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The impact of satellite sensor viewing geometry on time-series analysis of volcanic emissions

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ABSTRACT

Time-series analysis techniques are being increasingly used to process satellite observations of volcanic gas emissions and heat flux, with the aim of identifying cyclic behaviour that could inform hazard assessment or elucidate volcanic processes. However, it can be difficult to distinguish cyclic variations due to geophysical processes from those that are artefacts of the observation technique. Here, we conduct a comprehensive investigation into the origin of cyclicity in volcanic observations by analysing daily, global satellite measurements of volcanic SO_2 loading by the Ozone Monitoring Instrument (OMI) and thermal infrared anomalies detected by the Moderate Resolution Imaging Spectroradiometer (MODIS). We use a fast Fourier Transform (FFT) multi-taper method (MTM) to analyse multiple phases of activity at 32 target volcanoes, utilising measurements obtained from three NASA satellite instruments (Aura – OMI, Aqua – MODIS and Terra – MODIS), and identify a common cycle (period of ~2.3 days), which is not considered to be of volcanic origin. Based on the presence of this cycle in multiple satellite datasets, we attribute it to variations in viewing angle during the 16-day orbit repeat cycle of sun-synchronous satellites maintained in Low Earth Orbit (LEO). A 5-point averaging correction procedure is tested on satellite observations from Kilauea volcano, Hawaii, and is found to reduce the impact of higher frequency cycles and reveal the presence of longer-period geophysical signals. In addition to the identification of a signal common to different measurement techniques, an underlying cyclical pattern was found in the OMI SO_2 observations (periods of ~7.9 and 3.2 days) generated by the OMI Row Anomaly (ORA). We conclude that identification of the presence and magnitude of non-geophysical cyclic behaviour, which can suppress natural cycles in time-series data, and implementation of appropriate corrections, is crucial for accurate interpretation of satellite observations. The use of data averaging to suppress non-geophysical cycles imposes limits on the length of natural cycles that can be confidently identified in moderate resolution satellite observations from polar-orbiting spacecraft.

1. Introduction

Satellite remote sensing is an essential tool for the monitoring and assessment of environmental systems. Whether in the elucidation of subsurface processes (Lu, 2007), changes in land use (Lambin & Strahlers, 1994), natural hazard assessment and mitigation (Tralli, Blom, Zlotnicki, Donnellan, & Evans, 2005), or atmospheric conditions (Martin, 2008), satellite measurements are expanding our capability to assess the impacts of both natural and anthropogenic change in near real time and on a global scale. Volcanic systems are dynamic and unpredictable in nature with multiple mechanisms potentially responsible for initiating or sustaining eruptions. Due to this complexity, it is not feasible to quantify all the possible driving forces contributing to eruptions that would be necessary for accurate model construction (Sparks, 2003). Therefore, forecasting of volcanic eruptions tends to focus on past behaviour; i.e., the identification and classification of historic volcanic activity allowing the calculation of recurrence rate which can be incorporated into models (Denlinger & Hoblitt, 1999; Dzierma & Wehrmann, 2010; Odbert, Stewart, & Wadge, 2014; Sparks, 2003; Swanson & Holcomb, 1990; Voight et al., 1999). This method can be effective at volcanic systems characterized by relatively stable activity, where factors such as the chemical composition of the source magma and the conduit dimensions in the subsurface plumbing system show little temporal variability (Jaupart & Allègre, 1991; Papale, Neri, & Macedonio, 1998; Wilson, Sparks, & Walker, 1980). At volcanoes where activity displays repetitive characteristics, time-series analysis can be utilised to identify the duration and offset of the cycles present, with the goal of forecasting periods when resurgent activity should be expected (Odbert et al., 2014). The extended resurgence period typical

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of volcanic systems requires a data series of significant length and with appropriate temporal resolution to assess the characteristics of volcanic activity. Ground-based measurements have previously been employed in analysis of cyclic behaviour (Nicholson, Mather, Pyle, Odbert, & Christopher, 2013), but can be hindered by the high costs associated with the deployment and maintenance of ground-based equipment, or precluded entirely at very hazardous volcanoes with restricted access. In contrast, moderate resolution satellite-based instruments provide near global daily coverage without the associated cost or risks associated with ground-based monitoring. NASA's polar-orbiting A-Train satellite constellation includes two instruments capable of monitoring volcanic systems on a daily basis: the Ozone Monitoring Instrument (OMI) on Aura and the Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua. Both OMI and MODIS now offer data records spanning over 10 years, providing near-coincident measurements of volcanic sulphur dioxide (SO_2) emissions and heat fluxes, respectively, with an additional MODIS sensor available on the Terra satellite providing multiple MODIS overpasses per day. To date, there have been few efforts to exploit the synergy of OMI and MODIS in characterizing cyclic volcanic behaviour.

To identify any geophysical variability and trends in satellite observations, interference from instrumental or atmospheric effects must first be identified and removed. Whilst the major interference factors affecting satellite retrievals are generally documented before the release of data (e.g., Krotkov, Carn, Krueger, Bhartia, & Yang, 2006; Wright, Flynn, Garbeil, Harris, & Pilger, 2002), subtler variations can go unidentified in visual inspection of data in the time domain. Through the use of spectral density estimation, patterns can be distinguished in data obtained from satellite instruments (e.g., Murphy, Wright, Oppenheimer, & Souza Filho, 2013; Flower & Carn, 2015); these may be interpreted either as a result of natural processes or as artefacts of the measurement techniques employed. In this paper we discuss the identification of cycles in satellite-based time series data from active volcanoes and their attribution, based on an extensive analysis of OMI and MODIS observations. The near-coincidence of OMI and Aqua/MODIS measurements from the A-Train minimizes any impact of variable volcanic activity or atmospheric conditions on the analysis, and hence analysing the datasets in concert provides unique insight into the origin of cyclic signals. Our conclusions have broad implications for the interpretation of results from time-series analysis of moderate resolution satellite observations of volcanic activity, and are also relevant to any observations of sub-pixel scale phenomena from space.

2. Methodology

2.1. SO_2 emissions

SO_2 is commonly emitted in both effusive and explosive phases of volcanic eruptions and during passive, non-eruptive degassing (Bluth, Schnetzler, Krueger, & Walter, 1993; Carn et al., 2003; Carn, Clarisse, & Prata, 2016; McCormick et al., 2013). Due to its strong absorption bands in the ultraviolet (UV) spectral region (e.g., Bogumil et al., 2003), as well as its relatively low abundance in the atmosphere compared to other volcanic gases such as water vapour and carbon dioxide (CO_2), SO_2 is the main target for remote sensing of volcanic eruptions and degassing (Krotkov et al., 2006; Krueger, 1983). The dynamic and unpredictable nature of volcanic activity requires timely assessment and continuous monitoring of volcanic systems. However, due to safety and logistical concerns, in many locations continuous ground-based monitoring is not feasible, whereas satellite remote sensing provides a safe and effective means of global volcano monitoring (Carn, Krotkov, Yang, & Krueger, 2013). Whilst multiple UV satellite sensors provide tropospheric SO_2 measurements (e.g., the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography [SCIAMACHY]; Lee, Richter, Weber, & Burrows, 2008; OMI; Krotkov et al., 2006; the Global Ozone Monitoring Experiment-2 (GOME-2); Rix et al., 2009; the Ozone Mapping and Profiler Suite [OMPS]; Carn, Yang, Prata, & Krotkov, 2015), OMI currently provides the best spatial resolution (13×24 km at nadir) whilst maintaining near-global daily coverage (Krotkov et al., 2006). Operational Level 2 OMI SO_2 data (OMSO2) are publicly available from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC; http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2_v003.shtml), providing daily, global measurements of SO_2 total column amounts (in Dobson Units (DU); 1 DU $= 2.69 \times 10^{16}$ molecules/cm^2). Operational OMSO2 data are currently processed with a linear fit (LF) algorithm (Yang et al., 2007) using UV radiances measured by OMI in 10 discrete wavelength bands. The typical uncertainty on SO_2 columns retrieved by the LF algorithm is ~20% below 100 DU; above this column amount non-linear absorption effects, which are not accounted for in the algorithm, greatly increase the uncertainty (Yang et al., 2007). However, SO_2 column amounts >100 DU are only present transiently in the core of fresh volcanic eruption clouds and hence are not expected to impact our analysis significantly. The presence of cloud can impact the retrieval of SO_2, with overlying meteorological clouds masking volcanic plumes at lower altitude due to increased scattering of radiation, whilst plumes present above the cloud tops are susceptible to overestimation of SO_2 columns due to multiple scattering effects (Carn et al., 2013).

Accurate retrieval of SO_2 column amounts also requires a-priori knowledge of the injection altitude of the SO_2, which is not available at the LF algorithm runtime and hence must be assumed. Volcanic SO_2 column amounts in the OMSO2 product are calculated for three predefined SO_2 vertical profiles corresponding to the lower troposphere (TRL; SO_2 centre of mass altitude (CMA) of ~3 km), mid-troposphere (TRM; CMA of ~8 km) and the lower stratosphere (STL; CMA of ~17 km) (Yang et al., 2007; Carn et al., 2013). The most appropriate SO_2 vertical profile is selected based on the nature of the volcanic activity under observation. For predominantly passive degassing volcanoes the emissions may be assumed to be confined within approximately 1 km of the summit making the TRL (3 km) SO_2 columns the most appropriate for most active volcanoes (Carn et al., 2013) whilst the TRM and STL SO_2 products are representative of moderate and large eruptions (VEI ≤ 3 and VEI ≥ 4, respectively) (McCormick et al., 2013). Due to the major focus of this work on persistent SO_2 emissions, retrievals were obtained from the TRL (3 km) SO_2 product. This may result in overestimation of SO_2 emissions on days when stronger eruptions injected SO_2 to higher altitudes, but because our analysis focuses on temporal trends in volcanic emissions rather than the absolute values obtained, we believe occasional overestimation should not adversely affect the results.

For this analysis, time-series of SO_2 mass were generated by integrating TRL SO_2 column amounts measured by OMI in a 4° square region centred on each target volcano (Table 1). Data were obtained from individual OMI orbits to prevent issues with multiple retrievals from overlapping orbits at high latitudes. If multiple overpasses intersected a sampling region, data were obtained from the swath with the closest to nadir viewing angle over the volcanic target. Variability in the measured SO_2 mass can result from variations in the volcanic emissions, plume altitude, interference from neighbouring volcanoes or meteorological clouds, but are also modulated by variations in OMI pixel size or GIFOV (ground-projected instantaneous field of view) as the sensor viewing geometry changes during a 16-day satellite orbit repeat cycle (Krotkov et al., 2006). The latter effect is most pronounced for sub-pixel scale SO_2 plumes which are averaged over the OMI GIFOV. An additional interference affecting OMI measurements since 2008 is the OMI Row Anomaly (ORA), which has rendered a variable fraction of the OMI swath unusable due to a blockage in the sensor's field of view (FOV) (see: http://www.knmi.nl/omi/research/product/rowanomaly-background.php). Previous studies using time-series analysis techniques have been limited to periods before the development of the ORA to reduce the impact of this feature on output (Flower & Carn, 2015).