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Estimating volcanic ash hazard in European airspace

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ABSTRACT

The widespread disruption of European air traffic in late April 2010, during the eruption of Eyjafjallajökull, showed the importance of early assessment of volcanic hazard from explosive eruptions. In this study, we focus on the short-term hazard of airborne ash from a climatological perspective, focusing on eruptions on Iceland. By studying eruptions of different intensity and frequency, we estimate the overall probability that ash concentration levels considered hazardous to aviation are exceeded over different parts of Europe.

The method involves setting up a range of eruption scenarios based on the eruptive history of Icelandic volcanoes, and repeated simulation of these scenarios for 2 years' worth of meteorological data. Simulations are conducted using meteorological data from the ERA-Interim reanalysis set, which is downscaled using the Weather Research and Forecasting (WRF) model. The weather data are then used to drive the Lagrangian particle dispersion model FLEXPART-WRF for each of the eruption scenarios. A set of threshold values, commonly used in Volcanic Ash Advisories, are used to analyze concentration data from the dispersion model.

We see that the dispersion of ash is highly dominated by the mid-latitude westerlies and mainly affect northern UK and the Scandinavian peninsula. The occurrence of high ash levels from Icelandic volcanoes is lower over continental Europe but should not be neglected for eruptions when the release rate of fine ash ($<16\mu$ m) is in the order of 10^7 kg s $^{-1}$ or higher.

There is a clear seasonal variation in the ash hazard. During the summer months, the dominating dispersion direction is less distinct with some plumes extending to the northwest and Greenland. In contrast, during the winter months, the strong westerly winds tend to transport most of the emissions eastwards. The affected area of a winter-time eruption is likely to be larger as high concentrations can be found at a further distance downwind from the volcano, effectively increasing the probability of hazardous levels of ash reaching the European continent.

The concentration thresholds for aviation, which were adopted after the Eyjafjallajökull eruption in 2010, have strong influence on the hazard estimates for weaker eruptions but is less important for larger eruptions; thus ash forecasts for weaker eruptions are likely more uncertain in comparison to larger eruptions.

1. Introduction

Volcanic eruptions can lead to severe problems for society. While most volcanic hazards are constrained to a limited area around the volcano, emissions of fine ash from explosive eruptions can reach high concentrations and have long residence times in the atmosphere. Fine ash can therefore be transported long distances in the atmosphere before being diluted to harmless concentrations or removed through fallout, rain-out or washout processes.

One major concern with fine ash in the atmosphere is its potential impact on aviation (Casadevall, 1994; Guffanti et al., 2010), which was especially noted during the eruption of Eyjafjallajökull in April 2010, when air traffic in Europe was effectively shut down for several days. The event demonstrated how unprepared society was for such disasters, and the need for better risk assessment tools, an important part of which is estimating the natural hazards.

Several studies on hazard climatology from volcanic emissions exist but most focus on either continuous gas emissions (e.g., Graziani et al., 1997; Pareschi et al., 1999), or probabilistic methods to determine ash fall (e.g., Jenkins et al., 2012). Studies focusing on long-range transport of fine ash, the component responsible for the highest risk with regard to air traffic, are less common. However, there have been some additions in recent years. The long-range dispersion is the main focus of this study, in which case the gas emissions and bulk ash deposits are of less interest. Two studies with similar focus are Leadbetter and Hort (2011) and Sulpizio et al. (2012). The former determines the probability of airspace shutdown over Europe during or after an eruption of Hekla volcano on Iceland. Eruption parameters were fixed and the same eruption was modeled for different weather conditions. The latter study used a probabilistic approach to determine the eruption parameters for a violent Strombolian eruption of Vesuvius, Italy.

In more recent studies, Bonasia et al. (2013) estimated the long-range hazard of a Plinian eruptions at Popocatépetl volcano, Mexico. The study used probabilistic emission source parameters, and meteorological data for 300 simulations were randomly sampled over a 6-year period. Biass et al. (2014) and Scaini et al. (2014) made a thorough

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analysis of ash dispersion from eruptions of a number of volcanoes on Iceland, covering both hazards of ground deposition and airborne ash. In the study, probabilistic eruption scenarios were defined based on historic records and meteorological conditions, and simulations focusing on airborne ash were conducted using the FALL3D model.

The goal of this study is to estimate the probability of exposure of ash from future volcanic eruptions on Iceland. A modelling system is set up consisting of a regional meteorological model (WRF) and a Lagrangian particle dispersion model (FLEXPART-WRF), configured to describe volcanic emission sources. A selection of eruption scenarios was set up based on historic eruptions of different intensity and frequency. These scenarios cover a wider range than that used by Sulpizio et al. (2012) in terms of eruption intensities. However, our scenarios are predetermined and do not use a probabilistic representation of the source. This gives an insight in the probability of ash reaching different areas in the European airspace for several types of eruptions.

2. Experiment setup

2.1. Meteorological data

The meteorological data used in the dispersion runs were produced using the Weather Research and Forecast (WRF) model (version 3.4) (Skamarock et al., 2008). The WRF model is a highly modular three-dimensional, non-hydrostatic numerical model. It can either be run as forecast model using data assimilation techniques or for research purposes typically driven by reanalysis data or simulating idealized conditions. For our purposes, the WRF model is driven by data from the global reanalysis data set ERA-Interim (Dee et al., 2011), which provides 6-hourly data at a resolution of 0.75°.

Cloud microphysics were simulated using the WSM5 scheme (WRF Single Moment 5 classes) by Hong et al. (2004), which handles mixed phases of cloud water/ice, rain and snow. The scheme was chosen after some initial tests which showed that the WSM5 scheme agreed well with more complicated microphysics schemes. WRF was run using an adaptive time step, which allowed the WSM5 scheme to outperform the simpler WSM3 scheme in terms of simulation time. Planetary boundary layer (PBL) physics were computed using the Mellor–Yamada–Janjic scheme (Janjić, 1994).

The WRF model was set up for three nested domains, with horizontal resolutions of 45, 15 and 5 km. All domains have 42 vertical levels, with the top located near the 3 hPa level (approximately 40 km asl). This provides wind fields above the top of the tallest simulated emissions. The domains used in the WRF model are shown in Fig. 1. The middle domain (d02) is the main grid used in the dispersion runs, and the innermost domain (d03) is used to provide more detailed data for the early stage dispersion. The outermost domain (d01) serves two purposes. First, it provides a relaxation zone between the coarse ERA-Interim input and the main grid. Second, it defines the outer boundary for the dispersion model and, therefore, allows model particles to reenter the main domain (d02) instead of being terminated upon exit. This prevents mass loss in case particles leave the main domain with a curved trajectory. Allowing particle trajectories in the relaxation grid was chosen rather than having a larger main grid in order to achieve shorter simulation times and reduce overall file size.

The domains in WRF are initiated in every grid cell by data from ERA-Interim. Once the model is running, further nudging is made at the domain boundaries every 6 h. For smaller domains running shorter simulations (e.g., several days), the dynamics within the domain will closely follow that of the driving reanalysis data, with the added level of details from running at higher resolution. However, with larger domains and longer simulation times, the risk of deviating too far from the driving meteorological data increases. In order to prevent the model from developing its own dynamics and deviating too far from the reanalysis data, it was run in smaller segments, initiated once every 24 h. Each segment consisted of a cold start and 6 h of spin-up

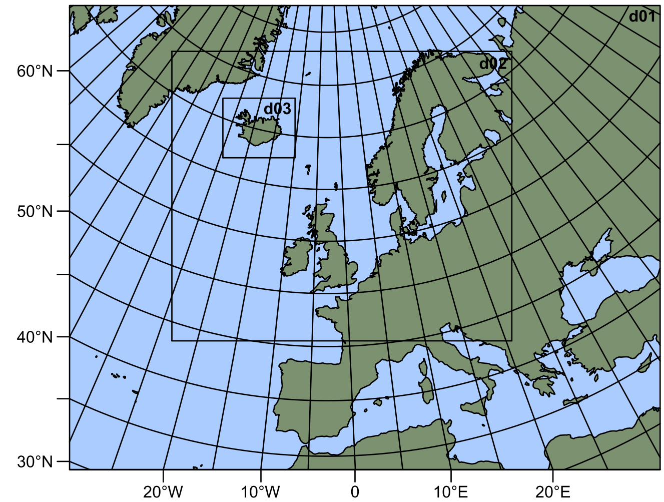

Fig. 1. Domain setup in WRF, the domains (d01, d02, d03) have horizontal resolutions of 45, 15 and 5 km, respectively.

followed by 24 h of simulation. Only the last 24 h were used as input for the dispersion model. Cold starts require some extra attention in order for the output to work together with the dispersion model. The dispersion model uses the accumulated precipitation fields to estimate precipitation rate. Therefore, the precipitation fields must be overwritten at the end of each spin-up period with data from the end of the previous run segment.

The main advantage of using the WRF model, as opposed to using ERA-Interim data directly, is to increase the spatial and temporal resolution of the meteorological data by allowing detailed topographic and land-use data to affect the dynamics. This increase in resolution is important for both wind and precipitation fields reducing the need for sub grid parametrization in the dispersion model. In addition, the flexibility in domain size and resolution allows the modeling system to be applied at a wider range of scales than a system limited the resolution of reanalysis data.

2.2. Dispersion model

FLEXPART is a Lagrangian Particle Dispersion Model (LPDM), which was originally designed to simulate long-range dispersion of air pollution from point sources but has over the years been extended to work with different cases of atmospheric transport modeling (Stohl et al. 2005). The dispersion model used in this study, FLEXPART-WRF, is a derivative of the FLEXPART model designed for multi-scale application by Fast and Easter (2006) and later improved by Brioude et al. (2013). The main difference between the models is the driving meteorological input, FLEXPART, requires global reanalysis data on latitude–longitude grid whereas FLEXPART-WRF, as suggested by the name, is built to run with mesoscale input from the WRF–model. Calculations in FLEXPART-WRF are made on the same map projection as is used in the WRF simulations, while FLEXPART uses a latitude–longitude grid but switches to a polar stereographic projection around the poles.

In general, LPDMs calculate trajectories of large numbers (typically > 10 000, depending on domain size and simulation time) of computational particles, representing infinitesimally small air parcels, each containing quantities of one or several tracer species. The output can be either on a purely Lagrangian format (i.e., positions and mass content of each parcel) or translated to an Eulerian grid. LPDMs are, unlike Eulerian models, not affected by numeric diffusion, which enables them to accurately represent the dispersion of small puffs or narrow plumes; this property makes them suitable for long-range dispersion of volcanic emissions. However, there are also downsides when compared