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ADVANCES IN UV SATELLITE MONITORING OF VOLCANIC EMISSIONS

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ABSTRACT

Measurements of volcanic degassing play a key role in monitoring and hazard mitigation at active volcanoes, and underpin assessments of volcanic impacts on the environment, climate and health. Satellite remote sensing has provided critical observations of volcanic sulfur dioxide (SO_2) emissions during major eruptions since 1978. Since the 1990s, advances in instrumentation and trace gas retrieval techniques have increased the sensitivity of ultraviolet (UV) satellite SO_2 measurements by several orders of magnitude. This now permits global monitoring of SO_2 emitted both during and between volcanic eruptions, increasing the viability of satellite data as a volcano monitoring tool. In this paper, we review recent developments in satellite instrumentation, SO_2 retrieval algorithms and data analysis techniques used to quantify global volcanic SO_2 emissions. The launch of a geostationary UV satellite constellation in the coming decade will further advance space-borne UV volcano monitoring.

Index Terms— Volcanic gases, ultraviolet satellite measurements, sulfur dioxide, volcano monitoring, remote sensing of volcanoes

1. INTRODUCTION

Active volcanoes emit gases both during quiescent, background activity (or 'passive' degassing), and during violent, short-lived eruptions. Measurement of volcanic gas fluxes, and their temporal variations, are of potential value for eruption forecasting and can be used to infer the quantity, composition, and storage conditions (pressure, temperature) of magma stored at depth. The detection of lower tropospheric volcanic plumes emitted by passively degassing volcanoes is of particular importance for volcano monitoring. Volcanic emissions are typically dominated by water vapor (H_2O; ~60 to >99 mol%) and carbon dioxide (CO_2; <1 to >30 mol%), followed by varying proportions of sulfur dioxide (SO_2; up to ~7 mol%) and hydrogen sulfide (H_2S; <1 mol%), halogen gases (HCl, HF), carbon monoxide (CO), and trace amounts of many other species. Although several of these volcanic gas species can now be detected from space, SO_2 is the major target species in volcanic emissions due to its low atmospheric background abundance, diagnostic value for volcano monitoring and eruption forecasting, accessible ultraviolet (UV) and infrared (IR) absorption bands and its key role as an agent of volcanic climate change [1].

Satellite measurements are the only effective way to quantify SO_2 amounts in volcanic clouds that can be hundreds of kilometers in spatial extent. NASA's UV Total Ozone Mapping Spectrometer (TOMS) instrument, first launched in 1978, made the first measurement of volcanic SO_2 emissions from space in April 1982 after the major explosive eruption of El Chichón volcano (Mexico). Subsequently, the entire TOMS data record (1978-2005) was used to generate a multi-decadal record of SO_2 production by all major volcanic eruptions, which has been extended to the present using more recent satellite data [1] (https://so2.gsfc.nasa.gov). Although the TOMS missions ended in 2005, refinement of the TOMS SO_2 retrieval algorithms is ongoing, leading to improved estimates of SO_2 emissions from past volcanic eruptions and consistent SO_2 measurements spanning multiple UV satellite missions [2].

Since the TOMS missions, UV sensors launched on NASA, European Space Agency (ESA) and other satellites have increased in spatial and spectral resolution and are now being operated from diverse orbits, offering new capabilities for the monitoring of volcanic emissions. In this paper we review recent developments in UV satellite remote sensing, focusing on how satellite sensor evolution has fostered advances in SO_2 retrieval algorithms, generating high-quality SO_2 measurements that provide an unprecedented space-borne perspective on global volcanic emissions.

2. UV SENSOR EVOLUTION

The multi-spectral (6-band) TOMS instruments had limited sensitivity to SO_2 and were unable to detect most lower tropospheric volcanic plumes due to their low spectral and spatial resolution (40×40 km or 50×50 km). Satellite sensitivity to SO_2 (i.e., the smallest detectable vertical column density [VCD]) depends on the spatial and spectral resolution of the sensor, with smaller pixels and higher spectral resolution (i.e., hyperspectral data) providing greater sensitivity to weaker volcanic SO_2 emissions (small eruptions and passive volcanic degassing). Since the TOMS missions the quality and sensitivity of UV satellite SO_2 measurements has steadily improved though the deployment of increasingly advanced instruments [1], permitting the development of more advanced SO_2 retrieval algorithms [3].

The ESA Global Ozone Monitoring Experiment (GOME; 1995-2003) was the first hyperspectral UV instrument to measure relatively small tropospheric volcanic SO_2 emissions from space. A significant advance occurred with the launch of the UV Ozone Monitoring Instrument (OMI) on NASA's Aura satellite in 2004, which provided the first daily measurements of volcanic SO_2 degassing at 'volcano scale' spatial resolution (13×24 km) [1]. The UV Tropospheric Monitoring Instrument (TROPOMI), launched on the ESA Sentinel-5 Precursor (S5P) satellite in 2017, is the most advanced space-borne UV sensor to date, measuring volcanic SO_2 with a spatial resolution of 5.5×3.5 km since August 2019. At the TROPOMI spatial resolution, individual tropospheric volcanic plumes can be resolved and analyzed, e.g., to extract sub-daily SO_2 fluxes for volcano monitoring applications or study volcanic SO_2 plume dispersion in unprecedented detail [4]. At the time of writing, there are at least 20 daily overpasses of UV and IR satellite instruments capable of detecting volcanic SO_2, many providing data in near real-time (NRT) within a few hours of the satellite overpass (e.g., the Support to Aviation Control (SACS) service: https://sacs.aeronomie.be/nrt/ [5]), enabling robust and timely detection of volcanic eruptions whenever and wherever they occur. UV-visible sensors can also measure other trace gas species in volcanic plumes, including BrO and OClO, which play important roles in ozone chemistry, and NO_2, which can be generated by lightning in explosive volcanic eruption columns (lightning NO_x).

3. ADVANCED SO_2 RETRIEVAL ALGORITHMS

The availability of hyperspectral UV satellite measurements has permitted the application of more advanced algorithms to retrieve VCDs of trace gases such as SO_2. The main goal of these algorithms is to minimize interference from other geophysical factors (notably, ozone absorption) and reduce the noise and other artifacts (e.g., due to wavelength shifts) in SO_2 retrievals, enabling the robust detection of lower SO_2 VCDs. A principal component analysis (PCA) retrieval technique has been successfully applied to OMI and Ozone Mapping and Profiler Suite (OMPS) data, generating satellite SO_2 measurements with exceptionally low noise [3], and a similar covariance-based algorithm has been developed for S5P/TROPOMI data. The strength of the data-driven PCA approach is that the dominant sources of noise (e.g., ozone) are extracted directly from the UV radiances in the spectral

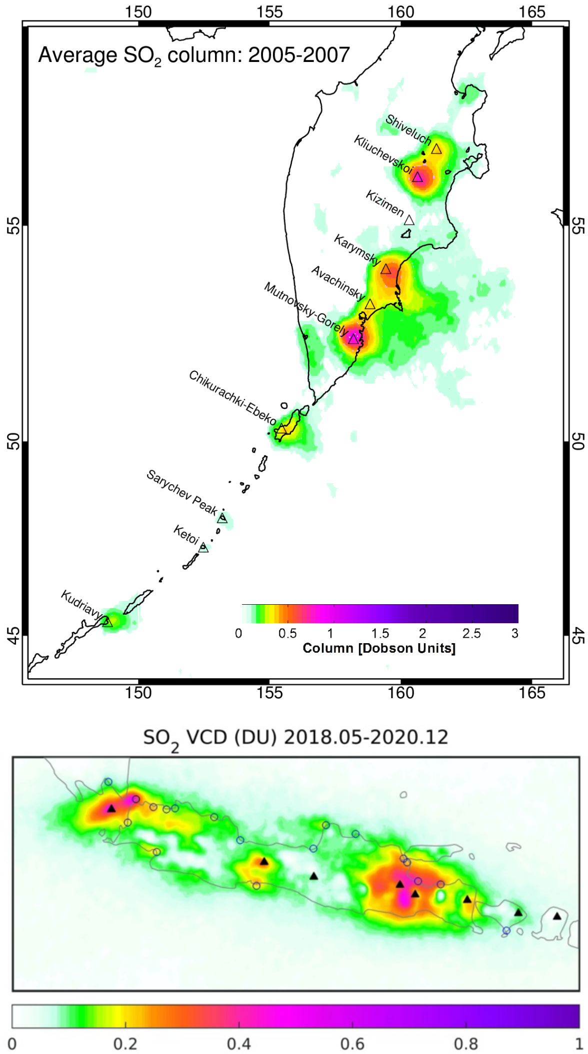

Figure 1. *Top* Average SO_2 VCDs measured by Aura/OMI in 2005-2007 over Kamchatka and the Kuril Islands (Russia), with the volcanic SO_2 sources indicated [6,7]; *Bottom* Average SO_2 VCDs measured by S5P/TROPOMI between May 2018 and December 2020 over Java, Indonesia, with active volcanoes (*triangles*) and power plants (*circles*) indicated. VCDs are reported in Dobson Units (DU; 1 DU = 2.69×10^{16} molecules cm^{-2}).

fitting, requiring minimal a-priori knowledge of their characteristics. Hyperspectral measurements also allow flexible wavelength selection to avoid saturation in the shorter (more strongly absorbed) UV wavelengths in the presence of very high SO_2 VCDs. This is critical for accurate quantification of volcanic SO_2 emissions since SO_2 VCDs in volcanic plumes can vary by several orders of magnitude. The PCA SO_2 algorithm iteratively adjusts the spectral fitting window to exclude shorter wavelengths when the SO_2 absorption is saturated [3].

4. VOLCANIC EMISSIONS INVENTORIES

Inventories of volcanic emissions (SO_2 and other gases) are needed to understand the impact of volcanism on global atmospheric composition and also represent a volcanic degassing 'baseline' for potential use in eruption forecasting. The production of daily, global, low-noise satellite SO_2 datasets (available from Aura/OMI since late 2004), offering high sensitivity to lower tropospheric SO_2, has in turn significantly improved constraints on the magnitude of global volcanic and anthropogenic SO_2 emissions and the location of major SO_2 sources [6]. Long-term averaging (e.g., monthly or annual means) and oversampling of satellite-derived SO_2 VCDs is used to further reduce noise and locate weaker SO_2 sources that may not be apparent in daily measurements (Fig. 1). New global volcanic SO_2 emissions inventories derived from Aura/OMI measurements since 2005 [6,7] are a major improvement over prior compilations, which were extrapolated from a relatively small number of ground-based SO_2 measurements at actively degassing volcanoes. The Aura/OMI volcanic SO_2 emissions inventory (valid from 2004 to present) indicates that ~90-100 volcanoes have persistent SO_2 emissions detectable from space (e.g., Fig. 1), collectively emitting a total SO_2 flux of ~23 ± 2 Tg/yr [7]. The global volcanic SO_2 flux should remain well constrained in the future and will include weaker SO_2 sources, since the required UV measurements continue with S5P/TROPOMI (e.g., Fig. 1), which has higher SO_2 sensitivity than OMI [4]. Volcanic SO_2 emissions inventories, combined with gas ratios measured in-situ, also provide improved constraints on volcanic emissions of other gases [8].

5. SO_2 ALTITUDE RETRIEVALS

The altitude of volcanic SO_2 injection is the primary control on SO_2 lifetime and of derived sulfate aerosol, and hence on the climate impact of volcanic emissions. When used as a proxy for volcanic ash, the altitude of volcanic SO_2 plumes also aids the mitigation of volcanic hazards to aviation. Altitude is also a critical factor in SO_2 retrievals by nadir imaging satellite sensors, as the absorption of UV and IR radiation by SO_2 is temperature dependent. Since the altitude of SO_2 injection is usually unknown at the time of measurement, a common approach is to prescribe a vertical profile of SO_2 (e.g., corresponding to a typical volcanic plume altitude) in the retrieval algorithm [3]. However, direct retrievals of SO_2 altitude from hyperspectral UV and IR measurements are possible [9,10], albeit with relatively coarse vertical resolution, and are becoming more common as computational power increases. Recently, machine learning algorithms have been adopted for rapid NRT SO_2 layer height retrievals for operational use [11] and such techniques are likely to become increasingly favored as satellite data volumes expand. Coupled with advances in passive and active satellite measurements of aerosols, current satellite assets provide unprecedented constraints on the mass and 3D distribution of volcanic SO_2 and aerosols.

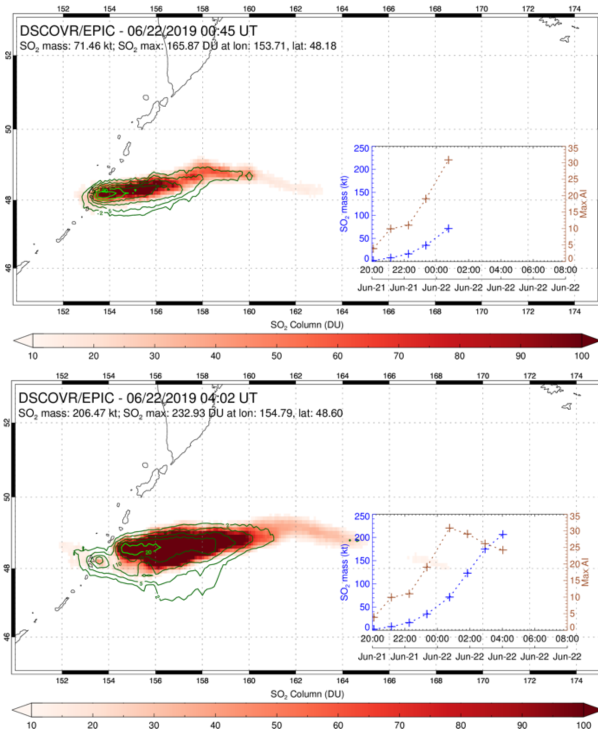

Figure 2. DSCOVR/EPIC measurements of the June 2019 Raikoke eruption (Kuril Is, Russia) at 00:45 and 04:02 UT on June 22, 2019. SO_2 VCDs are shown in red and the UV Aerosol Index (AI) in green; the inset shows the trend in hourly SO_2 mass and AI over time during the eruption.

6. UV OBSERVATIONS FROM L1 AND GEOSTATIONARY ORBIT

Until 2015, all UV satellite observations were made from polar or low-Earth orbit (LEO). LEO sensors provide global coverage (including high latitudes) at the expense of temporal resolution, but the latter can be of critical importance for volcano monitoring, e.g., during pre-eruptive volcanic unrest or eruptions. The low temporal resolution of single LEO sensors is mitigated by multiple UV and IR sensors capable of detecting SO_2 currently flying on a constellation of US and European LEO satellites, which can potentially provide ~20 daily SO_2 measurements under optimal conditions [5]. However, these observations are clustered around two daytime and nighttime satellite overpass times (~9:30-10:30 am/pm and ~1:30 am/pm local time), and so there can be gaps of several hours between consecutive LEO sensor overpasses.

Since 2015, a new paradigm for Earth observations has been demonstrated by the Deep Space Climate Observatory (DSCOVR) satellite, in orbit at the first Earth-Sun Lagrange point (L1), 1 million miles from Earth [12]. From L1, DSCOVR has a continuous view of the sunlit Earth disk, permitting high-cadence observations of solar backscattered radiation. Observations from L1 differ from geostationary

(GEO) views in that the latter omits the high latitudes, whereas the polar regions are visible from L1 in the summer hemisphere. DSCOVR carries the Earth Polychromatic Imaging Camera (EPIC), a UV-Visible sensor that provides 'sunrise-to-sunset' images of Earth with hourly cadence (https://epic.gsfc.nasa.gov/). A UV EPIC SO_2 retrieval algorithm has been developed and the measurements have detected all major volcanic eruptions during the DSCOVR mission to date [13]. The hourly cadence of the EPIC SO_2 observations provides novel information on SO_2 emission trends during major eruptions, such as the June 2019 eruption of Raikoke volcano (Kuril Islands, Russia; Fig. 2). EPIC is also sensitive to volcanic ash and quantitative ash retrieval techniques are in development.

The coming decade will see another major advance in UV satellite measurements: the deployment of a constellation of hyperspectral UV sensors in GEO orbit. Although the main goal of this constellation is air quality monitoring over specific areas, the sensors will all measure SO_2 at high cadence (hourly) and will observe some volcanic regions. The first satellite in this constellation, the South Korean Geostationary Environment Monitoring Spectrometer (GEMS), was launched in 2020 and observes East Asia, including volcanoes in Japan, the Philippines, and northern Indonesia. GEMS will be followed in 2022 by NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission which will observe North America, including some Mexican volcanoes. The GEO ESA Sentinel-4 mission will observe air quality over Europe from 2023.

7. SUMMARY

Since 1978, UV satellite remote sensing has evolved to become a viable tool for daily monitoring of volcanic SO_2 emissions and a valuable supplement to other satellite and ground-based volcano monitoring techniques. Its utility in some volcanic regions is set to increase in the near future with the deployment of a geostationary UV satellite constellation. Future challenges will include the need to rapidly process and analyze increasingly large volumes of satellite data, in order to realize the full potential of UV measurements for volcano monitoring at volcano observatories worldwide.

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