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Computation of probabilistic hazard maps and source parameter estimation for volcanic ash transport and dispersion

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ABSTRACT

Volcanic ash advisory centers are charged with forecasting the movement of volcanic ash plumes, for aviation, health and safety preparation. Deterministic mathematical equations model the advection and dispersion of these plumes. However initial plume conditions – height, profile of particle location, volcanic vent parameters – are known only approximately at best, and other features of the governing system such as the windfield are stochastic. These uncertainties make forecasting plume motion difficult. As a result of these uncertainties, ash advisories based on a deterministic approach tend to be conservative, and many times over/under estimate the extent of a plume. This paper presents an end-to-end framework for generating a probabilistic approach to ash plume forecasting. This framework uses an ensemble of solutions, guided by Conjugate Unscented Transform (CUT) method for evaluating expectation integrals. This ensemble is used to construct a polynomial chaos expansion that can be sampled cheaply, to provide a probabilistic model forecast. The CUT method is then combined with a minimum variance condition, to provide a full posterior pdf of the uncertain source parameters, based on observed satellite imagery. The April 2010 eruption of the Eyjafjallajökull volcano in Iceland is employed as a test example. The `puff` advection/dispersion model is used to hindcast the motion of the ash plume through time, concentrating on the period 14–16 April 2010. Variability in the height and particle loading of that eruption is introduced through a volcano column model called `bent`. Output uncertainty due to the assumed uncertain input parameter probability distributions, and a probabilistic spatial-temporal estimate of ash presence are computed.

1. Introduction

Ash clouds are produced by the explosive eruptions of volcanoes. These clouds, propagating downwind from a volcano eruption column, are a hazard to aircraft, causing damage to the engines [1]. On December 15, 1989, KLM Flight 867 lost all its engines when the airplane entered a plume of ash originating at the Redoubt volcano in the Aleutian Islands [2].

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That incident caused more than $80 million (US) in damage to the aircraft, but fortunately no lives were lost. The recent eruption of the Eyjafjallajökull volcano in Iceland wreaked havoc on European aviation after the eruption started on April 14, 2010. Decisions about the closure of European air-space, largely based on deterministic ash plume models, resulted in more than $4 billion in economic losses and left more than 10 million stranded passengers [3]. In addition to the large financial consequences of volcanic eruptions, there are significant health and environmental consequences of ash propagation and its subsequent fallout, ranging from inhalation of the ash particles to crop damage from tephra fallout. Clearly, those charged with volcanic risk management need accurate information for decision making. Among other components, this information flow should include a map of the probability of ash being present at a given location at a specified time.

Other hazardous events present similar needs. For example, the accidental release of radioactive gaseous material, such as occurred at the Chernobyl nuclear reactor explosion, or the oil spill resulting from the Deepwater Horizon accident in Gulf of Mexico, also demand tools and approaches, to accurately forecast the advection and dispersion of a material.

The primary objective of this work is to present an accurate and computationally efficient method to create probabilistic hazard maps for ash plume motion, which quantifies the uncertainties present in any model of ash advection and dispersion, and which integrates observation data whenever it is available. Providing such a map will enable public safety officials to make better decisions.

To be computationally tractable, the probabilistic framework presented here relies on a recently developed Conjugate Unscented Transformation (CUT) methodology to efficiently compute expectation integrals [4–7]. A linear unbiased minimum variance estimator is used in conjunction with the CUT methodology to provide estimates for source parameters and the associated uncertainty. A polynomial chaos-based emulation model is then used to compute a hazard map. Finally, numerical experiments are performed using data from the Eyjafjallajökull eruption, to validate the proposed methodology.

1.1. Current approaches and limitations

Often times volcanologists extrapolate information from past eruptions to create maps forecasting future events and areas at risk. Basing forecasts solely on past recorded events does not always provide a reliable estimate of likely eruption scenarios – prior events may have gone unreported, and site-specific conditions may have changed. Computer simulations using physics-based model equations, calibrated using field data, provide additional information on which to base hazard forecasts. To predict ash cloud movement, model systems may incorporate stochastic variability, such as uncertainty in source parameters or randomly varying wind fields, to better capture possible ash particle transport. A major source of uncertainty impacting the location of a volcanic ash cloud are the characteristics of the volcanic eruption column, including the distribution of grain size in the column and the column rise height [8]. Several investigations have tried to quantify the effect of source parameter uncertainty on the position of ash clouds. For example, during the Eyjafjallajökull eruption, the London Volcanic Ash Advisory Centers (VAAC) used the NAME computational model [9] for ash advection/dispersion to make forecasts of the position of the ash cloud, which in turn were used to issue advisories to the airline industry. In related work, Devenish et al. [10] applied NAME, with a specified set of input source parameters estimated from measurement data, to study the arrival of the Eyjafjallajökull ash cloud over the United Kingdom. Through a sensitivity analysis, this study demonstrated that the position and concentration of ash over a given region of interest were particularly dependent on eruption source parameters such as the column height and the particle profile within the column. O'Dowd et al. [11] simulated the dispersion of ash from Eyjafjallajökull using the REMOTE computational model, for a specified set of source parameters. In another study, Webley et al. [12] used the WRF-Chem dispersion and tracking model to forecast the ash cloud position, given the column height, particle grain-size distribution and mass eruption rate. Heinold et al. [13] simulated the Eyjafjallajökull emission, transport, and particle deposition over Europe by using the regional chemistry-transport model COSMO-MUSCAT, given the height of ash particles and their size distribution. Dispersion of the ash cloud from the Eyjafjallajökull eruption has also been simulated by using the FALL3D computational model [14], where the input parameters are approximated from the observed height of the eruption column and from the total grain size distribution as reconstructed from field observations. These investigations each apply different computational models to forecast ash cloud position as a function of time, each with its successes and limitations. In each instance, however, a specified set of the eruption source parameters, perhaps obtained retrospectively from radar or satellite data, is used to forecast ash cloud motion. Because there is great uncertainty in the model inputs, deterministic physics based models alone are limited in their ability to make meaningful forecasts.

In order to make accurate long-term forecasts, it is necessary to understand how the uncertainty in source parameters and the variability of wind fields propagate through the numerical advection/dispersion codes. Although a detailed sensitivity analysis can relate the variations in source parameters and wind data to ash cloud motion, uncertainty analysis provides a richer suite of tools, allowing an assessment of one's confidence in making forecasts based on all available information. Of course a successful application of uncertainty analysis must overcome the challenges posed by the large number of uncertain input parameters and the associated cost of computation. Data input and output drive the calculations of uncertainty quantification, and present additional difficulties for any analysis. Importantly, in real-time hazard assessment one is constrained by the need for rapid analysis. Each of these factors affects the trade-off between completeness and speed. In addition, propagating uncertain model inputs leads to forecasts with uncertainties that grow in time and which must be tamed in order to make useful forecasts; assimilating available observational data to refine the model forecast reduces these uncertainties.

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