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Spatial distribution of volcanic ash deposits of 2011 Puyehue-Cordón Caulle eruption in Patagonia as measured by a perturbation in NDVI temporal dynamics

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A B S T R A C T

Volcanic ash fallout is a recurrent environmental disturbance in forests, arid and semi-arid rangelands of Patagonia, South America. The ash deposits over large areas are responsible for several impacts on ecological processes, agricultural production and health of local communities. Public policy decision making needs monitoring information of the affected areas by ash fallout, in order to better orient social, economic and productive aids. The aim of this study was to analyze the spatial distribution of volcanic ash deposits from the eruption of Puyehue-Cordón Caulle in 2011, by identifying a sudden change in the Normalized Difference Vegetation Index (NDVI) temporal dynamics, defined as a perturbation located in the time series. We applied a sparse-wavelet transform using the Basis Pursuit algorithm to NDVI time series obtained from the Moderate Resolution Image Spectroradiometer (MODIS) sensor, to identify perturbations at a pixel level. The spatial distribution of the perturbation promoted by ash deposits in Patagonia was successfully identified and characterized by means of a perturbation in NDVI temporal dynamics. Results are encouraging for the future development of a new platform, in combination with data from forecasting models and tracking of ash cloud trajectories and dispersion, to inform stakeholders to mitigate impact of volcanic ash on agricultural production and to orient public intervention strategies after a volcanic eruption followed by ash fallout over a wide region.

1. Introduction

Volcanic ash fallout is a frequent environmental disturbance in forests, arid and semi-arid rangelands of Patagonia, Argentina (Inbar et al., 1995; Martin et al., 2009; Wilson et al., 2012). The ash deposits over large areas are responsible for several impacts on ecological processes such as regulation of insect populations (e.g. Fernández-Arhex et al., 2013; Masciocchi et al., 2013; Elizalde, 2014), macroinvertebrate and fish communities and dynamics of plant communities (e.g. Martin et al., 2009; Miserendino et al., 2012; Ghermandi and Gonzalez, 2012; Ghermandi et al., 2015). As well, many agricultural activities are negatively affected by the ash fallout such as in the cases of apiculture (Martínez et al., 2013) and livestock production (Easdale et al., 2014).

Livestock production is the main agricultural activity in arid and semi-arid Patagonian rangelands. The consequences of ash fallout on livestock production are i) direct (e.g. ash deposits over the body, sight problems, modifications of nutritional behavior and tooth wear, and ii) indirect impacts through the reduction of water and forage availability (Inbar et al., 1995; Wilson et al., 2010; Robles et al., 2012). These sudden changes in the environment reduces livestock productivity (i.e. worse quality of wool and less meat due to reduced offspring) and generates decapitalization due to animal death (Easdale et al., 2014), with economic and social implications. Public policy decision making needs early information of the spatial distribution of the ash fallout, highlighting the most affected zones, in order to better orient social, economic and productive aids. Then, monitoring and information about spatio-temporal durability of the perturbation and post-event recovering are crucial to support emergency response, near-real time hazard mitigation and further policy decisions.

The most frequent approaches to analyze the spatial distribution of ash deposits over large areas are: i) ground-based surveys combined with Geographical Information Systems (GIS), ii) modelling, and iii) remote sensing approaches. Ground-based surveys aimed at collecting information such as ash thickness and granulometry from several georeferenced points which are randomly distributed over a large area (e.g. Bosshard-Stadlin et al., 2014). Then, the information is analyzed

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with GIS such as interpolation methods to obtain a map with different classes that represent zones with different levels of ash deposits (e.g. Gaitán et al., 2011). This approach is costly in terms of time investment, which is difficult to implement during the early period after the eruption.

Another approach is based on modelling techniques aimed at forecasting and tracking the trajectories of ash clouds, dispersion and deposits (Webley and Mastin, 2009). For example, some proposals combine volcanic ash transport and dispersion models (VATDs), which are based on input parameters such as eruption cloud height and vertical distribution, mass eruption rate, particle size distribution and duration of the eruption (Mastin et al., 2009; Webley et al., 2009; Peterson et al., 2015). Other proposals use numerical weather predictions such as NAME model (e.g. Webster and Thomson, 2002; Witham et al., 2007; Turner et al., 2014), in which large number of model particles are released into and tracked through the computational atmosphere, using a random displacement model (Boughton et al., 1987). Other models predict ash concentration at relevant flight levels, expected deposit thickness and ash accumulation rates (Webster et al., 2012; Collini et al., 2013).

Remote sensing approaches refer to a variety of methods based on data collected by remote sensors situated on the ground, on an aircraft or a satellite such as optical sensor, radar or Lidar (Light Detection and Ranging). For example, thermal infra-red satellite data was used for ash cloud detection due to their sensitiveness to the cold temperatures of eruption clouds (Dean et al., 2004), which can be analyzed with different techniques (Tupper et al., 2004). Plume height can be estimated with satellite remote sensing data (Holasek et al., 1996) and weather radar (Oddsson et al., 2012). The Synthetic Aperture Radar (SAR) and MODIS were jointly used to assess some volcanological features of an eruption such as the relationship between surface deformation and the amount of ash and gases emitted by a volcano (Bignami et al., 2014). Volcanic ash clouds can be also tracked with airborne Lidar and in-situ measurements of aerosol and trace gases (Schumann et al., 2011). Finally, other applications of remote sensing data take advantage of the impact that ash deposits have on the reflectance of terrestrial surfaces (e.g. De Rose et al., 2011; Marzen et al., 2011; De Schutter et al., 2015). Deposits of ashes over plant communities and bare soil increases the portion of reflected radiation and reduces the photosynthetic activity of vegetation, which depends on the level of ashes covering plant photosynthetic tissues. Hence, changes in the relative proportion of reflected and absorbed radiation (i.e. red edge region) can be captured by spectral indexes such as the Normalized Differential Vegetation Index (NDVI; Tucker, 1979). Some studies compared images from different periods after the ash fallout in order to determine plant recovery rates (De Rose et al., 2011; Marzen et al., 2011). Recently, another application interpolated rainfall data in order to isolate NDVI values departing from the normal seasonal cycles, and linear temporal trends of monthly-NDVI in combination with multivariate analysis were used to identify the area over which ash fallout significantly affected vegetation (De Schutter et al., 2015). Although these are evidences supporting that ash deposits influence surface reflectance when comparing different moments or affected areas (e.g. before and after a volcanic eruption), less efforts were oriented to identify such impact by means of significant modifications in the dynamics of spectral indexes from a time series approach.

The aim of this study is to analyze the spatial distribution of volcanic ash deposits of 2011 eruption of Puyehue-Cordón Caulle Volcanic Complex in Patagonia as measured by the identification of sudden changes in NDVI temporal dynamics. In particular, we used time series analysis based on a sparse-wavelet transform to identify perturbations in NDVI time series at a pixel level using MODIS data. This approach can provide a new platform to inform stakeholders to mitigate impact of volcanic ash on agricultural production on a country-scale, and decision makers to orient intervention strategies after a volcanic eruption followed by ash fallout over a wide region.

2. Materials and methods

2.1. Study area and volcanic eruption event

The region of study was North Patagonia, including Argentina and Chile. The geomorphology of this region is dominated by the Andean range towards the West (across the international limit), hills and basaltic plateaus in inner Argentinean Patagonia, and great arid plains towards the East. Climate is Mediterranean with mean annual precipitation that ranges between over 4000 mm (W) to 150 mm (E), falling in autumn and winter. Mean annual temperature ranges spatially from 8° (W) to 12° (E) (Paruelo et al., 1998; Bran et al., 2000). Vegetation is dominated by forest of *Nothofagus* spp. in the Andean mountains. Semiarid rangelands of western and central zones of the study area (i.e. Subandean steppes, Patagonian Western District and Patagonian Central District, León et al., 1998; Bran et al., 2000) are dominated by low shrub-grass steppes of *Mulinum spinosum*, *Senecio* spp. and *Pappostipa speciosa*, and low shrub steppes dominated by *Nassauvia* spp. and *Chuquiraga avellanedae*. The eastern rangelands (i.e. Monte Austral, León et al., 1998) are dominated by medium shrub-grass steppes of *Larrea* spp., *Prosopis denudans*, *Atriplex lampa*, *Lycium* spp. and *Pappostipa humilis* (Cabrera, 1971; León et al., 1998). The agrarian structure is a matrix dominated by smallholders, with capitalized family-based farms and commercial farms. The dominant husbandry across different farm types in arid and semiarid rangelands is sheep mixed with goats in less capitalized farms, and with cattle in more capitalized and commercial farms (Easdale et al., 2009).

We studied the impact of the well documented eruption of the Puyehue-Cordón Caulle Volcanic Complex (PCCVC; 40°35′ S, 72°07′ W), which occurred on 4th June 2011. During the initial phase of the eruption (first 24 h), a 14-km-high plume dispersed a large volume of rhyolitic tephra over a wide area eastward towards Argentina. The resulting tephra deposits consisted of 13 main layers grouped into four units, whereas most of the tephra was emitted during the first 72 h of the event. The lowest part of the eruptive sequence, which recorded the highest intensity phase, was composed of alternating lapilli layers with a total estimated volume of ca. 0.75 km^3 (Pistolesi et al., 2015). We selected this eruption event because of the wide area affected by ash fallout in the North-western portion of Patagonia, Argentina (Gaitán et al., 2011). Since we were interested in the impact of ash depositions and the consequently modifications of surface reflectance, we selected this event because the main impact occurred across different ecological and geomorphological zones.

2.2. Data source

The Normalized Difference Vegetation Index (NDVI) is frequently used as a surrogate of ecosystem primary production, since it is an accurate indicator of the level of photosynthetic activity of vegetation (Tucker, 1979; Ruimy et al., 1994). We used the 2000 to mid-2017-time series of 16-day temporal resolution and 250 m spatial resolution of NDVI to study the perturbations in NDVI dynamics generated by the ash deposits after the volcanic eruption.

The NDVI was derived from Moderate Resolution Image Spectroradiometer (MODIS) sensor (product MOD13Q1). NDVI was calculated with the following equation:

$$NDVI = (NIR - R)/(NIR + R) \quad (1)$$

where R and NIR are the surface reflectances centered at 645 nm (visible) and 858 nm (near-infrared) portions of the electromagnetic spectrum, respectively.