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GLOBAL TRACKING OF THE SO_2 CLOUDS FROM THE JUNE, 1991 MOUNT PINATUBO ERUPTIONS

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Abstract. The explosive June 1991 eruptions of Mount Pinatubo produced the largest sulfur dioxide cloud detected by the Total Ozone Mapping Spectrometer (TOMS) during its 13 years of operation: approximately 20 million tons of SO_2, predominantly from the cataclysmic June 15th eruption. The SO_2 cloud observed by the TOMS encircled the Earth in about 22 days (~21 m/s); however, during the first three days the leading edge of the SO_2 cloud moved with a speed that averaged ~35 m/s. Compared to the 1982 El Chichón eruptions, Pinatubo outgassed nearly three times the amount of SO_2 during its explosive phases. The main cloud straddled the equator within the first two weeks of eruption, whereas the El Chichón cloud remained primarily in the northern hemisphere. Our measurements indicate that Mount Pinatubo has produced a much larger and perhaps longer-lasting SO_2 cloud; thus, climatic responses to the Pinatubo eruption may exceed those of El Chichón.

Introduction

Mount Pinatubo is an andesitic island arc volcano, located on southern Luzon Island, Philippines. Wolfe and Self [1983] briefly describe the volcano, and cite the most recent eruption as occurring approximately 635 years earlier (from carbon-14 dating of mudflow deposits), but noted that Pinatubo had never been studied in great detail and that there may have been more recent, undocumented eruptions.

In June 1991 the volcano erupted in a series of minor explosions leading up to a cataclysmic eruption June 14-15 [Lynch et al., 1991]. A large amount of solid and gaseous material was ejected from the volcano, and a significant proportion of the ash was deposited in the South China sea. The combined tephra and pyroclastics were estimated at 3-5 km^3 dense rock equivalent [Scott et al., 1991].

The TOMS instrument on board the Nimbus-7 satellite has provided global SO_2 and ozone data since 1978 by measuring the ultraviolet albedo, the ratio of backscattered Earth radiance to incoming solar irradiance. The satellite is in a polar sun-synchronous orbit and crosses the equator every 26 degrees (2900 km) of longitude at local noon, observing the whole earth once a day (13.7 orbits/day). The TOMS was designed with the intention of globally mapping total ozone only, but after the eruption of El Chichón in April 1982 anomalously high ozone values were noticed over Mexico. These high values were caused by sulfur dioxide interference, and it therefore became necessary to separate the volcanogenic SO_2 signal from the ozone data [Krueger, 1983]. Examination of absorption coefficients for SO_2 in the spectral range measured by the TOMS led to the development of an algorithm to quantify the SO_2 amounts [Krueger, 1985]. Since then, all eruptions (including 1978-1982 data) with potential for measurable amounts of erupted SO_2 have been routinely examined.

As a monitor of volcanism, the TOMS instrument is best used to detect and track SO_2 emitted from the explosive phases of eruptions. The TOMS observes sulfur dioxide primarily in the stratosphere, and its detection limit of a given eruption cloud is about 5 kilotons (kt) SO_2. Major advantages of the TOMS are its capability to detect explosive eruptions virtually anywhere on the sunlit Earth within 24 hours and its ability to measure the complete spatial extent of large, explosive eruptions. Previous volcanic events examined using the TOMS instrument include the 1982 El Chichón eruptions [Krueger, 1983], Nevado del Ruiz in 1985 [Krueger et al., 1990], the 1989 Redoubt activity [C. Schnetzler, unpublished manuscript, 1991], and the 1991 Cerro Hudson eruptions [Doiron et al., 1991].

Satellite Data

The TOMS instrument daily observations of the Mount Pinatubo eruptions are summarized in Table 1 and in Figure 1a-d. Total column amounts of SO_2 are given in units of milli atm-cm. This unit represents the amount of gas which is affecting the reflection of ultraviolet light through a scanning column (from the satellite to the Earth's reflecting surface), given in terms of the one dimensional thickness of the pure gas layer at STP. The mass of SO_2 is calculated by integrating over the cloud area to obtain a volume, then converting to tons. Typical volcanic SO_2 clouds detected by the TOMS range from 20 to several hundred milli atm-cm.

The error estimation for the TOMS SO_2 values has been described by Krueger et al. [1990]. The total error in reported values, ± 30%, is based on uncertainties in the algorithm calculation, absorption level measurements, and background noise.

Eruption Cloud Chronology

The initial sulfur dioxide detected by the TOMS instrument from Mount Pinatubo occurred as three small SO_2

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Table 1. Summary of TOMS Data for the 1991 Mount Pinatubo Eruption Clouds

Image Date	Areal Extent (km^2)	Measured SO_2 (kt)*	Height	Geographic Position	Comments
June 12	100	25	trop	West coast of Luzon Island	Cloud observed for 3 days; on June 13 measured 110 kt
June 13	100	15	trop	West coast of Luzon Island	New cloud observed for 1 day
June 14		-no new activity detected-			
June 15	7500	450	trop/strat	South China Sea, from 10 to 15°N	New, 1600 km long cloud over the volcano; observed 1 day
June 16	3.2×10^6	15,500 minimum	strat	Centered over South China Sea at ~15°N	New discrete cloud from major eruption, 200 km east of volcano
June 17	4.8×10^6	18,500	strat	Lead cloud over tip of India; main cloud over south Thailand at 10°N	Main cloud 2000 km from origin; overall length of clouds 4400 km
June 18	7.5×10^6	16,000	strat	From Malaysia to Gulf of Aden at ~10°N latitude	Main cloud 3000 km from origin; total cloud is 7000 km in length
June 19	7.4×10^6	14,000 minimum	strat	Lead cloud over Sudan; main cloud over northeast Indian Ocean	Main cloud 4300 km from origin; leading lobe breaking apart
June 20	8.6×10^6	14,500	strat	Lead clouds over E. Africa; main cloud over equatorial Indian Ocean	Main cloud 4500 km from origin, 6000 km in length
June 23	15.4×10^6	14,000	strat	Lead cloud over Mali; main cloud from Sumatra to central Africa	Main cloud 10,000 km long, main SO_2 mass no longer discernable
June 30	54.5×10^6	12,000	strat	From Indonesia to west Pacific Ocean, 10°S to 20°N	Main cloud over 16,000 km long; even, low level SO_2 distribution

* SO_2 calculated from near real-time TOMS data; actual values could be larger as discussed in the text. On June 16 and June 19 the TOMS instrument experienced problems in the area of the SO_2 cloud, where no data were reported.

clouds erupted from June 11-14. The first cloud was detected on June 12th (i.e., including any eruption activity from noon June 11 to noon June 12). This cloud measured 100 km^2 in area, and contained ~25 kt SO_2. By June 13th the cloud had drifted 1100 km to the west, over central Vietnam, and now measured 110 kt SO_2. By June 14th, the cloud could be barely discerned over the eastern Indian Ocean at about 15°N, and was not seen thereafter. A second cloud of 100 km^2 area and less than 15 kt SO_2 was detected June 13th over the western edge of Luzon island, but was only observed for one day. A third cloud was detected on June 15th, measuring 7500 km^2 in area and stretching 1600 km westward from Mount Pinatubo to southern Vietnam. The SO_2 cloud was composed of at least three distinct concentrations probably corresponding to individual eruption pulses occurring June 14th. This cloud totaled approximately 450 kt SO_2, but on subsequent days it had either dispersed below detection levels or was masked by the major eruption cloud.

The cataclysmic eruption of June 15th began before noon and lasted until the following morning [Lynch et al., 1991]. The timing of the eruption was such that it was not detected by the TOMS until the 16th. Figure 1a shows that in approximately 24 hours the center of the SO_2 cloud had drifted 1000 km to the WSW as a discrete mass. The measured amount of SO_2 in this cloud is 15,500 kt but, because of data losses and detector saturation, the actual amount must be greater than this.

On the June 17th image, approximately 36 hours after the end of the cataclysmic eruption, the SO_2 cloud as a whole had dispersed enough so that all the individual column values could be measured to yield a more accurate value: 18,500 kt of SO_2.

By June 18th the SO_2 cloud stretched 6500 km in length, with a concentrated mass connected to a long leading edge (Figure 1b). The main portion was centered over the Bay of Bengal, about 3300 km from the source. The leading edge of the SO_2 cloud was over the Gulf of Aden, corresponding to an 3-day average speed of 35 m/s. The cloud's movement was primarily westward, with some spreading slightly to the south towards the equator. The SO_2 estimate for the 18th was 16,000 kt.

The June 23rd image marked a change in the physical configuration of the SO_2 cloud (Figure 1c). The cloud no longer consisted of a main concentrated mass and a leading lobe or leading cloud. It now extended 10,000 km from Indonesia to central Africa in a fairly uniform distribution of SO_2, covering an area of about 15 million square kilometers. The leading cloud which had sheared away from the main cloud was largely dispersed below the TOMS detection limit, leaving only a trace visible over western Africa. The cloud crossed the equator to as far as 10°S latitude. The trailing end of the cloud remained nearly fixed over Sumatra. The relatively lower cloud SO_2/background ratios by this time made quantitative measurements more difficult; the estimate of SO_2 tonnage for the June 23 clouds was ~14,000 kt.

Figure 1d shows the SO_2 cloud on June 30th, two weeks after the main eruption. The cloud is spread over 16,000 km in length, straddling the equator, reaching from 10°S to 20°N. The cloud area extends over 50 million square kilometers. The leading edges of the visible cloud have reached the longitude of California, and the trailing edge (out of the picture) remains mired over Indonesia. This cloud measured 12,000 kt SO_2; thus, after 15 days the Pinatubo cloud still contained roughly 60% of its original SO_2.

The SO_2 cloud remained visible to the TOMS instrument long enough to observe its complete circuit of the Earth in 22 days. This pace was virtually identical to the El Chichón SO_2 cloud in 1982 (although in both cases SO_2 at lower concentrations probably made the round trip at a faster pace).

Discussion

The eruption cloud from Pinatubo is by far the largest that we have detected since the TOMS instrument began

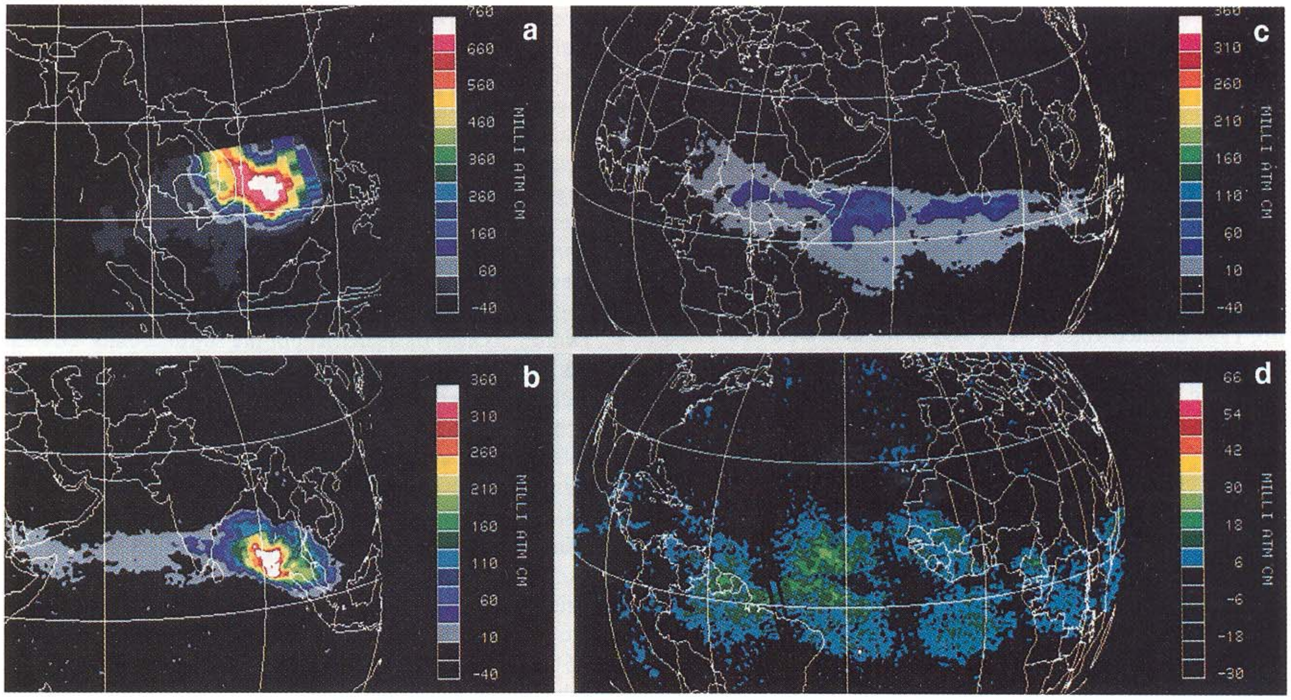

Fig. 1. False-color images of Mount Pinatubo SO_2 clouds produced from TOMS data. SO_2 volumes over column areas are in units of milli atm-cm (see text). Scales vary to compensate for cloud dispersion. (a) June 16th. Lines are 10 degrees of latitude and longitude. Cloud center values exceed the TOMS detection limits, and some data loss occurred over the northern edge of the cloud. (b) June 18th. Lines now denote 30 degrees latitude and longitude. (c) June 23rd. (d) June 30th.

collecting data in 1978. In Table 2 we compare some of the physical characteristics of Pinatubo to: Novarupta/Katmai in 1912, the last eruption of a comparable size in the northern hemisphere; and El Chichón, 1982 and Nevado del Ruiz, 1985, two recent eruptions which have also been observed by the TOMS. All four volcanoes are in island arc tectonic settings; Novarupta erupted mostly rhyolitic lava, but the other three volcanoes were andesitic in composition.

Combining the measured SO_2 from the June 12, June 13, June 15, and June 17 (which may contain some of the 450 kt measured June 15) cloud data gives a sulfur dioxide total of 19,100 kt. We stress that this total is *measured* SO_2: dispersion of the gas cloud, conversion of SO_2 to sulfuric acid, and saturation of the TOMS detector all suggest that the actual explosive output of SO_2 from Pinatubo could be higher. The 18,500 kt cloud was measured ~36 hours after the cataclysmic eruption ended. The SO_2 loss over the next five days suggests an average loss of 1,000 - 1,500 kt SO_2 per day. Therefore, we estimate that the total amount of SO_2 emitted from the June 14-15 explosive eruptions of Mount Pinatubo was approximately 20,000 kt.

The total SO_2 from Mount Pinatubo is nearly three times the 7 million tons SO_2 measured by the TOMS instrument from the El Chichón eruption (note that we have revised this value upward from the original estimate, 3.3 million tons, of Krueger, 1983). Although the SO_2 production of Novarupta was not directly measured, indirect methods suggest it produced a similar magnitude, 5,200-20,000 kt, of sulfur dioxide [Palais and Sigurdsson, 1989; Hammer et al., 1980]. Mass ratios of explosively outgassed SO_2 to solid ejecta, assuming an ejecta density of 2.5 g/cm^3, range over a factor of thirty among the four volcanoes.

TOMS data for the first two weeks of the eruption have been used to calculate the dispersion rate of SO_2. An exponential curve fit to the data yields an e-folding time of 35 days; however, in light of the preliminary nature of the data, the difficulty of measurement of spatially large clouds, and the data drop-out and saturation problems mentioned earlier, this value should be regarded as tentative.

It is generally accepted that El Chichón produced a measurable climate signal, but the magnitude of that effect is

Table 2. A TOMS Comparison of Mount Pinatubo to Other Large Eruptions

	Novarupta/ Katmai 1912	El Chichón 1982	Nevado del Ruiz 1985	Mount Pinatubo 1991
SO_2[1] (kt)	5,200 - 20,000	7,000	750	20,000
ejecta[2] (g)	3.4×10^{16}	3.0×10^{15}	4.8×10^{13}	1.0×10^{16}
SO_2/ejecta mass ratio	0.0002 - 0.0006	0.0023	0.015	0.0019
VEI[3]	6	4-5	3	5-6

[1]Novarupta SO_2 range from: (low) petrologic estimate of Palais and Sigurdsson [1989]; (high) ice-core acidity measurements of Hammer et al. [1980]. Others are TOMS measured amounts during explosive eruption phases.

[2]Ejecta (dense rock equivalents) for Novarupta: midrange value of Hildreth [1987]; El Chichón: Sigurdsson et al. [1984], and Carey and Sigurdsson [1986]; Ruiz: Naranjo et al. [1986], and Calvache [1990]; Pinatubo: midrange value of Scott et al. [1991].

[3]VEI estimates from Simkin et al. [1981]; Smithsonian Institution/SEAN [1989]; Pinatubo VEI estimated using parameters of Newhall and Self [1982].

less certain: from 0.2 to 0.5°C [Robock, 1984; Angell, 1988; Mass and Portman, 1988]. The Pinatubo eruption emplaced much more sulfur dioxide into the stratosphere than did El Chichón, and the SO_2 was distributed over the Earth by a more widespread and possibly longer-lasting cloud. The eruption of Mount Pinatubo offers the exciting prospect to observe and study potential climatic responses.

Conclusions

The cataclysmic eruption of Mount Pinatubo on June 15-16, 1991 emitted 18,500 kt of SO_2 as measured 36 hours later by the TOMS instrument. Based on the decrease of SO_2 exhibited by the cloud over the following days, we estimate that the total SO_2 erupted by the cataclysmic eruption was approximately 20,000 kt. The erupted SO_2 cloud appeared as a single pulse and the main cloud mass drifted WSW at approximately 20 m/s, although the leading edge of the cloud drifted ahead at nearly twice this velocity. The SO_2 cloud remained drifting in a concentrated mass for seven days after which it gradually spread into a broader, evenly dispersed cloud. After two weeks the visible SO_2 cloud had spread about ± 20° in latitude about the equator and stretched nearly continuously 10,000 km from Indonesia to the Galápagos Islands. The TOMS-observed portion of the cloud encircled the Earth in 22 days (~21 m/s).

The SO_2 tonnage of Mount Pinatubo was the greatest ever recorded in 13 years of TOMS operation, almost three times that of the 1982 El Chichón eruption (the next largest eruption observed by the TOMS). The sulfur dioxide injected by El Chichón into the stratosphere may have caused up to 0.5°C cooling in the northern hemisphere the following year; the eruption of Mount Pinatubo has injected a significantly greater amount of SO_2 into the stratosphere. Thus, within the next 12 months we should expect to see a measurable climatic signal originating from the Mount Pinatubo eruption. This natural experiment should provide a test of the accuracy of climate models.

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References

Angell, J.K., Impact of El Niño on the delineation of tropospheric cooling due to volcanic eruptions, *J. Geophys. Res.*, *93*, 3697-3704, 1988.

Calvache, M.L., V, Pyroclastic deposits of the November 13, 1985 eruption of Nevado del Ruiz volcano, Colombia, *J. Volc. Geotherm. Res.*, *41*, 67-78, 1990.

Carey, S. and H. Sigurdsson, The 1982 eruptions of El Chichón volcano, Mexico (2): observations and numerical modelling of tephra-fall distribution, *Bull. Volc.*, *48*, 127-141, 1986.

Doiron, S.D., G.J.S. Bluth, C.C. Schnetzler, A.J. Krueger, and L.S. Walter, Transport of Cerro Hudson SO_2 clouds, *EOS Trans. AGU*, *72*, 489-498, 1991.

Hildreth, W., New perspectives on the eruption of 1912 in the Valley of Ten Thousand Smokes, Katmai National Park, Alaska, *Bull. Volc.*, *49*, 680-693, 1987.

Krueger, A.J., Sighting of El Chichón sulfur dioxide clouds with the Nimbus 7 Total Ozone Mapping Spectrometer, *Science*, *220*, 1377-1378, 1983.

Krueger, A.J., Detection of volcanic eruptions from space by their sulfur dioxide clouds, *Am. Inst. Aero. Astro., 23rd Aerospace Sciences Meeting, AIAA-85-0100*, Reno, Nevada, 5 pp., 1985.

Krueger, A.J., L.S. Walter, C.C. Schnetzler, and S. D. Doiron, TOMS measurement of the sulfur dioxide emitted during the 1985 Nevado del Ruiz eruptions, *J. Volc. Geotherm. Res.*, *41*, 7-15, 1990.

Lynch, J.S., G. Stephens, and M. Matson, Mount Pinatubo: a satellite perspective of the June 1991 eruptions, *Geophys. Res. Lett.*, this issue, 1991.

Mass, C.F. and D.A. Portman, Major volcanic eruptions and climate: a critical evaluation, *J. Clim.*, *2*, 566-593, 1989.

Naranjo, J.L., H. Sigurdsson, S.N. Carey, and W. Fritz, Eruption of the Nevado del Ruiz volcano, Colombia, on 13 November 1985: tephra fall and lahars, *Science*, *233*, 961-963, 1986.

Newhall, C.G. and S. Self, The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism, *J. Geotherm. Res.*, *87*, 1231-1238, 1982.

Palais, J.M. and H. Sigurdsson, Petrologic evidence of volatile emissions for major historic and prehistoric eruptions, *AGU Monograph 52*, 31-53, 1989.

Robock, A., Climate model simulations of the effects of the El Chichón eruption, *Geof. Int.*, *23-3*, 403-414, 1984.

Scott, W.E., R.P. Hoblitt, J.A. Daligdig, G. Besana, and B.S. Tubianosa, 15 June 1991 pyroclastic deposits at Mount Pinatubo, Philippines (abstract), *EOS Trans. AGU*, *72*, 61-62, 1991.

Sigurdsson, H., S.N. Carey, and J.M. Espindola, The 1982 eruptions of El Chichón volcano, Mexico: stratigraphy of pyroclastic deposits, *J. Volc. Geotherm. Res.*, *23*, 11-38, 1984.

Simkin, T., L. Siebert, L. McClelland, D. Bridge, C. Newhall, and J.H. Latter, *Volcanoes of the World: A Regional Directory, Gazetteer, and Chronology of Volcanism During the Last 10,000 Years*, 240 pp., Hutchinson Ross, Stroudsburg, PA, 1981.

Smithsonian Institution/SEAN, *Global Volcanism 1975-1985*, 657 pp., Prentice-Hall, Englewood Cliffs, NJ, and AGU, Washington, DC, 1989.

Wolfe, J. and S. Self, Structural lineaments and Neogene volcanism in southwestern Luzon, in *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, part 2*, edited by D.E. Hayes, pp. 157-172, AGU Monograph 27, 1983.

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