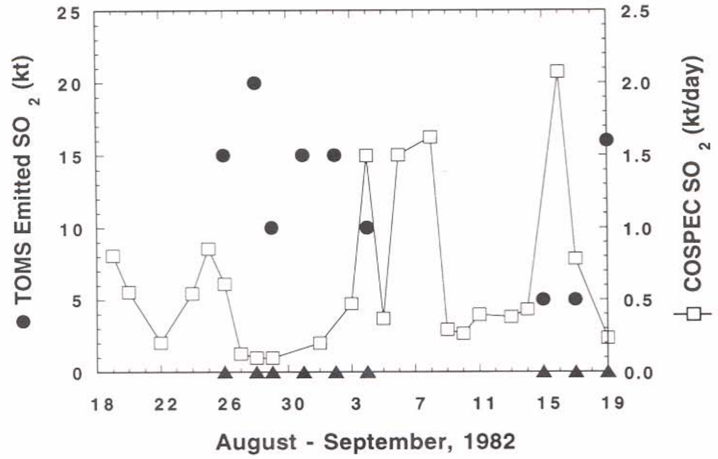


Fig. 2. Comparison of TOMS and COSPEC SO_2 data for a coincident period of record, August 19–September 19, 1982. ▲ = large Vulcanian eruptions reported by the Cikasasah Volcano Observatory. Note the different scales for TOMS and COSPEC data.

southwestern cloud, indicative of multiple eruptions from the July 13 activity. GMS also detected ash clouds from multiple eruptions during July 13 (Sawada, 1987). A strip of missing TOMS data scans (data lost between collection and transmission to the ground station) can be seen separating the southern end of the cloud from the main mass.

A period of explosive volcanism from August 19 to September 19 provided a unique opportunity to compare TOMS and COSPEC measurements (Fig. 2). During this time ten large eruptions were reported, with estimated VEI's ranging from 2 to 4. Nine of these eruptions produced SO_2 clouds that were also observed by TOMS. The COSPEC was operated for 25 measurement periods over 23 days during this interval. The measurement periods ranged from 5 to 165 minutes in length and the data were extrapolated to estimate daily amounts (Badruddin, 1986). However, during the months of August and September the COSPEC was never employed during a large explosive eruption; the instrument was in operation either several hours before or after the large events. In contrast to the TOMS results, the SO_2 peaks recorded from COSPEC measurements showed no systematic change with respect to the timing of the large eruptions. Thus it is probable that the two instruments were observing and measuring different SO_2 emissions from the volcano.

4. Discussion

4.1. Sulfur dioxide and ash cloud altitudes

A variety of data are available to estimate both ash and gas cloud altitudes including ground observations, ash cloud-top temperatures and meteorological conditions. For example, after the June 24 eruption, TOMS and GMS images both showed that the SO_2 and ash clouds drifted in similar trajectories. Sawada (1987) inferred an ash cloud-top altitude of 14.2 km from the GMS ash temperature data. Ground observations and ash cloud-top temperatures inferred from NOAA-7 satellite data cited in Katili and Sudradjat (1984) placed the maximum ash cloud altitude at 13–14 km. Hanstrum and Watson (1983) used meteorological data to conclude that the major dispersion of the ash cloud was occurring above 10 km altitude by fitting wind speed/trajectories to GMS-observed cloud positions. From TOMS data, the SO_2 cloud drifted to the west of the volcano at approximately 10 m/s and steadily dispersed (Fig. 1a–c). This drift speed and direction is consistent with winds at 10–15 km altitude, based on data from the National Meteorological Center (NMC). Thus, based on the above evidence it appears that the June 24 SO_2 cloud was slightly below the tropopause.

After the July 13 eruption, two ash and gas plumes were observed (by GMS and TOMS, respectively) west and southeast of the volcano, indicating fairly dramatic vertical shearing. Cloud-top temperatures from GMS data suggested a maximum altitude of 16.2 km for the southeastern ash cloud (Sawada, 1987). Hanstrum and Watson (1983) compared GMS images with meteorological data to indicate that the southeastern ash cloud was traveling at speeds consistent with winds at or above 10–12 km. They calculated that the western ash cloud was at or below 5 km altitude. The last view of the southeastern ash cloud by GMS on 09:00 July 16 showed the cloud approximately 1000 km southeast of the volcano. Advanced Very High Resolution Radiometer (AVHRR) data showed the ash cloud reaching Australia by July 17 (Hanstrum and Watson, 1983).

TOMS data for July 14 show SO_2 in one cloud approximately 500 km west-northwest of the volcano, and a larger cloud stretching from the volcano to 800 km southeast (Fig. 1d). By July 15 the two clouds appeared as a continuous mass, stretching from 1000 km west of Galunggung to 1000 km southeast (Fig. 1e). The July 16 TOMS image shows that the SO_2 cloud had moved very little from the previous day (a possible artifact of SO_2 dispersion around the cloud perimeters), and evidence of new activity over and 100–200 km west of the volcano (Fig. 1f). Comparing SO_2 cloud positions with NMC wind data and using estimates of coincident ash cloud altitudes again suggest tropospheric altitudes for the sulfur dioxide emissions: less than 5 km for the west-northwestern cloud, and between 5 and 15 km for the southeastern cloud.

The ash cloud-top altitudes inferred from ash-temperature data from GMS (Sawada, 1987) indicated that some of Galunggung's explosive eruptions may have reached the tropopause (Table 2). However, for both the June 24 and July 13 eruptions, Hanstrum and Watson (1983) indicated somewhat lower, tropospheric altitudes for the bulk of the ash clouds. The TOMS data suggest that most of the sulfur dioxide emitted from Galunggung's large eruptions did not reach the stratosphere, based on the observation that tropospheric SO_2 clouds are short lived compared with stratospheric clouds. Estimates of gas cloud altitudes by comparing TOMS images with meteorologic conditions, and altitude estimates from visual and satellite observations of coincident ash clouds, also indicate that the majority of the SO_2 erupted by Galunggung was emplaced in the troposphere.

In cases where both the gas and ash were carried in similar directions, it is likely that both were injected to similar altitudes or the vertical wind shear was low. However, the fates of erupted ash and gas were not always identical: in eight instances of mutual detection and tracking by GMS and TOMS either the SO_2 and ash were carried in slightly divergent directions, or the cloud configurations differed. In several instances, the ash clouds showed more evidence of vertical shearing, which may indicate a greater vertical distribution of ash than of sulfur dioxide.

Aircraft encounters with clouds occurred after the two largest explosive events of the eruption sequence on June 24 and July 13 (Hanstrum and Watson, 1983; Sawada, 1987; Smithsonian Institution/SEAN, 1989). On June 24, three hours after an explosive event began, a British Airways jet flew into an ash and gas cloud at 11.5 km altitude, approximately 150 km southwest of the volcano. On July 13, 9 hours after the start of an explosive event, a Singapore Airlines jet encountered a plume about 200 km southeast of the volcano at a similar altitude. In both instances the planes lost engine power but were able to restart after frightening losses of altitude (Tootell, 1985). These were the first major, generally reported encounters of commercial jet aircraft with volcanic eruption clouds.

4.2. Sulfur dioxide tonnages

We can summarize the TOMS and COSPEC results to derive a total SO_2 emission from Galunggung. From Table 1, the 24 explosive eruptions detected by the TOMS instrument total 1730 kt of SO_2. To estimate the amount of SO_2

emitted by the 64 reported eruptions which were not detected by TOMS, we must account for eruptions below the TOMS detection limit of about 5–10 kt, and SO_2 dispersion between these eruptions and TOMS observation; using a fairly conservative 5 kt per eruption gives an estimate of approximately 300 kt. This amount must be regarded as very uncertain, but it is unlikely that these undetected eruptions produced more than a small percentage of the SO_2 actually observed by TOMS from the larger explosive eruptions.

SO_2 emissions during Galunggung's non-explosive activity can be estimated from tandem use of TOMS and COSPEC data. Table 3 gives the monthly breakdown of sulfur dioxide outgassing. During a coincident period of TOMS and COSPEC operation, approximately 120 kt were outgassed by explosive eruptions (estimated from the TOMS data), compared with the 20 kt of SO_2 derived from COSPEC measurements of non-explosive activity (COSPEC data were interpolated through days of non-operation, for an average of 600 tons/day). If this ratio remained the same throughout the most explosive period of Mount Galunggung, from April 5 to late September, the non-explosive outgassing would total about 350 kt of SO_2 (i.e., approximately one-sixth of the total SO_2 observed and inferred from TOMS data). From September 20 until the end of January COSPEC measurements indicate an additional 50 kt of SO_2 were outgassed.

Combining the totals from explosive and non-explosive outgassing, we estimate that Galunggung emitted approximately 2500 kt of SO_2 (±30%) from April 1982 to January 1983.

Only four eruptions, since the start of TOMS operation in late 1978, have been estimated to have produced more sulfur dioxide than Galunggung: Sierra Negra, Galápagos in 1979, Nyamuragira, Zaire in 1981, El Chichón in 1982, and Pinatubo in 1991 (Bluth et al., 1993). However, Galunggung's total emitted SO_2 occurred over about 10 months, while the other four eruptions were shorter-lived explosions occurring over periods on the order of days.

Throughout 1982 there was a remarkable quantity of sulfur dioxide emplaced into the atmosphere from eruptions of low-latitude volcanoes. In late December 1981, Nyamuragira volcano in Zaire erupted 4000 kt of SO_2, of which one-quarter to one-third was estimated to have reached the stratosphere (Schnetzler et al., 1991). In late March and early April 1982, El Chichón (Mexico) violently erupted 7000 kt of SO_2, most of which entered the stratosphere (Krueger, 1983; Bluth et al., 1992). In August of

Table 3
Monthly comparison of COSPEC and TOMS SO_2 data

Month	N	COSPEC SO_2[a] (avg tons/day)	COSPEC SO_2 (kt)	TOMS SO_2 (kt)
April 1982	–	–	–	220
May	–	–	–	290
June	–	–	–	650
July	–	–	–	440
August	10	437	14	70
September	26	658	20	60
October	24	428	13	–
November	29	256	8	–
December	11	218	7	–
January 1983	17	312	10	–
Aug. 19–Sep. 19	25	600	20	120

N = number of reported measurements.
[a] Data from Badruddin (1986).

the same year, Wolf volcano on the Galápagos Islands sent over 1000 kt of SO_2 into the atmosphere (Bluth et al., 1993). Galunggung's 2500 kt, spread over 10 months of activity, appears to have largely remained below the tropopause. This production of nearly 15 million tons (Mt) of sulfur dioxide within a 12-month period is second in the TOMS record only to the >21 Mt emitted during 1991 by the combination of Mount Pinatubo (Bluth et al., 1992) and Cerro Hudson (Doiron et al., 1991). In contrast, after excluding 1982 and 1991, the other 11 years of explosive volcanism in the period of Nimbus-7 TOMS operation, from 1979 to 1993, averaged less than 1.5 Mt/yr.

5. Conclusions

Galunggung volcano, Java began erupting April 5, 1982 and during its most violent period, from April to September, the volcano had approximately 88 explosive eruptions of varying strengths. The eruptions became less violent towards the end of September, but the volcano continued to erupt sporadically through January 1983.

TOMS detected and measured 24 separate sulfur dioxide clouds from April 5 to September 19. Most of the clouds were detectable for less than 2–3 days. The rapid dispersion of the SO_2 clouds, altitude estimates of co-emitted ash clouds, and comparison of cloud motion with tropospheric winds, suggest that most of the SO_2 remained below the tropopause. Correcting for SO_2 dispersion between eruptions and the TOMS daily overpass, we estimate approximately 1730 kt (±30%) were produced by the 24 explosive eruptions. An additional 300 kt of SO_2 were estimated to have been emitted by the 64 explosive eruptions which were below the cloud detection limit of TOMS.

For the first time both the TOMS and a COSPEC instrument were in operation during a simultaneous period of explosive volcanism. COSPEC data suggest that the two instruments were measuring different SO_2 emissions, and their combined results give a more accurate assessment of total SO_2 degassing of a volcano than either sensor used separately. During a 32-day period of coincident operation, the explosive outgassing estimated from TOMS produced approximately six times the the non-explosive emissions estimated from COSPEC data. If this ratio did not radically change over the course of activity from April to September, approximately 350 kt would have outgassed non-explosively. COSPEC data indicate that an additional 50 kt of SO_2 were emitted by the less-violent activity from the end of September 1982 to the end of January 1983. Combining all the estimates of SO_2 emissions, we estimate that between April 1982 and January 1983, Mount Galunggung outgassed 2500 kt (±30%) of sulfur dioxide from both explosive and non-explosive activity.

Acknowledgements

This work was funded through the NASA Headquarters Solid Earth Program. We thank the Global Volcanism Program at the Smithsonian Institution for information and helpful comments, and L. McClelland for his review of an early manuscript. This paper was improved through a review by F. Le Guern, and an especially thoughtful review by S. Self. I. Sprod provided technical assistance for TOMS data processing.

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