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The December 1981 eruption of Nyamuragira Volcano (Zaire), and the origin of the "mystery cloud" of early 1982

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Abstract. The "mystery" volcanic aerosols observed in early 1982 were produced by the eruption of Nyamuragira in eastern Zaire. Large sulfur dioxide clouds associated with this volcano were found in the total ozone mapping spectrometer data beginning on December 26, 1981, continuing into early January 1982. This fissure eruption produced 3 million tons of sulfur dioxide in clouds that rose only to the tropopause level on the basis of winds and inferred chemical loss rates (about 20%/day), which are faster than stratospheric loss rates. Two thirds of the SO_2 was produced in the first 3 days of the eruption. In the 1980s this eruption was exceeded in sulfur dioxide output only by the April 1982 eruption of El Chichon.

Introduction

A significant decrease in solar irradiance in pyrheliometer data from Mauna Loa, Hawaii, after January 4, 1982 [*DeLuisi et al.*, 1983; *Dutton et al.*, 1985], was attributed to an unknown volcanic eruption. This decrease in atmospheric transmission was comparable to that produced by the eruption of Agung in 1963. From January 23 to February 2, 1982, an aerosol layer at 10–17 km altitude was observed by lidar at Fukuoka, Japan [*Hirono and Shibata*, 1983]; a similar layer was found in lidar data over Mauna Loa, Hawaii, on January 28 and February 4 [*DeLuisi et al.*, 1983; *DeLuisi et al.*, 1985] and over Garmisch-Partenkirchen, Germany, beginning on February 2 [*Reiter et al.*, 1982, 1983]. From late January to the middle of February, high aerosol concentrations were observed by ground-based and airborne lidar and balloon flights over Hawaii, North and Central America, and Germany [*McCormick et al.*, 1984; *Smithsonian Institute Scientific Event Alert Network (SEAN)*, 1989]. High-altitude aircraft aerosol samples in March 1982 suggested a "significant" volcanic event because of the relatively large sulfate concentrations [*Mroz et al.*, 1983].

This aerosol cloud remained in the lower and middle northern latitudes through at least early April 1982, when the gigantic eruption of El Chichon eclipsed the earlier cloud. Although this early 1982 cloud was clearly of volcanic origin, no eruption was unequivocally identified as its source; thus it was called the "mystery cloud".

We have used data from the total ozone mapping spectrometer (TOMS) sensor carried on NASA's Nimbus 7 satellite to examine volcanic eruptions in the period immediately prior to the detection of the cloud and have concluded that the cloud came from a fissure eruption of Nyamuragira volcano (1°24′S, 29°12′E) in the western rift of the East Africa Rift Valley of eastern Zaire. We observed SO_2 clouds over central Africa from December 26 until January 7, 1982. The emission of SO_2 during this eruption was second only to the April 1982 eruption of El Chichon as a producer of SO_2 in the 1980s.

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Nyamuragira, a symmetric shield volcano in the highly potassic Biringa volcanic field, has a record of violent eruptions; the 1981 eruption is the fifth since 1967 and the seventeenth since 1900, with the longest quiet period being 18 years [*Aoki et al.*, 1985]. Eruptions started about midnight on the night of December 25–26, 1981 (2200 UT; December 25), from a 1.5-km-long set of fissures on the saddle between Nyamuragira and Nyiragongo volcanoes [*Aoki et al.*, 1985]. Fountaining occurred along the length of these fissures initially but was later confined to the southeast end [*Smithsonian Institute SEAN*, 1989; *Kampunzu et al.*, 1984], producing a 23-km-long lava flow on the east flank of Nyamuragira [*Aoki et al.*, 1985].

TOMS Sulfur Dioxide Observations

TOMS was designed to measure atmospheric total ozone but also is capable of measuring volcanic sulfur dioxide [*Krueger*, 1983]. Because ozone and sulfur dioxide absorb differentially in the ultraviolet, they can be discriminated using the TOMS six wavelength bands [*Krueger et al.*, 1995]. The TOMS 2800-km swath width produces complete contiguous coverage of the sunlit Earth every 24 hours, with a spatial resolution of 50 km at nadir and a mean resolution across the scan of 66 km. The Sun-synchronous orbit crosses the equator at approximately 1200 LT. Sulfur dioxide index values are computed along with ozone in the Nimbus 7 TOMS level 2 (orbital) data tapes for each footprint viewed by the instrument. These index values are column integral SO_2 retrievals which have been empirically corrected for nonlinearity effects, as described by *Krueger et al.* [1995]. The noise level of the instrument is equivalent to about 500 metric tons SO_2 for an average-size pixel, but because of background variations, we consider our detection limit per pixel to be between 1 to 2 kilotons (kt). As we usually require several contiguous pixels above the detection limit to clearly delineate a cloud, our true cloud detection limit is about 5 to 10 kt.

Volcanic cloud mass determinations are made by summing the SO_2 over the cloud area and correcting for background offsets [*Krueger et al.*, 1995], which are measured in adjacent areas. These offsets become a significant source of errors as the area of a volcanic cloud becomes large. Generally, we pick a geographic box that is somewhat larger than the recognizable cloud to give some margin for dispersion of the plume. On the first day of an eruption, when the plume is compact, a small box can be used to estimate the total cloud mass. However, after the first day the outer boundaries of the complete cloud become hard to distinguish. The total daily cloud mass then was assessed using a large area box (7.5×10^6 km^2) containing the volcano and the largest recognizable volcanic cloud. Eight or more adjacent boxes of the same size were used to estimate background offset levels in areas seemingly free of SO_2. The SO_2 in the box east of the volcano increased until January 1, 1982, suggesting advection in the eastward direction. This SO_2 was included in the daily cloud total. A preeruption background correction, which varied with longitude, was selected and applied to the data. The one standard deviation in background levels of the large-area boxes is about 100 kt.

At approximately noon local standard time on December 26, TOMS observed a sulfur dioxide plume emanating from the vicinity of Nyamuragira and streaming about 150 km to the northwest (Plate 1a) at a nominal speed of 3 m/s. The calculated mass of SO_2 in this plume is approximately 165 kt. By noon on December 27 the SO_2 had expanded into a large southwest-northeast cloud over 2000 km in length (Plate 1b). Within the cloud there were three areas of higher concentrations, two about 450 km distant from the volcano (one to the northeast, one to the west northwest) and a very large concentration streaming northwest from the volcano. We ascribe the spreading of the cloud into the large arc and the two detached concentrations to convection of the hot volcanic material to various levels up to the tropopause, gravitational settling, and shearing of the column by winds at different altitudes. The volcano was still vigorously emitting SO_2 at the time of overpass, as evidenced by the high concentration of SO_2 (>200 matm cm) just northwest of the volcano. The total mass of the December 27 SO_2 cloud is about 1300 kt.

On December 28 (Plate 1c) the three regions of higher concentrations seen in the previous day became more diffuse and continued to move in the same general directions as before. While the western part moved about 1000 km from the volcano in two days or less at a nominal peak speed of >6 m/s, the eastern portion moved as much as 2200 km (peak speed >12 m/s). The total mass of SO_2 in this scene is about 1900 kt. About 600 kt SO_2 are in the eastern portion of the cloud, which extends from the volcano to the coast in southern Somalia. A plume of freshly erupted sulfur dioxide was observed streaming to the northwest from the volcano for a distance of about 500 km (speed >6 m/s). This new plume contains about 750 kt SO_2.

On December 29 (Plate 1d), continued activity produced high SO_2 levels over the volcano, and the fringes of the older clouds are dispersed in separate lobes; the western lobe, containing about 300 kt, is now about 1800 km away from the volcano. The northwestern lobe moved about an equal distance to the north northwest, and the eastern lobe, containing about 400 kt, moved over 3000 km to the Indian Ocean. The most recent portion of the emission, again streaming northwest from the volcano for about 800 km, contains about 300 kt SO_2. All the clouds are largely confined to the northern hemisphere. The total SO_2 in the scene is about 1800 kt.

TOMS observed continuing, albeit declining, SO_2 plumes from Nyamuragira through January 7, with the exception that no new SO_2 was observed on January 4. On December 30 (Plate 2a), new sulfur dioxide is visible in a plume to the northwest; on December 31 (Plate 2b), continued activity has produced a more northerly plume. The new material produced on January 1, 1982 (Plate 2c) is dispersing on January 2 (Plate 2d).

Cloud Altitude

TOMS data can be used to estimate the amount of SO_2 as a function of altitude when wind shear separates the cloud into components. This has been done very successfully at nonequatorial latitudes with a trajectory model [*Schoeberl et al.*, 1993]. In the present equatorial case, only monthly average winds were available to diagnose the cloud altitudes. The current height analysis is valid only if the variability is low such that the mean is representative of the winds at the time of the eruptions.

The December 1981 monthly average wind directions [*National Oceanic and Atmospheric Administration*, 1981] measured with radiosondes at Nairobi, Kenya, and Bangui, Central African Republic, are shown in Figure 1. Nairobi is about 700 km due east of Nyamuragira while Bangui is about 1100 km to the northwest. The wind directions at these sites were very similar, suggesting that the average winds across equatorial central Africa were uniform. The winds are from the east-northeast and east at altitudes below 10 km, rotate clockwise to south at 12 km and west at 14 km, then counterclockwise to south at 18 km and east at 20 km and above. Easterly stratospheric winds were consistent with the phase of the quasi-biennial oscillation in December 1981, as measured at Singapore. The tropopause was located near 17 km at both locations. The upper tropospheric westerly winds were far stronger at Bangui than at Nairobi. The lower tropospheric wind speeds were about 5 m/s at both stations.

The strong wind shear makes is possible to identify cloud elements by direction of motion. Portions of the plume below 5 km move to the west or southwest, between 5 and 10 km to the west northwest, between 10 and 11 km to the northwest, and between 12 to 13 km to the northeast. The only altitudes where cloud motion is in eastward directions is near the top of the troposphere between 13 and 17 km. Cloud motion in the stratosphere above 18 km is to the west.

The motion of the initial eruption cloud on December 26 (Plate 1a) was primarily to the northwest, with smaller components to the west and southwest. Assuming the winds on this day were similar to the monthly average, the main body of the cloud located 150 km northwest of Nyamuragira would have to be in the middle troposphere at approximately 12 km or in the lower stratosphere at 20 km. We believe this cloud is at 12 km, because no aerosols were found above the tropical tropopause in lidar data. Assuming a near midnight initial eruption, the speed of this cloud is about 3 m/s in good agreement with the Nairobi December monthly average wind speed at 12 km but 3 times faster than the wind at 20 km.

The cloud distribution in the fringe areas is nearly isotropic as the material spreads during the equilibration period in the early hours after the eruption. The only exception is a tongue

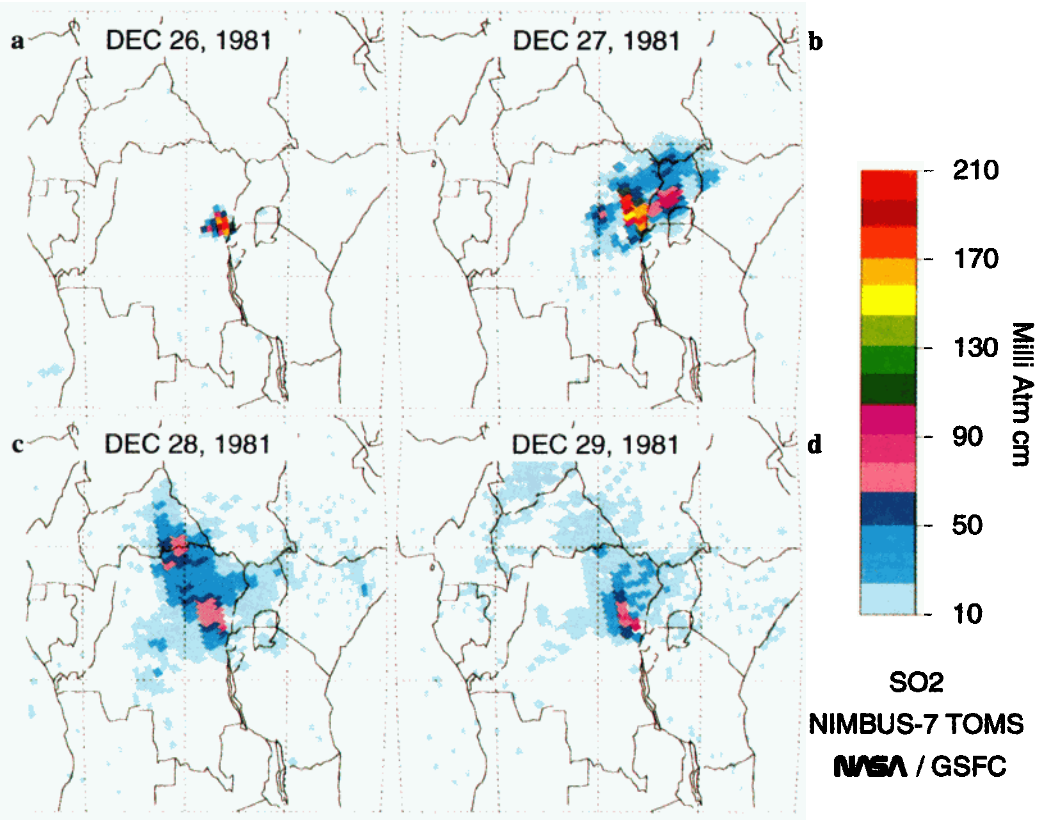

Plate 1. Total ozone mapping spectrometer (TOMS) images of the Nyamuragira sulfur dioxide clouds over central Africa near local noon from December 26 through 29, 1981. The volcano is located in eastern Zaire, near the boundary with Uganda and Rwanda, and can be identified in the images by very high SO_2 amounts, particularly on December 26 and 29. SO_2 column amounts are from 10 to 210 matm cm. The ground resolution of TOMS varies from day to day, according to the distance to the satellite as it passes the cloud.

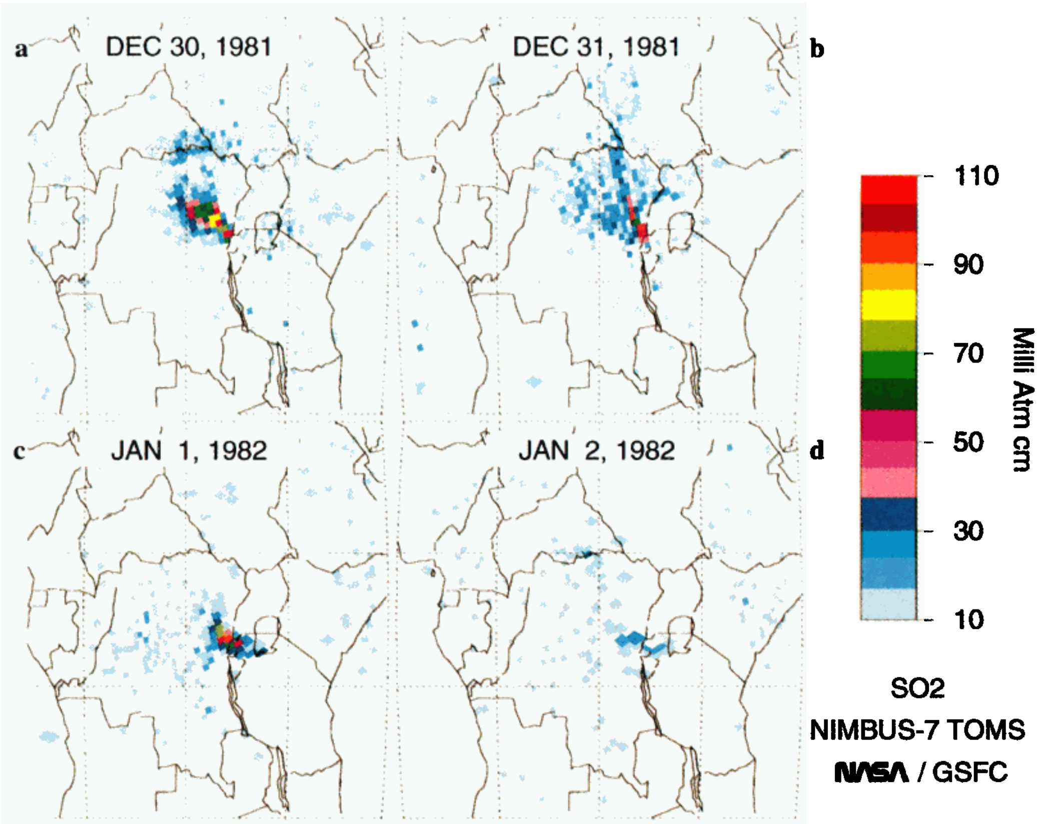

Plate 2. TOMS images of the Nyamuragira sulfur dioxide clouds on December 30, 1981, through January 2, 1982, with a sulfur dioxide scale of 10–110 matm cm.

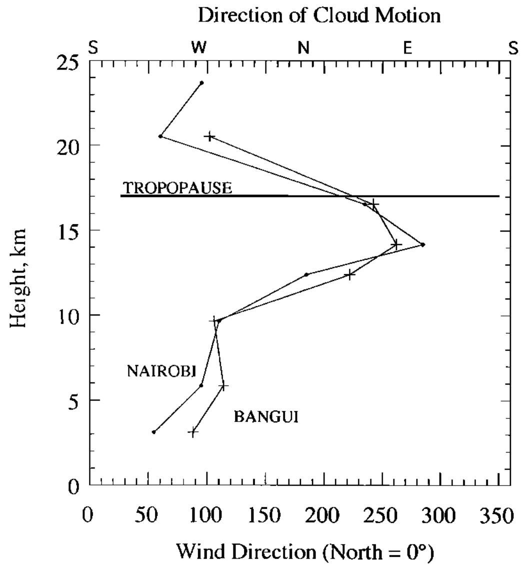

Figure 1. Average wind direction and cloud motion as a function of altitude during December 1981 at two equatorial African stations bracketing Nyamuragira.

of SO_2 moving to the southwest, which must be at a low altitude (~3 km) on the basis of the average winds. This may be a result of degassing of ash which is settling by gravitation from the main cloud element.

The quantity of sulfur dioxide in the eastward moving upper tropospheric cloud that was detected by the lidar stations is estimated to be about 350 kt on December 27 (Plate 1b), at least 600 kt on December 28 and 29, and greater than 850 kt on December 30. Continued eruptions in subsequent days appeared to add little more to the high-altitude, eastward streaming cloud. Although accurate determination is impossible, from the above it appears this high-altitude portion of the Nyamuragira eruption was approximately 1 megaton (Mt) at a minimum and may have been as high as 1.5 Mt, that is, from one third to one half of the total amount erupted.

Retrievals of tropospheric sulfur dioxide amounts are dependent on cloud altitude and surface reflectivity [*Krueger et al.*, 1995]. In general, SO_2 in the upper troposphere is overestimated by 10–20% for clear conditions and by 15–30% over clouds. The dependence on surface reflectivity diminishes with altitude, so that at 17 km the algorithm overestimates SO_2 by 14 ± 3%. The average surface reflectivity measured with TOMS in the Nyamuragira plume region was 25% because of broken clouds. This is consistent with less than 20% overestimation of SO_2. While this bias could be corrected, the errors are dominated by uncertainty in the background corrections over Africa.

Sulfur Dioxide Eruption Mass

One objective of our analysis is to estimate the total amount of sulfur dioxide produced by an eruption. Plinian eruptions, like the 1982 El Chichon eruption, produce a single burst of sulfur dioxide, which we can measure on a series of days as the SO_2 is lost because of dispersion and conversion to sulfate, which has no absorption at the TOMS wavelengths. The initial erupted amount is calculated by extrapolation of the time series back to the time of the eruption.

Fissure eruptions, on the other hand, extrude magma over a number of days, adding new sulfur dioxide to that remaining from earlier days. Separation of SO_2 into new (i.e., erupted since the last overpass) and old (i.e., seen in the previous overpass) is difficult, especially in a situation such as Nyamuragira where the eruption appears to be continuous and winds at different altitudes shear the cloud over the volcano into portions moving in different directions. Assumptions must be made as to the movement and dissipation of the cloud in 24 hours so that boundaries between new and old SO_2 clouds can be estimated. The daily SO_2 measurements, both of the total amount and the "new" amount erupted since the last overpass during the first 8 days of the eruption, are listed in Table 1. The amount produced in the last 24 hours was assumed to be the amount in the plume attached to the volcano. The boundary of the plume was defined as the 55 matm cm contour which includes the volcano. This is a conservative estimate, because it fails to account for any recently erupted SO_2 that has been dispersed. Adding the new SO_2 erupted daily gives a total amount of 3.0 Mt SO_2 in the first 8 days and 3.2 Mt for the 12 days of activity. Calculations of new SO_2 based on different reasonable assumptions vary by as much as a factor of 2, but an average "error" is perhaps ±25%.

Another approach to calculating the total new SO_2 requires only a measure of the total daily amount and an estimation of the loss rate, as follows. The total amount on the ith day, $M(\text{total})_i$, is the sum of the newly erupted SO_2, $M(\text{new})_i$, and a fraction of the previously erupted SO_2, $M(\text{old})_i$:

$$M(\text{total})_i = M(\text{new})_i + M(\text{old})_i \tag{1}$$

However, the residual mass from yesterday's cloud is given by

Table 1. Mass of Sulfur Dioxide Versus Time

Date	Total Observed SO_2 Mass, kt	Estimated New SO_2 Production, kt	Computed New SO_2 at 3% Loss Per Day, kt	Computed New SO_2 at 10% Loss Per Day, kt	Computed New SO_2 at 20% Loss Per Day, kt
Dec. 26, 1981	165	165	165	165	165
Dec. 27, 1981	1,300	1,200	1,140	1,152	1,168
Dec. 28, 1981	1,900	750	639	730	860
Dec. 29, 1981	1,800	300	−43	90	280
Dec. 30, 1981	1,600	200	−146	−20	160
Dec. 31, 1981	1,300	220	−252	−140	20
Jan. 1, 1982	1,500	120	239	330	460
Jan. 2, 1982	1,350	45	−105	0	150
Total eruption mass, kt	10,915	3,000	1,637	2,306	3,263

$$M(\text{old})_i = M(\text{total})_{i-1} f \quad (2)$$

where f is the fraction of SO_2 observed on day $i - 1$ that remains on day i. Thus the new SO_2 production is given by

$$M(\text{new})_i = M(\text{total})_i - M(\text{total})_{i-1} f \quad (3)$$

On December 26, 1981, the first day of the eruption, no old SO_2 exists and the total is equal to the new amount (see Table 1). Thereafter the fraction of old SO_2 that remains depends on the loss rate $(1 - f)$. A low fraction corresponds to a high loss rate, while a high fraction would remain with a low loss rate. In the tropical lower stratosphere the chemical lifetime is known experimentally to be about 1 month [*Krueger*, 1983; *Bluth et al.*, 1992]. This lifetime corresponds to a loss rate of 3% per day or a residual fraction of 0.97. In the boundary layer the lifetime is less than a day and the residual fraction is near zero. The lifetime in the troposphere is expected to be shorter than in the stratosphere because of larger water concentrations.

Figure 2 illustrates the daily new SO_2 production from Nyamuragira as a function of daily loss rate, $1 - f$, from 100% per day (top curve) to 3% per day (bottom curve) for the first 8 days of the eruption, when daily totals could be determined with a reasonable degree of accuracy. The top curve (100%) corresponds to the total observed SO_2 each day because 100% of the prior day's sulfur dioxide has been lost. The bottom curve (3%) assumes the stratospheric loss rate. Thus the family of curves corresponds to loss rates for altitudes from the ground to the stratosphere.

Some loss rates produce impossible results. For example, a stratospheric loss rate of 3% per day implies that the production would have to be negative near the end of December. Thus no significant portion of the cloud can be at stratospheric altitudes. In practice, tropospheric loss rates are poorly known, but the new production estimates from plume morphology can be used to suggest a loss rate. These data points, shown in Figure 2 by the heavy dashed line, are consistent with loss rates of 10–40% per day. The cloud motions were initially northeast at an altitude of 13 to 17 km and changed to northwest for an inferred altitude of 10 km after the third day of the eruption. Because the SO_2 lifetime increases with altitude, this implies that the initial eruption clouds should have a lower loss rate than the later clouds. Indeed, the loss rate is near 10% on December 27 and increases to 20–30% on later days. This behavior of an initial high-altitude injection from a vigorous outpouring of lava in effusive eruptions followed by a more benign eruptive activity is similar to that observed during the eruption of Mauna Loa in 1984 [*Casadeval et al.*, 1984].

Given estimates of the loss rate, it is then possible to sum up all of the new SO_2 during all days of the eruption to produce a total production. The bottom line in Table 1 is the eruption total under the different assumptions. The totals range from 11 Mt in the unlikely case of complete loss of prior SO_2 in a very low altitude cloud to 1.6 Mt if the cloud were completely in the stratosphere. The total, given a 20% daily loss, is, as expected, 3.3 Mt, in close agreement with the 3.0 Mt plume estimate. Thus we believe that Nyamuragira produced a cloud containing about 3 Mt SO_2 with a loss rate of 20%/day. This is consistent with the cloud drift observations indicating an upper tropospheric cloud.

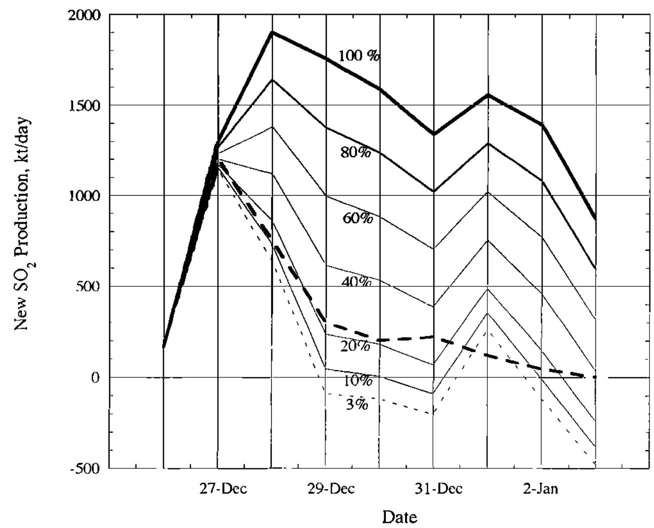

Figure 2. New SO_2 production from Nyamuragira as a function of time with fractional loss per day as a parameter. The top line corresponds to complete loss of old SO_2 each day. Estimates of newly produced SO_2 are shown by the heavy dashed line, suggesting about 20% loss per day.

Conclusions

Numerous ground observing stations and aircraft flights detected a mystery cloud in the first 3 months of 1982 at altitudes between 11 and 18 km. A major effusive eruption of Nyamuragira was detected in TOMS SO_2 data beginning on December 26, 1981, and is believed to be the source of this volcanic cloud. Lidar sightings at Kyushu, Japan, on January 23, 1982, followed by Mauna Loa, Hawaii, on January 28 indicate that clouds were within 1 km of the January average tropopause heights. This is consistent with the wind direction in the upper troposphere over equatorial Africa. Also, the eastern portion of the SO_2 cloud disappeared more slowly than the western cloud. On these bases we conclude that the westward portion was in the lower troposphere. The eastward portion was near the tropopause and was the portion detected by the ground stations.

Nyamuragira erupted about 3 Mt of SO_2 over 8 days and was the second most prolific SO_2 producer in the 1980s, exceeded only by the 1982 El Chichon eruption. A comparison between Nyamuragira and El Chichon, however, is misleading in terms of the magnitudes of their global impact. They differ in that El Chichon erupted in one cataclysmic explosion and ejected most of its 7 Mt of SO_2 into the stratosphere, while Nyamuragira produced approximately half that amount of SO_2 over 8 days, and very little, if any, of the SO_2 reached the stratosphere.

Other eruptions of Nyamuragira were observed with TOMS. On January 30, 1980, a small eruption produced up to 150 kt of SO_2 that drifted westward from the volcano. On July 17–19, 1986 an SO_2 plume was observed extending west from the volcano. The total mass is estimated to be 750 kt. Most recently, Nyamuragira was observed by the Meteor 3/TOMS instrument to be erupting on July 5–10, 1994. The total SO_2 production was about 1200 kt.

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