Inversion of field data for reconstructing plume dynamics of past eruptions: state of the art and perspectives

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Eruptive columns commonly comprise three distinct regions characterised by different flow regimes: a lower basal gas-thrust or jet region, an intermediate convective region, and an upper umbrella region. Typically, the gas-thrust region extends only up to a small fraction of the total column height and it is characterised by a steep decrease of the gas particle mixture velocity due to loss of momentum. In contrast, the convective region is dominated by buoyancy forces acting on the hot erupted gases and heated entrained air. Finally, above the neutral buoyancy level, the erupted material spreads under the effect of winds and atmospheric turbulence to form the umbrella region. Sizes of erupted particles may vary by several orders of magnitude, ranging from very fine sub-micron ash to clasts larger than one meter in diameter. The largest and heaviest particles leave the column at lower levels and follow complicated ballistic and non-ballistic trajectories, whereas the finest particles may remain entrapped by geostrophic winds for several years affecting the global climate. Particles within the intermediate to fine size range are advected by wind, diffused by turbulence, settled by gravity and deposited finally on the ground at medium to distal distances. Therefore, the physics of volcanic plumes depends by different several factors, which can be summarised as total mass and its distribution (total grain size), initial momentum, available heat, efficiency of air entrainment and interaction with the atmospheric wind field. The definition of these parameters is essential for having models able to predict ground ash loading and atmospheric ash concentrations, which are of fundamental importance for public safety in volcanic areas. However, The characterisation of these parameters is hard to obtain from direct observation of eruption plumes, and are even more challenging to gain from inversion of data from pyroclastic deposits.

Here, a critical overview about models (field, experimental and numerical) for inversion of field data to gain insights on the physics of volcanic plumes is proposed. A special focus is devoted to some physical parameters that are far from a satisfactory inversion (e.g. reconstruction of total grain size distribution), and clues for future research are suggested.

Unsteady turbulent jet dynamics with implications for volcanic plumes

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To investigate the response of volcanic plumes to unsteady vent conditions, an analogue study of laboratory jets was conducted. Lab jets were driven with injection rates that varied over time in a Gaussian-like history. Resultant jet heights showed a logarithmic dependence on time; this trend is in contrast to the power law dependence on time expected for jet heights from steady-state or instantaneous injection rates. The logarithmic time dependence may reflect the dominance of coherent vortices that were detected in the unsteady jet interiors. These vortices are large and extend from beyond the visible boundary of the jet through the jet interior. They are also persistent with lifetimes that are comparable to the jet rise time. The large and long-lived coherent vortices may not transport mass, momentum and energy in a way that is reasonably described by homogeneous turbulence concepts that underlie steady-state and instantaneous models of volcanic plumes and jets. Consequently, this work implies that it is first necessary to understand transport by large and long-lived coherent vortices before that process can be parameterized for use in models of unsteady turbulent jets. Despite this need for a complex transport description, the behavior of the flow front can be described with a simple expression that consolidates the jet rise behavior from a range of experimental conditions to a single trend. This expression is non-dimensional using a length and time scale derived from a linear fit of jet height and the logarithm of time. Data from a single volcanic plume observation (Mori and Burton, 2009, JVGR, 188, p. 395-400) also follows the same trend as that discovered in the laboratory. This synthesis lends a tenuous confidence to the relevance of the experimental model to the natural system. Successful comparison with a larger natural data set may better delimit the model applicability but such data is absent from the literature. Nevertheless, the logarithmic time dependence contrasts the power law dependence commonly employed to interpret volcanic plume observations, and suggests that this new experimental model may be more appropriate for interpreting short-lived volcanic events.

Buoyancy of plume-sourced ash clouds: implications for ash transport modelling.

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Volcanic plumes ascend high into the atmosphere where they spread out at a level of neutral buoyancy to form intrusions. The structure of these intrusions depends on the relative strength of the intrusions, the ambient wind and the local atmospheric stratification. In a strong wind, moderate to weak sized eruptions form bent over plumes while in more powerful eruptions or in eruptions with a weak wind, they typically form umbrella clouds, which spread in all directions. Irrespective of the wind the plumes reach dynamical equilibrium with the wind field further from the volcanic source. The motion of such plume-fed intrusions is governed by buoyancy. The spreading of intrusions is controlled by the volumetric flux of the feeding plume at the height of neutral buoyancy and the density stratification in the atmosphere, but not by the density of the intrusion itself. For the case of a symmetrically spreading umbrella cloud the thickness decreases with distance. Although more complex in detail, intrusions affected by the wind also thin quite rapidly with distance. Buoyancy thinning can explain why ash clouds are observed to become very thin quite close to source. Advection diffusion models are now widely used to forecast ash clouds dispersal and ash deposition. Such models typically assume ash is dispersed vertically above the source and assume ash particles act as heavy (sedimenting) tracers that are spread by atmospheric diffusion. Buoyancy effects are ignored. We contend that such models are not a correct description of the physics of ash clouds in regions where buoyancy effects are significant. For very powerful eruptions buoyancy effects are dominant to distances of hundreds of kilometres or more; it seems unlikely that an advection-diffusion model could reproduce observed ash distributions since such models cannot have upwind or very extensive cross-wind spreading. For weaker plumes that are markedly affected by wind, advection-diffusion models are useful mathematical descriptions that can be calibrated to give good forecasts of ash transport. However, this does not mean they are good physical models of the process. Models of buoyancy spreading suggest that it can be the main cause of lateral spreading of wind blown clouds to significant distances (perhaps tens or hundreds of kilometres). Operational models of ash dispersal are likely to remain structured as advection diffusion models, so they may need some empirical adjustments to take account of buoyancy. For example it might be better to have source terms, which assume ash is concentrated in narrow height intervals above the source (at one or more discrete levels rather than distributed vertically). It seems unwise to continue using such models for very powerful eruptions.

Quantifying the uncertainty in estimation of the volcanic source mass flux from observed plume dynamics

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Estimates of volcanic source mass flux, currently deduced from observations of eruption plume height, are crucial for ash dispersion models for aviation and population hazard. Recent modelling studies have shown that the effect of the atmospheric wind on a volcanic plume can significantly reduce its height compared with the case of no wind, and so source mass flux can be underestimated by up to two orders of magnitude (Degruyter and Bonadonna, 2012; Woodhouse et al., 2012). Volcanic and atmospheric input parameters have associated measurement uncertainty, and the models incorporate epistemic uncertainty due to their formulation. In this study we quantify the magnitude of these uncertainties in order to identify which input parameters introduce the greatest uncertainty into estimates of volcanic source mass flux, and to identify where improvements in measurement capability would provide the greatest improvement to mass flux estimates.

The integral model of Woodhouse et al (2012) is used as a candidate model for uncertainty quantification, and it is formulated as a set of four coupled differential equations to express conservation principles for mass, momentum and enthalpy, and algebraic relationships for entrainment of atmospheric air, plume density and variation of atmospheric properties with height. Input parameters from the volcanic source include the ash mass flux, initial velocity, vent radius and ash temperature, and atmospheric properties can be taken from radiosonde, NWP or ECMWF reanalysis sources. The model can be rapidly solved numerically, so Monte Carlo methods have been used to explore the effect of parameter uncertainty. The greatest uncertainty in the source mass flux arises from the estimation of source temperature, with much weaker dependence on solid mass fraction in the initial plume. Woodhouse et al (2012) also identified a dimensional relationship between plume height, wind shear and source mass flux, which was fitted to their numerical model output. We also explore the uncertainty in this relationship, as a form of simplified model emulator, finding that variability in the wind shear has a much stronger affect that the other properties of the atmosphere.

Integral models of wind-affected volcanic plumes can also be fitted to observations of plume trajectory to provide tools to rapidly estimate the source mass flux. We use webcam imagery of the 2010 Eyjafjallajokull eruption to explore how the uncertainty in meteorological data compares with uncertainty in the parameters that are used to estimate the volcanic source mass flux. From this we are able to identify the parameters whose values have the greatest influence on the uncertainty in volcanic source term estimation.

References: Degruyter, W. and Bonadonna, C. (2012) Geophys. Res. Letts. doi:10.1029/2012GL052566; Woodhouse, M.J. et al (2012) J. Geophys. Res. doi:10.1029/2012JB009592

Integral models of volcanic plumes in a cross wind.

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Explosive volcanic eruptions can inject large quantities of ash into the atmosphere which can be transported over large areas. The recent eruptions of Eyjafjallajökull 2010, Grimsvötn 2011 and Cordón-Caulle 2011 demonstrate the fragility of international transport infrastructure to relatively small volcanic eruptions. Managing airspace during volcanic crises by forecasting atmospheric ash dispersion requires, as an input, estimates of the source conditions at the volcanic vent. The source conditions are currently difficult to measure directly during an eruption.

Integral models of volcanic plumes can be used to estimate the source conditions during eruptions by comparing model predictions with observations. The simple mathematical structure of integral models allows solutions to be readily obtained, allowing an assessment of source and atmospheric controls to be made. We formulate an integral model of volcanic eruption columns that utilizes meteorological observations to determine the trajectory of the plume motion. We demonstrate, for weakly-explosive eruptions, atmospheric conditions have a strong effect on the rise of the plume. In particular, atmospheric winds strongly influence the rise of volcanic plumes, with the wind restricting the rise height such that obtaining equivalent rise heights for a plume in a windy environment would require an order of magnitude increase in the source mass flux over a plume in a quiescent environment.

The mixing of atmospheric air with the magmatic gases and pyroclasts plays a crucial role in the dynamics of the ascent of the plume. The entrainment process is typically parameterized in integral models using simple, phenomenological closures based on the classical entrainment assumption of Morton, Taylor & Turner (1957). Here we discuss the parameterization of entrainment, investigate the effect of wind enhanced entrainment on plume dynamics, and assess the sensitivity of integral model results to the entrainment coefficients employed.

Impact of wind on the condition for column collapse of volcanic plumes

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Collapse of volcanic plumes has significant implications for eruption dynamics and associated hazards. We show how eruptive columns can collapse and generate pyroclastic density currents (PDCs) as a result of not only the source conditions, but also of the atmospheric environment. The ratio of the potential energy and the kinetic energy at the source quantified by the Richardson number, and the entrainment efficiency quantified by the radial entrainment coefficient have already been identified as key parameters in controlling the transition between a buoyant and collapsing plume. Here we quantify how this transition is affected by wind using scaling arguments in combination with a one-dimensional plume model. Air entrainment due to wind causes a volcanic plume to lower its density at a faster rate and therefore to favor buoyancy. We identify the conditions when wind entrainment becomes dominant over radial entrainment and quantify the effect of wind on column collapse. We propose a generalized regime diagram based upon (i) the ratio of the Richardson number and the radial entrainment coefficient and (ii) the ratio of the wind entrainment rate and the radial entrainment rate. Previously used diagrams under the condition of choked flow can be considered as a special case within this diagram. The mass flow rate is shown to be an ambiguous parameter to assess column collapse as both an increase and decrease can lead to collapse. Rather the effects of its independent constituents (density, exit velocity, and vent radius) should be considered.

Wind significantly affects eruption dynamics as it can (i) reduce the final height of the plume, (ii) be the dominant entrainment mechanism, and (iii) prevent a plume from collapsing. Therefore, strong winds are natural allies in reducing hazards present at volcanoes both on a proximal (less PDCs) and regional scale (reduced height). Observations of several eruptions qualitatively confirm this behavior. In particular, the parameter range derived for the 2010 Eyjafjallajokull eruption suggests the wind enhanced the buoyancy of the plume, where in a still environment this plume would have probably collapsed.

A fast Eulerian multiphase flow model for the three-dimensional numerical simulation of non-equilibrium effects in turbulent volcanic plumes

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We have developed a fast Eulerian model for the Large Eddy Simulation (LES) of turbulent volcanic plumes. The model is based on the equilibrium-Eulerian approximation (Ferry and Balachandar, Int. J. Multiph. Flow 2001; Cantero et al., J. Geophys. Res., 2008) for a polydisperse flow.

This approach gives particular attention to the particle grain size distribution and its interaction with the turbulence. We are indeed particularly interested in the disequilibrium between the ash and the gaseous part of the volcanic mixture, our aim being to properly simulate phenomena like preferential concentration and plume entrainment.

In the limit of fine particles (at Stokes number < 0.2) and dilute regimes (particle volume concentration < 1.e-3), such method allows to overcome the limitations of the pseudogas models (assuming a perfect kinematic and thermal equilibrium between gas and particles - Oberhuber et al, J. Volcanol. Geoth. Res., 1998; Suzuki et al., J. Geophys. Res., 2005) without entailing the complexity and computational cost of the fully coupled multiphase flow Eulerian models (Neri et al., J. Geophys. Res., 2003; Dufek and Bergantz, Theor. Comput. Fluid Dyn., 2007).

To model the non-linear coupling between turbulent scales and the effect of sub-grid turbulence on the large-scale dynamics, we have adopted the LES formalism (which is preferable in transient regimes) for compressible flows.

Our computational work is based on development and exploitation of these models into the numerical solvers of OpenFOAM, which is one of the best known CFD open source parallel software packages.

Preliminary numerical benchmarks demonstrate that the model is able to capture important non-equilibrium phenomena in gas-particle mixtures, such as particle clustering and ejection from large-eddy turbulent structures, as well as compressibility and thermal effects.

A quantitative assessment of the reliability of Direct Numerical Simulation (DNS) and LES results with respect to modeling approximations and numerical errors has been carried out by comparing numerical results to experimental and computational studies of homogeneous, isotropic turbulence.

In such a simplified geometry, the numerical solver is able to accurately reproduce the turbulent spectrum and the Kolmogorov energy cascade.

Preliminary three-dimensional numerical simulation of volcanic plume dynamics demonstrate that gas-particle non-equilibrium phenomena have a significant impact on turbulent structures and can affect the entrainment rate and the atmospheric dispersal of volcanic ash.

Do Prince Ruperts Drops provide insight into phreatomagmatic fragmentation?

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Prince Ruperts Drops (PRDs) are tadpole-shaped glass beads that are known for their unusual fracture properties: the head of the bead is very strong, but the entire bead will shatter explosively if the tail is broken. These properties result from residual stresses within the glass beads. Compressive stresses on the outer margin of the PRDs provide the strength. Tensile stresses inside the beads drive explosive fracture propagation when the outer compression zone is damaged. Fractures propagate at a rate determined by the terminal crack speed for the glass. Key to the residual stress geometry is the process by which PRDs are made, which involves dripping molten glass into water.

Water-quenching of silicate melts also occurs when rising magma encounters shallow water bodies in subglacial, submarine and sublacustrine environments. Such eruptions are known to generate more energetic eruptions, and finer particle sizes, than eruptions that do not involve an external water source. Most studies of explosive melt-water interaction are based on concepts of molten fuel-coolant interaction (MFCI), with experimental studies designed to study mechanisms of melt-water mixing. From this perspective, the energy release is determined by the efficiency of heat transfer and resulting volume expansion generated by the transformation of water to steam. Generation of fine ash particles is assumed to require brittle fragmentation, with the resulting grain size attributed to (1) the pore geometry, (2) a single episode of quench granulation, or (3) turbulent shedding of successive quenched layers.

To date, no examination of hydromagmatic volcanism has considered the role of residual stress on the fragmentation process. However, residual stress is common in air-quenched basaltic glass, as evidenced by the spontaneous ejection of glass flakes from pahoehoe flow surfaces. The blocky form of many hydromagmatic pyroclasts also suggests that fragmentation occurs in the brittle regime, although particles with the more fluidal shapes of Peles hair and Peles tears (i.e., tadpole-shaped glass beads) are not uncommon in phreatomagmatic deposits. Evidence of thermal contraction is also common as cracked outer surfaces of water-generated ash particles, as partially disaggregated surface skins on Peles tears, and as striations on the surface of blocky particles. Fragments generated by explosive disruption of PRDs show similar blocky to plately forms and surface striations. On the basis of these similarities, we suggest that residual stresses such as those that control explosive fragmentation of PRDs may contribute to fine ash production in hydrovolcanic eruptions. Spontaneous disruption of rapidly quenched glass provides a mechanism for the proposed model of fragmentation by turbulent shedding and suggests that studies of crack propagation in glasses and glass ceramics may contribute to our understanding of fragmentation processes.

A new model for the predication of drag of non-spherical volcanic particles

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Estimation of drag of non-spherical particles is the most important parameter in many multi-phase flow processes in both industry and nature. Although many experimental results on the drag of non-spherical particles exist in the literature, only a few of them are based on measurements in air. We present a new model for the prediction of the drag of non-spherical solid particles of regular and irregular shape that travel in air. Reynolds numbers investigated are between 10 and 10^5 (i.e. laminar to turbulent regimes). The results are obtained from experiments performed on micron size particles in a falling column and on millimetric size particles suspended in a vertical wind tunnel. Both apparatus were designed and built at University of Geneva for the study of sedimentation and aggregation of volcanic particles. Particle shape factors are measured based on various methods existing in the literature and benchmarked against our experimental results. Shape factors are calculated with different instruments depending on the size of particles such as 3D-scanning and image analysis. New easy to measure shape factors are introduced which have the highest correlation with the measured drag coefficient of particles. Performance of the models is benchmarked against well-known spherical and non-spherical models. As an example, we have found that both existing spherical and non-spherical models can estimate settling velocity of volcanic particles with an average error of about 30%. We have also found that the effect of surface roughness on terminal velocity of non-spherical particles of millimetric size is almost negligible. Finally, we observed that secondary motions of particles are considerably higher at high Reynolds numbers. This implies that particles falling in the turbulent regime are better characterized by a range of terminal velocities instead of a single value especially in case of particles with high variation in their projected area. Our experimental benchmarks show that our new model is a reliable and easy to apply model for estimating drag coefficient of non-spherical particles of various shapes in a wide range of Reynolds number.

Determination and evolution of source parameters in volcanic eruptions; the FUTUREVOLC supersite approach

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Recent explosive eruptions in Iceland and South America have highlighted the need for reliable near real time estimates of eruption rates. At present the method most frequently used for all but the smallest events, is applying the theoretically and empirically derived relations between eruption plume height and mass eruption rate; often using weather radar data to derive plume heights. In recent years several new methods have been developed that provide independent estimates of volumetric flow rate, plume particle concentrations, exit velocities, electric field generation, gas fluxes, lightning intensity in eruption clouds as well as satellite based methods for plume tracking and atmospheric mass loading. Each method has its strengths and drawbacks. By combining measurements of the all the above parameters into a single system, a much more reliable estimate of eruption rate should be obtained. The compilation of such a system is one of the aims of FUTUREVOLC, a European collaborative project funded through the EU FP7 Environment call encompassing 26 partners in 10 European countries. The main objectives of FUTUREVOLC are to establish an integrated volcanological monitoring procedure, develop new methods to evaluate volcanic crises, increase scientific understanding of magmatic processes and improve delivery of relevant information to civil protection and authorities. FUTUREVOLC is a supersite project, where Iceland has been selected as the target area. In its comprehensive approach to the study of volcanic phenomena, subsurface magma tracking is combined with physical volcanology and atmospheric science. The integrated system for estimation of eruption source parameters will be composed of arrays of sensors that are already in place will be set up in the summer of 2013. The components of the monitoring system include continuously recording real time devices: two C-band weather radars, two mobile X-band radars, radiosondes for ambient atmosphere monitoring, infrasound arrays, arrays of time lapse cameras, electric field sensors, automated tephra samplers and analysers, gas monitoring systems and lightning detection systems. The signals from these systems will be supplemented by aircraft observations and the deployment of a mobile field lab for rapid characterization of tephra. The data from all these sources will be fed into an integrated near real-time system that will evaluate the eruption rate. New algorithms for analysis of radar backscatter and both physics-based and empirical plume models will be implemented as a part of the system. Various data from previous eruptions, including ground truth information, will be used to calibrate the system, which is expected to be operational in 2016.

Full bandwidth remote sensing for total parameterization of volcanic plumes

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If we are to adequately track the emission, ascent and dispersion of a volcanic plume, we first need to measure a number of source condition parameters. These include mass flux, exit velocity, particle size distribution, and plume density or ash concentration. Because of the difficulty of close approach to an active volcanic vent, such measurements need to be remote. Moreover, these need to span a broad range of the electromagnetic spectrum in order to fully parameterize the volcanic plume. With this in mind, we designed in 2012 an experiment involving the full range of modern ground-based remote sensing capabilities, from microwave to ultraviolet wavelengths. Stromboli (Italy) was selected for this test deployment, both for its ease of access and reliability as particle emitter. Our aim was to: characterize explosive eruption dynamics at the highest possible spatio-temporal resolution, test the combined deployment of a complete instrument package, and evaluate its potential for operational plume tracking with a special emphasis on extracting source condition parameters. The equipment package deployed involved the following instruments, beginning with the longest wavelength: (i) 1 Doppler radar (VOLDORAD2, 23.5 cm wavelength) sampling at 10 Hz, used to quantify the ejection velocities and mass fluxes, (ii) 2 thermal infrared cameras (FLIR Systems, 8-14 micrometers) sampling at 200 Hz and 30 Hz, used to track the near-vent emission and the plume ascent and dispersion, (iii) 1 very high frame rate camera (Photron Fastcam SA3, visible and near-infrared) sampling up to 2000 Hz, used to characterize the highest velocities for particles carried by the gas phase, (iv) 2 stereoscopic cameras (IP Basler, visible and near infrared) sampling at 25 Hz, used to reconstruct 3-D particle trajectories and further constrain their sizes, (v) 1 SO_2 camera (310 and 330 nm) and 1 OP-FTIR, used to quantify the mass of gas. In addition, a permanent seismic and infrasonic array was used to characterise the seismic and acoustic signal associated with explosive activity, and in-situ sampling of particles landing in well-defined areas was done to carry geochemical, density, vesicle, and crystal analysis of the ejecta. The ongoing work involves creating code to process and integrate all data sets so as to output the source terms in a rapid-to-real-time frame. We here give special emphasis on the mutual feedback between infrared cameras and Doppler radar, where the first provide particle size distribution to the second to constrain the mass flux.

Eruptions on the fast track, part b): The variability of strombolian explosions from high speed thermal and optical videos

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Strombolian activity style is characterised by discrete explosions at variable frequency, lasting a few to tens of seconds, and ejecting pyroclasts at heights of tens to hundreds of meters. New imaging techniques, including high speed camera observations, have already shown that these explosions are complex phenomena that include pyroclast ejection pulses, typically lasting tenths of seconds, characterized by a non-linear decay on the ejection velocity over time and related to individual pressure release events. Here, we show the results of a new computing techniques (described in a companion abstract, Eruptions on Fast Track, part a), based on joint application of Particle Image Velocimetry (PIV, providing information on the ash and gas clouds) and Particle Tracking Velocimetry (PTV, providing information on the cm-to m-sized pyroclasts) to high-speed visible and thermal videos of Strombolian explosions at Stromboli (Italy) and Yasur (Vanuatu) volcanoes. In comparison to previous studies, which manually analysed the videos, the techniques we use increase by ten-fold the number of identified and measured particles, allowing a significant advancement in the study of Strombolian dynamics.

A variable number (a few to several tens) of well-defined ejection pulses are present in all analyzed explosions. Pulses sometimes are organised in larger ejection events, or super-pulses, lasting up to a few seconds, characterised by a velocity decay following the same non-linear trend shown by pulses. The mean source depth of the pulses, modeled from the velocity decay trends, are mostly in the tens of meters range and remains constant on the whole explosion, while super-pulses seems to originate deeper (up to hundred of meters) in the conduit.

Within each pulse, we observe a strong correlation of ejection parameters: the spread of the ejection angle and the size of particles increases while the number of particles and their velocity decreases. This correlation is tentatively linked to the explosion dynamics of gas pockets at the surface, where maximum pressure differential is initially released through a small, ventral opening that gets wider with time, with possible effects of inter-particle collisions also playing a role.

At the time scale of the whole explosion, ejection angle is a reflection of the overall vent orientation. The temperature of the bombs and ash decrease over time and height above the vent, more slowly for the bombs, to be compared with theoretical predictions. The total mass of the pyroclasts ejected during a single pulse ranges from tens of kg to several tons, while the comulative one for an explosion can reach hundreds of tons. The ejection mass rate tends to decrease during one explosion, suggesting that, despite the presence of ejection pulses, each explosion still represent one well-identified and impulsive energy release event.

Using infrasound to infer volcanic jet parameters: revisiting acoustic power vs. jet velocity scaling laws

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A basic goal of volcano acoustics is to relate observed airborne acoustic signals (usually infrasound) to the eruptive processes generating them. A quantitative link between a volcanic jet flow and its radiated infrasound would allow volcanic jet parameters to be inferred from infrasound data. A promising approach is to use the results from man-made jet-noise studies as a starting model for understanding the infrasound produced by the larger and more complex volcanic jet flows, assuming that the source mechanisms are analogous. A classic paper by Woulff and McGetchin [1976] introduced the idea of using observed acoustic power P to infer volcanic gas exit velocity U. They proposed scaling laws of the form $P \sim U^n$, where the exponent n = 4, 6, or 8 for equivalent monopole, dipole, and quadrupole sources, respectively. This formulation was based on the prevailing acoustic analogy of jet noise. However, jet noise research has changed dramatically since then with the discovery of coherent structures in turbulence. Jet-noise studies in the last decade have largely abandoned the idea that jet noise is composed of equivalent monopoles, dipoles, and quadrupoles. New empirical scaling laws have been proposed for pure-air jet flows based upon detailed laboratory studies. The new scaling laws take into account the strong temperature and directional dependence of jet noise. We discuss the implications of these results for volcano acoustics. We explore the basic issues with trying to infer gas exit velocity from acoustic power using examples of volcano-acoustic data, as well as acoustic recordings of rocket and military aircraft jet noise. This work demonstrates that Woulff and McGetchin's formulation can lead to large errors when inferring eruption dynamics from infrasound. We propose a replacement framework based on modern aeroacoustics research, which is being developed through quantitative integration of field, numerical, and laboratory studies and could lead to a more accurate relationship between volcanic infrasound and eruption column parameters.

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Infrasonic Crackle from the 2011 Eruption of Nabro Volcano, Eritrea: Evidence for Supersonic Jet Noise

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An understanding of volcanic jets is critical to determining eruption column dynamics and mitigating volcanic hazards. However, volcanic jets are inherently difficult to observe directly due to their violence, opacity, and complex multi-phase and multi-component flow features. Recent work has shown similarities between the sound produced from explosive volcanic jets and man-made jet engines and rockets [Matoza et al., 2009]. We show that infrasound generated by the eruption of Nabro Volcano, Eritrea has waveform features highly similar to waveforms associated with the crackle phenomenon uniquely produced by supersonic jet engines and rockets. Crackle is characterized by repeated asymmetric pressure pulses with higher-amplitude compressions than rarefactions and can be quantified by the skewness (a measure of the asymmetry of the waveform probability density function). The infrasonic crackle from Nabro reported here strongly indicates that infrasound from some volcanic eruptions is produced in similar ways to man-made jet noise from heated, supersonic jet engines and rockets. Noise sources and flow dynamics of jet engines and rockets are better characterized and understood than volcanic jets, suggesting volcanologists could utilize the modeling and physical understandings of man-made jets.

Nabro Volcano, Eritrea erupted explosively on 12 June 2011 and injected vast quantities of SO_2 into the upper troposphere and stratosphere, disrupted air traffic, and severely affected communities in this remote region. Significant infrasound was recorded by two infrasound arrays: IS19 (Djibouti, 264 km) and IS32 (Kenya, 1708 km). The IS19 infrasound array detected the eruption with high signal-to-noise and provides the most detailed eruption chronology available, including eruption onset, duration, and changes in intensity. As seen in numerous other studies [Fee and Matoza, 2013], sustained low-frequency infrasound from Nabro is coincident with high-altitude emissions. The unique, distinctive infrasonic crackle from Nabro highlights the potential to use infrasound to determine some volcanic jet characteristics and parameters such as velocity, mass eruption rate, temperature, etc. Additionally, we reiterate the potential to use infrasound as a real-time, remote means to detect hazardous emissions, particularly in remote and poorly monitored regions.

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A-Train satellite observations of young volcanic eruption clouds

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NASA's A-Train satellite constellation (including the Aqua, CloudSat, CALIPSO, and Aura satellites) has been flying in formation since 2006, providing unprecedented synergistic observations of numerous volcanic eruption clouds in various stages of development. Measurements made by A-Train sensors include total column SO_2 by the ultraviolet (UV) Ozone Monitoring Instrument (OMI) on Aura, upper tropospheric and stratospheric (UTLS) SO_2 column by the Atmospheric Infrared Sounder (AIRS) on Aqua and Microwave Limb Sounder (MLS) on Aura, ash mass loading from AIRS and the Moderate resolution Imaging Spectroradiometer (MODIS) on Aqua, UTLS HCl columns and ice water content (IWC) from MLS, aerosol vertical profiles from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument aboard CALIPSO, and hydrometeor profiles from the Cloud Profiling Radar (CPR) on CloudSat. The active vertical profiling capability of CALIPSO, CloudSat and MLS sychronized with synoptic passive sensing of trace gases and aerosols by OMI, AIRS and MODIS provides a unique perspective on the structure and composition of volcanic clouds. A-Train observations during the first hours of atmospheric residence are particularly valuable, since in-situ sampling of fresh eruption clouds is highly challenging, and yet the fallout, segregation and stratification of material in this period determines the concentration and altitude of constituents that remain to be advected downwind. This represents the eruption 'source term' essential for dispersion modeling, and hence for aviation hazard mitigation. In this presentation we focus on A-Train data collected during eruptions of Redoubt (March 2009), Eyjafjallajökull (April 2010) and Grimsvötn (May 2011), supplemented with high-temporal resolution SEVIRI measurements of ash mass loading in the Eyjafjallajökull plume. The A-Train data provide unique evidence for ash aggregation or hydrometeor-enhanced ash loss in the Redoubt and Eyjafjalljökull plumes, perhaps enhanced by the prevailing meteorological conditions in the latter case. We also present results from a UV ash retrieval algorithm that provides new constraints on ash mass loading in volcanic plumes, to complement commonly used IR retrieval techniques. Although of limited operational use due to data latency issues, the A-Train observations provide unique insights into the complex evolution of volcanic plumes after eruption.

Source conditions and eruptive processes governing the injection of volcanic ash during the 2009 eruptions of Redoubt volcano, Alaska

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We present an integrated dataset combining information from field deposits, remote sensing and eruption column modeling of the 2009 eruptions from Redoubt volcano, Alaska. The nineteen major ash-generating explosions between 15 March and 4 April 2009 deposited a bulk ash volume of approximately 0.05 km^3. Explosive events 5 and 19, in particular, were documented with high-resolution satellite, airborne thermal infrared, and Doppler radar, and then linked with field deposits to establish the spatial distribution and vertical structure of the volcanic plumes. A key focus of this study is to establish the impact of magma-water interaction, followed by abundant ash aggregation, on the overall ascent of the volcanic clouds and corresponding ash transport. Additional near-vent processes, such as partial column collapse and interaction between buoyant and non-buoyant cloud components are also assessed. Using detailed analysis of radar and satellite imagery, local weather conditions and examination of preserved ash aggregates, we develop a comprehensive picture of the eruption source conditions and plume dynamics that impacted volcanic ash dispersal. Preliminary simulations using the Active Tracer High-resolution Atmospheric Model (ATHAM) provide insights into the microphysical structure of the Redoubt clouds, highlighting links between the volcanic and meteorological feedbacks (e.g., surface water versus atmospheric moisture and volcanic exit velocities versus ambient wind fields) involved in ash cloud injection, transport and sedimentation.

Meteorological interactions with volcanic plumes in the moist tropics: implications for volcanic plume monitoring

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The development of the International Airways Volcano Watch in the early 1990s created an operational requirement for real time global monitoring for volcanic ash at all observable concentrations (more recently formalised as visible or discernable ash through the work of the International Volcanic Ash Task Force). One of the more interesting areas of the world to do that has been the moist tropics, with many active volcanoes, relatively poor seismic monitoring, and a highly active atmosphere dominated by deep convection.

The frequency of showers and thunderstorms (particularly around volcanoes and other mountains), poor observing conditions on the ground, satellite obscuration by long-lasting cirrus anvils, and challenges in funding and maintaining ground based infrastructure such as radar and lidar together mean that the occurrence and heights of volcanic plumes have certainly been under observed in the moist tropics. Volcanic Ash Advisory Centre data also demonstrates a strong observational bias towards the drier seasons. As a result, even large eruption plumes such as from the 2010 eruptions of Merapi in Indonesia can be very difficult to monitor.

In addition, within a moist tropical environment there is an active interplay between active volcanoes and the meteorological environment. In an unstable or potentially unstable environment, tropical convection to high altitudes (17+ km) is frequently triggered by very subtle influences such as low level sea breezes or differential heating. Modelling suggests and observations demonstrate that active volcanoes, with a range of influences extending to the very unsubtle, can act as triggers to produce volcanic cumulonimbus such as those observed at Pinatubo, or volcanic plumes that have been very significantly increased in height and in ice content through moist convective processes. Eruption heights tend to cluster near the height of the tropical tropopause; relatively weak volcanic eruptions can trigger deep tropospheric convection that transports volcanic material to the tropopause or above. Because of the role of hydrometeors in enhancing particle aggregation and removal, the smaller modelled eruptions also produce a relatively small proportion of fine ash in the umbrella cloud compared to eruptions in a dry atmosphere.

It is therefore difficult to reliably infer the strength of a tropospheric or lower stratospheric volcanic plume in the moist tropics using its reported height alone. Additional volcanological and meteorological observations, including seismic, visual, lidar and radar observations, and geostationary remote sensing can be added to satellite height observations to assist in rapidly assessing eruption magnitude and the real-time response required. Close collaboration between the volcanological and meteorological science communities will help to attain these additional observations on a routine, operational basis.

Inverting for hourly volcanic SO_2 flux using plume satellite imagery and chemistry-transport modelling: application to the 2010 Eyjafjallajökull eruption

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Depending on the magnitude of their eruptions, volcanoes impact the atmosphere at various temporal and spatial scales. The volcanic source remains the major unknown to rigorously assess these impacts. At the scale of an eruption, the limited knowledge of source parameters, including time-variations of erupted mass flux and emission profile, currently represents the greatest issue that limits the reliability of volcanic cloud forecasts. However, various satellite and remote sensing observations of distant plumes are available today and indirectly bring information on these source terms. Here, we develop an inverse modeling approach combining satellite observations of the volcanic plume with an Eulerian regional chemistry-transport model (CHIMERE) to better characterise the volcanic SO_2 emissions during an eruptive crisis. The 2010 Eyjafjallajokull eruption is a perfect case-study to apply this method as the volcano emitted substantial amounts of SO_2 during more than a month. We take advantage of the SO_2 column amounts retrieved from a vast set of observations by the IASI (Infrared Atmospheric Sounding Interferometer) instrument on board the METOP-A satellite to reconstruct retrospectively the time-series of the SO_2 flux emitted by the volcano with a temporal resolution of about 2 hours, spanning the period from 1 to 12 May 2010. The initialisation of chemistry-transport modelling with this reconstructed source allows a reliable simulation of the evolution of the long-lived tropospheric SO_2 cloud over thousands of kilometres. Heterogeneities within the plume, which result from the temporal variability of the emissions, are also correctly tracked over a time scale of a few days. The robustness of our approach is also demonstrated by the broad similarities between the SO_2 flux history determined by this study and the ash discharge behaviour estimated by other means during the phases of high explosive activity at Eyjafjallajokull in May 2010. Finally, we show how a sequential IASI data assimilation allows for a substantial improvement in the forecasts of the location and concentration of the plume compared to an approach assuming constant flux at the source. As the SO_2 flux is a good indicator of the volcanic activity, this approach is also of interest for volcanologists to monitor from space poorly instrumented volcanoes.

Rotating volcanic plumes

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In contrast to the classical models of strong volcanic plumes, where the plume is assumed to be non-rotating, we provide direct evidence that the entire plume rotates about its axis. By drawing analogy with the meteorological phenomenon of a tornadic thunderstorm, we argue that the plume rotates due to the interaction between the updraft in the plume and the shear in the atmosphere, resulting in the formation of a cyclonically rotating columnar vortex—a "volcanic mesocyclone." The volcanic mesocyclone provides a unified explanation to a disparate set of poorly understood phenomena in volcanic plumes, including the development of lobate umbrellas, the spawning of tornadoes, and the formation of lightning sheaths. We conclude by illustrating how the volcanic mesocyclone entails a fundamentally different plume dynamics than that inferred from the classical models.

The 1815 Tambora distal ash fall: Implications for transport and deposition on land and in the deep sea

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The 1815 Tambora eruption deposited an estimated 100 km^3 of tephra over large parts of Indonesia and the adjacent sea, providing a good example to compare the grain size distribution of distal ash samples on land with ash recovered from the deep sea. Subsequently, grain size analysis can contribute information on the transport and distribution during the Tambora eruption. The results show a continuous trend towards a finer-grained ash distribution with distance, indicating that the depositional environment does not influence the ash particle distribution. Indeed the finest ash particles (2-4 μm) are still present in the same relative proportions in the deep sea ash layers as seen on land. The gravity current model has been modified to simulate the ash transport in the Tambora cloud, and includes now an ash fraction depositing while the cloud advances, as well as an ash fraction accounting for the remaining ash in the cloud falling out once the eruption stops. The contribution of the two components depends mainly on particle fall velocity and eruption duration, as fall velocity and/or eruption duration increases, the amount of ash depositing from the advancing cloud increases. With the eruption duration (24 hours) and cloud velocity (1.5-2.5x10^{11} m^3 /s) calculated from historical records, and assuming a 3h Plinian and 21h co-ignimbrite phase, the new model estimate reduces the mean absolute error by half if both ash components are considered

Scaling of volcanic eruptions

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Volcanic eruption where the plume is carried away with the wind can be geometrically similar to another eruption in length scale and time scale that are determined by the plume height and the wind velocity. They can also be dynamically similar if the dispersion factor scales according to the same scales. The median grain size in different distances from the crater scale according to a self similarity rule so 1 over(dist) is a measure for the grain size. Different phases of the same eruption need to be scaled to same plume height and wind velocity to find the self-similarity rule, this is demonstrated using data from the Eyjafjallajokull eruption in 2010. A satellite photo of the Eyjafjallajokull plume is used to demonstrate a new method of estimating the dispersion coefficient from the linear expansion rate of the visible boundary of the plume. Finally a measurement of in-situ ash concentrations in a volcanic cloud from Sakurajima mountain is scaled up to a larger cloud using wind from the east and a plume magnitude relation recommended by Sakurajima Volcanological Observatory.

Probabilistic volcanic ash dispersal modelling using PF3D: An example from Gunung Ciremai, West Java Indonesia

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Volcanic ash represents a serious hazard to communities living in the vicinity of active volcanoes in developing countries like Indonesia. Geoscience Australia, the Australia-Indonesia Facility for Disaster Reduction (AIFDR) and the Indonesian Centre for Volcanology and Geohazard Mitigation (CVGHM) have adapted an existing open source volcanic ash dispersion model for use in Indonesia. The core model is the widely used volcanic ash dispersion model FALL3D. A python wrapper has been developed, which simplifies the use of FALL3D for those with little or no background in computational modelling. An application example is described here for Gunung Ciremai in West Java, Indonesia. Scenarios were run using eruptive parameters within the acceptable range of possible future events for this volcano, granulometry as determined through field studies and a meteorological dataset that represented a complete range of possible wind conditions expected during the dry and rainy seasons for the region. Implications for varying degrees of hazard associated with volcanic ash ground loading on nearby communities for dry versus rainy season wind conditions is discussed. Communities located on the western side of Gunung Ciremai are highly susceptible to volcanic ash ground loading regardless of the season whereas communities on the eastern side are found to be more susceptible during the rainy season months than during the dry. This is attributed to prevailing wind conditions during the rainy season that include a strong easterly component. These hazard maps can be used for hazard and impact analysis and can help focus mitigation efforts on communities most at risk.

Infrasound of sustained volcanic eruptions, a laboratory and field study

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Volcanic plumes represent a significant hazard both near to and at distance from source. Unfortunately, high temporal resolution monitoring, especially in the case of more remote systems, is often lacking. Due to their turbulent nature, these plumes are a substantial source of sub 10 Hz sound; meaning infrasonic methodology has the potential to fill the monitoring void. Recent studies of volcano infrasound have drawn upon research from the aero-acoustics industry, fitting the large scale jet noise spectrum (LSS) to that observed during column generating eruption events (Matoza et al 2011). However, due to the differences between volcanic plumes and the pure gas jets, from which the aero-acoustics spectra are created, further laboratory studies are required to investigate the true source of the volcanic signals.

In the absence of industrial standard anechoic chambers, and indeed in terms of the field application of experimental findings, successful source localisation methods are paramount. Adaptive beamforming, as opposed to the commonly used delay and sum methodology, offers a means to achieve the required spatial resolution of the generated sound field.

In a set of experiments at the University of Bristol, an omni-directional microphone array was used to demonstrate the ability of the adaptive method. The acoustic signatures of a series of subsonic jets were recorded using the GFAL 36 and 48 element GFAL Acoustic Camera arrays and subsequently analsyed using both GFAL and in house built software. The experiments were housed in a purpose built test structure lined with 10cm pyramid foam. A flow settling chamber and baffle box, upstream of the test section, were used to prevent the transmission of rig noise to the recorded signals. A synchronous PIV dataset was also obtained enabling visualisation of the jet structure. The level of PIV seeding was varied to enable assessment of the effect of particulate matter upon the acoustic signature. Furthermore a range of different nozzle shapes have been test to better reproduce the fully turbulent conditions of volcanic jets.

In addition to the laboratory dataset, the beamforming methodology has been applied in the field setting at Santiaguito volcano, Guatemala. A 4 element infrasound array consisting of a 1 Chaparral Physics Model 25Vx and 3 Hyperion Technology IFS-3114 Infrasound Sensors with an inter-element spacing of 100 m was installed at the Santiaguito Volcano Observatory 6 km from the vent and used to retrieve dominant source locations and powers.

The adaptive methods employed here offer the potential to remove dominate acoustic sources, which preliminary findings show to be related to the nozzle/vent exit. Such source removal has the potential to reveal any weaker flow related sources which may be present.

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3D Lattice-Boltzmann strategies: New insights into Volcanic Jet Dynamics and Infrasound

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Recent studies highlighted the great potential of infrasound measurements for real time detection of volcanic plume source parameters. This is especially relevant in the case of bent over plumes, where the relation between mass eruption rate and plume height is made more complex by the interaction with the surrounding wind field and classical formulation do not apply. Pressure variation detected through acoustic data could be used to determine the exit velocity of the gas jet, which can be related to mass eruption rate, based on the geometric constrain of the vent and the mixture density. However, a source theory for volcanic infrasound is far from being complete. Woulff and McGetchin (1976), based on Lighthill's classical source model theory, proposed that small-scale volcanic jet turbulence may produce infrasound waves as quadrupole or dipole-type source when boundaries or solid particles are present. More recently, Matoza et al. (2009) on the base of the spectral shape infer large-scale turbulence to explain the infrasonic signal generated by large explosive eruptions at Mount St. Helens (USA) and Tungurahua (Ecuador). Even if the gas-thrust region of large Vulcanian and Plinian eruptions is made up by a turbulent free-shear-jet flow the application of the classical source models is challenged by sound radiation pattern measurements.

A better knowledge of the link between the acoustic radiation and actual volcanic fluid dynamics processes is required. New insigths in this subject could be given by the study of realistic areoacustics numerical simulation of a volcanic jet. Lattice Boltzmann strategies provide the opportunity to devolop an accurate, computationally fast, 3D physical model for a volcanic jet and wave propagation. Our work mainly focuses on developing and validating such numerical model to determine when and how classic model source theory can be applied to explain volcanic infrasound data. Here we present the first test results for our model.

Effects of vent asymmetry on plume dynamics for explosive eruptions

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Models of volcanic eruptions are typically based on symmetric vent and conduit geometries. However, in natural settings, these features are rarely perfectly symmetric. For example, the May 18, 1980 eruption of Mount St Helens (MSH) took place through a highly asymmetrical crater due to the preceding landslide and subsequent vent erosion. In supersonic, high pressure eruptions, such as what may have occurred at MSH, vent and crater asymmetry can strongly affect the directionality of the gas-thrust region. These effects on eruption direction have implications for spatial distribution of the initial blast phase, tephra fallout patterns, and plume stability.

Here we explore flow dynamics resulting from supersonic, high pressure eruptions though asymmetric volcanic vents using a combination of numerical and semi-analytic methods. Our time-dependent numerical simulations are performed using CartaBlanca, a Java based simulation tool for non-linear physics from Los Alamos National Laboratory. Preliminary results from these numerical tests suggest that vent asymmetry may have a first-order effect on the dynamics of the initial phases of explosive eruptions. Semi-analytic methods are used to determine the combinations of eruption explosivity (overpressure) and vent asymmetry (shapes) where this effect will be most pronounced.

Smoluchowski kernels for dry particle aggregation: Cellular Automata and experimental investigations

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Particle aggregation is considered as a key process that may affect dispersal and sedimentation of volcanic ash, with significant implications for the associated hazards. Smoluchowski coagulation equation is commonly used to describe the expected time evolution of the size distribution of ash particles that can collide and stick together. This approach is based on the use of theoretical kernels that come from the theory of diffusion and turbulent motion of charged and uncharged particles. We propose a wind-tunnel experiment to estimate Smoluchowski kernels and compare the results with numerical simulations. We focused mainly on dry ash aggregation dominated by electrostatic charges. Particles are suspended in a vertical wind tunnel for a period of time sufficient to create collisions and to produce consequential electrostatic charging by friction. Temperature and humidity are parameters that can affect the results so are kept under control in the device during the experiments. Using a high-speed camera and a dedicated Particle Tracking Velocimetry software is then possible to monitor the change of the initial mass distribution in time due to aggregation. Knowing the time evolution of aggregates gives us the opportunity to estimate empirically the kernels of the Smoluchowski coagulation equations and to make some comparisons with the theoretical kernels for a pure dry phenomenon dominated by electrostatic forces. Moreover it is possible to have a first validation of the use of Smoluchowski coagulation equations with a real laboratory experiment. The experimental kernels were integrated within a dedicated cellular automata model for ash sedimentation. This study represents a first step to merge theoretical and experimental studies of particle aggregation.

Water-isotope evidence of a persistent plume observed in snow and ice samples at Erebus volcano, Antarctica

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A volcanic δ^2H / δ^{18}O signature is present in snow samples and cores through the walls of fumarolic ice towers on the flanks of Erebus volcano, Antarctica. Of 213 samples analyzed, 61% plotted outside the field of all isotopic measurements of snow recorded for the entire continent of Antarctica. The isotopic data for Erebus samples are shifted from isotopically light Antarctic snow towards a typical magmatic water box.

The signature is thought to result from the release of magmatic water from Erebus' persistently degassing lava lake. Ice crystals may nucleate and fall from the plume directly, or plume vapor may mix with storm fronts and enrich meteoric snow. Fumarolic release of water from the volcano's flanks may also contribute to the signature. Samples from ice towers above fumarolic vents do not show a significantly higher enrichment than other snow samples, indicating that the plume is the main source of volcano water.

S, Cl, and F concentration was measured for the majority of the snow samples. Notably, there is poor spatial correspondence between the anionic volcanic signature and the water isotope volcanic signature. The transport and deposition mechanisms for plume water appear to be decoupled ffrom those of gaseous aerosols in the plume.

Towards improved characterisation of volcanic ash

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Explosive volcanism can generate large volumes of volcanic ash, with potentially significant economic and environmental implications. Recent eruptions, such as that of Eyjafjallajokull in 2010, have highlighted gaps in our knowledge regarding both the fragmentation mechanisms that produce ash and their effect on the resulting size distributions and morphologies of erupted pyroclasts. Mafic eruptions, in particular, exhibit a wide range of eruption styles that generate pyroclasts with highly variable sizes, shapes, vesicularities and crystallinities. We are investigating links between eruption style and pyroclast characteristics, with the goal of using these data both to gain insight into the processes governing fragmentation and to develop characteristic source parameters for different eruption conditions.

The 2011 subglacial eruption of Grimsvotn, Iceland, involved the explosive interaction of volatile-rich basaltic magma with subglacial meltwater. The tephra produced in this eruption contains a high proportion of fine ash, with 90 percent of grains less than 100 microns in diameter, and is texturally diverse. The ash-fall samples used in this study were collected 50-115 km southwest of the vent immediately following the eruption. We explore variation in quantitative shape parameters as a function of both grainsize and transport distance using multiple image analysis techniques, including Morphologi and Scanning Electron Microscopy (SEM). Sample componentry comprises two dominant particle classes (dense/vesicular) that can be further subdivided (blocky and platy/highly, moderate, and elongate vesicular), with less than 5 percent crystalline material. Systematic trends in the relative proportions of each particle class are evident within the fine ash fraction (10-125 microns), the most striking of which is the increase in the percentage of dense relative to vesicular grains with decreasing grainsize.

Vesicle size distributions (VSDs) were measured on vesicular clasts and fragments where greater than 50 percent of individual bubble walls were preserved. VSD modes lie between 30 and 50 microns. By combining morphological data on particle shapes with textural data on vesicular fragments we can reconstruct the state of the magma at the point of fragmentation. Fragmentation style appears strongly controlled by the VSD: the dominant particle morphology, as measured by both componentry and shape parameters, changes significantly as the particle size approaches the modal size of the vesicle population. The presence of several different morphological components suggests fragmentation of an inhomogeneously vesicular primary magma, such as the internal textures commonly observed within Peles tears quenched from Hawaiian fire fountains. Determining how the particle size and shape distributions of volcanic ash are linked to the style of magma fragmentation will guide the development of characteristic input parameters for ash dispersion models.

Effects of subgrid-scale turbulent models on spatial structure in large-eddy simulation of an eruption column

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In the transport of volcanic ash in an explosive eruption, the turbulence is one of the important elements which determine the eruption styles such as an eruption column and a pyroclastic flow. The conventional steady one-dimensional models for an eruption column assume that the effect of turbulence is represented as a constant in a theoretical formula, although it is indicated that the assumption has measurable uncertainty (Suzuki et al. 2005, Ishimune 2006). In recent years, unsteady three-dimensional eruption column models, which represent turbulence more directly, have been developed. However, the turbulence modeling in the transports of gas and pyroclastic materials are left unclarified. For instance, subgrid-scale (SGS) turbulence stresses are differently modeled in Neri et al. (2007) and in Suzuki and Koyaguchi (2010), although the contribution of SGS models to simulations of real-scale eruption column and the consequences of different SGS models applied are not well understood. In this research, the unsteady three-dimensional simulation code for an eruption column is developed. The effects of SGS models are discussed through the comparisons between the simulation results using two kinds of the models.

In this code, the model concept of Neri et al. (2007) is adopted, which is advantageous in its applicability to various volcanic styles and to the transport of pyroclastic materials of various sizes. The large-eddy simulation (LES) technique based on a SGS model is adopted as expression of turbulence. The gas component and pyroclastic materials of various diameters are classified into two or more phases (the multi-fluid approximation). The SGS model is a part of the submodels in the stress term and the diffusion term in the basic equations. As the SGS models, the Smagorinsky model, which is generally used, and the Yuu model, in which the effect of SGS drag is considered (Yuu et al. 2001), are adopted for the gas phase, and the equation proposed by Hinze, in which the relation between the relaxation time of particles and the temporal duration of vortex is considered (Hinze 1975), for the particle phases.

The following results were obtained from the LES results for an eruption column and laboratory simple flows: (1) When fine grid systems that enable the capture of the major spectral bands in a turbulence field are used in the simulation, the LES results show general agreement with those of the existing experiments and the theoretical solution in laboratory simple flows, and qualitative agreement of cloud shapes with those of the one-dimensional model in an eruption column. (2) The SGS models for gas and particle phases cause variations in eruption cloud shape. Possible causes of the variations are the strong dependence of the whole diffusion process in the LES of an eruption column on the SGS model used and the high sensitivity of the eruption cloud shape to the strength of turbulent diffusion.

Reconstruction of volcanic plume properties through integration of infrared imagery and analytical one-dimensional models

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The most effective approach to understanding the dynamics of volcanic ash plumes is through synergy of data acquisition (in field and/or laboratory settings) and data modeling (with analytical and/or numerical methods). The aim of this study is to explore the feedbacks between these two aspects, using infrared thermal videos of short-lived ash plumes imaged at Santiaguito (Guatemala). The first step was to carry out a stationary analysis of the video data, by filtering the time-dependent dynamic fluctuations of the plume. To do so, we reconstructed a mean image out of the entire movie sequence, where each pixel ascribed a time-averaged temperature. This image was then compared with the plume characteristics predicted by mean analytical models (e.g., spreading rate and vertical variations of temperature, velocity and particle concentration), in which electromagnetic radiation equations were introduced to simulate a synthetic radiometric image. The end objective is to use inversion models to recover the best input parameters (e.g., source ash mass, particle size distribution and air entrainment coefficient) that reproduce the observed data. The second step was to carry a time-dependent analysis of the plume dynamics. Data processing here mainly consisted of the algorithm development to analyze the video sequences, and extract key parameters that characterize the ash plumes through time, such as ascent velocities, volume, heat budget, etc. These algorithms were managed using an open-source user-friendly interface plumeTracker developed in Matlab, which can deal with a variety of video data collected at any wavelength (IR, VIS, or UV). Output was then compared with transient integrated models, which simulate the bulk plume motion through time. The end objective was to identify the most relevant features to track from the plume motion to inform on the source parameters, and in particular to yield the mass flux at the source.

Three-dimensional acoustic source localization of explosion and degassing events at Karymsky Volcano, Kamchatka, Russia.

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Recent research has drawn links between the acoustic signals of volcanic jets and those of man-made jet engines (jet noise), but this relationship has yet to be firmly established. Turbulent jet flows have been observed to produce acoustic signals extending from the nozzle to a finite distance downstream. One of the challenges of observing potential analogous acoustic sources from volcanoes is due to most microphone deployments being below the volcanic vent and restricted to topography that is predominantly two-dimensional. At Karymsky Volcano, Kamchatka, Russia, the topography of an eroded edifice adjacent to the volcano provides a platform for the deployment of an array of infrasound sensors in three dimensions. 5 infrasound microphones were deployed on this eroded edifice for 11 days in July 2012. The microphone deployment spanned a volume of approximately 2 kilometers horizontally, and covering 600 meters of elevation. When permitted by weather and daylight, continuous acoustic recording at 250 Hz was accompanied by FLIR, video, and gas emission data. During this time period, observed activity at Karymsky Volcano consisted of periods of semi-continuous high frequency (up to about 90 Hz) jetting and degassing, punctuated by a small number of discrete ash explosions. Here we present acoustic source localization results using a novel time-difference-of-arrival technique developed by Wilson Infrasound Observatories. Preliminary results in horizontal space show that events are clustered about the vent in a region 140 by 310 meters across. However, vertical distributions show only one explosion event located immediately at the vent, while other located explosions and degassing signals cluster persistently in a region between 175 and 650 meters above the vent. These results can be interpreted in three ways: (1) Bias in the locator algorithm or array geometry; (2) atmospheric or plume effects influencing sound propagation; or (3) sources decoupled from and above the vent region. Current work will attempt to determine which of these three cases is most plausible. This will be accomplished through forward model simulations for this array geometry, comparison with alternative location methods such as grid-based semblance, and evaluation of FLIR and video data. Development of this 3D localization technique may allow the identification of distinct sounds sources from volcanic eruptions. This helps to refine current understanding of the relationship between acoustic signals and the eruptive processes that generate them, and improves the effectiveness of acoustic monitoring of volcanoes.

Direct Numerical Simulation of (pocket-size) volcanic jets

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Direct Numerical Simulation (DNS) provides an accurate and well proven tool to compute flows in any detail and for every flow quantity of interest. The model are the Navier–Stokes equations and a Lagrangian-particle model (a sixth order compact scheme for the flow and a two way coupling for the particles in our case). No turbulence closures are needed since the turbulence is fully resolved from the largest scales down to the dissipation range. DNS is thus the ideal tool to study such kind of flow and reveal quantities which are not accessible in practical measurement. The only minor glitch is, that most of us will not work long enough to see even a small strombolian eruption fully resolved: The Reynolds-number accessible by today's biggest supercomputers under exclusive usage for one year is 66000 whereas a tiny volcanic jet ranges in a Reynolds number of about 500 million. Given Moore's law of doubling the computer power in 18 months one can predict the computability of the volcanic jet in about 45 years.

But that does not mean we should just wait: meanwhile DNS is still very useful since it provides everything about small scale experiments which are feasible to be computed, including many quantities not accessible by measurement.

In this presentation, we show simulations of supersonic jets at Re=5000 using on $2 \cdot 10^9$ grid points and $2 \cdot 10^6$ of particles for different pulse lengths of the event, ranging from $tD/U = 1$ to 30.

The flow morphology of the jet will be discused in detail and time histories of instantaneous and sampled data like shock-cell structure, turbulence intensities and acoustic radiation will be presented.

Premature fallout of fine ash: the role of convective instabilities

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Tephra fallout is one of the most widespread natural hazards and can significantly affect several economical sectors. In addition, volcanic fine ash suspended in the atmosphere can represent a significant threat to aviation as shown by the 2010 Eyafjallajökull eruption (Iceland). A good understanding and description of tephra dispersal is crucial to the mitigation of the associated risk. Processes that might significantly affect sedimentation of volcanic ash and that have not been yet well parameterized include particle aggregation and convective instabilities (gravitational instabilities which occur at the base of volcanic clouds where a denser fluid, the ash cloud, is emplaced above a lighter one, the atmosphere). Convective instabilities develop in series of discrete particle-rich protrusions (i.e. fingers), which seem to generate preferential paths for fine ash to settle. Both aggregation and convective instabilities make fine particles fall closer to the vent than expected, and due to the associated high concentration of fine ash in the fingers, aggregation processes could also be enhanced by convective instabilities.

Fingering is observed at the base of many volcanic clouds but we have been able to quantify their motion for the plume generated during the 2010 Eyafjallajökull eruption. Considering the measured finger speed and the volcano topography we found that fingers started sedimenting at about 10 km from vent, and this distance corresponds to the first observations of particle aggregation (Bonadonna et al. 2011).

We have conducted a series of laboratory experiments in a tank of 50x 30.3x 7.5 cm. A removable barrier was placed at a height of 25.1 cm to separate two different layers of fluid and ensure an impermeable separation and an initially sharp interface before the beginning of the experiments. The upper part was filled with a suspension of water and particles; the lower part was completely filled with a denser sugar solution. Experiments consisted of removing the separation and analysing the formation of fingers. Various initial conditions were investigated (including mixed and unmixed layers) resulting in different variation of concentration with time. However, in all cases, after removing the separation, particles started to sediment at the bottom of the upper particle-rich layer and the gravitational instabilities started developing. In all cases, results show that convective instabilities do not affect the sedimentation rate in the upper layer but strongly affect sedimentation in the lower layer. In presence of convective instabilities, particles reach the bottom of the tank faster than predicted by individual settling velocities. Particle sedimentation rates in the experiments can be described using a model of dilute particle suspensions which takes into account the role of the interface layer between the two fluids with different density and the behaviour of fingers.

Effects of complex plume morphology on tephra dispersion modeling in ATHAM 3D

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Ambient wind conditions play a critical role in plume morphology and, therefore, tephra dispersion. Models for tephra dispersion and deposit inversion have historically been required to simplify wind-plume interactions in order to accommodate computational expense; the Active Tracer High-resolution Atmospheric Model (ATHAM) takes advantage of cluster computing to calculate 3D wind-plume interaction using the Navier-Stokes equations with a Lagrangian Eddy Simulation turbulence closure. With the inclusion of a large pyroclast dispersion module, it is possible to use ATHAM to model tephra deposition from complex plume morphologies, including bent plumes resulting from strong ambient winds. Strong low-elevation windshear or interaction with the jetstream produce markedly different plume morphologies and mass loading in the atmosphere. The resulting deposition patterns reflect the increased plume complexity and influence of lateral sorting of equal-mass pyroclasts, a consequence of differing drag effects from horizontal flow exacerbated by the wind-plume interaction.

Eruptions on the fast track, part a): computational routines for processing visible and thermal high-speed videos of explosive eruptions

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Recent advancements in the use of high speed thermal and visible cameras allowed a precise quantification of key parameters of explosive eruptions. However, the large volume of video data poses several processing issues and hinders parameter extraction. In this methodological investigation we show how computing techniques based on Particle Image Velocimetry (PIV, measuring the displacement of sub-areas of an image between successive frames by correlating features identified in any sub-area) and Particle Tracking Velocimetry (PTV, detecting and tracking single particles along a series of images) allows for the automatic processing of high-speed videos and explosion parameterization.

We developed a 3-steps automatized routine for volcanic high-speed video processing. Step 1 pre-processes the images, removing image background with different techniques to improve image contrast and possibly accounting for camera shaking. Step 2 involves running the custom-made PTV and PIV softwares. Step 3 processes the softwares outputs while operating a first filtering for numerical errors, and then operates the post-processing of the results, where several additional filters can be applied to the results and volcanologically-relevant parameters are finally computed. A sensitivity study was used to define the best settings for each of the above steps and their effect on output parameters.

The overall suitability of our routine and its limitations have been tested on high-speed videos of explosions of Stromboli (Italy) and Yasur (Vanuatu) volcanoes, including a variety of recording conditions and styles of explosive activity.

From the above videos, PTV enables us to construct, for each explosion, a database including the size and trajectory of a large number (order of 10000) of cm-to m-sized pyroclasts. From the database a broad variety of key parameters are then extracted, from single particle ones (e.g., temperature, drag coefficient, deviation from theoretical ballistic trajectories), through explosion evolution ones (e.g., time variation of mean exit velocity, angle, mass and related standard deviations), up to whole-explosion ones (e.g., grain-size distribution and total mass of ejecta, thermal to kinetic energy balance, depth of the explosion, geometry of the vent). PIV provides the velocity vectors of diffuse features, i.e., gas and ash clouds, from which the time and space evolution of: 1) gas ejection velocity; 2) total ejected volume of gas plus pyroclasts; and 3) plume buoyant rise can be assessed.

Automatized results are in general agreement with previous manual estimations on the same videos but on a limited number (order of thousands) of particles, supporting the robustness of out procedure. An illustration of the variety of the volcanological application of this routine is presented in the companion abstract Eruptions on Fast Track, part b.

The effect of pre-existing craters on the initial development of explosive volcanic eruptions: an experimental investigation

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Most volcanic eruptions occur in craters formed by previous activity. The presence of a crater implies specific confinement geometries, variably filled by loose fragmental deposits, which are expected to exert a strong, yet poorly studied, control on the violent gas expansion that drives the eruption. Here we analyze patterns of ejection from buried explosions in analog experiments, in order to investigate how the presence of a crater and changes in explosion depth and intensity may affect the formation of eruptive ejecta jets. Different explosive charges were detonated at variable depth in prepared pads of granular material, resulting in variable scaled depth (charge burial depth divided by the cubic root of charge energy). Explosions were filmed at 600 frames per second, and video analysis provided information on: 1) jet morphology and evolution; 2) jet vertical speed; 3) jet spread angle. Results show that explosions with progressively smaller scaled depth produced exponentially faster-growing jets with linearly larger spread angles. Deeper scaled depth explosions are marked by more-complex jets, featuring a central, narrower, faster portion that pierces upward through a larger, slower annulus having a stronger component of lateral expansion. For a fixed scaled depth, the pattern of expansion of the jet seems to be largely controlled by the initial presence of a crater, which limits the development of a laterally expanding annulus.

The relationship between jet velocity and scaled depth holds true independently of the presence of a pre-existing crater infill, while jet spread angle shows, overprinted on a major control exerted by scaled depth, also an effect of the presence of a crater. Finally, the presence of a crater around the explosion site does exert a strong control on the expansion pattern of the jet. The complex development of explosions with both a vertically-expanding central core and a peripheral, lateral expanding annulus seems promising for characterizing the intra-crater evolution of an eruption. This distinction has also implications for both hazard assessments and for investigations of eruptive products. The vertical core and radial annulus could be associated with the formation of buoyant jets and ballistic showers, and dilute pyroclastic density currents, respectively. Since the radial annulus tends to be inhibited by the presence of a relatively deep crater, this could promote a decrease in the occurrence of coarse-grained pyroclastic surges (and their deposits) extending beyond a crater as an eruption and the respective crater evolve over time. Conversely, the fallback of a vertically-focused jet could trigger a fine-grained pyroclastic surge, potentially leaving fine-grained, bedded deposits.

Particle detection and velocity prediction for volcanic eruptions : a preliminary study

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Measuring parameters of all particles as they exit the vent during an explosive eruption is the best way to gather size, shape, velocity and mass statistics for the solid (particulate) fraction of the plume. We propose to compute velocities, particle size distributions and mass fluxes using high spatial resolution (cm-to-mm pixel) thermal infrared imagery collected at 200 Hz for small explosive eruptions at Stromboli (Italy). In order to tackle this problem, we developed a new method based on a pyramidal Lucas and Kanade optical flow algorithm. This allows particles to be detected, and velocities to be predicted, through time. First, a corner detection algorithm is used to allow segmentation of the whole image. This procedure of feature identification is based on the motion of the particle. Then, a differential method is used: the Lucas-Kanade algorithm. This provides a solution of the optical flow equation. Thus, it enables the computation of the local velocity vector that can be used as an indicator for the tracking step. Using this method, we were able to obtain both the distribution of particle sizes and velocities. We examined during one eruption around 650 particles per frame which, for 2637 frames, resulted in around 2152639 particles.