The contribution of explosive volcanism to global atmospheric sulphur dioxide concentrations

G. J. S. Bluth*, C. C. Schnetzler†, A. J. Krueger‡ & L. S. Walter‡

* Universities Space Research Association, Code 921, NASA/GSFC, Greenbelt, Maryland 20771, USA
† Geography Department, University of Maryland, College Park, Maryland 20742, USA
‡ Earth Sciences Directorate, NASA/GSFC, Greenbelt, Maryland 20771, USA

SULPHUR dioxide from volcanic eruptions may have a significant effect on the Earth's climate and atmospheric chemistry, and it is therefore important to quantify outgassing rates for all types of volcanic activity. Non-explosive volcanoes (for example, Mount Etna) outgas at relatively constant rates, providing an annual flux of about 9 million tons (Mt) SO_2 (ref. 1). By contrast, the outgassing from volcanoes prone to explosive eruptions (such as Mount Pinatubo) is sporadic and much more difficult to quantify. The total annual volcanic SO_2 flux is therefore poorly constrained, with ground-based estimates[1-8] ranging from 1.5 to 50 Mt—up to one-quarter of the estimated current anthropogenic contribution. The Total Ozone Mapping Spectrometer aboard the NASA satellite Nimbus 7 recorded SO_2 emissions from explosive eruptions from November 1978 to May 1993. We use these data to show that the annual flux from explosive volcanism is of the order of 4 Mt SO_2, less than half of the non-explosive output. Thus it seems that the total volcanic emission of SO_2 to the Earth's atmosphere is about 13 Mt yr^{-1}, which is only 5–10% of the current anthropogenic flux.

The recent eruption of Mount Pinatubo has rejuvenated the question of volcanic effects on global climate. The climatic impact of volcanic activity is potentially large because, in addition to the relatively consistent degassing of non-explosive volcanoes into the Earth's atmosphere, the infrequent bursts of explosive volcanoes such as Pinatubo have the ability to inject sulphur dioxide directly into the stratosphere. However, constraints on the SO_2 production from global volcanism have been elusive. Previous estimates of the annual sulphur dioxide flux due to volcanic activity, using ground-based methods, vary by more than a factor of 30 (Table 1)[1-8]. These estimates range from insignificant amounts to >25% of the present annual anthropogenic flux of ~190 million tons (Mt)[9]. Previous efforts to partition global SO_2 production into explosive and non-

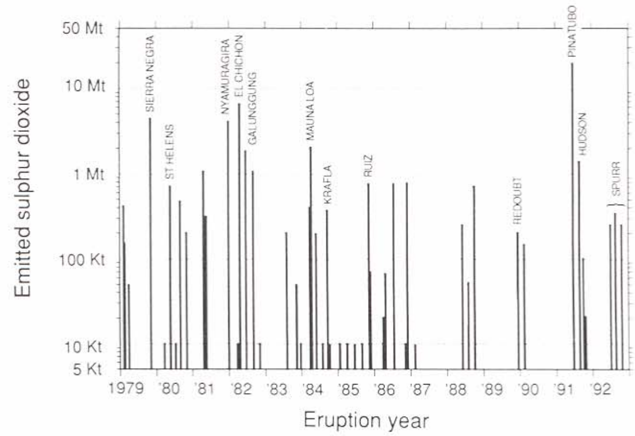

FIG. 1 Inventory of TOMS SO_2 data from explosive volcanic eruptions, 1979–1993. Most of the larger or well-known eruptions are labelled. Multiple eruptions from a single volcanic episode are combined, except for the three eruptions of Mt Spurr in 1992. The higher frequency of small eruptions observed before 1986 resulted from detailed searches through the TOMS database for all known eruptions using the Smithsonian Global Volcanism Network (GVN) database[12].

explosive activity suggest vastly different contributions: from SO_2 per year ratios of 1:14 (ref. 7) to 1:1 (ref. 1), caused primarily by their disparate evaluations of explosive outgassing. Thus, in order to determine the global volcanic emissions of sulphur dioxide, there is considerable need to constrain the production by explosive volcanoes.

Given the worldwide distribution of volcanoes in often inaccessible regions, and their unpredictable and hazardous natures, satellite observation can be an invaluable tool in assessing potential climatic effects of global volcanism. Volcanic SO_2 clouds since 1979 have been detected and tracked using data collected by the Total Ozone Mapping Spectrometer (TOMS) instrument. Total column sulphur dioxide in the Earth's atmosphere is calculated from the decrease in reflected ultraviolet sunlight due to absorption by this gas[10], with an estimated error of $\pm30\%$[11]. The

TABLE 1 Global sulphur dioxide flux from volcanoes (Mt yr^{-1})

Total annual	Explosive	Non-explosive	Method	Ref.
1.5			Calculated using a fixed percentage of SO_2 in magma, and total extruded material over the past 400 yr.	2
4			Same basic method as in ref. 2, but using (undefined) annual average volcanism.	3
10			Extrapolation from selected Central American volcanoes; submarine and 'very active' vents not included.	4
7.8			Using ref. 2 method but with a higher % SO_2 in the magma.	5
50			Extrapolated mainly from selected 1971–1980 volcanic activity.	6
15.2	1	14.2	Extrapolated from selected 1961–1979 volcanism to estimate several types of eruptive activity.	7
18.7	9.8	8.9	Surveyed non-explosive activity from 1981–82; extrapolated explosive activity using VEI/SO_2 outgassing of selected eruptions.	1
50			Calculated global annual volcanic Polonium output, and used an average measured SO_2/Po ratio for several volcanoes.	8

TOMS, with an average ground resolution of 66 km, is the only instrument capable of measuring the full extent of SO_2 emissions from large, explosive eruptions. However, smaller events and diffuse, non-explosive emissions are often below the level of TOMS sensitivity. Another limitation exists in assessing high latitude volcanic activity in the winter (for example, eruptions in Kamchatka, Alaska and Iceland) because of decreased daylight hours, and longer path lengths due to low sun angles reduce the precision of the SO_2 algorithm; however during the past 14 years most explosive eruptions have occurred at low and mid-latitudes[12].

From 1979 through 1992, the TOMS instrument detected 55 different volcanic eruptions out of more than 350 examined, with SO_2 ranging from 10 kilotons (the approximate detection limit) to 20 Mt emitted by the recent eruption of Mount Pinatubo[13] (Fig. 1). Some of these 55 eruptions represent consolidation of multiple events from the same volcano; for instance, 24 individual SO_2 clouds were detected from the eruption of Mount Galunggung over a six-month period in 1982 but are counted as a single volcanic event (G. J. S. B. *et al.*, manuscript submitted).

The simplest estimate of annual SO_2 output by explosive volcanism from the TOMS data is obtained from the sum of SO_2 from the 55 detected eruptions, 52 Mt, produced over 14 years of observation—an average of 4 Mt yr^{-1}. It can be seen from Fig. 1, however, that the distribution of this 'average output' is rather sporadic. The dataset is sensitive to the SO_2 emissions of the few largest eruptions. For example, one could argue that the TOMS database is simply dominated by two eruptions, El Chichón and Mount Pinatubo; removing these would halve the calculated annual SO_2 flux. Is the occurrence of these two eruptions in such a short timespan anomalous?

We may answer this question by linking the TOMS SO_2 data to a longer-term dataset, the Smithsonian Global Volcanism Network (GVN) compilation of eruption explosivity and frequency over the past 200 years. The Volcanic Explosivity Index (VEI)[14] categorizes volcanic eruptions primarily from the height of the eruption column and amount of emitted tephra. Based on this scale, the TOMS instrument detected every highly explosive eruption in the past 14 years (that is, the ten eruptions of VEI $\geq$ 4). Below VEI 4, the TOMS is less effective: its detection rate is ~33% for VEI 3 eruptions and ~10% for VEI 2 eruptions, using the GVN database[12] from 1979 to 1985 as the reported ground truth. The GVN data are incomplete below VEI 2, and thus we cannot directly evaluate TOMS SO_2 detection rates for VEI 0–1.

Among the TOMS-observed eruptions, there is a poor correlation between SO_2 output and explosivity of individual eruptions (Fig. 2). For example, the SO_2 emitted by El Chichón exceeded that of Mt St Helens by an order of magnitude, yet both were VEI 5 eruptions. Among the VEI 4 eruptions, TOMS SO_2 ranges over two orders of magnitude. Clearly, the SO_2 release of a given volcanic eruption cannot be inferred solely on the basis of VEI.

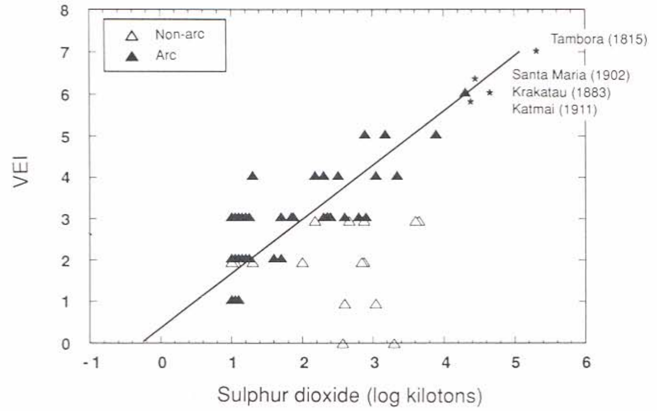

FIG. 2 SO_2 outgassing by explosive eruptions. Data are separated by tectonic regimes to show relative contributions of volcanic activity 1979–1993 as a function of explosivity. The TOMS SO_2/VEI regression line for VEI 2–6 ($r^2 = 0.999$) is determined from the average SO_2 for all VEI 4–6 eruptions, whereas VEI 2 and 3 averages are calculated using the respective TOMS detection rates (see text). Estimates of SO_2 emissions (asterisks) from several historical, highly explosive eruptions are added for comparison[16-18].

A general relationship between average sulphur dioxide emission and VEI has been observed, however[1]. Likewise in Fig. 2, a TOMS SO_2/VEI relationship is determined from average SO_2 amounts for each VEI level (VEI 2 and 3 averages reflect the TOMS' detection rates of these eruptions). We then used the relationship of eruption frequency to VEI over the past 200 years[15] to determine the annual eruptive activity for each VEI category. Multiplying the two (average SO_2 and number of eruptions from VEI 0–7) produced a total SO_2 flux from explosive volcanism of ~4 Mt, in agreement with the simple average of the total TOMS SO_2 database. This suggests that the dominance of the total by a few large eruptions is not unique to the past 14 years.

Differences in volcanism between non-arc (hot spot and rift zones) and arc (subduction zones) tectonic regimes are also important. Non-arc volcanoes typically erupt more frequently than arc volcanoes, but are less numerous worldwide; arc eruptions are by far the most violent[12]. The TOMS data in Fig. 2 show, for arc eruptions, a general increase in outgassed SO_2 with explosivity but non-arc activity is less dependent on VEI. Non-arc volcanoes typically degas more sulphur-rich magmas and emit relatively more sulphur dioxide for a given VEI. But when considering the two regimes on a global basis, we find a 2:1 ratio of arc to non-arc SO_2 outgassing—a ratio dominated by two arc eruptions, El Chichón and Pinatubo.

The TOMS instrument gives no direct information on cloud altitude; however, we may infer a stratospheric component of the global emission of SO_2, based on the associated explosivity of the eruptions. At VEI 3 and below, most plumes should, by definition[14], remain below the tropopause. Above VEI 3, eruption clouds should reach the stratosphere: in the TOMS database, 65% of the total 52 Mt SO_2 was emitted by eruptions of VEI 4 and above (Table 2).

We can use the TOMS instrument's ability to quantify SO_2 emitted by large, explosive eruptions to evaluate previous estimates of explosive volcanism (Table 1). Our study suggests that, even disregarding the influences on our dataset from El Chichón and Pinatubo, 1 Mt SO_2 per yr (ref. 7) is low; likewise, 9.8 Mt yr^{-1} (ref. 1) is too high. The latter determination was also calculated by relating SO_2 emissions (using data from a variety of techniques) to VEI and eruption frequency using the GVN database. We believe that the discrepancy between our degassing rates occurs because the earlier study used only SO_2 data from a small number of selected eruptions, as opposed to our inclusion of all reported eruptions during the 14-year period of TOMS operation.

The TOMS data can also help put important constraints on the SO_2 flux from total global volcanism. Based on the TOMS data, explosive eruptions produce an average of 4 Mt SO_2 per year (produced from a few large, infrequent events). The other component of the total volcanic sulphur budget, non-explosive volcanoes, degas at relatively consistent rates; the most recent evaluation of production from degassing but non-erupting and low-level, continuously erupting volcanoes (both of which cannot be evaluated from TOMS surveillance) is ~9 Mt SO_2 yr^{-1} (ref. 1). Combining explosive and non-explosive volcanic outgassing, the present-day volcanic contribution of SO_2 to the Earth's atmosphere can be approximated by an annual flux of 13 Mt SO_2. Previous estimates of total SO_2 emissions from global volcanism <10 Mt yr^{-1} (refs 2, 3, 5) are probably too low. Similarly, determinations of >20 Mt SO_2 yr^{-1} (refs 6, 8) appear to overestimate global volcanism. Thus, using satellite data in conjunction with previous ground-based work, we estimate that the total volcanic contribution of SO_2 to the Earth's atmosphere totals only ~5–10% of the annual anthropogenic flux. □

TABLE 2 TOMS SO_2 inventory of explosive volcanism 1979–1993

VEI	Non-arc (*N*) (Mt SO_2)*	Arc (*N*) (Mt SO_2)*
0	2.4 (2)	(0)
1	1.5 (2)	0.03 (3)
2	1.6 (6)	0.12 (8)
3	9.9 (5)	3.4 (19)
4	(0)	3.8 (6)
5	(0)	10 (3)
6	(0)	20 (1)
7		
14 yr total (Mt)	15 (15)	37 (40)
Annual average (Mt yr^{-1})	1.1	2.6

* Totals from TOMS database; *N*, number of eruptions observed.

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