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El Chichon: The genesis of volcanic sulfur dioxide monitoring from space

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ABSTRACT

The 1982 eruption of El Chichon inspired a new technique for monitoring volcanic clouds. Data from the Total Ozone Mapping Spectrometer (TOMS) instrument on the Nimbus-7 satellite were used to measure sulfur dioxide in addition to ozone. For the first time precise data on the sulfur dioxide mass in even the largest explosive eruption plumes could be determined. The plumes could be tracked globally as they are carried by winds. Magmatic eruptions could be discriminated from phreatic eruptions. The data from El Chichon are reanalyzed in this paper using the latest version of the TOMS instrument calibration (V8). They show the shearing of the eruption cloud into a globe-circling band while still anchored over Mexico in three weeks. The measured sulfur dioxide mass in the initial March 28 eruption was 1.6 Tg; the April 3 eruption produced 0.3 Tg more, and the April 4 eruptions added 5.6 Tg, for a cumulative total of 7.5 Tg, in substantial agreement with estimates from prior data versions. TOMS Aerosol Index (absorbing aerosol) data show rapid fallout of dense ash east and south of the volcano in agreement with Advanced Very High Resolution Radiometer (AVHRR) ash cloud positions.

1. Introduction

In 1982, anomalously high total ozone appeared above Mexico in data from the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus-7 satellite at the same time as the eruption of El Chichon (Krueger, 1983). After 6 centuries of repose, El Chichon erupted violently on March 28 through April 4, 1982. This volcano and the eruptions are well documented in terms of chronology, petrology, stratigraphy, and motion of the ash clouds (Robock and Matson, 1983; Matson, 1984; Varekamp et al., 1984; Luhr et al., 1984; Rose et al., 1984; Sigurdsson et al., 1984). The detailed behavior of the April 4 eruption gas and ash clouds was analyzed by Schneider et al. (1999) using data from TOMS and AVHRR instruments. The atmospheric effects of the eruption were reviewed by Hofmann (1987).

The TOMS instrument (Heath et al., 1975; Krueger, 1989), launched in October 1978, was designed, as its name implies, to determine the spatial structure in total ozone through daily, contiguous mapping of the earth. Prior ozone data from ground stations showed high variability with time scales similar to meteorological changes, but the relations with weather were elusive because of the sparse distribution of stations. The TOMS was built with the best spatial resolution available with 1970′s technology (50 km at nadir) to resolve anticipated gradients in total ozone. The spacecraft data rate also limited the spectral coverage to 6 discrete ultraviolet wavelengths for total ozone soundings (Dave and Mateer, 1967). The contiguous mapping proved to be at least as valuable for volcanology as for atmospheric ozone.

The TOMS total ozone algorithm was developed with the assumption that ozone was the only absorbing gas at near UV wavelengths (310–380 nm). Other gases were ignored because they were normally present in far lower optical depths than ozone. In 1982, the strange cloud of apparent high total ozone over Mexico (Fig. 1a) at the time of the El Chichon (small black triangle on Fig. 1a) eruption required an explanation. Krueger (1983) showed that the spectral anomalies were consistent with sulfur dioxide, making it the most likely volcanic constituent to account for the anomalous absorption. A simple scheme to separate sulfur dioxide from ozone absorption was proposed. The sulfur dioxide absorption spectrum overlaps the ozone spectrum but with different structure. Other gases, such as carbon disulfide, also absorb at these wavelengths, but would produce different spectral anomalies. Sulfur dioxide amounts were estimated from the deviation of the observed radiances from an interpolation of unperturbed radiances on either side of the volcanic cloud. Agreement at the two TOMS wavelengths within the SO_2 band was within 10%, but absolute amounts were not certain because at the time only room temperature SO_2 cross sections had been measured (Wu and Judge, 1981) while the cloud temperatures were near −50 °C. An average column SO_2 amount over the cloud, multiplied by the cloud area obtained from the TOMS images yielded a total mass in the April 5th cloud of 3.3 Tg. New cross section data at low temperatures (McGee and Burris, 1987) are now used to produce more accurate results.

With the contiguous coverage and moderate spatial resolution of TOMS it now became possible to measure the mass of sulfur dioxide in

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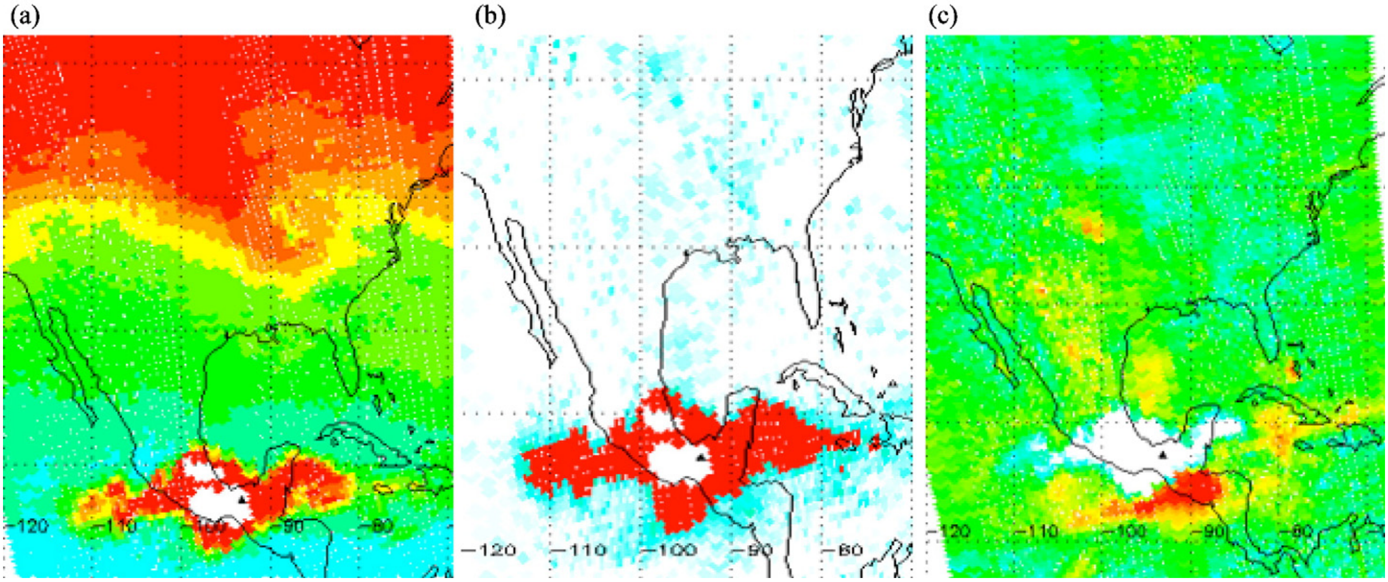

Fig. 1. a. Image of the total ozone field from the Nimbus-7 satellite Total Ozone Mapping Spectrometer (TOMS) on April 5, 1982 showing anomalous high ozone retrievals (yellow, red, white colors) above Mexico. Normal tropical ozone levels are the blue and green colors while the red and yellow colors across the northern United States are usual midlatitude ozone values. The volcanic anomaly is due to failure of the ozone retrieval algorithm to account for sulfur dioxide absorption. El Chichon's location is shown by the black triangle over southern Mexico. All Nimbus-7 data are taken about an hour before local noon. b. A revised TOMS ozone data production algorithm flags SO_2 contaminated ozone retrievals with a sulfur dioxide index (SOI). The red area represents SOI levels above 100 DU (1 mm of pure SO_2 gas at STP conditions) in the April 5, 1982 El Chichon eruption cloud. This algorithm fails for greater than 205 DU of SO_2 (white areas in the center of the cloud). c. A TOMS Aerosol Index (AI) is a measure of absorbing aerosol optical depths. This image of the April 5. 1982 eruption shows ash clouds in yellow and red colors. The white central cloud region represents failed AI retrievals from large sulfur dioxide amounts. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

eruption clouds that were far too large to be assessed from the ground or from aircraft. This began an extended effort to improve the sulfur dioxide retrieval algorithm and to map all of the volcanic eruption clouds in the TOMS database.

The volcanic sulfur dioxide data are derived in part from the standard Level 2 TOMS datasets and in part from special off-line analysis of the Level 1 orbital data. The special analysis is required whenever high sulfur dioxide amounts are present. The retrieval algorithm is implemented in the TOMSPlot utility software.

2. Volcanic products in TOMS production data

Three useful products are available for eruption analysis in the standard TOMS output data, available in Level 2 (orbital) format from the Goddard Distributed Active Archive Center (DAAC) (McPeters et al., 1993). They include total ozone anomalies, Sulfur Dioxide Index, and Aerosol Index. Over the years the standard TOMS data production has gone through eight versions as the ozone algorithm and instrument calibration were updated. However, the production algorithm only calculates effective total ozone, as illustrated in Fig. 1a using the most recent (Version 8) ozone data (Bhartia and Wellemeyer, 2004). The ozone anomaly due to sulfur dioxide on April 5, 1982 is the irregular red/white area over Mexico. Sulfur dioxide clouds always produce erroneously high total ozone. Thus, even small eruptions may appear as anomalous bumps in the ozone field, especially in the tropics, where the ozone is nearly constant.

A second useful product is the Sulfur Dioxide Index (SOI), designed for flagging contaminated ozone retrievals (Fig. 1b). The SOI has been calibrated to yield approximately correct sulfur dioxide amounts for small SO_2 amounts. SOI is the radiance residual at a short TOMS wavelength from the best total ozone solution obtained at a longer wavelength. However, if the ozone is wrong, the residual is wrong. So, SOI is valid only for low SO_2 amounts (<30 Dobson units). Nevertheless, SOI is a convenient tool for locating volcanic clouds [Note: 1 Dobson unit $= 2.69 \times 10^{16}$ molecules/cm^2].

A third standard V8 TOMS parameter, Aerosol Index (AI), a residual at a long TOMS wavelength, is a measure of the deviation of the backscattered spectrum from a Rayleigh spectrum. The light scattering properties of the atmosphere at UV wavelengths are dominated by Rayleigh scattering, except when absorbing aerosols, such as volcanic ash, are present. Ash produces large positive AI deviations, shown in red in Fig. 1c just south of the large white area over the El Chichon sulfur dioxide cloud. Near zero AI values are in green and blue colors. The white areas are invalid retrievals due to the effect of large SO_2 amounts on the ozone retrievals.

The TOMS Aerosol Index has proved very useful for tracking volcanic ash clouds, which are a hazard to aviation. Other absorbing aerosols, such as dust and smoke, can produce the same signal as ash, so that AI is not unique to volcanic clouds. However, sulfur dioxide is unique to volcanic clouds, so that a combination of the two parameters is a valuable tool for aviation safety.

3. Off-line sulfur dioxide retrieval algorithms

In the original analysis of the El Chichon eruption it became obvious that the TOMS total ozone algorithm could not be used when volcanic clouds were present. In fact, because sulfur dioxide and ozone had similar absorption spectra, it was necessary to solve for both species simultaneously. Jim Kerr of the Atmospheric Environment Service had faced a similar problem with Brewer Spectrophotometer data. He suggested using the Brewer algorithm for the TOMS SO_2 retrievals, adding two other free parameters to account for the scattering properties of the atmosphere and surface. This algorithm was later reformulated as a matrix problem (Krueger et al., 1995). With ground-based instruments using direct sunlight to measure an overhead absorber the path is simply geometric. The satellite solutions using geometric paths are approximately correct for stratospheric sulfur dioxide clouds but fail with lower altitude clouds.

Satellite-borne observations must consider other factors to determine the path. At UV wavelengths, the paths of photons are rarely geometric; from the sun to the surface and reflected to the satellite, except for snow or ice covered terrain. For more typical low reflectivity surfaces, Rayleigh scattering in the mid-troposphere returns most of the light that is not absorbed by ozone or sulfur dioxide back to space. Absorbers below the scattering layer are only partially sensed. Thus, the optical path must be computed using a multiple scattering