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Comment on the paper "The atmospheric SO_2 budget for Pinatubo derived from NOAA-11 SBUV/2 spectral data" by R. D. McPeters

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A recent Geophysical Research Letters paper (McPeters, 1993) reported the use of the Solar Backscatter Ultraviolet Spectrometer (SBUV/2) to measure the mass of sulfur dioxide clouds produced by the June, 1991 explosive eruption of Pinatubo. In this paper McPeters compared SBUV/2 values with measurements reported by us (Bluth et al.,1992) on the same eruption using the Total Ozone Mapping Spectrometer (TOMS). McPeters claimed that TOMS values for the Pinatubo SO_2 budget are too high by as much as 50%. In this Comment we wish to clarify and respond to the arguments presented with respect to the capabilities and limitations of both TOMS and SBUV/2.

McPeters presented essentially four lines of evidence to support his contention that the SBUV was more accurate than TOMS. The first argument is that SBUV gives a more accurate instantaneous field of view (IFOV) measurement than TOMS. This is based on the optimum selection of wavelengths from the continuous scan mode of SBUV, compared to the TOMS four operative bands which are fixed at wavelengths optimized for measuring ozone, not sulfur dioxide. McPeters estimates an SO_2 accuracy within a SBUV/2 IFOV of approximately 10 to 20%, derived from the variation of four SO_2 calculations using the four narrow SO_2 absorption bands between 300 and 310 nm. His evidence regarding the poorer accuracy of TOMS is based on undocumented model results at two different SO_2 concentrations. TOMS errors, like SBUV errors, are a function of a number of complex, interdependent parameters such as accuracy of SO_2 UV absorption coefficients; aerosol, ash and ozone concentrations; water-cloud reflectivity; SO_2 cloud altitude; view and solar zenith angles; signal to noise ratio; algorithm nonlinearity, etc. Any serious attempt to evaluate a complex procedure such as volcanic SO_2 retrieval must be more rigorous than the single non-referenced sentence devoted to it in McPeters (1993).

We do not dispute the possibility of large errors under certain conditions, but the errors are a function of all the parameters listed above, not just SO_2 concentration. We have been using TOMS data to measure volcanic SO_2 emissions for over a decade and we continue to study the question of accuracy. Each eruption cloud must be evaluated individually. Under favorable conditions (e.g., low solar zenith angle, moderate view angles) we generally assign a cloud mass error estimate of ±30% (Krueger et al., 1990), and under poor viewing conditions or long temporal extrapolation we often assign much higher error estimates. A detailed description of TOMS errors, including extensive modeling results, is in preparation.

Secondly, McPeters (1993) noted "the tendency of TOMS to infer small background amounts of SO_2 when no SO_2 is present", implying a potentially large source of error. He neglected to add, however, that TOMS SO_2 cloud mass results are always corrected for this background. Along with measurements of an SO_2 cloud, areas adjacent to the cloud, comparable in size and viewing angle, are also measured to determine background SO_2. The background is then subtracted from the SO_2 cloud mass (Krueger, 1983; Krueger et al., 1990; Bluth et al., 1992).

The third argument is based on a comparison of the SO_2 cloud mass as determined by the two instruments on consecutive days. The first day McPeters (1993) could use SBUV/2 to measure the Pinatubo cloud was July 1, when he calculated the cloud contained 8.4 million metric tons (Mt) of SO_2. He compared this with the TOMS estimate on June 30 of 12 Mt and ascribed the difference to a 50% overestimation by TOMS due to "limitations in the absolute accuracy of the TOMS retrieval" and TOMS background "problems", rather than to any uncertainty in the SBUV results.

McPeters did not evaluate errors associated with the SBUV/2 measurement of the cloud. The only error estimate reported was ~10 to 20%, but that was for point measurements, i.e., a single IFOV. A fundamental assumption by McPeters was that because SBUV/2 can make a more precise measurement of column SO_2 than TOMS, it can also make a more accurate assessment of an entire volcanic SO_2 cloud. But SBUV/2 is a fixed nadir-viewing instrument and can only measure about 1% of the cloud area. TOMS is a scanner with contiguous IFOVs and measures 100% of the cloud area. Clearly, the accuracy of SBUV/2 measurements of the mass of a volcanic cloud depend on sampling and the homogeneity of the cloud at the time of the measurement. McPeters found that on the previous day of SBUV/2 measurement, June 19, the cloud was too heterogeneous for the sampling of SBUV/2 to give a meaningful mass. Using the SO_2 values in Fig 4. of McPeters (1993) yields a total of 2.4 Mt for the June 19 cloud, clearly

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inconsistent with his 8.4 Mt 12 days later. But no evidence was given by McPeters that the cloud had become sufficiently homogeneous by July 1 to obtain an accurate tonnage.

Actually, many sources attest to the heterogeneity of the cloud. Aircraft measurements taken during the time period of SBUV observations show equatorial SO_2 column variations of a factor of at least five (Hoff, 1992). The Microwave Limb Sounder (MLS) instrument on the UARS satellite measured an order of magnitude range of stratospheric SO_2 in the mid-latitudes in September, more than two months after the SBUV/2 measurements (Read et al., 1993). More importantly, McPeters' own SBUV/2 observations themselves indicate the great heterogeneity of the cloud. The average and coefficient of variation of the SBUV/2 observations of the Pinatubo SO_2 clouds on June 19, July 1 and July 17 are 3.5 DU±77%, 2.9 DU±72% and 1.4 DU±57%, respectively. It is clear that even over a month after the eruption the cloud is still quite heterogeneous. Without contrary evidence, there is no reason to conclude that the difference in SBUV/2 and TOMS values is due to errors in TOMS.

Lastly, McPeters uses the SBUV/2 cloud measurements to calculate the initial amount of SO_2 produced by the explosive eruption on June 15 (12 to 15 Mt), and again compares this with our TOMS estimate (20 Mt). The amount of SO_2 produced is calculated by observing the decay of the cloud with time, due to loss of sulfur dioxide through conversion to sulfate; an exponential curve is fit to the measured cloud masses and the curve is extrapolated back to the time zero, the time of eruption. This erupted mass has an uncertainty due to the errors in measurement of the individual cloud masses and the length of the extrapolation. McPeters used measurements on only July 1 and July 19, 16 and 32 days after the eruption, each with unstated errors. As discussed above, the error on July 1 might be large due to the inhomogeneity of the cloud. The July 17 cloud, while more homogeneous, had thinned-out so a larger portion of the cloud was above zero but below the limit of detectability. Errors in either of these two measurements magnify the errors in calculating both the amount of SO_2 actually erupted on June 15 and the e-folding time, due to the long period of time between eruption and observation. McPeters did not report this error, but it is potentially quite large, and is certainly larger than the only error reported in the paper, i.e., his IFOV error of ~10 to 20%. In contrast, Bluth et al. (1992) extrapolated the amount erupted from five TOMS observations, made 2, 3, 5, 8 and 15 days after the eruption. Again, without a detailed error analysis on the SBUV/2 measurements, it is premature to ascribe the difference in the amount erupted to inherent errors in the TOMS procedure. Actually, McPeters (1993) failed to note that in both comparisons (the cloud tonnage on July 1 and total amount erupted) that the SBUV and TOMS values agree within the stated errors of each instrument, i.e., 30% for TOMS and the (underestimated) ~10 to 20% for SBUV.

Validation of TOMS results with ground based instruments has proved to be difficult because it depends on chance observation of a volcanic cloud as it passes over a station. This happened only once during the 14 year lifetime of Nimbus-7 TOMS. Thus, the SBUV could be very useful for this purpose. However, it is necessary to get simultaneous samples at a time when the cloud is compact, with SO2 amounts greater than 50 DU such that the quantization noise of TOMS does not dominate the comparison. The Pinatubo cloud illustrates the difficulty. The average of all 16 TOMS IFOVs within each SBUV/2 IFOV was computed and compared with SBUV/2 data on June 19, July 1, and July 17. Because Nimbus-7 passed over earlier than NOAA 11, the TOMS data points were shifted 2° west in longitude to account for cloud motion. The highest SBUV/2 observations on each of the three days were 6.5, 10.4, and 3.3 DU, all within 2 TOMS standard deviations of the background level. TOMS observed values as high as 800 DU just after the eruption, and values greater than 100 DU until late June. As might be expected, the correlation coefficients on the three days are low (0.285, 0.502, and 0.113). On the best day, July 1, the slope of a linear fit is 0.767 with a standard error of 0.288. Statistically, a slope of unity is within the 90% confidence interval. It is clear that coincident SBUV observations of much larger sulfur dioxide amounts are necessary before they become useful for comparison with TOMS observations.

The capability of TOMS for detection and measurement of SO_2 in explosive volcanic eruption clouds, and in tracking the motion and dispersion of these clouds is unequaled by any other current technique, ground or satellite. During its fourteen year lifetime, the Nimbus-7 TOMS measured SO_2 clouds from over 100 separate eruptions.

Both TOMS and SBUV have a role to play in the measurement of SO_2 clouds from explosive volcanic eruptions. TOMS is ideally used for detecting numerous small eruptions which last for only short periods, and for capturing the full extent of large eruption clouds during the first few weeks after eruption. In the two instances where SBUV instruments have observed volcanic SO_2 clouds (El Chichon and Pinatubo) there is evidence that SBUV may be better suited to sampling spatially extensive homogeneous volcanic clouds where SO_2 concentrations approach the TOMS analysis threshold. Thus, data from both instruments could be used together for optimum results. However, in using SBUV to estimate the total SO_2 produced from such eruptions the errors introduced by sampling must be carefully evaluated and clearly stated. Unfortunately, neither were done in the paper by McPeters (1993).

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