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Characterising volcanic cycles at Soufriere Hills Volcano, Montserrat: Time series analysis of multi-parameter satellite data

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A B S T R A C T

The identification of cyclic volcanic activity can elucidate underlying eruption dynamics and aid volcanic hazard mitigation. Whilst satellite datasets are often analysed individually, here we exploit the multi-platform NASA A-Train satellite constellation to cross-correlate cyclical signals identified using complementary measurement techniques at Soufriere Hills Volcano (SHV), Montserrat. In this paper we present a Multi-taper (MTM) Fast Fourier Transform (FFT) analysis of coincident SO_2 and thermal infrared (TIR) satellite measurements at SHV facilitating the identification of cyclical volcanic behaviour. These measurements were collected by the Ozone Monitoring Instrument (OMI) and Moderate Resolution Imaging Spectroradiometer (MODIS) (respectively) in the A-Train. We identify a correlating cycle in both the OMI and MODIS data (54–58 days), with this multi-week feature attributable to episodes of dome growth. The ~50 day cycles were also identified in ground-based SO_2 data at SHV, confirming the validity of our analysis and further corroborating the presence of this cycle at the volcano. In addition a 12 day cycle was identified in the OMI data, previously attributed to variable lava effusion rates on shorter timescales. OMI data also display a one week (7–8 days) cycle attributable to cyclical variations in viewing angle resulting from the orbital characteristics of the Aura satellite. Longer period cycles possibly relating to magma intrusion were identified in the OMI record (102-, 121-, and 159 days); in addition to a 238-day cycle identified in the MODIS data corresponding to periodic destabilisation of the lava dome. Through the analysis of reconstructions generated from cycles identified in the OMI and MODIS data, periods of unrest were identified, including the major dome collapse of 20th May 2006 and significant explosive event of 3rd January 2009. Our analysis confirms the potential for identification of cyclical volcanic activity through combined analysis of satellite data, which would be of particular value at poorly monitored volcanic systems.

1. Introduction

The identification of cyclical activity on various timescales at active volcanoes has been used to draw conclusions about the subsurface processes driving these systems (Spampinato et al., 2012; Costa et al., 2013) and can also inform volcanic hazard assessment. Factors such as cycle duration and volume of erupted material have been assessed through modelling to infer the size and structure of subsurface features such as magma chambers and conduits (Costa et al, 2007; Lensky et al., 2008). However, to identify these cycles a time-series dataset of significant duration and resolution is required, which can be difficult to obtain for remote or unmonitored volcanoes. In these situations measurements by operational satellite instruments can constitute an invaluable resource, and since the advent of daily, global measurements of volcanic sulphur dioxide (SO_2) by sensors such as the Ozone Monitoring Instrument (OMI; Carn et al., 2013) the collection of SO_2 data for persistently degassing volcanoes has become routine (e.g., Carn et al., 2013; McCormick et al., 2012). These SO_2 observations complement long-term thermal infrared (TIR) measurements that have been collected for more than a decade by sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS; e.g., Wright et al., 2002). In this contribution we test the feasibility of using time-series satellite measurements to identify cyclical activity at persistently active volcanoes.

We posit that synergistic analysis of multiple satellite datasets (e.g., SO_2 and TIR data) to assess eruption dynamics will result in a more robust interpretation of the nature of the volcanic activity, by reducing the impacts of individual sensor limitations, and providing coincident information on fluxes of SO_2 and TIR radiance. Daily, near-coincident, multi-spectral observations have been provided since 2004 by NASA's A-Train satellite constellation, consisting (in February 2015) of the GCOM-W1, Aqua, CALIPSO, Cloudsat and Aura platforms (NASA, 2010). SO_2 can be measured remotely due to significant absorption bands in the ultraviolet (UV) portion of the electromagnetic spectrum (Platt and Stutz, 2008; Yang et al., 2009). NASA's Aura satellite, launched

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in 2004, carries the UV–Visible OMI sensor currently used to measure multiple atmospheric trace gases including SO_2 (Carn and Prata, 2010; Krotkov et al., 2006, 2010; Prata et al., 2007; Yang et al., 2007). The detection of surface thermal anomalies or 'hotspots' is facilitated by MODIS, using radiance measurements in multiple bands of the short-wave IR (SWIR) and TIR (Wright et al., 2002). MODIS instruments are flown on-board NASA's Terra and Aqua satellites, and since September 2004 Aqua/MODIS has provided daytime TIR observations coincident with Aura/OMI SO_2 measurements. The presence of OMI and MODIS in the A-Train permits cross-correlation due to the fixed orbital formation of the Aura and Aqua satellites, with no more than a 15-min lag between the measurements collected by the overpass of the first (Aqua) and last (Aura) satellites.

The combination of SO_2 and TIR measurements should permit the identification of a wider variety of volcanic activity types than either dataset in isolation. For example, whilst an ongoing effusive eruption may feature minimal variation in SO_2 mass loadings and therefore a constant SO_2 emission rate, the corresponding TIR measurements may vary due to the development of lava flows from surface to tubular flow features (Koeppen et al., 2011). Additionally vigorous degassing may produce opaque plumes that could obscure subjacent thermal features (e.g., active lava lakes or domes), and thus potentially result in anti-correlations between SO_2 emissions and TIR radiance. Based on any co-variations in the two datasets we aim to identify the types of activity that may be occurring (e.g. lava dome growth, waxing/waning of lava lakes). By identifying dominant cycles we aim to provide insight into not only the processes occurring but also the timescales upon which certain forms of activity are likely to reactivate.

We use Soufriere Hills volcano (SHV; Montserrat) as an initial test of the viability of this methodology, as a similar analysis was applied to ground-based gas measurements at SHV in 2002–2009 by Nicholson et al. (2013), thus providing some independent validation. For consistency with Nicholson et al. (2013), we focus on coincident OMI and MODIS data collected between January 2005 and December 2009, which encompasses three phases of lava dome growth at SHV: August 2005–April 2007, July 2008–January 2009 and October 2009 (Wadge et al., 2010). An additional motivation for selecting this timeframe is minimisation of the impacts of data gaps caused by the OMI Row Anomaly (ORA; see Section 2.1). For comparative purposes, Table 1 lists previous studies that have identified cycles in datasets from SHV as well as the identified source of each cycle. In addition to the observed cycles identified at SHV, Carn et.al. (2007) identified the possible presence of a 6-day cycle in OMI SO_2 measurements induced by the cyclical divergence of the viewing angle from nadir. In addition to this, the orbital path of the A-Train results in variations of viewing angle for fixed targets with a repeat cycle of 16 days. Hence, in order to identify cycles relating to volcanic processes in satellite measurements, we first identify and eliminate any signal modulations due to instrumental or other non-volcanic sources.

Table 1
Cycles identified in previous studies of Soufriere Hills Volcano, Montserrat.

Reference	Data type	Cycle period(s)
Odbert et al., 2014	Review of previous work: Seismic, lava flux, observations,	Sub-daily Sub-annual Multi-annual Multi-decadal
Lamb et al., 2014	Earthquakes	~200 days ~100 days ~50 days
Costa et al., 2013	Combined model and seismic data	40 days
Vitturi et al., 2013	Deformation, seismic and visual observations	4–36 h 5–7 weeks
Michaut el al., 2013	Deformation	6–30 h
Nicholson et al., 2013	Ground-based DOAS SO_2	171 days 54 days 19 days 12 days 8 days
Loughlin et al., 2010	Discharge pulse and rockfall events	2–6 weeks 11–16 days
Wadge et al., 2010	Identified short period pulses in lava flux	10–15 days
Odbert and Wadge, 2009	Lava flux and deformation data	10 h 50 h
Elsworth et al., 2008	Observations	2–3 years (interspersed by 1.5-2 year)
Costa et al., 2007	Model of dyke embedded in elastic media	38–51 days (i.e., 5–7 weeks)
Jaquet et al., 2006	Coupled seismic and model data	40 days
Melnik and Sparks, 2005	Models	6–7 weeks
Carn et al., 2004	Observations	7–10 h
Edmonds et al., 2003	SO_2 emissions post-rockfalls and pyroclastic flows	60–180 min
Druitt et al., 2002	Deformation and seismic	2.5–63 h (av. 10 h)
Sparks and Young, 2002	Observed resurgence of lava extrusion (1997)	36–52 days
Watson et al., 2000	Deformation, seismic and gas	8–14 h
Denlinger and Hoblitt, 1999	Deformation and seismic	4–30 h
Voight et al., 1999	Deformation	6–30 h
Voight et al, 1998	Deformation	6–18 h

2. Data

2.1. OMI SO_2 measurements

Operational OMI SO_2 measurements (Yang et al., 2007) comprise the primary dataset for this analysis since they provide a ~10-year record of daily, global SO_2 observations, and sensitivity to lower tropospheric volcanic SO_2 emissions (i.e., passive degassing; Carn et al., 2013). Currently, daily OMI SO_2 data for volcanic regions can be viewed on the Global Sulfur Dioxide Monitoring website at NASA Goddard Space Flight Center (http://so2.gsfc.nasa.gov) and the Support to Aviation Control Service website (http://saca.aeronomie.be/nrt). For our quantitative analysis of SO_2 emissions we use the operational Level 2 OMI Sulphur Dioxide product (OMSO2 collection 3), which is 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). In order to analyse SO_2 emissions from SHV, OMSO2 data were extracted from a 4° × 4° latitude-longitude box (~450 × 450 km) centred over the volcano. Since SO_2 retrievals depend on the assumed altitude of the gas, the OMSO2 data product includes three volcanic SO_2 column amounts retrieved assuming different a-priori SO_2 plume altitudes (~3, ~8 and ~17 km; Carn et al., 2013). Recorded plume heights at SHV in the 2005–2009 period (Global Volcanism Program, 2009) indicate that plumes were typically confined to the lower troposphere (~1.5–4 km altitude), and hence we use the lower tropospheric (TRL) SO_2 columns which assume a SO_2 plume altitude of ~3 km (Carn et al., 2013). Overestimation of SO_2 altitude leads to underestimation of SO_2 column amounts and vice versa; based on linear interpolation of OMI TRL and mid-tropospheric (TRM; ~8 km SO_2 altitude) SO_2 columns we estimate that SHV plume altitude variations in the 1.5–4 km range would result in up to ~20% variation in SO_2 mass. Sources of error in the operational OMI SO_2 measurements (including SO_2 profile, non-linear absorption and cloud effects) are also discussed by Yang et al. (2007), who estimate an overall uncertainty of 20%. In the case of SHV we expect meteorological clouds to be the most significant source of error, assuming that there are relatively minor variations in the SO_2 profile (i.e., plume altitude) and negligible non-linear absorption effects due to low SO_2 column amounts in the SHV plume. Variability in the measured SO_2 mass can also result from the variation in OMI pixel size or GIFOV (ground-projected instantaneous field of view) during the 16-day Aura repeat cycle (Krotkov et al, 2006). The effect is most pronounced for sub-pixel sized SO_2 plumes which are averaged over the OMI GIFOV. In order to better