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Estimation of eruption source parameters from umbrella cloud or downwind plume growth rate

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ABSTRACT

We introduce a new method to estimate mass eruption rate (MER) and mass loading from the growth of a volcanic umbrella cloud or downwind plume using satellite images, or photographs where ground-based observations are available. This new method is compared with pre-existing models and documented mass eruption rate given in the research literature. We applied the method to five well-studied eruptions (Mount St. Helens, 1980; Redoubt, 1990; Pinatubo, 1991; Hekla, 2000 and Eyjafjallajökull, 2010) and to five less well-documented eruptions (Kliuchevsko'i, 1994; Okmok, 2008; Kasatochi, 2008; Sarychev Peak, 2009 and Bezymianny, 2012). The mass eruption rate is obtained by estimation of the radius of the umbrella cloud with time or by estimation of the width of the downwind plume with distance from the volcano. The results given by the new method show a more fully characterized MER as a function of time than do the results given by pre-existing methods, and allow a faster, remote assessment of the mass eruption rate, even for volcanoes that are difficult to study. The method thus may provide an additional important path to the estimation of source parameters and the forecasting of ash cloud propagation. In addition, in cases where numerous methods are available, use of the method yields new, independent measures of mass eruption rate, hence an ability to estimate uncertainty in mass eruption rate, which could be used in probabilistic estimations of ash cloud propagation.

1. Introduction

The explosive eruption of Eyjafjallajökull, Iceland, in April and May, 2010, brought to light the hazards of airborne volcanic ash and the importance and limitations of volcanic ash transport and dispersion models (VATD) to estimate the concentration and the position of ash with time (Bursik et al., 2012). These models require Eruption Source Parameters (ESP) as input, which typically include information about the plume height, the mass eruption rate, the duration of the eruption and the particle size distribution. However much of the time these ESP are unknown or poorly constrained *a priori*. Satellite imagery is often available during the early minutes and hours of an eruption. We are only beginning to use the information contained therein to aid in source parameter estimation, *e.g.*, (Rose et al., 2003; Rybin et al., 2011). One piece of data (typically satellite) that is not used, yet is easily retrieved and could potentially be an accurate measure of mass flux or mass eruption rate (MER) and eruption duration hence mass loading, is the growth rate of the umbrella cloud or downwind plume early in the eruption. We show that the mass eruption rate can be estimated from the plume or umbrella cloud growth, using several different models. This is particularly important as ash loading is difficult to estimate.

To test our methodology, we compared our results with others for five well-studied and well-characterized historical eruptions: Mount St. Helens, 1980; Redoubt, 1990; Pinatubo, 1991; Hekla, 2000 and Eyjafjallajökull, 2010 (Sparks et al., 1986; Woods and Kienle, 1994; Holasek et al., 1996; Lacasse et al., 2004; Thorkelsson, 2012).

We then applied the methodology to umbrella clouds produced by the eruptions of Okmok, 12 July 2008, and Sarychev Peak, 12 June 2009, and to the downwind plume produced by the eruptions of Kliuchevsko'i, 1 October 1994; Kasatochi 7–8 August 2008 and Bezymianny, 1 September 2012. For some of these, no other estimate of MER is available or even possible (Bursik et al., 2009; Waythomas et al., 2010; Neal et al., 2011; Rybin et al., 2012).

In the present contribution, we explore whether it is possible to estimate the mass eruption rate from the downwind plume or umbrella cloud growth rate using several different models. We then compare individually estimated eruption rates and mass loadings one against another, and evaluate for accuracy, and then apply the models to other eruptions. We finally evaluate how the resulting

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estimated mass eruption rate could be used as an ESP in a volcanic ash transport and dispersal (VATD) model as a best estimate of the total amount of ash that is drafted downwind in advected ash clouds.

1.1. Background

Five eruptions (Mount St. Helens, 1980; Redoubt, 1990; Pinatubo, 1991; Hekla, 2000; Eyjafjallajökul, 2010) have been selected for testing of the estimation method because they were well studied and are well documented in the literature (Sparks et al., 1986; Koyaguchi and Tokuno, 1993; Woods and Kienle, 1994; Lacasse et al., 2004; Thorkelsson, 2012). These eruptions were used previously to design or test some of the basic models of cloud growth. We then explore how the techniques can be used for a new event by applying them to the Kliuchevsko'i, 1 October 1994; Okmok, 12 July–19 August 2008; Kasatochi, Aleutian Islands, 7 August 2008; Sarychev Peak, Kurile Islands, 12 June 2009, and Bezymianny, 1 September 2012 eruptions (Bursik et al., 2009; Levin et al., 2010; Waythomas et al., 2010).

Since our interest for this study is on the plume and cloud, we introduce here the term used and only the evolution of the plume for each of these events. In the present contribution, the general term for any volcanic cloud containing ash is ash plume or volcanic plume. When a volcanic plume forms a radially driven intrusion into the atmosphere, it is called an umbrella cloud. This phenomenon is the result of axisymmetric spreading at the neutral buoyancy. When the windspeed becomes comparable to the spreading speed, this distorts the umbrella cloud into an elongated shape. This we call a downwind plume. Further downwind, the plume approaches pressure balance in the atmosphere, starts thinning and spreading due to turbulence. At this point, we term it an ash cloud. For intense eruptions, the downwind plume can be followed over hundreds of kilometers, *e.g.*, the downwind plume from Mount St. Helens (18 May 1980) could be followed for about 1100 km. For a weak plume, the downwind plume may persist over only a few kilometers (Sparks et al., 1997).

1.1.1. Mount St. Helens, 18 May 1980

The eruption of Mount St. Helens (Washington, USA) in 1980 started at 15:32 UTC on the morning of 18 May 1980 with a rising eruptive column, which rapidly generated an umbrella cloud. Within 20 min, the cloud reached a height of 30 km ASL (Sparks et al., 1986). Satellite data showing the growth of the umbrella cloud are available: Geostationary Meteorological Satellite (GMS) every 5 min for the first half hour Sparks et al. (1986), and then Geostationary Operational Environmental Satellite (GOES) every 30 min (Holasek and Self, 1995). This initial cloud was fed by a Plinian eruption that continued throughout the day. The analysis of Sparks et al. (1986) suggests that the initial, giant umbrella cloud was the result of relatively instantaneous emplacement of an atmospheric intrusion that then spread with time due to gravitational instability. By further analyzing the shape of the umbrella cloud with time, it was found that the wind had an important impact on its shape after the first hour (Sparks et al., 1986). The umbrella cloud began to be advected in a windfield of a speed averaging 28 m/s, which resulted in the elongation of the cloud in the downwind direction Bursik et al. (1992a), as it spread in the crosswind direction due to gravity. This downwind plume was studied on a GOES image from 18 May taken at 20:20 UTC.

1.1.2. Redoubt, 21 April 1990

Mount Redoubt (Alaska, USA) was active from 15 December 1989 to 21 April 1990. On that last day, at 14:12 UTC a relatively small explosive eruption created a pyroclastic flow which generated a large ash (phoenix) cloud due to buoyancy development in the flow (Woods and Kienle, 1994). This thermal plume was observed rising and spreading into an umbrella cloud at an altitude of 12 km ASL by two different methods: video camera and still photography (Kienle et al., 1992). Only the still photography was used to study the umbrella cloud spreading, since the video camera was focused on the near-vent activity. The cloud tripled its radius in less than 10 min, and rose to its maximum altitude in about 3 min (Woods and Kienle, 1994). The series of photographs shows that the cloud grew with no major asymmetry, but that the multiphase nature of volcanic flows was reflected in the creation of two intruding discs. We used the sketch of the outlines of the cloud made from the original photographs and scaled by (Woods and Kienle, 1994).

1.1.3. Pinatubo, 15 June 1991

The eruption of Pinatubo (Luzon, Philippines) was the most intense eruption of the modern, satellite era. After weeks of precursory activity, repetitive explosive eruptions started on 9 June until reaching a paroxysmal phase on 15 June (Koyaguchi and Tokuno, 1993). The umbrella cloud from the 15 June eruption was the result of the longest observed ash injection in the atmosphere (for more than 9 h) and the largest of the modern era (Holasek et al., 1996). It is unclear when the eruption column of the paroxysmal phase started rising, since direct observations were not possible. Based on seismic data, the starting plume observed at 22:41 UTC could be the result of high-amplitude tremor that began to be recorded at 22:15 UTC. For this eruption, visible and infrared GMS data were available every hour, and were analyzed by (Holasek et al., 1996) to show the growth of the umbrella cloud. They found that the umbrella cloud spread symmetrically for the first 4 to 5 h before getting elongated in the East–West direction by a wind of an average speed 4–5 m/s. The images used by (Holasek et al., 1996) were also used in this study.

1.1.4. Kliuchevsko'i, 1 October 1994

After a month of activity, the eruption of Kliuchevsko'i volcano (Kamchatka, Russia) reached a paroxym on 1 October 1994 at 18:00 UTC UTC. The plume reached a maximum height of 18 km ASL and was elongated toward the southeast due to the strong wind at the time (Bursik et al., 2009). This eruption is an important example of the effect of the ash on aircraft since a Boeing 747 flew through the cloud (van Manen and Dehn, 2009). The downwind plume was studied on an image taken at 06:40 UTC by the Advanced Very High Resolution Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration (NOAA) 12 satellite.

1.1.5. Hekla, 26–27 February 2000

In February 2000, Hekla (Iceland) erupted at 18:17 UTC for a duration of 11 days, and produced a 12 km above sea level (ASL) high plume during the first phase of its eruption (Lacasse et al., 2004; Hoskuldsson et al., 2007). This plume was distorted by strong southerly winds leading to its elongation (Rose et al., 2003). We used the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image taken at 21 UTC February 26th as the basis for making estimates from the downwind plume.

1.1.6. Okmok, 12 July–19 August 2008

Okmok volcano (Aleutian Islands, USA) erupted on 12 July 2008 after little seismic warning. Seismic studies put the eruption start time at 19:43 UTC (Arnoult et al., 2010; Johnson et al., 2010). The eruption was most intense and continuous in the first 10 h (Arnoult et al., 2010). A dark ash-rich plume was noticed first on Geostationary Operational Environmental Satellite (GOES) images at 20:00 UTC (Neal et al., 2011), and was followed an hour after by a white vapor-rich plume (Larsen et al., 2009). Both of these grew into a large umbrella cloud that started being distorted by the wind at about 23:00 UTC.

1.1.7. Kasatochi, 7 August 2008

Kasatochi (Aleutian Islands, USA) erupted on 7 August 2008 for two days producing a series of ash-gas plumes (Waythomas et al., 2010). Three main pulses, at 22:01 on 7 August, and at 01:50 and 04:35 UTC on 8 August, ejected ash into the stratosphere, which caused aircraft delays and cancellations (Fee et al., 2010). Windy conditions led to distortion and drifting of the plumes southwest on the first day of the eruption. On the second day, the wind shifted to the