Journal of Volcanology and Geothermal Research 352 (2018) 26–37

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

An algorithm for the detection and characterisation of volcanic plumes using thermal camera imagery

Maxime Bombrun[a,b,*], David Jessop[a], Andrew Harris[a], Vincent Barra[b]

[a] Université Clermont Auvergne, CNRS, IRD, Observatoire de Physique du Globe de Clermont-Ferrand, Laboratoire Magmas et Volcans, Clermont-Ferrand F-63000, France
[b] Université Clermont Auvergne, CNRS, Laboratoire d'Informatique de Modélisation et d'Optimisation des Systèmes, Clermont-Ferrand F-63000, France

ARTICLE INFO

Article history:
Received 21 July 2017
Received in revised form 10 January 2018
Accepted 10 January 2018
Available online 3 February 2018

Keywords:
Plume segmentation and tracking
Thermal-image processing
Parameters extraction

ABSTRACT

Volcanic plumes are turbulent mixtures of particles and gas which are injected into the atmosphere during a volcanic eruption. Depending on the intensity of the eruption, plumes can rise from a few tens of metres up to many tens of kilometres above the vent and thus, present a major hazard for the surrounding population. Currently, however, few if any algorithms are available for automated plume tracking and assessment. Here, we present a new image processing algorithm for segmentation, tracking and parameters extraction of convective plume recorded with thermal cameras. We used thermal video of two volcanic eruptions and two plumes simulated in laboratory to develop and test an efficient technique for analysis of volcanic plumes. We validated our method by two different approaches. First, we compare our segmentation method to previously published algorithms. Next, we computed plume parameters, such as height, width and spreading angle at regular intervals of time. These parameters allowed us to calculate an entrainment coefficient and obtain information about the entrainment efficiency in Strombolian eruptions. Our proposed algorithm is rapid, automated while producing better visual outlines compared to the other segmentation algorithms, and provides output that is at least as accurate as manual measurements of plumes.

1. Introduction

Explosive volcanic eruptions emit turbulent mixtures of particles (solidified magmatic fragments and lithics) and volcanic gases (e.g. Sparks et al., 1997; Carey and Bursik, 2010) which rise above the volcanic vent, entraining atmospheric air in the process. These emissions are collectively known as plumes. Despite a large body of work and input from a range of scientific communities, including volcanologists, physicists, engineers and mathematicians now spanning nearly 40 years (e.g. Wilson and Sparks, 1976; Woods, 1988; Valentine and Wohletz, 1989; Carazzo et al., 2008), there remain features of volcanic plumes dynamics that are still poorly understood. Therefore, volcanic plumes are still able to surprise and bewilder scientists and government authorities alike (e.g. Eyjafjallajökull 2010), while being a possible threat to both air traffic, buildings, infrastructure, agriculture, air quality, and human health (e.g. Baxter, 2010; Horwell et al., 2013; Guffanti and Tupper, 2014; Wilson et al., 2014). Volcanic plumes are complex objects (see Fig. 1) that may contain a very wide range of particle sizes (micron- to centimetric- or decimetric-scale, Kaminski and Jaupart, 1998, for example), often have very strong gradients of velocity, density, pressure and temperature in both radial and vertical directions, are highly turbulent (with Reynolds numbers in the order of 100 000 or more), and can be overpressured at the vent (e.g. Woods, 1988). Furthermore, their dynamics are strongly influenced by coupling with one or more classes of particle sizes (see Jessop and Jellinek, 2014 for example). Much of our understanding of how plumes behave comes from scaled analogue experiments (e.g. Carey et al., 1988; Ernst et al., 1996; Carazzo et al., 2014; Chojnicki et al., 2014; Manzella et al., 2015; Jessop et al., 2016) from simplified theoretical models (e.g. Woods, 1988, 1995, 2010; Carazzo et al., 2008), and, more recently, from detailed numerical simulations (e.g. Neri et al., 2002; Esposti Ongaro et al., 2012; Suzuki and Koyaguchi, 2013; Costa et al., 2016) though, for varying reasons, none of these methods is able to simultaneously capture the full range of dynamical features observed in nature.

Although the imaging of volcanic plumes and subsequent analysis are an essential component in improving our understanding of plume dynamics, relatively few plumes have had their motion recorded with the specific intention of making scientific measurements (Sparks et al., 1997). Furthermore, even fewer of these data

* Corresponding author at: Department of Information Technology, Division of Visual Information and Interaction, and Science for Life Laboratory, Uppsala University, Lägerhyddsvägen 2, Uppsala 751 37, Sweden.
E-mail address: maxime.bombrun@it.uu.se (M. Bombrun).

https://doi.org/10.1016/j.jvolgeores.2018.01.006

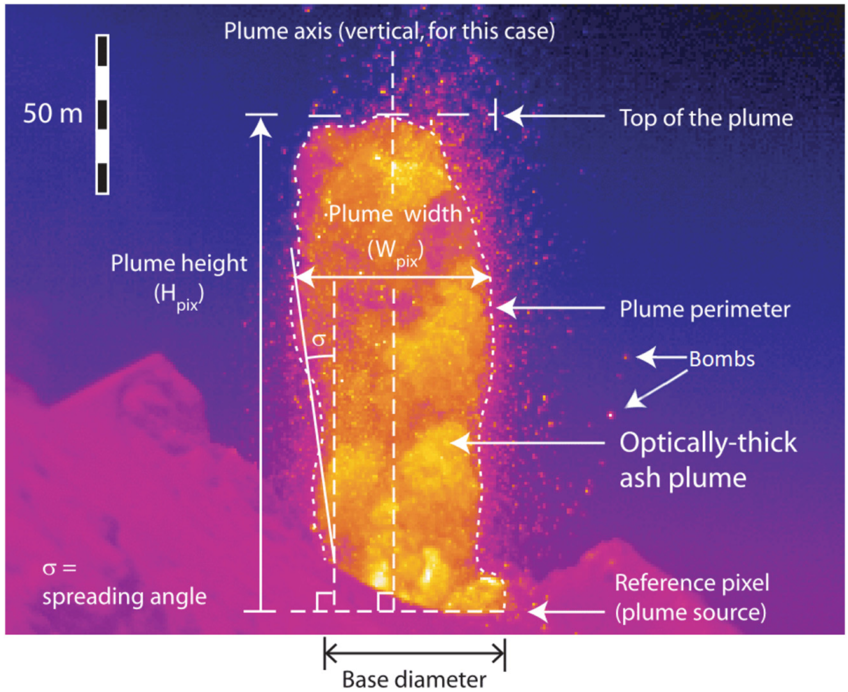

Fig. 1. Plume parameters overlying a typical thermal image. The image is a mixed plume of ash, lapilli and bombs taken at Stromboli during July 2004 (modified from Harris, 2013).

sets have been acquired at a frame rate or spatial resolution sufficient to capture dynamic processes occurring in the plume (Clarke et al., 2002; Formenti et al., 2003). In the past decade, studies such as Patrick et al. (2007), Patrick (2007), Harris et al. (2012), Harris et al. (2013), Bombrun et al. (2015) have used thermal infrared (TIR) video to record small, ballistic-dominated and coarse-ash eruptions at Stromboli (Fig. 1). Sahetapy-Engel and Harris (2009a) and Valade et al. (2014) also used TIR to image explosive eruptions at Santiaguito, while a recent study proposes a plume parameterisation from high-speed visible light and thermal imaging (Tournigand et al., 2017). Such analyses can reveal important dynamical information such as the thermal evolution of a plume, morphological aspects such as its height and width and, when inverted with a physical plume model, the GSD and particle concentration can be revealed (Cerminara et al. (2015)). However, there remains no canonical methodology for the rapid and reliable processing of such images.

In the aftermath of the 2010 Eyjafjallajökull eruption, work on the automated extraction of source terms has become a necessity as part of the pipeline of permanent monitoring stations to produce information on plume motion in near real-time and thus set up a trigger alarm. However, few dedicated software packages are available and, those that do exist do not aim for a near real-time analysis. For example, the Matlab-based Plume Ascent Tracker tool of Valade et al. (2014) involves manual processing steps and interventions, and thus can only be invoked in the post-processing of eruption footage. For these reasons, this present work focuses on the use of thermal video and image-processing algorithms through filtering techniques to provide a fast and robust automated process that may be incorporated into the image acquisition workflow. Here, we build on the characterisation of volcanic components through thermal videos (e.g. Bombrun et al., 2014) by developing an algorithm to track and parametrise plume s of any class. Here we aim to provide a fast and fully-automated algorithm for basic plume segmentation and tracking, which allows for the extraction of dimensional measurements, and from these for spatial and temporal derivatives to be output for higher-level modelling. We validated our method through applying two different approaches. First, we test the algorithm on four videos, consequently parametrising and quantitatively describing the ascent dynamics for natural plumes, as well as man-made plumes created by controlled detonation or depressurisation, and compare the segmentation with manual parameter extraction, a user-controlled filtering method (Valade et al., 2014), and another method based on machine-learning techniques (Sommer et al., 2011). Next, we extract parameters focusing on the entrainment coefficients and relate them to plume form and type. We find that our algorithm is more robust to changes in the surrounding environment and plume motion, and therefore, performs far better than the two other image-processing techniques and outputs plume parameters (e.g. height) that are practically identical to those found by manual extraction.

2. Methodology

2.1. Motivation

Our primary objective was to develop an operational algorithm capable of detecting a moving plume and recording its dynamics through time. Regardless of the style of eruption, be it Strombolian, Vulcanian, sub-Plinian, a critical part of the processing images acquired by any of the waveband methods is to unambiguously identify pixels of the image corresponding to the foreground (i.e., the plume), and pixels corresponding to the background, here, the volcano itself, other landscape features, and the sky behind the plume. Typically this is done by using thresholding and thus relies upon a strong difference in pixel intensity (i.e. temperature for TIR images) between the plume and its surroundings. However, when the plume is relatively cool compared to its surroundings, which would be the case for entraining and diluted plumes, an unambiguous differentiation is not possible as dilution due to entrainment at the plume margins leads to “fuzzy” boundaries which are difficult to discern from the background in an automated manner through the application of a single, global threshold. Steps in the process can be guided