



# Characterising, quantifying, and accessing eruption source parameters of explosive volcanic eruptions for operational simulation of tephra dispersion: a current view and future perspectives

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## Abstract

Eruption source parameters (ESPs) are crucial for characterising volcanic eruptions and are essential inputs to numerical models used for hazard assessment. Key ESPs of explosive volcanic eruptions include plume height, mass eruption rate, eruption duration, and grain-size distribution. Some of these ESPs can be directly observed during an eruption, but others are difficult to measure in real-time, or indeed, accurately and precisely quantify afterwards. Estimates of ESPs for eruptions that cannot be observed, for example, due to the remote location of a volcano or poor weather conditions, are often defined using expert judgement and data from past eruptions, both from the volcano of interest and analogue volcanoes farther afield. Analysis of such information is time intensive and difficult, particularly during eruption response. These difficulties have resulted in the production of datasets to aid quick identification of ESPs prior to or during an eruption for use in operational response settings such as those at volcano observatories and Volcanic Ash Advisory Centres. These resources include the Mastin et al. (2009a) ESP dataset and the Catalogue of Icelandic Volcanoes and European Catalogue of Volcanoes aviation tables. Here, we review and compare these resources, which take different approaches to assigning ESPs. We identify future areas for development of these resources, highlighting the need for frequent updates as more knowledge of volcanic activity is gained and as modelling capabilities and requirements change.

**Keywords** Eruption source parameters · Volcanic ash · Datasets · Eruption response · Explosive eruptions

## Introduction

Eruption source parameters (ESPs) are the key inputs in models used to simulate areas affected by ash during explosive volcanic eruptions. When used during unrest or eruptions, their accuracy has a great influence on the accuracy

of ash-hazard forecasts. During periods of quiescence, the values of ESPs anticipated during future events affect the accuracy of long-term assessments of the hazard. ESPs are broadly of two types: (1) those that can be directly observed during an eruption, such as plume height or eruption start time, and (2) those that must be constrained through detailed analysis or numerical relationships. The second type includes, for example, the grain-size distribution of erupted material, which is typically constrained through studies of deposits and some assessment of the likelihood that a future eruption will resemble past eruptions. Another example is the mass eruption rate, which is typically constrained from plume height, either by empirical correlations (e.g. Mastin et al. 2009b, eq. 1), analytical equations (e.g. Degruyter and Bonadonna 2012; Wilson and Walker 1987; Woodhouse et al. 2013), or one-dimensional (1D) plume modelling (e.g. Costa et al. 2016b; Degruyter and Bonadonna 2012). Thus, ESPs are assigned using insights from past eruptive behaviour and

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observations of current behaviour, whether at the volcano of interest or by drawing on observations from analogue volcanoes (e.g. Del Negro et al. 2013; Biass et al. 2014; Tierz et al. 2019; Hayes et al. 2020; Tadini et al. 2022). ESPs vary in type (ranges versus a discrete value), the time scales over which they apply (e.g. hours to years), and spatial coverage (e.g. volcano- versus region-specific) with the selected parameters dependent on the user and their needs.

There are several types of modelling studies that use these ESPs. One is numerical model comparison and validation studies (e.g. Bonadonna et al. 2012; Mastin et al. 2013; Costa et al. 2016b). Several numerical models for simulating volcanic plumes and ash dispersal exist, each using slightly different numerical methods and assumptions and therefore input parameters (Bonadonna et al. 2012). These studies require well-constrained and independently estimated input parameters from well-characterised events to validate model outputs against observations, and specific datasets have been produced to address these needs (e.g. IVESPA; Aubry et al. 2021; Table 1). It is through this critical application of ESP input data and models that the global modelling community aims to produce reliable models. Such approaches enable conceptual models of physical process to be tested and ultimately improved. Validation studies require data from well-documented eruptions in which as many parameters as possible are well-constrained: for example, eruption start time, duration, plume height, and grain-size distribution. The number of events with these data are limited.

A second type of modelling study involves probabilistic assessments to quantify the potential hazards associated with a future event at a volcano or location (e.g. Houghton et al. 1987; Bonadonna et al. 2005; Marzocchi et al. 2010; Sandri et al. 2014; Becerril et al. 2014; Alatorre-Ibargüen-goitia et al. 2021; Titos et al. 2021). Such analysis requires an understanding of the range of potential activity, which is typically informed from analysis of deposits and observations from past eruptions. Limitations in the geological and historical record of eruptions are well-known. Smaller events are generally underreported, and the quality of the record for larger events also diminishes going back through time (Deligne et al. 2010). Therefore, expert judgement is often required to inform parameter selection and fill data gaps. Probabilistic hazard analysis involves the initiation of numerous simulations using an array of input parameters representing the range and relative frequency of different types of eruptive activity to quantify probabilities of parameters such as tephra concentration, mass, or thickness at a given location (e.g. Macedonio et al. 2016; Barsotti et al. 2018; Dioguardi et al. 2020). National and regional probabilistic hazard assessments, such as those for tephra fall, require ESPs for all volcanoes in the area of interest (e.g. Jenkins et al. 2012; Bonadonna et al. 2021). However, knowledge regarding eruptive activity for different volcanoes, even

those in close proximity, is often highly variable in amount and quality meaning that one set of ESPs may be applied to all volcanoes in a region (Jenkins et al. 2012).

A third type of modelling study, generally run by volcano observatories or meteorological organizations, involves daily simulations of an eruption under current wind conditions for a volcano that is in a state of unrest and threatening to erupt (Hurst and Davis 2017, Coombs et al. 2019, Scollo et al. 2019, Barsotti et al. this issue). In this case, a small number of scenarios are defined, which cover the range of potential activity at a volcano, given past eruptive activity, scale of unrest and, where appropriate, information from other similar volcanoes. The scenarios use different values for parameters such as plume height, eruptive volume, and duration; but it is common for multiple scenarios to share particle characteristics such as grain-size distribution due to limited amounts of available data.

Both volcano observatories and Volcanic Ash Advisory Centres (VAACs) also conduct near-real-time hazard assessments immediately prior to and during an eruption. The simulations that inform these hazard assessments require information specific to the volcano and event of interest in as close to real-time as possible. While the ideal situation involves ESP information, such as plume height, to be available in real-time, the reality is that operational response usually involves working with information that is hours to days old and commonly with information from previous events. Several factors affect the speed at which observations can be obtained and used to inform inputs for numerical modelling. These include the ability to make observations either in the field or via remote sensing, which may be limited due to poor weather, or the remote nature of a volcano. Additional delays may arise due to communication challenges between those conducting observations and those initiating numerical models.

In this contribution, we detail some of the issues involved with defining ESPs specific to tephra dispersion. We briefly discuss those parameters most frequently required for initiating simulations, difficulties in defining these parameters, and available resources designed to inform them when observations are not available. While we focus on tephra dispersion, many of the approaches, difficulties, and uncertainties discussed are applicable to simulating other hazards, including those not related to volcanic eruptions.

## Eruption source parameters for simulating tephra dispersion

Tephra poses a significant risk to aviation (e.g. Guffanti and Tupper 2015; Prata and Rose 2015, Mastin et al. 2022). The abrasive nature of tephra means that it can damage aircraft, for example, by abrading windows resulting in reduced visibility,

**Table 1** Available resources containing eruption source parameter information. Asterisks highlight those resources used in this study. <sup>i</sup>C refers to dominant eruption composition, *H* to plume height, *D* to eruption duration, *M* to eruptive mass, *V* to eruptive volume, MER to mass eruption rate, *Dd* to deposit density, GSD to grain-size information, *Pd* to particle density, *Vd* to vent diameter, *Ev* to exit velocity, *Mt* to magmatic temperature, and *Atm* to atmospheric conditions.

<sup>+</sup>Value refers to all volcanoes in the dataset, some of which do not have recent eruptions or comprehensive source parameter information. Datasets accessed on 01 Nov 2023. Many additional studies have collated data for defining empirical relationships between MER and plume height. These are reviewed in Table 1 of Aubry et al. (2021) and are therefore not discussed further here.

Name of Dataset/ Reference	Published	Intended Application	Number of Volcanoes	Geographical extent	Data <sup>i</sup>	Uncertainty information
IAVCEI Eruption Source Parameter Dataset <a href="https://thm.iavceivolcano.org/datasets/">https://thm.iavceivolcano.org/datasets/</a>	2004	Testing and validation of tephra dispersal models	8	Global	C, H, D, V, Dd, GSD, Pd, Atm	No
Eruptions of Alaskan Volcanoes Cameron et al. 2022 <a href="https://avo.alaska.edu/explore/eruptions/">https://avo.alaska.edu/explore/eruptions/</a>	2005	Record of eruptive activity at Alaskan volcanoes	80 <sup>+</sup>	Alaska, US	C, H, V	No
*Eruption Source Parameter Dataset (M-ESP) Mastin et al. 2009a <a href="https://webapps.bgs.ac.uk/research/volcanoes/esp/">https://webapps.bgs.ac.uk/research/volcanoes/esp/</a>	2009	Provides parameters for tephra dispersal modelling	1535	Global	H, D, MER, V, GSD	No
Large Magnitude Explosive Volcanic Eruptions (LaMEVE) Croswell et al. 2012 <a href="https://www2.bgs.ac.uk/vogripa/">https://www2.bgs.ac.uk/vogripa/</a>	2012	Provides information on characteristics of large explosive eruptions within the Quaternary Period	480	Global	C, H, V, M	Error and Quality flags
Eruption data for ash-cloud model validation Mastin et al. 2013 <a href="https://thehub.org/resources/2431">https://thehub.org/resources/2431</a>	2013	Testing and validation of tephra dispersal models	4	Global	C, H, D, M, Pd, GSD	Ranges for some parameters provided in text
*Catalogue of Icelandic Volcanoes (CIV) Aviation Table <a href="https://icelandicvolcanos.is/">https://icelandicvolcanos.is/</a>	2016	Provides information on past Icelandic volcanic activity, in addition to parameters for tephra dispersion modelling	34	Iceland	H, D	Ranges provided for H and D
Total Grain Size Distribution in Selected Icelandic Eruptions Hoskuldsoon et al. 2018	2018	Provide grainsize information for several Icelandic eruption for tephra dispersion modelling	6	Iceland	C, H, V, GSD	Ranges provided for H and V
Independent Volcanic Eruption Source Parameter Archive (IVESPA) Aubry et al. 2021 <a href="https://ivespa.co.uk/">https://ivespa.co.uk/</a>	2021	Testing and validation of eruption column models	45	Global	H(s), D, M, MER, Vd, GSD, Ev, Mt, Atm	Provided for key parameters
Mass Eruption Rate, Column Height and Duration dataset for Volcanic Eruptions Deligne et al. 2021	2021	Informs probabilistic tephra fall modelling inputs	37	New Zealand & Global	C, H, D, MER	Quality information provided
*European Catalogue of Volcanoes (ECV) Aviation Table <a href="https://volcanoes.eurovolc.eu/">https://volcanoes.eurovolc.eu/</a>	2021	Provides information on past European volcanic activity, in addition to parameters for tephra dispersion modelling	51	Europe	H,D	Ranges provided for H and D

while ash ingested into aircraft engines can soften and coat or obstruct moving parts, in the worst cases leading to engine failure (Clarkson et al. 2016). On the ground, tephra can damage and disrupt infrastructure, affect agriculture, and impact human and animal health (e.g. Horwell and Baxter 2006; Wilson et al. 2012; Wilson et al. 2014; Jenkins et al. 2015; Bonadonna et al. 2021). Therefore, identifying the areas potentially affected by tephra, both in the air and on the ground, is key for hazard mitigation.

Several models and workflows exist to simulate the transportation of tephra through the atmosphere (e.g. Bonadonna et al. 2005; Macedonio et al. 2005; Barsotti et al. 2008; Scollo et al. 2008a; Folch et al. 2009; Schwaiger et al. 2012; Folch 2012; Beckett et al. 2020). While the approach and numerical models applied vary depending on the application, there are several parameters used to describe volcanic activity that are common to most applications that simulate tephra dispersion in the atmosphere. These include plume height and mass eruption rate, eruption duration, erupted volume, grain-size distribution, and the vertical distribution of tephra above the volcanic source.

## Methods used in the estimation of eruption source parameters for explosive eruptions

### Evaluating eruption source parameters in nearreal-time

In this contribution, we focus on the ESPs required for simulating dispersal of volcanic ash and therefore on those eruptions which have an explosive component. During an eruption, ESPs can be defined in near real-time through observation and analysis of an event (note that this near real-time capability is absent for many volcanoes and eruptions). At a few exceptionally well-instrumented volcanoes such as Mount Etna, Italy, combined sensors (e.g. satellites, radar, lidar, visible and thermal cameras; Bonadonna et al. 2012; Bonadonna 2014) are available that can provide information on plume height, eruptive mass, mass eruption rate, and grain-size. In such cases, multi-sensor strategies may provide a comprehensive characterisation of ESPs and allow for near real-time forecasting (e.g. Corradini et al. 2016; Scollo et al. 2019; Scollo et al. 2020; Freret-Lorgeril et al. 2021). Below, we describe each key ESP used in tephra dispersion modelling in turn and provide information on how each parameter is measured.

Plume height is perhaps the most important ESP in the sense that it is required to initiate every cloud dispersal model; as such, it exerts a primary control on forecast results. At most volcanoes, plume height, reported in kilometers or meters above sea level (a.s.l.) or above vent level (a.v.l.), is the only ESP that can be observed or measured

in near real-time. It is typically determined from satellite retrievals, radar and lidar data, visible and thermal camera observations, and/or pilot reports (e.g. Holasek and Self 1995; Prata and Turner 1997; Arason et al. 2011; Petersen et al. 2012; Marzano et al. 2013; Scollo et al. 2014; Bonaccorso and Calvari 2017; Pailot-Bonnétat et al. 2020; Barnie et al. 2023). The accuracy of plume height obtained using ground-based radar generally depends on the spatial distribution of the instruments in relation to the active vent, the temporal resolution of the data, the scanning strategy used, and the working frequencies that define the sensitivities to a given part of the grain-size distributions (e.g. Marzano et al. 2006, 2020). Limitations exist when using webcams in low light or poor weather conditions, and observations of volcanic plumes in satellite imagery are often obscured by meteorological clouds. As such, each sensor is characterised by intrinsic uncertainties and observes the plume at different times. As a result, significant discrepancies have been reported between plume heights obtained from satellites and ground observations (Tupper and Wunderman 2009; De Michele et al. 2016; Cahalan et al. 2023). These discrepancies reflect, in part, that plume heights estimated using these methods represent different parts of the plume, for example, the plume top versus spreading height of the plume (Aubry et al. 2021, 2023; Deligne 2021). In addition to measurement considerations, temporal and spatial variability in plume height means that a single plume height value might not be representative of volcanic plume behaviour during an eruption, especially if emissions are pulsatory or continue for several hours to weeks.

Duration describes the length of time over which volcanic products are emitted from the vent, typically during a given event. However, in the literature, duration can be used to describe an entire eruption, which may include multiple explosive events that occur over a period of weeks to months, to single explosive events with durations of seconds to hours. This makes compilation of duration information from the literature difficult, with estimates prone to large uncertainties. One reason for this is that it is often easier to identify the start than the end of an eruptive event, particularly for those that are fluctuating, long lived or end gradually (Aubry et al. 2023). Given this, eruption or emission start time is more commonly found in literature than eruption end time. Sources such as infrasound, lightning, thermal cameras, direct observations, and seismicity are used to identify the start of an event, or confirm that an event is ongoing, and therefore may inform eruption duration estimates. It is important to consider that an ash cloud can continue dispersing in the atmosphere long after the end of an event (i.e. when volcanic material is no longer emitted from the vent, Engwell et al. 2013).

Erupted volume and mass denote the amount of material emitted during an eruption, and the mass eruption rate

(MER, sometimes also referred to as the mass discharge or mass flow rate (MDR and MFR, respectively)) is the rate at which this material is discharged. Mass and MER, reported in kilograms and kilogram per second, respectively, can be derived either from plume height, based on empirical and analytical/numerical expressions (e.g. Wilson and Walker 1987; Mastin et al. 2009b; Degruyter and Bonadonna 2012; Woodhouse et al. 2013; De Michele et al. 2016; Dürig et al. 2018; Aubry et al. 2023), or estimated from geophysical sensors such as satellites (Wen and Rose 1994; Prata and Grant 2001; Corradini et al. 2018), Doppler radar (Marzano et al. 2006; Freret-Lorgeril et al. 2018; Marzano et al. 2020), infrasound (e.g. Ripepe et al. 2013; Freret-Lorgeril et al. 2021), and seismic tremor (Bernard et al. 2016). A mean estimate of MER can also be calculated after an event from measurements of eruptive mass and duration (Aubry et al. 2021). In this way, uncertainties on plume height and duration often propagate through to estimates of MER and other parameters (e.g. Bonadonna et al. 2015; Dioguardi et al. 2020).

Numerical model results are sensitive to particle parameters such as grain-size distribution (GSD), particle density, and shape (e.g. Beckett et al. 2015; Saxby et al. 2018). It is very difficult to measure grain-size during an eruption in a timely manner, with no one remote method able to measure the complete size range of particles emitted. Particle shape and density are also difficult to measure in real-time, with methods often associated with large uncertainties. In the rare cases where GSD is determined by near-real-time measurements, the narrow size range detectable by different sensors requires multi-sensor strategies for the determination of total grain-size distribution (TGSD). For example, Doppler radar used in volcano monitoring tends to be sensitive to coarse size fractions ( $>100\ \mu\text{m}$ ), while lidar and satellite instruments are sensitive to fine size fractions ( $<100$  and  $<20\ \mu\text{m}$ , respectively) (e.g. Scollo et al. 2012; Freret-Lorgeril et al. 2021). A standard strategy does not yet exist, despite land disdrometers and the combination of satellite and radar data with complementary size detection limits providing promising results for near-real-time characterisation (Freret-Lorgeril et al. 2021, 2022). More commonly, real-time simulations are initiated using a default GSD. Depending on the model and application, the full TGSD or a portion of the TGSD (e.g. Beckett et al. This issue) may be used as an input.

Vertical distribution of mass describes how tephra is distributed in the plume above the vent. In comparison to the other parameters, the vertical distribution of mass cannot be directly measured during an eruption. Instead, it is typically assigned based either on a plume model simulation (e.g. De Michele et al. 2016; Cao et al. 2021; Folch et al. 2020), an assumed uniform distribution (e.g. Beckett et al. 2020), or a Suzuki distribution (Suzuki 1983) with a tephra distribution

profile that has been calibrated using inversion studies of specific eruptions (e.g. Kristiansen et al. 2012).

Given their variability and intrinsic uncertainty, the accuracy of ESPs can be improved during long-lasting explosive eruptions through data assimilation, whereby information from several sources is used (e.g. Pardini et al. 2020; Mingari et al. 2022). However, knowledge of the value of most parameters is incomplete when initiating an operational forecast simulation, such as those conducted by VAACs, particularly in the early stages of an eruption. Some parameters may not be accurate or even available. Others, such as TGSD, eruption duration, or the vertical distribution of mass in the plume, must still be inferred from previous events, often using inversion modelling techniques. Some insights into the scale of an eruption and therefore appropriate ESPs can be gained through the monitoring of volcanoes in conjunction with knowledge of previous activity at the volcano. However, a significant proportion of volcanoes worldwide are unmonitored (Loughlin et al. 2015), limiting potential insight from unrest. Many unmonitored volcanoes also have limited or no information on past eruptions, resulting in numerous geographical blind spots in terms of our ability to accurately assign ESPs.

### Evaluating eruption source parameters from past eruptive activity

Despite advances in near real-time estimation of ESPs, there is often the need for easily accessible information on potential eruptive behaviour for operational response. The use of data from past eruptions to inform future activity relies on the fundamental yet standard assumption that the size and nature of hazards derived from a volcano during past eruptions, at analogue volcanoes, and/or at analogue eruptions are reflective of future hazards (e.g. Loughlin et al. 2015). This assumption also underpins the assignment of ESP values in datasets and modelling (e.g. Mastin et al. 2009a, 2009b). Some eruptive sequences have produced strings of similar explosive events that would appear to justify this assumption. Examples include Crater Peak (Mount Spurr) in 1992 (Neal et al. 1995) and Bogoslof in 2017–2018 (Coombs et al. 2019). Others, such as Mount St. Helens (May through October 1980; Sarna-Wojcicki et al. 1981), have systematically varied in size; and still, others, such as Merapi 2010, were outliers in an otherwise consistent pattern. Thus, this approach should be considered in light of other observations.

Information from the published record on past eruptive activity at a volcano is often used to supplement that from recent or unpublished observations. Like those uncertainties associated with near-real-time measurements, significant unknowns and biases are inherent in both historical and geological records and our use of these data to inform ESPs (e.g. Mastin et al. 2009a, 2009b; Aubry et al. 2021).



The estimation of plume height, erupted mass, and in many cases eruption duration often relies on the analysis, interpretation, and numerical inversion of eruptive deposits (e.g. Connor and Connor 2006; Volentik et al. 2010; Connor et al. 2019; Aubry et al. 2021). Deposits are commonly affected by erosion and remobilisation (Jarvis et al. 2020; Buckland et al. 2020), and uncertainties may arise in measurement (Engwell et al. 2013), analysis (Nathenson 2017), and interpretation (Bonadonna et al. 2015). The scale of these uncertainties varies according to the age of the eruption (older deposits tend to be less well-preserved and exposed) and the geographical location of the volcano: deposits in tropical regions are affected by remobilisation and erosion due to heavy rates of rainfall while those in high wind regions are frequently affected by wind remobilisation. These assumptions and data limitations contribute to uncertainty and potential errors in the determination of model inputs and, therefore, in the compilation and choice of hazard scenarios and the application of numerical models (e.g. Scollo et al. 2008b; Macedonio et al. 2016; Harvey et al. 2018; Dioguardi et al. 2020).

Measurement uncertainties are compounded by inconsistent reporting of ESP data in the published record. Plume height commonly varies with time during an eruption, and in published records, it is often not clear whether a measurement represents the average, initial, maximum, or another measure of eruption plume height, or what specific phase or event of an eruption an estimate relates to. Most ash dispersal models use input plume height as the height at which the plume is spreading laterally in the atmosphere, which may be several kilometres lower than the maximum plume height. Variability in characteristics during an eruption is not limited to plume height estimates, but also affects other parameters such as grain-size distribution. The grain-size of particles emitted during an eruption can vary depending on fragmentation process, or eruption style, for example, whether an eruption produces pyroclastic density currents that mill ash (Darteville et al. 2002) or involves interaction with snow or water. Collecting and processing grain-size information are time intensive, and several studies have focused on the production of guidelines for accurate and comparable measurements (Bonadonna et al. 2013; Wallace et al. 2022). Given the time and amount of data needed, TGSDs required to initiate tephra dispersal simulations are relatively sparse in the published record. There is therefore a reliance on distributions from a small number of studies to inform grain-size inputs for volcanoes and eruptions worldwide (e.g. Costa et al. 2016a; Pioli et al. 2019).

On a more basic level, uncertainties in the use of information from past eruptions arise due to a lack of supporting metadata. For example, it is often unclear whether published plume height values refer to height above sea level or above

vent. Similarly, accounts of eruption duration frequently do not explain the observations used to define the start or end of an eruption (Jenkins et al. 2007; Deligne 2021). Some of these difficulties relate to how eruptions are defined, whether duration refers to the whole eruption or a single phase or event and the difficulty in assigning an end to an event that gradually diminishes with time. These considerations make the estimation of appropriate ESPs a time-intensive process, complicating the use of information for operational response purposes.

Given the range of studies and uses of plume and tephra dispersal modelling, from research to operational, several datasets have been produced, each with different intended applications and geographical coverage. These include the Large Magnitude Explosive Volcanic Eruptions (LaMEVE; Crossweller et al. 2012) database, which contains ESP information for large eruptions within the Quaternary and the IVESPA dataset (Aubry et al. 2021), which includes a large range of ESPs and other information. An overview of these resources and other related resources is provided in Table 1. Both the LaMEVE and IVESPA datasets were developed primarily for research purposes, i.e. understanding global volcanic activity and validation of numerical models, respectively. Here, we focus on resources developed specifically to inform operational response to volcanic eruptions, in particular those developed for simulating tephra dispersion to inform hazard to aviation. Below, a global and two regional datasets of ESPs specific to ash-aviation hazard assessment purposes are described in detail: the ESP dataset of Mastin et al. (2009a) (MESP; global dataset) and the Catalogue of Icelandic Volcanoes and the European Catalogue of Volcanoes (CIV and ECV, respectively; regional datasets). We reflect on the background of these datasets, their contents, and limitations and look to future requirements of such resources.

## Eruption source parameter datasets for operational applications

### Global resources: the Mastin et al. (2009a) Eruption Source Parameter (MESP) dataset

During the first meeting of the International Civil Aviation Organization (ICAO) International Airways Volcano Watch Operations Group (IAVWOPSG) in 2004, ESP uncertainties were identified as a key factor limiting the accuracy of tephra dispersal forecasts (ICAO 2004, Conclusion 1/24). The issue was raised again during the second meeting in 2005, and it was decided that a dedicated effort would be made to improve the quality in ESPs used in VAAC forecast models (ICAO 2005, Conclusion 2/27). Several workshops and meetings on ESPs followed, resulting in the publication of

a special volume on volcanic plumes by the *Journal of Volcanology and Geothermal Research* (v. 259., 2009). A key paper in that volume (Mastin et al. 2009b), co-authored by representatives from the nine VAACs, described a multi-disciplinary effort to improve ESP estimates during eruptions.

Mastin et al. (2009b) identified 11 eruption types, characterised by a specific magma type, eruption size, or process (Table 2). Each eruption type was assigned a characteristic plume height, duration, erupted volume, and mass fraction of fine ash in the erupted debris based on a well-described eruption of this type (Table 2). For example, a ‘medium silicic (S2)’ eruption, based on the 1992 Mount Spurr (Alaska) eruptions (Neal et al. 1995), was assigned a plume height of 11 km above the vent, a duration of 3 h, a mass eruption rate of  $4 \times 10^6$  kg/s, a volume of 0.015 km<sup>3</sup>, and a grain-size distribution that contains 40% ash finer than 63 microns. The selected analogue eruptions were

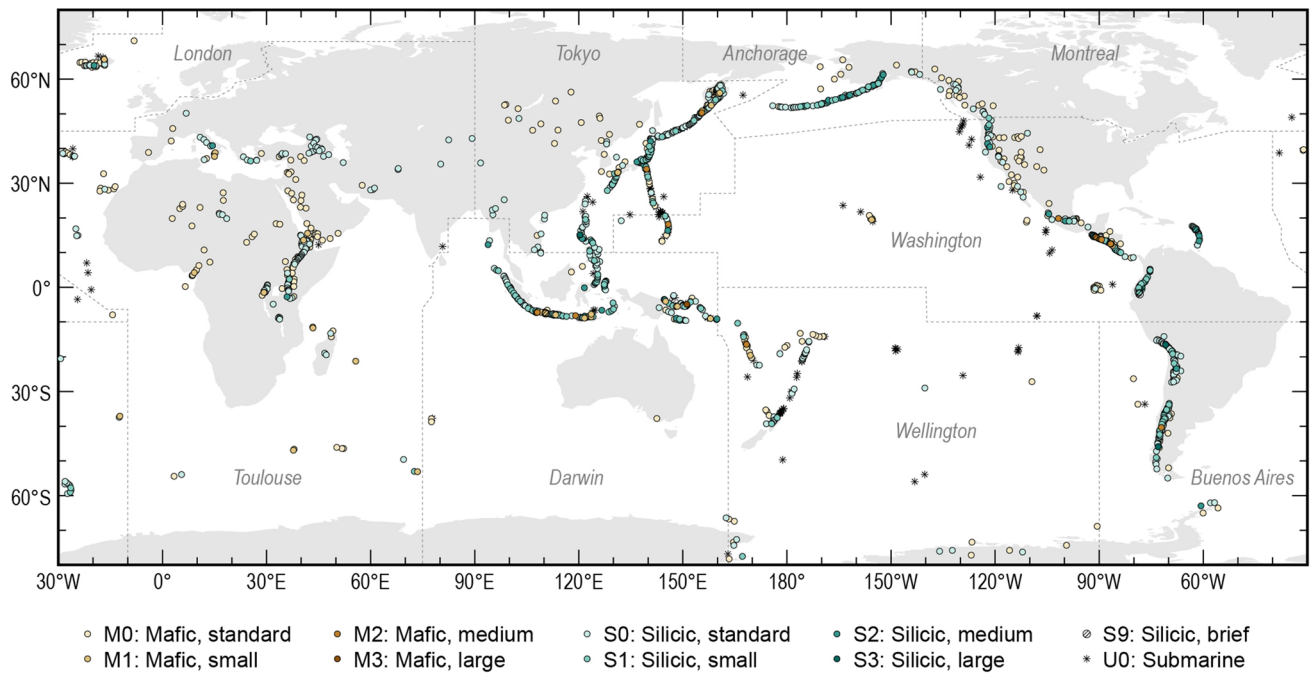
well-described and represent a wide range of eruptive behaviour. The sister publication (Mastin et al. 2009a) presented a spreadsheet that assigned eruption types to each of the 1535 Holocene volcanoes listed at the time in the Smithsonian Institution’s Global Volcanism Program database (Global Volcanism Program 2023; Figure 1). The assignments were based on patterns of eruptive behaviour at each volcano, or, for volcanoes that had not erupted in historical time, on the type of volcano or magma type according to information in the Smithsonian Institution’s Global Volcanism Program database and in the published record. The use of categories meant that consistent information could be provided and negated decisions on the amount of information required to characterise eruptive activity at each volcano.

The MESP dataset was intended to provide ESPs for simulations in cases where no observations were available, including the following:

**Table 2** Categories and ESPs assigned to Holocene volcanoes in the Mastin et al. (2009b) Eruption Source Parameter (MESP) dataset, where *H* refers to plume height, *D* eruption duration, MER mass

eruption rate, *V* volume, and m63 the fraction of the grain-size distribution less than 63 microns.

Type	Magma type	Historical eruption characteristics	Eruption type	Example	H_MESP: H km above vent	D (h)	MER (kg/s)	V (km <sup>3</sup> )	m63
M0	Basalt or other mafic	Insufficient historical data to characterise	Mafic, standard	Cerro Negro, Nicaragua, 9–13 April 1992	7	60	$1 \times 10^5$	0.01	0.05
M1		$H \leq 5$ km or VEI $\leq 2$	Mafic, small	Mount Etna, Italy, 19–24 July 2001	2	100	$5 \times 10^3$	0.001	0.02
M2		$H = 5\text{--}8$ km or VEI = 3	Mafic, Medium	Cerro Negro, Nicaragua, 9–13 April 1992	7	60	$1 \times 10^5$	0.01	0.05
M3		$H > 8$ km or VEI $\geq 4$	Mafic, Large	Fuego, Guatemala, 14 October 1974	10	5	$1 \times 10^6$	0.17	0.1
S0	Andesite, dacite, rhyolite, or other explosive composition	Insufficient historical data to characterise	Silicic, Standard	Mount Spurr, USA, 18 August 1992	11	3	$4 \times 10^6$	0.015	0.4
S1		$H \leq 6$ km or VEI $\leq 2$	Silicic, small	Mount Ruapehu, New Zealand, 17 June 1996	5	12	$2 \times 10^5$	0.003	0.1
S2		$H = 6\text{--}12$ km or VEI = 3	Silicic, medium	Mount Spurr, USA, 18 August 1992	11	3	$4 \times 10^6$	0.015	0.4
S3		$H > 12$ km or VEI $\geq 4$	Silicic, large	Mount St. Helens, USA, 18 May 1980	15	8	$1 \times 10^7$	0.15	0.5
S8		Major pyroclastic flows with an elutriated column rising above the flows	Co-ignimbrite cloud	Mount St. Helens, USA, 18 May 1980 (pre-9 AM)	25	0.5	$1 \times 10^8$	0.05	0.5
S9		Active lava dome present	Brief	Soufriere Hills, Montserrat (composite)	10	0.01	$3 \times 10^6$	0.0003	0.6
U0	All magma types	Submarine vent with a water depth $\geq 50$ m	Submarine	None	0	-	-	-	-



**Fig. 1** Map showing distribution of volcanoes for each category within the Mastin et al. 2009a Eruption Source Parameter (MESP) dataset together with Volcanic Ash Advisory Centre (VAAC) areas of responsibility. S0 and M0 were assigned to volcanoes that have not

erupted within historical times. Dashed lines represent the boundaries of the VAAC areas of responsibility. The map projection is ITRF 2014 and the base map is a modified version of the ESRI Light Gray Canvas Map

- (i) Before an eruption, for volcanoes that are in a state of unrest, to anticipate where ash might go if an eruption started
- (ii) In the first minutes of an eruption, when no direct observations are available (e.g. when seismicity or infrasound suggests an eruption but no satellite data are available)
- (iii) For source parameters, such as grain-size distribution or duration, that are not observable or unknown early in an eruption.

The MESP dataset provides an informed estimate of parameters for the world's Holocene volcanoes in an easily accessible format. Parameters in the dataset are the plume height above vent, eruption duration, mass eruption rate, erupted volume, and the fraction of particles emitted that are less than 63 microns in size.

Limitations in the parameters exist because the dataset covers such a large area: parameters are not unique to a specific volcano and only one set of parameters is provided, essentially defining one eruption scenario per volcano. A volcano may exhibit a range in activity during an eruption, but insufficient information exists to define specific activity at each volcano globally. This is particularly true for those volcanoes that have not erupted in the period with written documentation, such as many volcanoes across sub-Saharan Africa and East Asia (Fig. 1),

where intermediate ESPs were assigned given the lack of available eruptive information.

## Regional resources

Volcano specific data, including ESPs such as plume height and eruption duration, have been assembled for some specific regions. For example, plume heights and (where available) erupted volumes for Alaskan volcanoes are accessible on the Alaska Volcano Observatory website (<https://www.avo.alaska.edu/>, accessed 1 March 2023, Cameron et al. 2022), while source parameters for New Zealand volcanoes have been compiled by Deligne (2021) to aid in probabilistic hazard analysis. Here, the CIV, ECV, and, in particular, the associated aviation tables which were designed to provide input parameters for tephra dispersal modelling are discussed in detail.

## Catalogue of Icelandic Volcanoes (CIV)

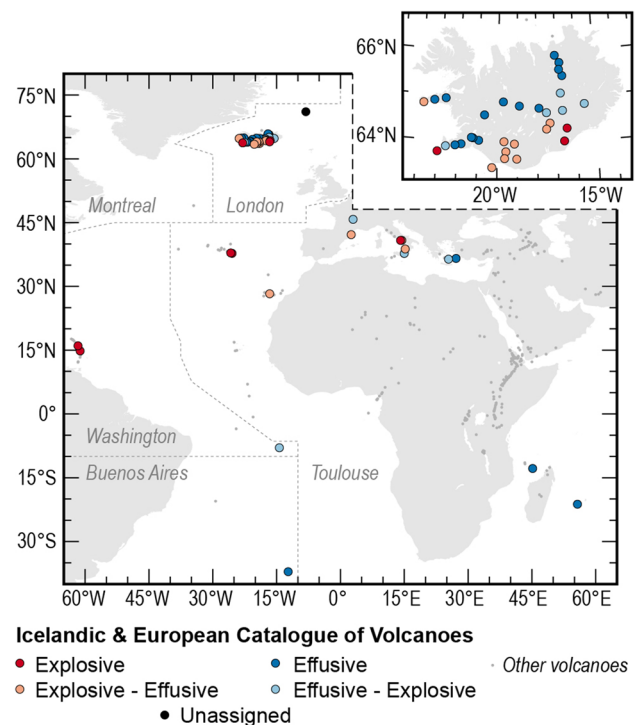
In the aftermath of the Eyjafjallajökull eruption in 2010 and its extended impact on air traffic, the ICAO funded a project aimed at collecting and making accessible information on Icelandic volcanoes (Karlsdóttir et al. 2012). The CIV, which was initially designed in 2011, was further developed and finalized within the European project FUTUREVOLC thanks to a strong collaboration between the Icelandic



Meteorological Office (IMO), the University of Iceland, and the Icelandic Department of Civil Protection. The CIV presents a portal to up-to-date knowledge on volcanoes and volcanic activity in Iceland. It is composed of several parts and it delivers information customized to a variety of users. Amongst other features, including the eruption search functionality, the CIV hosts a table (labelled the ‘aviation table’), which summarizes key information of relevance for VAACs and those running ash dispersal codes. It includes data for 33 Icelandic volcanoes and one Norwegian volcano (Beerenberg) and contains general volcano information such as coordinates (in a format directly usable by aviation users), elevation, last eruption date, and the volcano ICAO code. Instead of single values for parameters, the table contains two different estimates of plume height based on the current knowledge of past eruptive activity: a reasonable worst and most likely vertical limit. A single value is provided for reasonable worst-case plume height, while a range of plume heights is provided for the most likely plume height. Several volcanoes are listed as having an unknown plume height due to a lack of data and eruptions in historical times. For all Icelandic volcanoes, notes are provided on predominant activity (effusive, explosive, effusive-explosive, explosive-effusive) and associated probable durations (weeks to months for effusive eruptions and hours or days to weeks for explosive eruptions). The CIV is frequently updated, and an editorial board reviews the contained information. Further, the information contained in it are regularly used for designing eruption scenarios adopted to run the monthly exercises by IMO, London VAAC, and Icelandic Air Service Provider (ISAVIA; Beckett et al. this issue). In 2019, the Icelandic language version of the CIV was launched and facilitated a wider access by the local community and Icelandic users.

### European Catalogue of Volcanoes (ECV)

The CIV was expanded to include information for volcanoes in other locations across Europe and associated territories (Fig. 2) as part of the Horizon 2020 EUROVOLC project resulting in the European Catalogue of Volcanoes (ECV, <https://volcanoes.eurovolc.eu/>, accessed 1 Dec 2022). The ECV was the result of a standardization in data provision across most volcano observatories in Europe, and the information provided was collected and prepared by local experts from the different monitoring institutions. A total of 51 volcanoes (including 34 that are also in the CIV) are currently listed. The ECV aviation table contains all of those parameters in the CIV aviation table and additionally includes the responsible VAAC for each volcano. Both unrest and eruptive activity since 2018, alongside information from the geological record, have informed the ESPs provided in the aviation tables. Given that the ECV also contains information for the volcanoes in the CIV, we use information from the



**Fig. 2** Map of volcanoes within the Catalogue of Icelandic Volcanoes (CIV) and European Catalogue of Volcanoes (ECV) where marker color represents the eruptive category and dashed lines represent the boundaries of the relevant Volcanic Ash Advisory Centre (VAAC) areas of responsibility. Inset shows an expanded view of Iceland. The projection of the main map is ITRF 2014 and the projection of the inset map is ISN2006 Lambert 2016 and the base map is a modified ESRI Light Gray Canvas Map

ECV throughout the rest of this contribution. While the ECV aviation table provides volcano specific ESPs, these ESPs do not include information on parameters such as grain-size, eruption volume, or mass eruption rate.

### Comparison and use of eruption source parameter resources

Comparison of the MESP dataset and the ECV aviation table highlights gaps in information and informs future development of these and other related resources. While both the MESP and the ECV aviation tables were produced for the same purpose, there are significant differences. The MESP provides parameters for a much larger number of volcanoes. This is only possible through categorisation of volcanoes and use of analogue eruptions: there is not enough information available to provide tailored parameters for each volcano worldwide. This use of categories and analogues means that other parameters for which there is less information in the published record, e.g. grain-size, can also be assigned. In comparison, the ECV aviation tables contain

volcano-specific information for a more limited number of volcanoes and parameters and only when sufficient information is available to inform parameters.

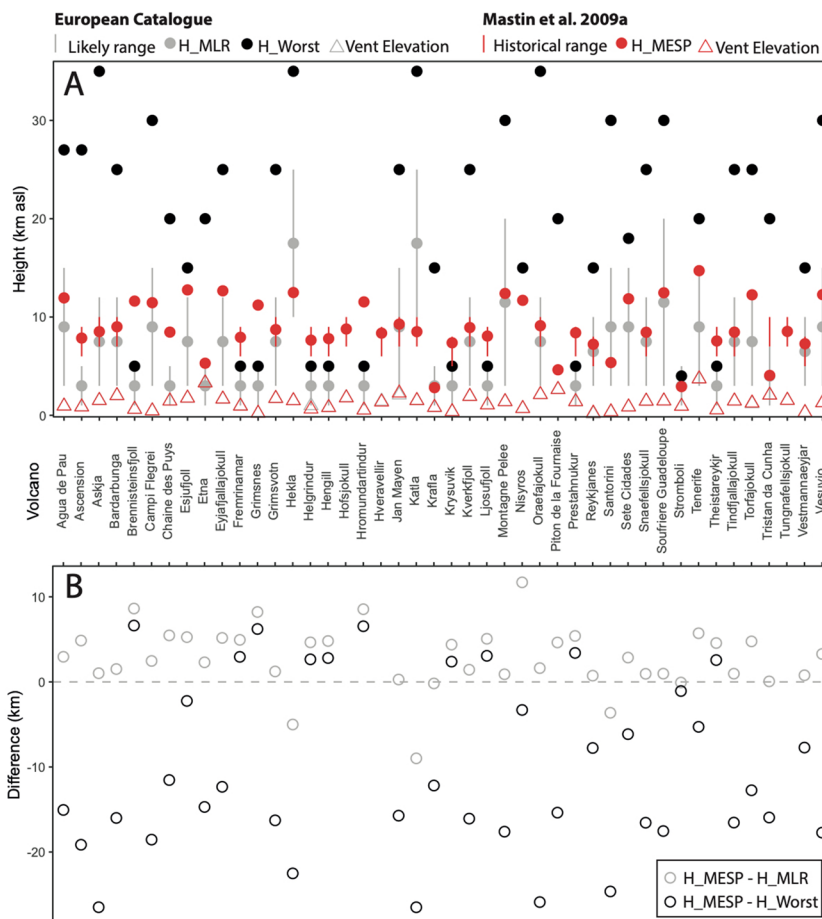
The MESP and the ECV aviation tables can both directly inform parameters used in modelling and be used to initiate and inform discussions around appropriate parameters. The MESP provides single values while the ECV aviation table contains ranges for many parameters. This range in parameters aids ensemble modelling but a decision on the most appropriate parameter(s) to use is needed where procedure or limits in time or application constrain the number of simulations that can be run to a small number. Such a decision could be made in collaboration with the relevant volcano observatory and other appropriate experts.

In addition to the type of parameters, the assigned parameters also vary between the MESP dataset and the ECV aviation table (Fig. 3, Table 3, Supplementary Information 1). For comparison of the values assigned to the volcanoes within these databases, we focus on plume height. Plume height is common to both datasets and is the most commonly collated piece of eruption information, enabling comparison with eruption information from the published record and from recent operational reports of eruptive activity. For this

comparison, plume height in the MESP was converted from height above vent level to above sea level using the vent elevation provided in the dataset (Mastin et al. 2009a; Supplementary Information 1). We note that for all but two volcanoes for which there is information in both datasets, the vent elevations are comparable (within 100 m, Table 3), with the exception of Helgrindur (ECV 986 m asl, MESP dataset 647 m asl) and Beerenberg volcanoes (ECV 2085 m asl, MESP dataset 2277 m asl). These discrepancies may be due to different sources of elevation information; for example, the MESP used elevation information from the Smithsonian Institution’s Global Volcanism Program database at the time of publication, while the ECV information was provided by local experts, who may use different measurements or references.

In general, the MESP dataset plume heights ( $H_{MESP}$ ) lie between the minimum of the ECV most likely vertical limit and ECV reasonable worst vertical limit ( $H_{LMIN} < H_{MESP} < H_{Worst}$ ; Figure 3A). However, there are several exceptions. The MESP dataset plume height is smaller than the minimum plume height given in the ECV for Katla ( $H_{LMIN} > H_{MESP}$ ) and larger than the ECV reasonable worst case for several Icelandic volcanoes ( $H_{MESP}$

**Fig. 3** Comparison of plume height assigned to volcanoes common to the Mastin Eruption Source Parameter dataset (MESP; Mastin et al. 2009a) and the European Catalogue of Volcanoes (ECV). **A** The most likely range, middle of the most likely range ( $H_{MLR}$ ), and reasonable worst plume height ( $H_{Worst}$ ) per volcano from the ECV aviation table and historical plume height range and assigned plume height ( $H_{MESP}$ ) for each volcano according to its category within the MESP dataset. Open triangles show the vent elevation for each volcano in the two datasets. **B** Calculated difference between the assigned plume height in the MESP dataset and both the mid likely range ( $H_{MESP} - H_{MLR}$ , grey circles) and the reasonable worst vertical limit ( $H_{MESP} - H_{Worst}$ , black circles) in the ECV. Examples of the plume heights for selected volcanoes are provided in Table 3 and for all volcanoes common to the datasets in Supplementary Information 1



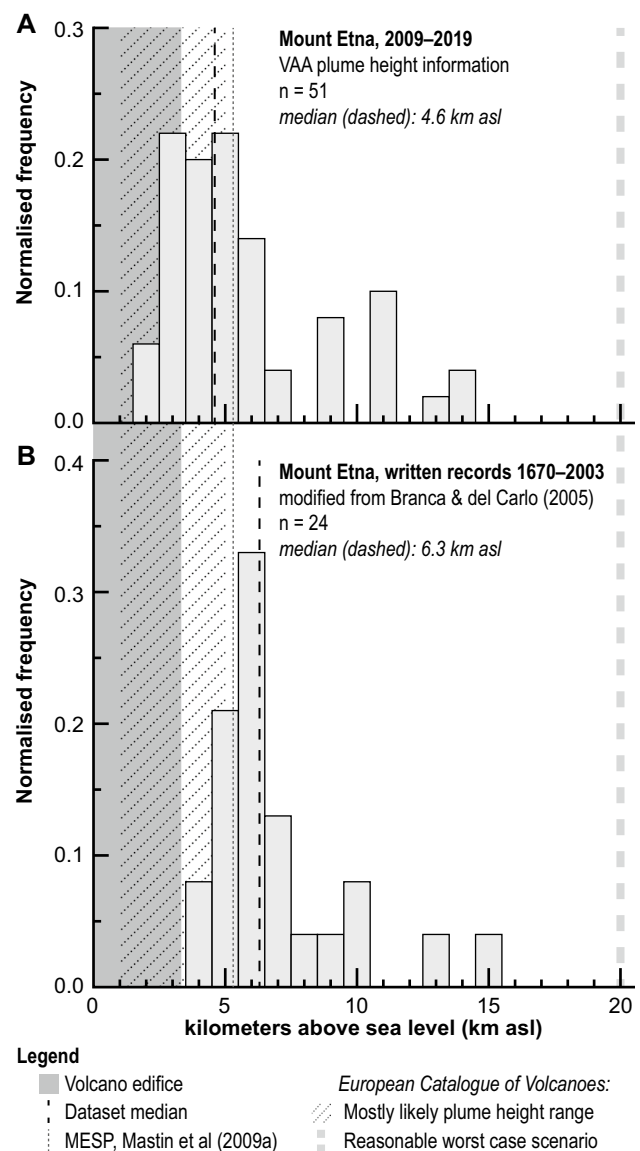
**Table 3** Plume height and vent elevation data from the European Catalogue of Volcanoes (ECV) and Mastin et al. (2009a) Eruption Source Parameter (MESP) dataset for select volcanoes. MESP plume height data were converted from above vent level to above sea level using the vent elevation data in the dataset. Data for all volcanoes within the datasets can be found in Supplementary Information 1

SI volcano name	Piton de la Fournaise	Nisyros	Santorini	Grimsvotn	Hekla	Katla	Reykjanes	Mount Etna	Tristan da Cunha
European Catalogue Volcanoes									
Vent Elevation ASL (m)	2632	698	320	1722	1490	1490	140	3328	2060
H_Worst: Reasonable Worst Vertical Limit ASL (km)	20	15	30	25	35	35	15	20	20
H_LMIN: Most Likely Vertical Limit Min ASL (km)	< 1	< 1	3	3	10	10	3	1	1
H_LMAX: Most Likely Vertical Limit Max ASL (km)	1	1	15	12	25	25	10	5	7
H_MLR: Most Likely Vertical Limit Mid ASL (km)			9	7.5	17.5	17.5	6.5	3	4
Mastin ESP dataset (2009)									
Vent Elevation ASL (m)	2632	698	367	1725	1491	1512	230	3300	2060
Historical Eruption Characteristics Min AVL (km)				7		7	5		7
Historical Eruption Characteristics Min ASL (km)				8		8	5		9
Historical Eruption Characteristics Max AVL (km)	8		6	10		10	8	8	10
Historical Eruption Characteristics Max ASL (km)	10		7	11		11	8	12	12
Assigned Height AVL (km)	2	11	5	7	11	7	7	2	2
H_MESP: Assigned Height ASL (km)	4.63	11.70	5.37	8.73	12.49	8.51	7.23	5.3	4.06
H_MESP-H_MLR	4.63	11.70	- 3.63	1.23	- 5.0	- 8.99	0.73	2.3	0.06
H_MESP-H_Worst	- 15.37	- 3.30	- 24.63	- 16.28	- 22.51	- 26.49	- 7.77	- 14.70	- 15.94

> H\_Worst) (Brennisteinsfjoll, Fremrinamar, Grimsnes, Helgrindur, Hengill, Hromundartindur, and Krysuvik). These differences are highlighted in Fig. 3B, where the MESP dataset plume height is compared with the mid value (H\_MLR) of the ECV likely range and the ECV reasonable worst (H\_Worst) vertical limit for those volcanoes present in both datasets. In this example, zero means the heights are the same and positive values show examples where the MESP dataset plume height is greater than heights in the ECV and negative values where they are smaller. Figure 3B shows that the MESP dataset plume heights are closer to the middle of the range of likely plume heights (within 10 km), than to the ECV reasonable worst limit (approximately 20 km greater).

The difference in the two datasets relates to the information and methods used to assign parameters (Fig. 3). Parameters within the ECV were assigned based on expert knowledge of a specific volcanic system and on current knowledge of previous activity, while the MESP dataset values are based primarily on volcano category. To further investigate differences in the assigned parameters and how they relate to observations, we compare plume heights from the two datasets with eruption information from Mount Etna volcano (Fig. 4). Mount Etna is one of the best monitored and most frequently active volcanoes in the world and numerous datasets contain information about its eruptive activity. The large amount of available plume height data in the published record enables a comparison of information in the MESP and the ECV aviation table with observations and published data. We note that the MESP dataset used the 19–24 July 2001 eruption of Mount Etna to set parameters of all volcanoes in the small mafic volcano (M1) category (Table 2). For our purpose, the plume height from the MESP dataset is converted from height above vent to height above sea level by adding the elevation of Mount Etna as reported in the MESP (3300 m). We show in Fig. 4 that for Mount Etna, the MESP dataset plume height (dotted line) falls at the upper end of the ECV most likely vertical limit range in the aviation table (hatched area), while the ECV aviation table reasonable worst vertical limit (thick dashed grey line) is considerably larger, at 20 km.

We compare the ESP Mount Etna designation with eruption data from two sources: a contemporary and a historical dataset. The contemporary dataset is composed of information extracted from volcanic ash advisories (VAAs) issued by the responsible VAAC, VAAC Toulouse, in the period between 2009 and 2021. VAAs contain information on the timing of an eruptive event, the observed extent and plume height, and forecast plume extents. The VAA dataset contains information gathered from various sources including the volcano observatory, webcam, and satellite images. This information is presented at 6-h intervals to inform civil aviation of the presence of ash in the atmosphere. Therefore, they provide high temporal



**Fig. 4** Histograms of **A** Volcanic Ash Advisory (VAA) plume height information from eruptive events at Mount Etna in the period 2009–2021. **B** Information from the historical record (Branca and Carlo 2005), for Mount Etna since the 1600s. Elevations above sea level that are within the volcanic edifice are indicated with a dark grey bar (note that eruptions can occur on the flanks with plumes that remain below the summit). The hatched area represents the most likely plume height interval and the thick dashed grey line the reasonable worst-case scenario according to the European Catalogue of Volcanoes (ECV). The dark grey dotted vertical line is the assigned plume height in the Eruption Source Parameter (M-ESP) dataset (Mastin et al. 2009a) and the black dashed line is the median plume height for each dataset

resolution plume height information for events that do not necessarily produce significant deposits, capturing smaller events. However, the temporal requirement for issuing a VAA means that plume heights may not be validated and therefore certain. VAAs also report on any volcanic ash in the atmosphere and so the height reported may refer to

ash that has been transported far from the volcano; i.e. the plume height may not be that of the plume directly above the eruptive vent (Engwell et al. 2013).

Historical datasets such as that in Branca and Carlo (2005) and the ECV contain eruptive information dating back to the 1600s and are based on a combination of geological and historical information. Geological and historical records such as those collated in Branca and Carlo (2005) and the ECV tend to emphasise larger, or more scientifically interesting or societally relevant eruptions. In many cases, information may exist about the occurrence of an eruptive event, but details such as plume height and duration are not available. This data availability issue also affects contemporary datasets. The limited time span covered by the VAAs and to a lesser extent the historical dataset of Branca and Carlo (2005) mean that much larger events are not captured. It is also important to note that the measurement techniques used and the eruptive vent location have changed during the time scales covered by each of these datasets with potential impact for uncertainty on volcanic plume height.

The VAA plume heights produce an incomplete distribution, with a peak at low plume heights and a tail to greater plume heights and a median plume height (black dashed line) of 4.6 km asl. The historical data show similarities to the VAA data, with a patchy distribution with a tail towards larger plume heights. However, this distribution is shifted to greater plume heights, with fewer observations of smaller plumes resulting in a median plume height of 6.3 km asl.

The most likely range of plume heights provided in the ECV aviation table capture most of the plume heights given in the VAAs, but only a small proportion of the heights within the historical record fall within this range. In comparison, the worst-case vertical limit is much greater than any of the heights given in the VAAs and 5 km higher than the maximum plume height in the historical record. Given that the MESP dataset provides one plume height, we compare this with the median plume height of each of the datasets. The MESP dataset plume height is almost identical to the median plume height from the VAAs but is lower than the median plume height given by historical observations. These comparisons highlight the role of expert judgement in addition to information on previous eruptions to inform ESPs.

The comparison of plume height data and MESP dataset parameters for Mount Etna builds on previous analysis by Engwell et al. (2013), who compared parameters for all volcanoes that have been active between 2009 and 2019 with plume height information presented in VAAs. This analysis showed that for some categories, particularly those related to volcanoes with no historical information (S0 and M0; Figure 1 and Table 2), the MESP dataset lists greater plume heights than those based on observed activity within that 10-year period. This is likely related to bias in the record, with VAAs recording very small plumes (< 2 km above

vent) where observed, while the ESP dataset categories were informed using a range of information, including historical and geological data which encompasses larger events.

Comparison of the two datasets shows that there are some significant differences in the parameters assigned to certain volcanoes. The CIV and ECV use expert judgement, based on recent information to inform parameters within the aviation tables. The differences in the datasets, therefore, show the value in detailed analysis of eruptive histories but also highlight the requirement to maintain datasets to ensure that parameters are aligned with current knowledge. For many volcanoes, however, where the eruption record is poorly known, it is not possible to assign tailored parameters and therefore, categorisation methods such as those used in the MESP dataset are required.

## Eruption source parameter dataset maintenance and responsibilities

Estimation of ESPs is non-trivial, and as shown above, considerable time is required to gather and process data to produce datasets such as the global MESP dataset and the regional CIV and ECV datasets and aviation tables. However, there is the need to maintain and update these datasets, to reflect changes in understanding of potential activity as informed by recent activity, to reduce uncertainty, and to ensure datasets remain fit for purpose. For example, Mayotte volcano is in the ECV and aviation table but not in the MESP dataset; in 2009, Mayotte volcano was not listed in the Global Volcanism Program database and therefore, no ESPs were assigned. Another similar example is that of Fagradalsfjall, which has been recently added to the CIV following the eruption in 2021.

Hosting data on websites means that ESP data are easily accessible, can be more easily updated than information in the published record and insight from across the volcano community can be incorporated in the update process. For example, the MESP dataset has recently been transformed from a dataset to an SQL database and a searchable website dedicated to the database now exists (<https://webapps.bgs.ac.uk/esp/>). Efforts have been made to enable the volcanic community to contribute to updates to the MESP dataset through providing feedback options for each volcano. This enables experts to assess the current data and provide values, which upon validation can be used to update the dataset. In this way, the dataset can evolve as more information and greater insight become available. This relies on engagement from volcano experts, dedicated efforts to version control, and communication of dataset updates. These maintenance efforts require continued funding and staff support. Maintaining regional catalogues also requires coordination and availability of funding.



While the CIV has an ICAO funded editorial board, this is not yet the case for the ECV. However, a long-term plan exists for the ECV to become a full service through the European Plate Observing System (EPOS) Volcano Observatory portal (Puglisi et al. 2022).

As computational efficiency improves, modelling is moving away from running a single or small number of simulations towards probabilistic and ensemble modelling. The aviation tables provide a range of plume heights that can be sampled in probabilistic or ensemble modelling but lack probabilistic information such as that provided by Trancoso et al. (2022). Changes to operational procedures highlight the need to update ESPs, not only according to advances in understanding volcanic activity but also alongside users to ensure datasets suit changing needs.

A further key challenge to widespread implementation and use of ESP datasets is the development of user interfaces. Such interfaces make the setup and processing of model ensembles a routine task that can be done by non-specialists, for example, by producing interfaces where ESP information can be automatically ingested into models. These interfaces are likely to be model specific but will aid accessibility of modelling approaches.

## Future perspectives

### Towards better eruption source parameter data

Regardless of the increasing number and capability of observations, a variety of challenges in the determination and comprehensive characterisation of ESPs remain. First, analysis of plume height data for Mount Etna shows that the combined eruption record (combining information from geological, historical, and instrumental eras) lacks plume height information for both small and large eruptions. This is non-unique to Mount Etna and the eruptive record is likely to be significantly poorer for many other volcanoes, in particular remote and poorly monitored volcanoes. Second, the 2021 eruption of Cumbre Vieja volcano (La Palma, Canary Islands, Spain) highlighted the challenges of forecasting ash dispersal of small eruptions characterised by pulsatory activity at multiple vents with highly variable source and atmospheric conditions (Bonadonna et al. 2022). In that case, daily reports of plume height were provided by Plan de Emergencias Volcánicas de Canarias (PEVOLCA) reports, but models were initiated using plume heights from the Volcano Observatory Notice for Aviation (VONA), which considered observations over multiple days (Bonadonna et al. 2022) and could be out of date by the time they are used in model setup. Third, geological and historical records tend to favour those eruptions closer to geographical regions of interest (e.g. cities or flight routes) meaning that there is spatial variability

in the completeness and quality of eruption information globally. These limitations mean that improving estimates of ESPs often requires information beyond analysis of eruptive activity at the volcano of interest. Trancoso et al. (2022) addressed this issue when considering ESPs for volcanoes in New Zealand through combining information from multiple different data sources and assessing eruptions at several different volcanoes to produce probability density functions (PDFs) for key ESPs (plume height, eruptive volume, duration). This highlights the significant amount of information required to inform more complex ESP estimates and difficulties in producing such estimates for each volcano worldwide, particularly those that have not erupted in recent times. The development of new tools for identifying analogue volcanoes (e.g. VOLCANS, Tierz et al. 2019) may provide a quantitative means for categorising volcanoes based on information in addition to that used in the ESP dataset (magma type and eruption size) allowing more targeted assignment of parameters and addressing some of these problems.

A key aspect of understanding potential future volcanic behaviour and estimating ESPs is the analysis of data describing past activity. Questions exist around how to ensure data are of a similar standard and the effect of uncertainties that may arise from the use of uncertain data from the published record (Deligne 2021). Data quantity and quality can vary significantly between different regions, i.e. those regions with good monitoring infrastructure versus those without or regions with frequent eruptions compared to those without eruptions in historical times, and also on procedures and training in place to capture eruptive data. Recent efforts have applied different methods to categorise unknowns and uncertainties in data. For example, Deligne (2021) presented guidelines for the use of uncertain ESP data from the published record, while Aubry et al. (2021) used flags to characterise the amount of interpretation of information from the published record required to inform parameters. Both studies relate to a relatively small number of eruptions and volcanoes, but similar methods could be used in datasets such as the MESP dataset to provide information on the amount and quality of available data and therefore uncertainty. This becomes increasingly important when there is a move away from assigning ESPs according to categories and analogue eruptions, versus assigning volcano-specific ESPs.

Recent recommendations on recording ESP information (Aubry et al. 2021), the development of protocols to aid extraction of eruption information from published literature (Deligne 2021), and the development of eruption datasets (e.g. IAVCEI Commission on Tephra Hazard Modelling; <https://thm.iavceivolcano.org/datasets/>) mark a move towards formal recognition of these issues, with the aim of improved data in the future. In the meantime, methods have been explored to limit the impact of uncertainties in

eruption data when defining ESP information. Trancoso et al. (2022) hoped that bringing together information from a range of sources and volcanoes would enable uncertainties in eruption ESP to be encapsulated within their resultant PDFs—i.e. the contribution of uncertainties in ESPs is small in comparison to the range of activity observed at different volcanoes.

Improvements in computational efficiency enable changes to the approach used, not only in modelling of volcanic ash dispersal but also in simulating hazards more generally (Mastin et al. 2022). The move towards probabilistic and ensemble modelling requires more complex ESPs, in the form of ranges or PDFs. Limited observations mean that for ash dispersion modelling, empirically based ranges can only be determined for certain parameters, such as plume height and, in some cases, duration. Determination of representative PDFs for parameters for an individual volcano is challenging given currently available data, meaning that PDFs need to be produced from composite data (Trancoso et al. 2022).

There is a continued need for efforts to focus on accurately and precisely recording volcanic eruptions and their behaviour to improve the determination of ESPs in the future. This includes the continued development of methods for measuring ESPs, particularly those for which there is limited information, such as grain-size, and procedures for clearly and accurately recording and communicating eruption information. For example, in published reports and papers, adding information regarding the time of an observation and how it was collected and other metadata (for example, height above sea level or vent for plume height) is imperative for improving estimates of ESPs for operational modelling, hazard assessment, and research purposes. Conversations need to continue between volcano observatories, researchers, and VAACs to ensure that ESPs are available in the required format, while acknowledging that format may differ depending on institution and use as highlighted by the different inputs describing grain-size used by the different VAACs (Hort and Witham 2018).

### Emerging methods for estimating eruption source parameters

Currently available ESP resources commonly use past observations or geological insight to inform knowledge of potential future behaviour. Insight into future activity can also be gained from observation and analysis of unrest and an ongoing eruption. The availability of high temporal resolution unrest information, such as deformation rate, seismicity, and gravity, provides a potential opportunity for informing parameters. The 2011 eruption of Grímsvötn, Iceland, provided an opportunity to relate an unrest parameter, surface deformation, with plume height

(Hreinsdóttir et al. 2014). Post-eruption analysis showed that Global Positioning System (GPS) and tilt data displayed a correlation between rate of pressure change in the magma chamber and the eruptive plume height (Hreinsdóttir et al. 2014). These results highlight the gains still to be made through better understanding of volcanic processes and monitoring of volcanoes. Such approaches are still in their infancy and are not widely applied and their associated uncertainties not fully understood. Further work is required comparing unrest and eruption characteristics at different volcanoes before application of these techniques is possible in eruption response.

### Eruption source parameters for SO<sub>2</sub> plumes

Current pre-eruption ESP resources relate specifically to ash plumes. The impact of SO<sub>2</sub> on aircraft and the health implications of SO<sub>2</sub> are the focus of much research (e.g. Kristiansen et al. *in review*). While published eruption and plume height data exist (e.g. Carn et al. 2017), understanding of the relationship between SO<sub>2</sub> plume parameters, such as plume height, SO<sub>2</sub> mass released, and other eruptive conditions, is still relatively limited compared to that of ash plumes. Efforts are underway to better understand ESPs of SO<sub>2</sub> plumes, through collation of SO<sub>2</sub> plume height data and by relating characteristics such as SO<sub>2</sub> plume height to MER (Aubry et al. 2023). Results may be used to inform SO<sub>2</sub>-specific ESPs in the future.

### Operational communication of eruption source parameters

An important aspect related to the correct and timely use of ESPs in near real-time is timely communication between observers and numerical modellers. To this end, the VONA was developed with the purpose of aiding and standardising communication between different volcano observatories and the responsible VAAC. Some institutions have developed systems to enable easy completion and distribution of VONAs. For example, the US Geological Survey developed the Hazards Notification System for Volcanoes (HANS; <https://volcanoes.usgs.gov/hans2/>), which provides a template to produce and format the VONA. Such systems are reliant on reliable internet and digital infrastructure and, as such, are not accessible to all observatories worldwide. In addition, there are large discrepancies in the capabilities of different observatories worldwide in their ability to provide ESP information due to differences in monitoring infrastructure. Continued efforts need to be made to support volcano observatories in the collection and communication of timely ESP data.

## Updates to eruption source parameter datasets

Despite progress in near-real-time ESP estimates, there is still a need for datasets such as the MESP dataset and the CIV and ECV aviation tables. By providing information where direct observations are impossible, they aid not only decisions on appropriate ESPs for hazard modelling, but they also inform discussions between different groups (e.g. volcano observatories, civil protection authorities, VAACs, and researchers). There are significant differences between these datasets, related to their development and scope. Through providing ESPs for all of the world's volcanoes, it is not possible for the MESP dataset to have the same data resolution as in the ECV and CIV aviation tables, which cover smaller geographical areas containing volcanoes where eruptive information is relatively well-known. There is a role for both types of datasets in operational response with the potential to improve both datasets as our understanding of past eruptive activity worldwide continues to improve. The key to the continued use of these resources is to maintain and update ESPs as more eruptive information and insight become available. Specific strategies for improvement of the ESP datasets include the following:

- (1) Designing a flexible dataset that allows for statistical approaches to be applied to inform ESPs and provide results in different formats, for example, single values versus probability density functions. There is increasing recognition that different applications require different formats of ESPs. Techniques such as hierarchical Bayesian modelling could be applied to data-rich examples to aid definition of ESPs for data-sparse volcanoes, while still considering available data for that volcano (e.g. Ogburn et al. 2016).
- (2) Improving entries within the MESP for specific volcanoes using information from resources such as the CIV and ECV and others as volcanoes become active.
- (3) Working with volcano experts, e.g. at volcano observatories, to define volcano-specific ESPs that can be modified over time as more information becomes available.
- (4) Ensuring data provenance information is available for each entry for transparency.
- (5) Ensure version control practices are in place and communicated.
- (6) Application of emerging techniques, for example, artificial intelligence, to better identify analogue volcanoes, particularly for dormant volcanoes for which limited data are available.

Following such strategies will not only improve available ESP information but would also provide the information required to track eruption and volcano knowledge through

time. Over time, as our understanding of volcanic activity and eruption histories improves, it is anticipated that resources such as the ECV aviation tables and the MESP dataset may converge on similar input values for many volcanoes.

## Conclusions

Eruption source parameters (ESPs) are key for describing eruptive behaviour to enable the application of numerical models. A crucial aspect of response to volcanic eruptions is the simulation of tephra transport in the atmosphere. Numerous techniques have been developed to estimate ESPs such as plume height, mass eruption rate, and grain-size distribution in near real-time. However, there are occasions when direct observation of an event is not possible. In such cases, operational tephra dispersal modelling, such as that conducted by Volcanic Ash Advisory Centres and volcano observatories, requires information from other sources. In response to this need, the Mastin et al. (2009a) ESP dataset (a global dataset) and the Catalogue of Icelandic Volcanoes and European Catalogue of Volcanoes aviation tables (regional datasets) were developed. The spatial coverage of these resources means that there are differences in the information contained within the datasets. The aviation tables cover many active volcanoes in Europe, whose activity is relatively well-understood. In comparison, the Mastin et al. (2009a) dataset contains ESPs for all volcanoes active within the Holocene worldwide. Given this difference in spatial range, the way in which ESPs are assigned varies between the two resources. ESPs in the Mastin et al. (2009a) datasets are assigned using analogue volcanoes and eruptions while the aviation tables provide volcano-specific information. Despite differences in approach, the ESPs provided for volcanoes are largely consistent with the plume height within the Mastin et al. (2009a) dataset, falling within the range of heights provided in the aviation tables. Differences arise for volcanoes with recent eruptive activity, which is not captured by the Mastin et al. (2009a) dataset. This contribution highlights the need for continued maintenance and development of ESP resources to meet changing user needs such as the increased use of probabilistic and ensemble modelling in forecasting volcanic hazards.

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