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Multi-decadal satellite measurements of passive and eruptive volcanic SO_2 emissions

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Periodic injections of sulfur gas species (SO_2, H2S) into the stratosphere by volcanic eruptions are among the most important, and yet unpredictable, drivers of natural climate variability. However, passive (lower tropospheric) volcanic degassing is the major component of total volcanic emissions to the atmosphere on a time-averaged basis, but is poorly constrained, impacting estimates of global emissions of other volcanic gases (e.g., CO_2). Stratospheric volcanic emissions are very well quantified by satellite remote sensing techniques, and we report ongoing efforts to catalog all significant volcanic SO_2 emissions into the stratosphere and troposphere since 1978 using measurements from the ultraviolet (UV) Total Ozone Mapping Spectrometer (TOMS; 1978-2005), Ozone Monitoring Instrument (OMI; 2004 - present) and Ozone Mapping and Profiler Suite (OMPS; 2012 - present) instruments, supplemented by infrared (IR) data from HIRS, MODIS and AIRS. The database, intended for use as a volcanic forcing dataset in climate models, currently includes over 600 eruptions releasing a total of $\sim$100 Tg SO_2, with a mean eruption discharge of $\sim$0.2 Tg SO_2. Sensitivity to SO_2 emissions from smaller eruptions greatly increased following the launch of OMI in 2004, but uncertainties remain on the volcanic flux of other sulfur species other than SO_2 (H2S, OCS) due to difficulty of measurement. Although the post-Pinatubo 1991 era is often classified as volcanically quiescent, many smaller eruptions (Volcanic Explosivity Index [VEI] 3-4) since 2000 have injected significant amounts of SO_2 into the upper troposphere - lower stratosphere (UTLS), peaking in 2008-2011. We also show how even smaller (VEI 2) tropical eruptions can impact the UTLS and sustain above-background stratospheric aerosol optical depth, thus playing a role in climate forcing on short timescales. To better quantify tropospheric volcanic degassing, we use $\sim$10 years of operational SO_2 measurements by OMI to identify the strongest volcanic SO_2 sources between 2004 and 2015. OMI measurements are most sensitive to SO_2 emission rates on the order of $\sim$1000 tons/day or more, and thus the satellite data provide new constraints on the location and persistence of major volcanic SO_2 sources. We find that OMI has detected non-eruptive SO_2 emissions from at least $\sim$60 volcanoes since 2004. Results of our analysis reveal the emergence of several major tropospheric SO_2 sources that are not prominent in existing inventories (Ambrym, Nyiragongo, Turrialba, Ubinas), the persistence of some well-known sources (Etna, Kilauea) and a possible decline in emissions at others (e.g., Lascar). The OMI measurements provide particularly valuable information in regions lacking regular ground-based monitoring such as Indonesia, Melanesia and Kamchatka. We describe how the OMI measurements of SO_2 total column, and their probability density function, can be used to infer SO_2 emission rates for compatibility with existing emissions data and assimilation into chemical transport models. The satellite-derived SO_2 emission rates are in good agreement with ground-based measurements from frequently monitored volcanoes (e.g., from the NOVAC network), but differ for other volcanoes. We conclude that some ground-based SO_2 measurements may be biased high if collected during periods of elevated unrest, and hence may not be representative of long-term average emissions.