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Long-range transport of SO_2 over South Africa: A case study of the Calbuco volcanic eruption in April 2015

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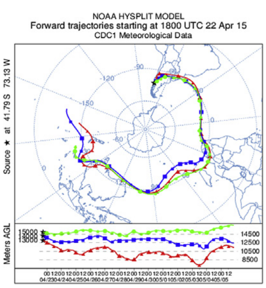
GRAPHICAL ABSTRACT



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ABSTRACT

South Africa (SA) is influenced by anthropogenic SO_2 emissions, however, no studies exist detailing the atmospheric or climatic effects resulting from volcanic eruptions at this location. In this work, the Calbuco volcano situated in southern Chile (41.79°S, 73.13°W), was used as a case study to investigate the transport of volcanic SO_2 plumes over SA in 2015. The Calbuco volcano underwent a series of eruptive phases starting from 22 April 2015. In this study, HYSPLIT forward trajectories and cluster analysis were carried out in order to estimate the altitude level of air parcels entering the SA subcontinent. These analyses along with Ozone Monitoring Instrument (OMI) assessments confirmed that trajectories beginning in Calbuco arrived in SA during the last few days of April (~28 April 2015) and stayed until the 1st week of May 2015 (~2 May 2015). In order to estimate the rise in SO_2 columnar concentrations at various altitudes and surface SO_2 levels, OMI data and 19 ground-based (GB) monitoring stations (situated throughout SA) were utilized. A comparative analysis employing SO_2 data from pre-2014 and post-2016 volcanic eruption periods were also included in this study. Results showed that a major increase in SO_2 concentration was observed at the Planetary Boundary Layer (~ 2 DU) when compared to its upper layers during April and May 2015. Although some GB stations in North West province namely Damonsville, Mmabatho and Phola showed a moderate increase in SO_2 values during April and May 2015, there was no significant rise in GB measurements at the surface in other locations However, we are not certain due to data gaps in the measurements and non-availability of ground-based measurements.

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1. Introduction

Volcanic eruptions are a natural emission source of SO_2 and can inject SO_2 deep into the atmosphere, sometimes reaching stratospheric altitudes (Prata et al., 2015). Although volcanic gases and particles in the troposphere and stratosphere do not influence human health directly, they may still exhibit significant, adverse environmental impacts. It has been shown that even limited interaction between volcanic clouds (in the mid and upper troposphere) and aircraft can result in major damage or interruption of air traffic (Prata, 2009). This damage can span the range from a sulphur smell or light dust in the cabin to major consequences including heavy dust, electrical and computer systems failure and temporary engine malfunction (Guffanti et al., 2010). Aircraft using North Atlantic and *trans*-Pacific air routes are more susceptible to traffic disturbances due to volcanoes in Iceland and Japan (Prata, 2009). Between 1953 and 2009, volcanoes responsible for significant damage to aircraft included Augustine (USA), Mount St. Helens (USA), Redoubt (USA), Sakura-jima (Japan) and Pinatubo (Philippines) (Guffanti et al., 2010). In the stratosphere, the residence time of SO_2 is longer than that in the troposphere. This is because surface SO_2 reacts with aerosol particles to form sulphate aerosols. Furthermore, the measurement of volcanic SO_2 emissions is challenging due to the aperiodic and unpredictable nature of eruptions (Khokhar et al., 2005). It has been estimated that nearly 11.9 Tg of SO_2 is released into the atmosphere every year as a result of active volcanoes together with 6.8 Tg contributed by passive degassing of volcanoes (Stoiber et al., 1987). Of the six, routinely monitored volcanic gases measured by remote sensors, SO_2 is the dominant species. This is due to the large amounts emitted, short residence time and simple structure of its absorption bands in the UV and IR. The result is that it is easily measured by both UV and IR spectral-based sensors (Carn et al., 2016).

Satellite-based instruments can provide valuable information on volcanic emission sources by tracking the path of plumes released and reaction of gases in the upper atmosphere remotely. They have good spatial, spectral and temporal resolution and are therefore able to provide continuous global coverage. As a result, they may help in mitigating damage caused to aircraft by unexpected volcanic emissions. Infrared (IR) and ultraviolet (UV) based techniques are capable of measuring increased gas column levels due to volcanic eruptions (Prata et al., 2007). IR satellite sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS), Atmospheric Infrared Sounder (AIRS) and Advanced Very High-Resolution Radiometer (AVHRR) have captured near real-time images of plumes rising from the Kasatochi volcano (Corradini et al., 2010). On 8 August 2008, the second Global Ozone Monitoring Experiment (GOME-2), a UV based instrument, detected SO_2 plumes from the same volcano and traced their path across North America until they reached Spain one week after the eruption. Additionally, GOME-2 daily SO_2 data has been used to investigate variations in degassing volcanoes (Rix et al., 2009). On 30 September 2007, the Infrared Atmospheric Sounding Interferometer (IASI) was the first instrument to record an image of volcanic plumes rising from the Jebel volcano at Tair (located in the Red sea, Republic of Yemen) a few hours after a major eruption. The IASI maps showed SO_2 plumes passing from Sudan, travelling through the Gulf countries and west Asia and finally reaching India on 11 October 2007 (Clarisse et al., 2008).

The Ozone Monitoring Instrument (OMI), a sensor employing UV/Visible wavelengths, is currently the best satellite-based monitoring instrument in terms of its spatial resolution, sample rate and sensitivity. As a result, OMI is able to detect and differentiate multiple, densely packed sources (Fioletov et al., 2013). During September 2004–September 2006, OMI was able to discriminate SO_2 loadings between multi-volcanic sources in Ecuador and South Colombia and showed that the major portion of SO_2 emissions resulted from the Tungurahua volcano. For the same volcano, OMI observed increasing SO_2 levels prior to a major eruptive phase in July and August 2006 (Carn et al., 2008). OMI satellite images also identified SO_2 emissions from the Nyamuragira volcano in the Eastern Congo as a result of the eruption on 8 November 2011. It was shown that emissions increased to 9 times that of its counterpart, the Nyiragongo volcano. This geological activity produced a deep lava lake, which is now considered the largest lava lake on the planet (Campion, 2014). During November 2011, good agreement was found between daily SO_2 fluxes derived from OMI and GOME-2 data for the Nyamuragira volcano (Theys et al., 2013). An inventory of continuously emitting global SO_2 point sources was completed by OMI for the period 2005–2014. In this list, SO_2 sources were classified into 4 main categories. Of the total number of SO_2 sources identified, 76 volcanic sources accounted for 30% of global SO_2 emissions. It should be noted that explosive volcanic emissions were excluded from this list and that this may have the effect of increasing the overall total if included (Fioletov et al., 2016). Such eruptions can play an important role in increasing SO_2 levels at locations distant from the site of the volcanic activity. The above studies therefore illustrate the capacity of OMI to effectively detect volcanic SO_2 sources.

The main aim of this study was to explore any potential increase in tropospheric SO_2 levels over South Africa as a result of the Calbuco volcanic eruption in Chile (41.79°S, 73.13°W) held during 22–23 April 2015. This analysis was undertaken through the use of OMI and ground-based (GB) SO_2 data sets for the period 2014–2016. Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) analysis for various altitudes was completed in order to compute air parcel trajectories from the source location and to confirm South Africa as their final location. The SO_2 columnar amounts at 4 vertical levels over all of South Africa during the pre- and post-volcanic periods were investigated through the application of OMI data. This was performed to determine prime locations where SO_2 levels had increased or not. The rise in SO_2 at some of these locations (especially in north west provinces, such as Damonsville, Mmabatho and Phola) was verified with the help of 19 GB monitoring stations located throughout South Africa.

The study is organized as follows: Section 2 describes the selected study regions and section 3 outlines the instruments employed. The obtained results are described in section 4 and the measured conclusions are given at the end.

2. Study regions

In this study, two regions were defined namely, the source (Calbuco volcano) and destination (South Africa). Calbuco volcano is an active stratovolcano located in Southern Chile (41.79°S, 73.13°W) (Fig. 1). The first eruptive pulse occurred on 22 April 2015 at 18:08 local time (21:08 UTC) and lasted for 2 h. This was followed by a second strong eruption on 23 April at 01:00 local time (04:00 UTC) which lasted for approximately 6 h and produced eruptive columns up to an altitude of 15 km. A third phase of seismic activity was seen on the same day at 23:30 local time (2:30 UTC). This resulted in plumes which reached an altitude of 2 km and travelled towards the northeast (https://www.volcanodiscovery.com/calbuco/news/22april2015/major-eruption.

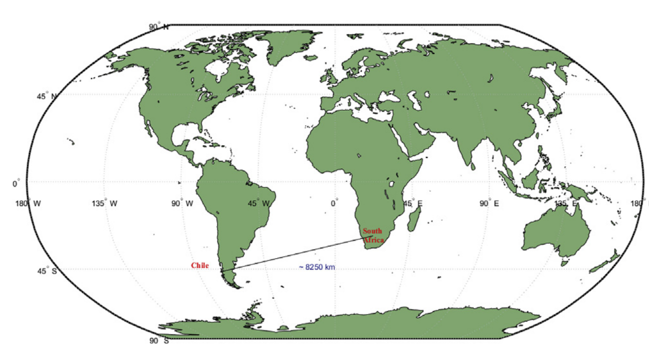

Fig. 1. Location of Calbuco volcano, Chile and South Africa and distance between these locations.