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The impact of persistent volcanic degassing on vegetation: A case study at Turrialba volcano, Costa Rica

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ABSTRACT

Although the impacts of large volcanic eruptions on the global environment have been frequently studied, the impacts of lower tropospheric emissions from persistently degassing volcanoes remain poorly understood. Gas emissions from persistent degassing exceed those from sporadic eruptive activity, and can have significant long-term (years to decades) effects on local and regional scales, both on humans and the environment. Here, we exploit a variety of high temporal and high spatial resolution satellite-based time series and complementary ground-based measurements of element deposition and surveys of species richness, to enable a comprehensive spatio-temporal assessment of sulfur dioxide (SO_2) emissions and their associated impacts on vegetation at Turrialba volcano (Costa Rica) from 2000 to 2013. We observe increased emissions of SO_2 coincident with a decline in vegetation health downwind of the vents, in accordance with the prevalent wind direction at Turrialba. We also find that satellite-derived vegetation indices at various spatial resolutions are able to accurately define the vegetation kill zone, the extent of which is independently confirmed by ground-based sampling, and monitor its expansion over time. In addition, ecological impacts in terms of vegetation composition and diversity and physiological damage to vegetation, all spatially correspond to fumigation by Turrialba's plume. This study shows that analyzing and relating satellite observations to conditions and impacts on the ground can provide an increased understanding of volcanic degassing, its impacts in terms of the long-term vegetation response and the potential of satellite-based monitoring to inform hazard management strategies related to land use.

1. Introduction

Although the impacts from large volcanic eruptions on the global environment have been frequently studied (e.g. Hofmann, 1987; Grattan and Charman, 1994; Grattan and Pyatt, 1994; Parker et al., 1996; Oppenheimer, 2002; Gu et al., 2003; Self, 2006; Self et al., 2006) the impacts of lower tropospheric emissions from persistently degassing volcanoes remain poorly known. On a time-averaged basis, gas emissions from persistent, passive volcanic degassing (i.e. the process by which magma loses its volatiles to the atmosphere without erupting) greatly exceed those from sporadic eruptive activity (e.g. Andres and Kasgnoc, 1998; Oppenheimer et al., 2003), and can have significant long-term (years to decades) effects on local and regional scales, both on humans (e.g. Baxter et al., 1982; Longo et al., 2005; Amaral and Rodrigues, 2007; Longo and Yang, 2008; Longo et al., 2008; Longo, 2009; Longo et al., 2010a,b; Weinstein et al., 2013; Selinus, 2013; van Manen, 2014) and the environment (e.g. Delmelle et al., 2002; Delmelle, 2003). It is generally accepted that anomalous soil chemical conditions (e.g. on active volcanoes) can influence vegetation, and the spatial variation of soil temperature gradients has been shown to influence vegetation communities (e.g. Taupo Volcanic Zone, New Zealand; Burns, 1997; Boothroyd, 2009). However, despite the potential impacts, volcanic degassing remains one of the least studied volcanic hazards, with minimal scientific literature available on the relationship between geothermal surface manifestations and the effects on vegetation (cfr. van Manen and Reeves, 2012; van der Meer et al., 2014). Improved understanding of these relationships could also contribute to volcanic hazard mitigation; e.g. at vegetated volcanoes, reactivating after a period of dormancy, identification of vegetation damage due to volcanic degassing could provide advance warning of impending eruptive activity.

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This contribution focuses on the impacts of persistent volcanic degassing on vegetation, where volcanic degassing is defined as the process by which magma loses its volatiles to the atmosphere, the extent and temporal evolution of which can be effectively mapped using satellite remote sensing techniques. We also, for the first time, include satellite measurements of volcanic sulfur dioxide (SO_2) emissions in an assessment of the timing of vegetation impacts at an actively degassing volcano. The two most common causes of vegetation damage (ranging from defoliation to tree death) due to direct volcanic impact are: (i) diffuse carbon dioxide (CO_2) soil degassing of intrusive bodies (e.g. Mammoth Mountain, Eastern California; Sorey et al., 2001), depriving vegetation root systems of crucial oxygen; and (ii) acid deposition (wet and dry) from a volcanic plume (e.g. Masaya volcano, Nicaragua; Delmelle et al., 2002), leading to defoliation and reduced ability to photosynthesize. Another indirect cause of vegetation damage related to volcanic emissions is soil acidification due to long-term acid precipitation (e.g. Kilauea, Hawaii; Nelson and Sewake, 2008). By combining satellite-derived maps of the extent and severity of vegetation impacts, measurements of volcanic SO_2 emissions, and ground-based sampling, we aim to analyze the damage due to acid deposition from a volcanic plume and highlight a range of satellite-based analysis techniques that can be applied to investigate vegetation impacts at degassing volcanoes worldwide.

In this study we analyze the evolution of the vegetation surrounding Turrialba volcano (Costa Rica) from 2000 to 2013. Turrialba is an active stratovolcano located in the Central Cordillera of Costa Rica (Fig. 1) with an elevation of 3340 m. The edifice is located only 35 km east-northeast of Costa Rica's capital city (San José) and poses a threat to Costa Rica's central valley, the social and economic hub of the country where more than half of the population resides. After more than a century of quiescence, Turrialba resumed activity in 1996 (Martini et al., 2010), which to date has resulted in the temporary evacuation of two villages, indefinite closure of the National Park that comprises the summit region of the volcano, and visible devastation of the local vegetation. Our approach is to exploit a variety of high temporal and high spatial resolution satellite-based time series data, along with ground-based measurements such as element deposition and surveys of species richness, to facilitate a comprehensive assessment of Turrialba's SO_2 emissions and their associated impacts on vegetation.

2. Geological setting

Turrialba is a large vegetated basaltic-to-dacitic active stratovolcano located at the southeastern terminus of the Central American volcanic arc (Fig. 1). Its approximately 800 × 2200 m elliptical-shaped caldera contains three craters. Recent activity has been confined to the central and western craters. The central crater is characterised primarily by fumarolic gas emissions and it contains an intermittent water body subject to precipitation in the region. The westernmost crater is associated with the most recent magmatic eruptive activity (Reagan et al., 2006; Vaselli et al., 2010; Conde et al., 2014).

Activity in the western crater commenced in the mid-1990s with signs of seismic activity in the area surrounding the volcanic edifice (Martini et al., 2010). From May 1996 onwards, degassing and seismic activity progressively increased, with a dramatic increase in March 2007 attributed to a shallow magmatic intrusion (Martini et al., 2010; Vaselli et al., 2010). Since 2007, gas emissions have been continuous. More recently Turrialba renewed its eruptive activity during a series of short-lived phreatic explosions on January 5, 2010 (Campion et al., 2012). Since then, the persistent degassing has been punctuated by intermittent phreatic explosions accompanied by ash emissions that have occasionally reached San José (Martini et al., 2010; Conde et al., 2014).

Prior to the current activity, Turrialba's last eruptive period, from 1864 to 1866, saw ash fallout up to 125 km from the volcano (Reagan et al., 2006). These historical accounts, combined with the impacts of the 1963–1965 eruption at neighboring Irazú (Lemieux, 1977), highlight the potential for activity to affect the densely populated and economic hub that is Costa Rica's Central Valley, located just southwest of the edifice. Additional acute hazards at Turrialba include Strombolian- to Plinian-size explosions, pyroclastic flows, lateral blasts, lahars, lava flows and landslides (Reagan et al., 2006; Soto, 2012). The acute hazard with the highest probability of occurrence is minor volcanic explosions, whose impacts are constrained to the summit region. However, the continuous gas emissions pose an ongoing chronic hazard with the potential for health, socio-economic and environmental impacts, the latter of which we address in this paper.

3. Data & methods

3.1. Satellite data

The satellite data used includes a variety of low, moderate and high spatial resolution imagery at ultraviolet (UV) to microwave wavelengths from the Ozone Monitoring Instrument (OMI), the Moderate-Resolution Imaging Spectroradiometer (MODIS), Enhanced Thematic Mapper Plus (ETM+), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Phased Array type L-band Synthetic Aperture Radar (PALSAR).

Because cloud coverage is an issue in the tropics, radar-derived products can be of relevance for continuous monitoring of volcanoes in these regions. Indeed, the vast majority of the cloud-free images utilized in this study were acquired in the boreal winter (i.e. dry season), and only a handful in the summer (Fig. 2). Although reduced in the tropics, given the significant effects of seasonality of vegetation growth on satellite remote sensing analysis, we excluded the images recorded from April to October of each year from the analysis to facilitate more objective comparisons.

3.1.1. Aura OMI

OMI is a hyperspectral UV–vis spectrometer on-board NASA's Aura spacecraft, in orbit since July 2004. Aura is part of the A-Train satellite constellation and operates in a sun-synchronous, near polar orbit at an altitude of ~705 km (Levelt et al., 2006a). Each OMI orbit has a swath width of 2600 km and pixel size of 13 × 24 km at nadir (Levelt et al., 2006b), allowing continuous global measurements of ozone and various other trace gases including SO_2 (Carn et al., 2013). In the absence of significant meteorological cloud cover, OMI can provide daily remote measurements of volcanic SO_2 emissions if they exceed the sensor's lower detection limit (Carn et al., 2008; 2013).

We use the operational level 2 OMI SO_2 data product (OMSO2, collection 3), which is available from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC; http://disc.sci.gsfc.nasa.gov/). The operational OMI SO_2 algorithm retrieves total SO_2 column densities in volcanic plumes based on three different assumptions of the SO_2 vertical profile (i.e. Lower Troposphere (TRL; ~3 km, altitude for the plume resulting from Turrialba's persistent degassing), Mid-troposphere (TRM; ~8 km) and lower stratosphere (STL; ~18 km) (Yang et al., 2007), and the total SO_2 mass is calculated by integrating the SO_2 vertical column densities over the plume area (Lopez et al., 2012). SO_2 burdens measured by OMI were calculated with OMIplot (Carn, 2011; Palma et al., 2014), a software package designed to analyze and visualize