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# SIMULATION OF THE ICELAND VOLCANIC ERUPTION OF APRIL 2010 USING THE ENSEMBLE SYSTEM

R. L. Buckley
Savannah River National Laboratory
773A, A1008, Aiken, SC 29803
robert.buckley@srnl.doe.gov

## ABSTRACT

The Eyjafjallajokull volcanic eruption in Iceland in April 2010 disrupted transportation in Europe which ultimately affected travel plans for many on a global basis. The Volcanic Ash Advisory Centre (VAAC) is responsible for providing guidance to the aviation industry of the transport of volcanic ash clouds. There are nine such centers located globally, and the London branch (headed by the United Kingdom Meteorological Office, or UKMet) was responsible for modeling the Iceland volcano. The guidance provided by the VAAC created some controversy due to the burdensome travel restrictions and uncertainty involved in the prediction of ash transport.

The Iceland volcanic eruption provides a useful exercise of the European ENSEMBLE program, coordinated by the Joint Research Centre (JRC) in Ispra, Italy. ENSEMBLE, a decision support system for emergency response, uses *transport* model results from a variety of countries in an effort to better understand the uncertainty involved with a given accident scenario. Model results in the form of airborne concentration and surface deposition are required from each member of the ensemble in a prescribed format that may then be uploaded to a website for manipulation. The Savannah River National Laboratory (SRNL) is the lone regular United States participant throughout the 10-year existence of ENSEMBLE. For the Iceland volcano, four separate source term estimates have been provided to ENSEMBLE participants. This paper focuses only on one of those source terms. The SRNL results in relation to other modeling agency results along with useful information obtained using an ensemble of transport results will be discussed.

*Key Words*: volcano, atmospheric modeling, ensemble, transport and dispersion

## 1 INTRODUCTION

The Savannah River National Laboratory (SRNL) of the Department of Energy (DOE) Savannah River Site (SRS) has been involved with predicting the transport and dispersion of hazardous atmospheric releases for many years. Because the emphasis during emergency response situations is to provide accurate guidance quickly, the SRS incorporates an automated, real-time capability for consequence assessment during emergency response to local releases. Increased computing capabilities have led to the use of more sophisticated three-dimensional prognostic models and the application of using ensemble meteorological forecasts.

A decision maker (DM) tasked with providing guidance during an actual event benefits from use of an ensemble of model results because it provides a measure of uncertainty. Although the DM would like to use the "best" model each time an accident occurs, due to the non-unique nature of solutions to nonlinear equations governing the atmosphere, a given model may not always perform better than other models. Therefore, it is not always possible to distinguish which model performs "best" during an emergency response forecast situation.

Meteorological forecasts generated by numerical models provide individual realizations of the atmosphere and ensemble results from meteorology have been utilized for many years. An extension to this is to provide an ensemble of transport and dispersion results based on input wind and turbulence fields. This is the focus of the European ENSEMBLE program, coordinated by the Joint Research Centre (JRC) in Ispra, Italy. ENSEMBLE uses transport model results from a variety of countries in an effort to understand better the uncertainty involved with a given accident scenario. Data in the form of airborne concentration and surface deposition are required from each member of the ensemble in a prescribed format that may then be uploaded to a website for manipulation. The recent Eyjafjallajökull volcanic eruption in Iceland provided a unique opportunity to utilize the ENSEMBLE system, and is the subject of this paper.

## 2 ENSEMBLE BACKGROUND

The ENSEMBLE project is rooted in forecast differences encountered during the Chernobyl nuclear accident, resulting in problems associated with emergency management decisions between the neighboring European countries. It is an extension of earlier model intercomparison projects sponsored by the European Commission (Atmospheric Transport Model Evaluation Study (ATMES[1]), the European Tracer Experiment (ETEX[2]) and the Real Time Model Evaluation (RTMOD)[3]). ENSEMBLE is a real-time Web-based decision support system for long-range atmospheric dispersion data exchange and model evaluation. Interactive evaluation packages for immediate display, inter-comparison, and decision-making support were initially built into the system, allowing for quick interpretation of an ensemble of meteorological and transport forecast predictions for nuclear releases spreading across Europe. However, generalization of the input format for dispersion results allows for the uploading of an unspecified number of species of any nature. The application is no longer restricted to nuclear releases from Europe, with several exercises having been conducted in other locations (e.g. Canada, South Africa, China, and Pakistan) and for non-nuclear sources.

The primary objective of the ENSEMBLE project is to allow for effective communication procedures and software tools to reconcile between different national atmospheric modeling predictions. An ancillary benefit is the ability for model developers to compare their new models with existing ones through evaluation standards, monitoring data, and case studies. More information may be found at the ENSEMBLE Website[4].

## 3 VOLCANO DESCRIPTION AND MODEL SETUP

The Regional Atmospheric Modeling System (RAMS, version 4.3[5] is a three-dimensional, finite-difference numerical model used to generate the meteorological forecasts needed to model transport and dispersion. It is used routinely by SRNL for regional and local forecasts often in a nested grid configuration. Basic features of the model include the use of non-hydrostatic, quasi-compressible equations and a terrain-following coordinate system with variable vertical resolution allowing for the incorporation of topographic features.

Larger-scale meteorological data are used to generate initialization files in RAMS as interpolated to a (polar-stereographic) model grid. The initialization file in RAMS corresponding to the starting time in the simulation is then used to create an initial condition for the entire three-dimensional RAMS model grid. A Newtonian relaxation scheme is used to provide lateral boundary conditions by driving (nudging) the prognostic variables toward the forecasted large-scale values using linear interpolation in time.[6] Data for the initialization come from the National Oceanic and Atmospheric Administration (NOAA) Global Forecast System (GFS) model with ~95 km grid spacing and forecast information at 3-hr intervals. Ensemble results were required on a 0.25º×0.25º grid resolution spanning -30ºE to 45ºE and 30ºN to 75ºN (for a total of 301×181 grid points). This implies use of a domain covering all of Europe and western Asia. For this larger scale exercise, a two-grid system with horizontal grid spacing of 60 km (centered at 22ºE, 52.5ºN) and 15 km (centered about the release point) was used for RAMS. A Lagrangian particle dispersion model (LPDM[7]) is then applied for stochastic transport calculations using the three-dimensional winds and turbulence (Gaussian) fields from RAMS. Numerical solution of the Langevin stochastic differential equation for subgrid-scale turbulent velocities[8]and subsequent tracking of a large number of particle positions allows for calculation of concentration and deposition. The results are interpolated to the ENSEMBLE grid where available. Points not covered by the RAMS grid are assigned missing values.

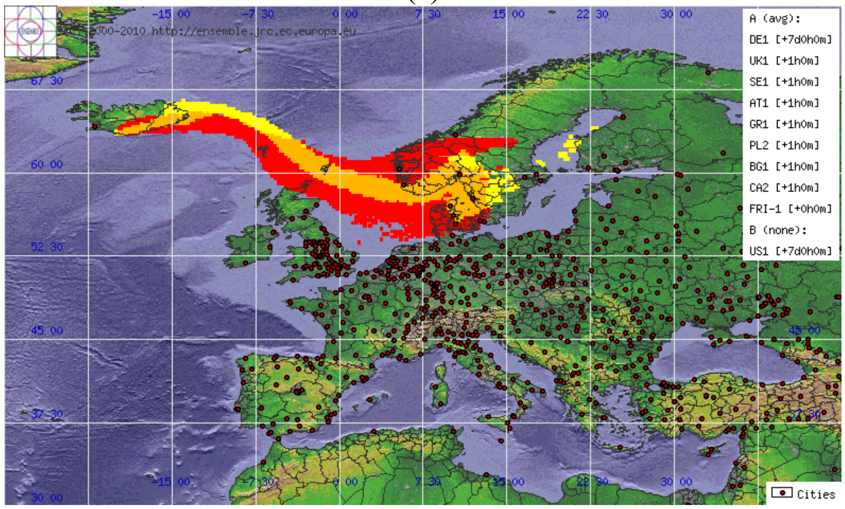
For this problem, atmospheric concentration at hourly intervals for four separate scenarios was required at ten separate levels (0, 100, 500, 1000, 2500, 4000, 6000, 8000, 10000, and 12000 m above ground level, units of μg/m3) for a week-long period spanning 06 UTC, April 14, 2010 to 06 UTC, April 21, 2010. In addition, hourly integrated wet and dry deposition results (μg/m2) were required for one of the scenarios. The different scenarios involved variations to the assumed source term.

**Table I. Time-Variation in Volcano Source Term**

| Eruption Height m (AGL) | Start Time (UTC) | Stop Time (UTC) | Source strength (g/s) |
|---|---|---|---|
| 6830 | 06 UTC, April 14 | 06 UTC, April 18 | 1.34E+08 |
| 3330 | 06 UTC, April 18 | 18 UTC, April 18 | 1.72E+07 |
| 1378 | 18 UTC, April 18 | 09 UTC, April 19 | 2.55E+06 |
| 2902 | 09 UTC, April 19 | 00 UTC, April 21 | 1.22E+07 |
| 2902 | 00 UTC, April 21 | 06 UTC, April 21 | 1.22E+07 |

Specifying the source term is an important aspect of any atmospheric release. For the Iceland volcano, the intensity and eruption height (above ground level, AGL) varied as a function of time. The Volcanic Ash Advisory Centre (VAAC) is responsible for providing guidance to the aviation industry of the transport of volcanic ash clouds. There are nine such centers located globally, and the London branch (headed by the United Kingdom Meteorological Office, or UKMet) was responsible for modeling the Iceland volcano. Three estimates of the source term were modeled. The initial estimate used in this study came from the VAAC. A second source term was developed by the Canadian Weather Service, whose large-scale meteorological model is the Canadian Model, or CMC. The CMC source term is considerably higher in magnitude than the original VAAC source term. Both of these estimates were provided to ENSEMBLE users several months after the eruption. Finally, a third estimate of the source term was provided nearly six months after the eruption. The first scenario (0050-001) uses the VAAC source term

(a)

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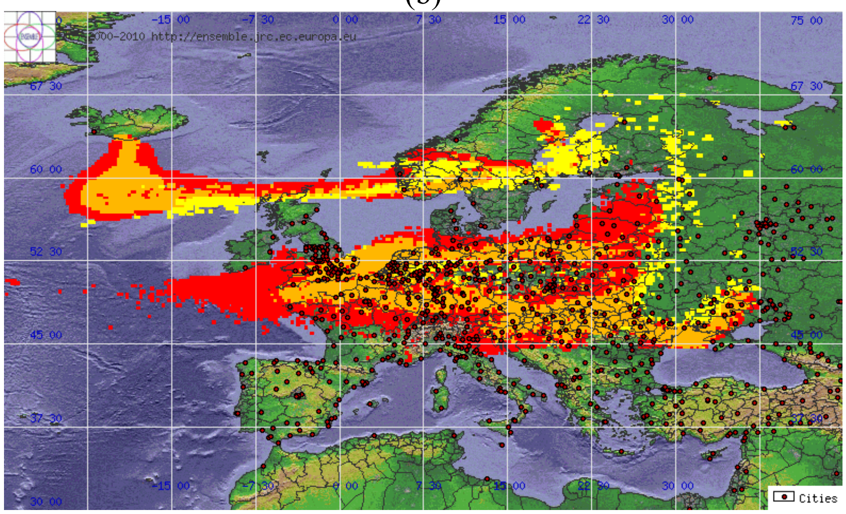


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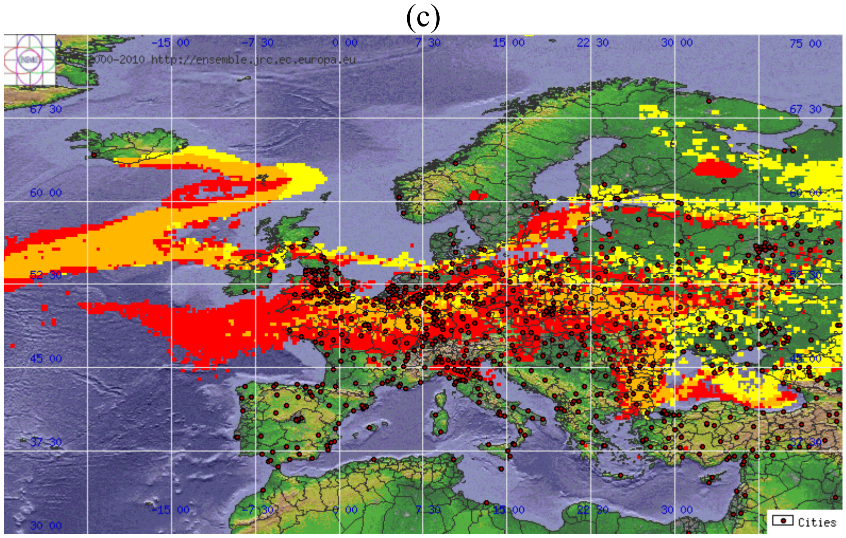



**Figure 1: Spatial overlap of surface concentrations of 100 μg/m3 at different times comparing the SRNL result (yellow) and the average of nine other models (red). The overlap is shown in orange. Times shown are (a) 00 UTC, April 16, (b) 00 UTC, April 18, and (c) 00 UTC, April 19.**

assuming no deposition to the surface, while the second scenario (0050-002) uses the CMC source term (again, no deposition). For the third scenario (0050-003), the CMC source term is used assuming both wet and dry deposition to the surface. For the deposition, it was assumed to use the deposition properties of $^{137}Cs$ (without the radioactive decay). For the fourth scenario (0050-004), the more recent source term estimate was used, assuming no deposition. The emphasis of this study is on the CMC source term with deposition (0050-003). The time-variation in source for this scenario is given in Table I.

## 4 RESULTS

There are numerous ways in which to disseminate results using the ENSEMBLE Web-based system. We discuss just a few of those here.

### 4.1 Spatial overlap

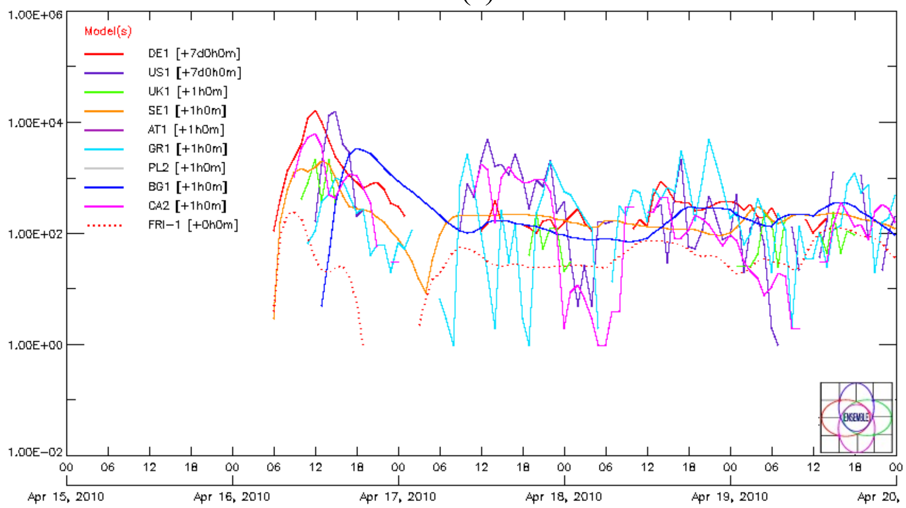
One obvious way to compare results is to examine the spatial overlap among models for a given time. The plots shown in Figure 1 illustrate the spatial variability of the ash plume as it transports away from Iceland, impacting first the Scandinavian countries roughly 40 hours after initial release (00:00 UTC, April 16). The relative agreement between the SRNL result and the average of the other models indicates similar meteorological results and source term strength. The spatial overlap later in the simulation (~30%) is seen to be reduced somewhat from earlier times (35 to 45%) as the plume has had the chance to disperse. Similar plots at other levels are also easily generated. It should be noted that a recent article[9] shows a similar plume at 22 UTC, April 18 (for a vertically averaged plume over the lowest 1000 m of the atmosphere). There is a distinct westward bend in the plume some distance east of Iceland, followed by another bend back to the east at roughly 20ºW and 55ºN. It is also of note that measurements of surface PM10 concentrations show local maxima in northeastern France on April 19, which qualitatively agrees with the spatial plot shown in Fig. 1c.

### 4.2 Time Series

Another interesting way of viewing the results is through the use of time-series plots at given locations. Table II shows three significant cities in Europe. These locations are spread out geographically to illustrate variations in concentration. A time-series plot showing surface concentrations for each of these cities is given in Figure 2 for the five day period spanning April 15 to April 20. It can be seen from here that the ash cloud reaches Berlin first (early on April 16), then Paris (late on April 16), and finally Milan (April 17, and by very few models). A DM would have less confidence that the plume reached Milan in this instance since fewer of the models predict transport to this location. It can also be seen from these time series that some models have a smoother trace than others, indicating perhaps use of a Gaussian plume dispersion model with wider plumes.

A box and whisker plot at two vertical levels for Paris is shown in Figure 3 for the same time period. This provides a measure of the spread between different models for concentration at a given time. It is seen from Figure 3a that the spread in surface concentration between models is roughly one order of magnitude, although there are numerous times in which an individual

(a)

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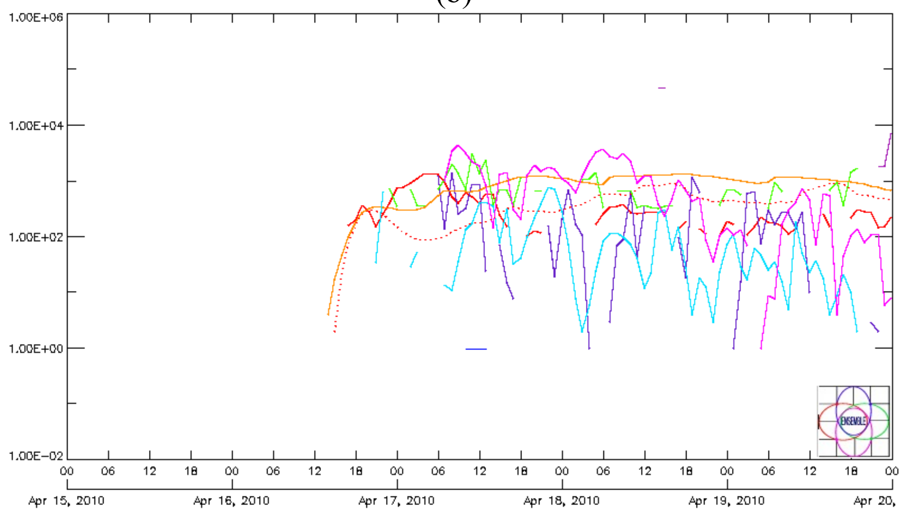


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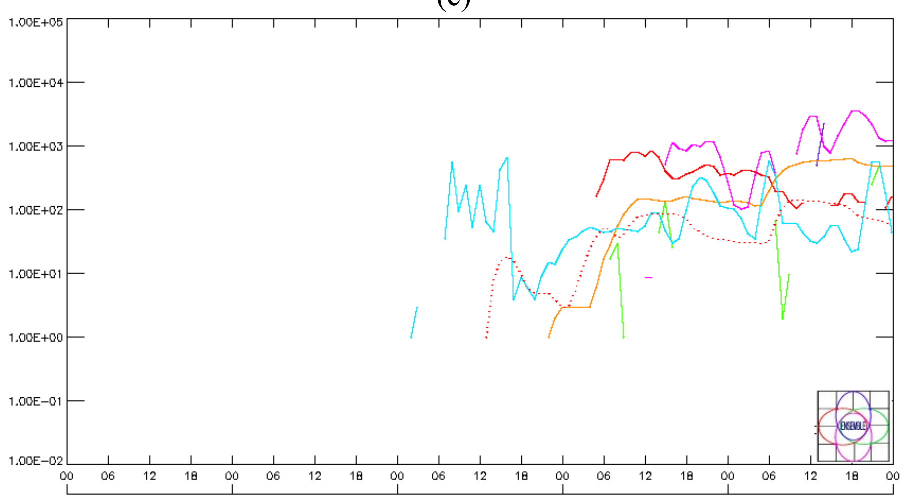
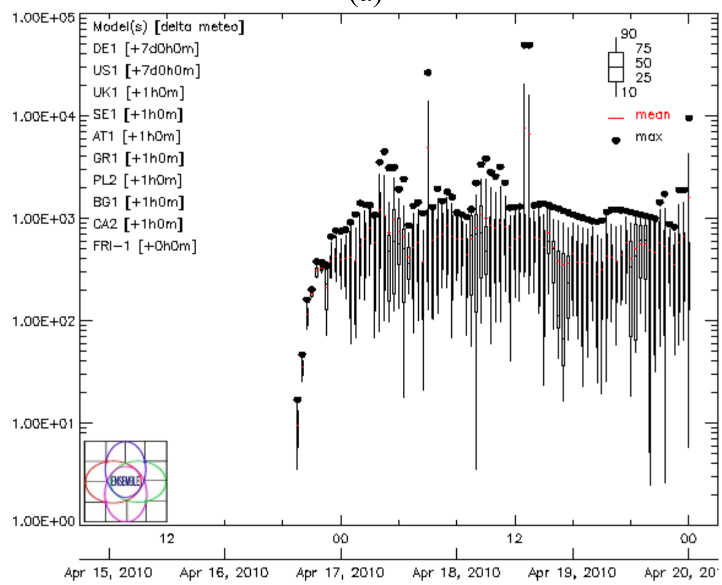



**Figure 2: Time-series of simulated surface concentrations (µg/m3) from 00 UTC, April 15 to 00 UTC, April 20 for each of the ten ENSEMBLE members. The locations shown are: (a) Berlin, Germany; (b) Paris, France; and (c) Milan, Italy. Note that the concentration scale differs for (c).**

**Table II. Locations Used in Time-Series Analysis**

| City | Lat (E) | Lon (N) | Grid Point Lat (E) | Grid Point Lon (N) |
|---|---|---|---|---|
| Berlin, Germany | 13.40 | 52.52 | 13.50 | 52.50 |
| Milan, Italy | 09.20 | 45.40 | 09.25 | 45.50 |
| Paris, France | 02.33 | 48.87 | 02.25 | 48.75 |

(a)

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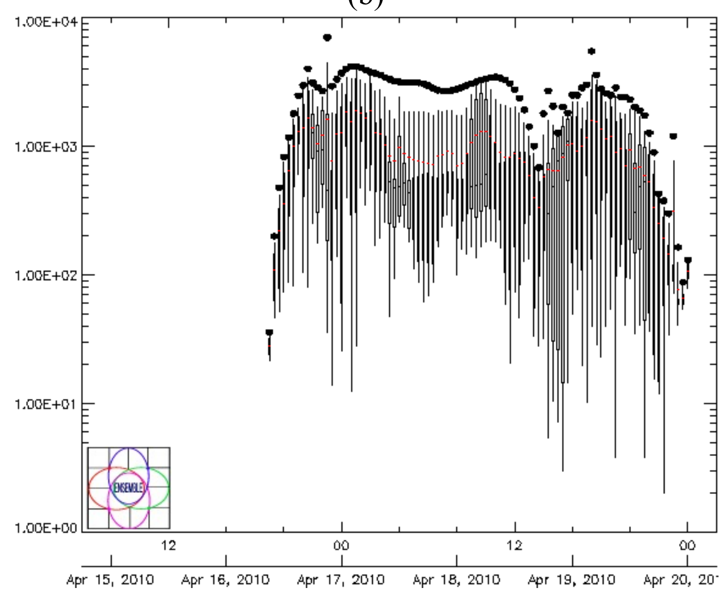


**Figure 3: Box and Whisker plots in time for simulated concentrations (μg/m3) from 00 UTC, April 15 to 00 UTC, April 20 using results from ten ENSEMBLE members for Paris, France for concentrations at (a) surface level, and (b) 4000 m above ground. Maximum predicted concentration at each time is indicated by the large black circle. Note that the concentration scales differ.**

model predicts extremely low (or high) concentrations relative to the other models. Note that the spread is larger for the 4000 m level (Figure 3b), especially at later times, indicating greater uncertainty in model results. It is also evident that the plume is predicted to reach Paris at higher altitude before impacting the surface.

### 4.3 Dry Deposition

Assumptions for deposition modeling are quite varied, and often results in very large discrepancies between model outputs. Figure 4 illustrates spatial overlap of cumulative dry deposition at four times for a threshold of $1\times10^4$ Bq/m$^2$ comparing the ensemble average of nine European models with the SRNL result. In each, the overlap area is represented by the orange shading. The spatial overlap area is roughly 55 to 60% in all cases for this threshold value.

This type of plot does not indicate differences in maximum deposition between models. Figure 5 shows agreement at varying thresholds, indicating that the SRNL model predicts higher deposition amounts than the average of the European models (as noted in the drop in overlap percentage at higher thresholds). This implies differences in the formulation of deposition processes in the dispersion part of the modeling. In this instance, a constant deposition velocity was assumed in LPDM for the volcanic ash. In reality, this value will vary with meteorological conditions, surface type, and particulate size[10], which may or may not have been accounted for by other modeling agencies. Note that since the red shaded area represents an average of European models, it is also possible that one or several of these models contains deposition values similar to those of SRNL, but the averaging process is lowering the overall deposition amounts.

### 4.4 Time Series of Vertical Profiles

Finally, one can get a sense of the vertical variations in concentration by generating plots comparing time-series of concentration at the different levels above ground in which results were required. This is especially important in a scenario such as this, where volcanic ash has a direct impact on the status of airline flights. Figure 6 illustrates a comparison of vertical profiles in time at Berlin, Germany between the ensemble average of nine model results (top band) with the SRNL model results (bottom band) over a two day period beginning 00 UTC, April 16. It is evident that the plume arrives several hours earlier aloft (i.e. 4000 to 8000 m) than at the surface. The time over which the ensemble average predicts impacts at Berlin is much larger than the individual SRNL result. However, both sets of data predict strong concentrations of ash plume impacting Berlin in the lowest 1000 m of the atmosphere between roughly 10 UTC and 20 UTC, April 16, and from 09 UTC, April 17 to 00 UTC, April 18, with a drop in concentration in between. Figure 6 also indicates that concentrations at levels 2000 m and above will be lighter (or non-existent) during the latter period. The SRNL result does not indicate concentrations above 6000 m, while the average of the nine European models does, although at generally lighter concentrations than at the surface.

## 5 CONCLUSIONS

The Eyjafjallajokull volcanic eruption in Iceland in April 2010 disrupted transportation in Europe which ultimately affected travel plans for many on a global basis. The initial guidance provided at the time of the event created some controversy due to the burdensome travel

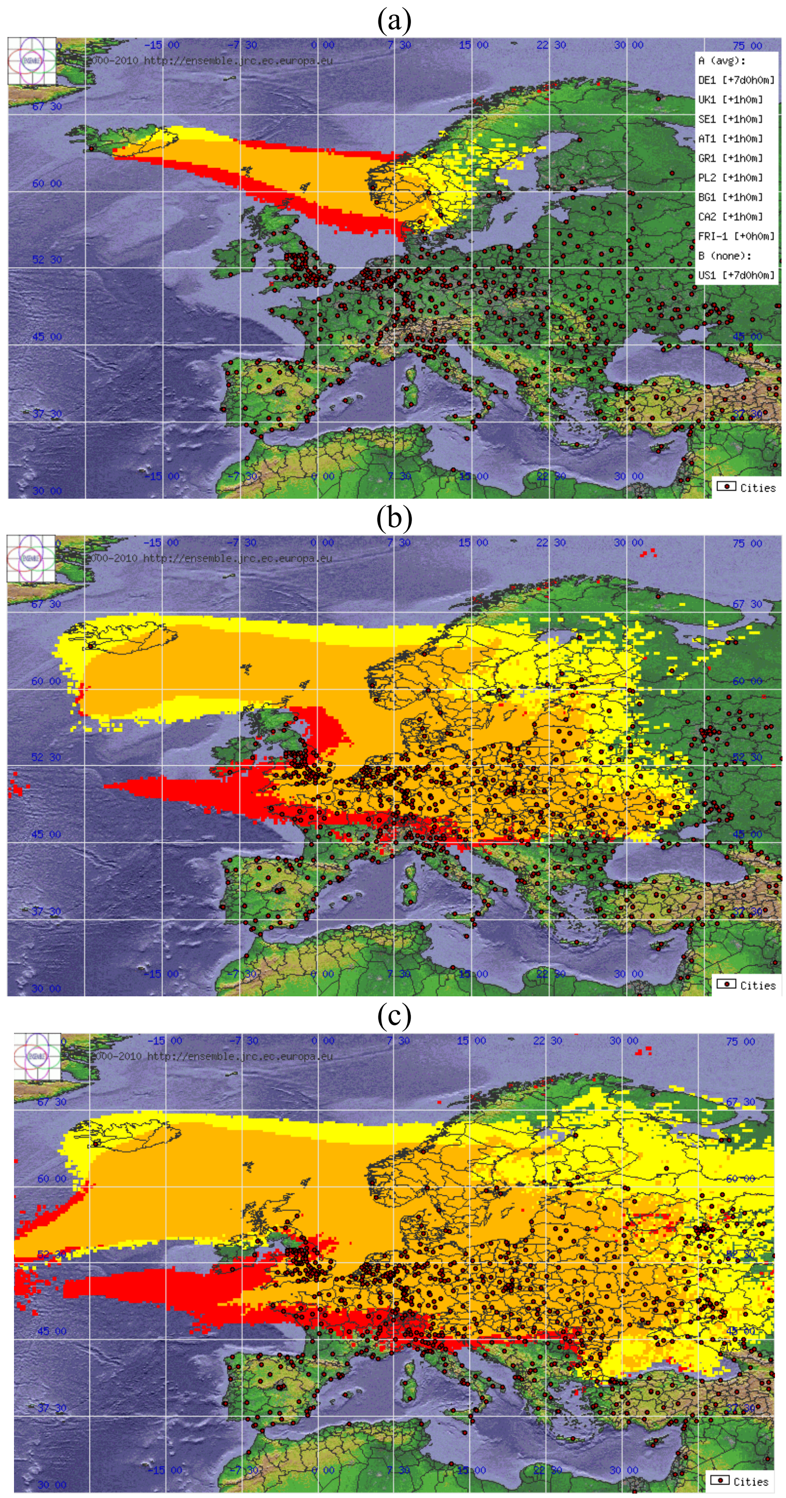


**Figure 4: Spatial overlap of integrated deposition of 10000 Bq/m2 at different times comparing the SRNL result (yellow) and the average of nine other models (red). The overlap is shown in orange. Times shown are (a) 00 UTC, April 16, (b) 00 UTC, April 18, and (c) 00 UTC, April 19.**

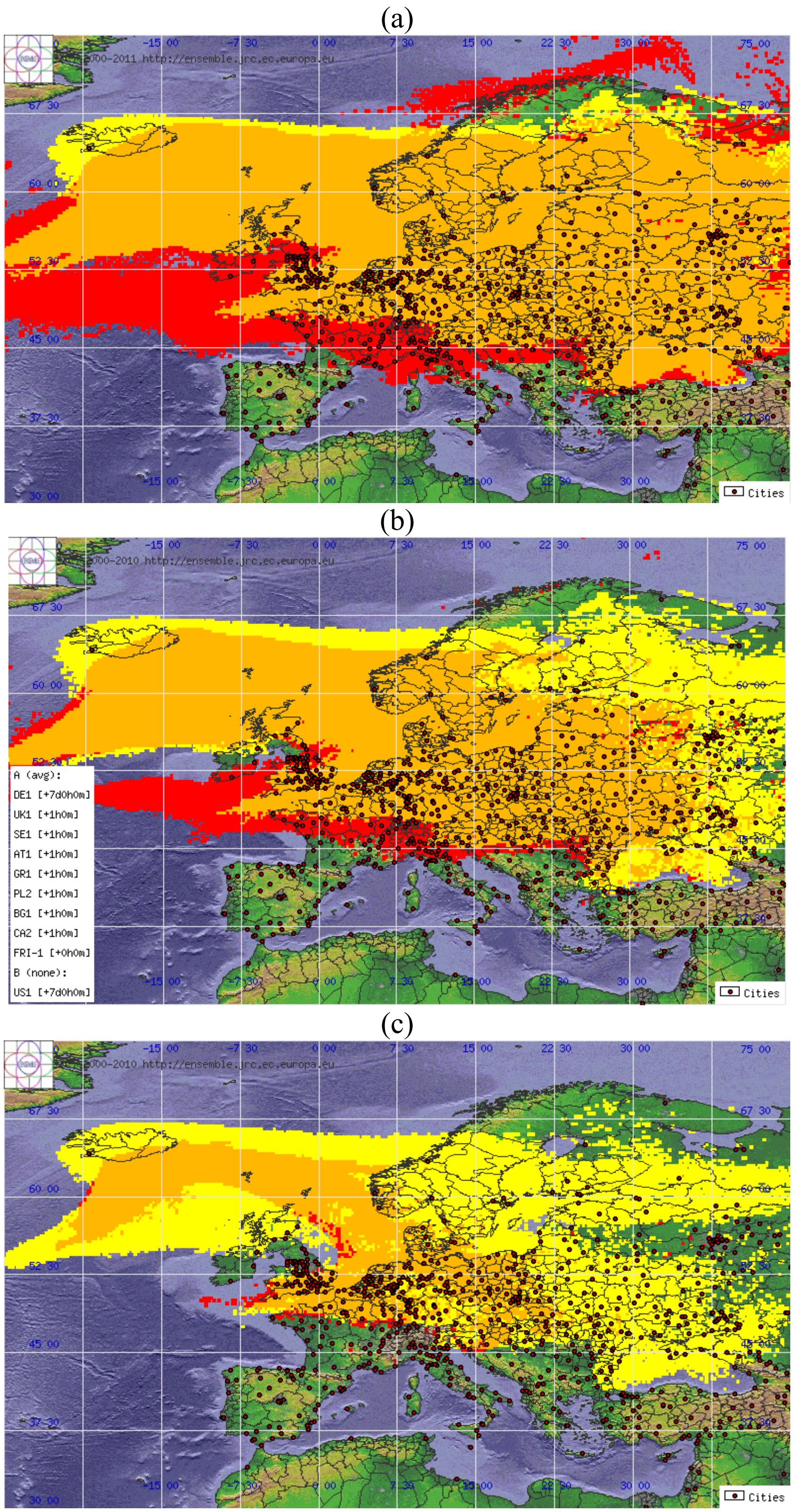


**Figure 5: Spatial overlap of integrated deposition at 00 UTC, April 19 for varying thresholds, comparing the SRNL result (yellow) and the average of nine other models (red). The overlap is shown in orange. Assumed thresholds are (a) $10^3$, (b) $10^4$, and (c) $10^5$ Bq/m$^2$.**

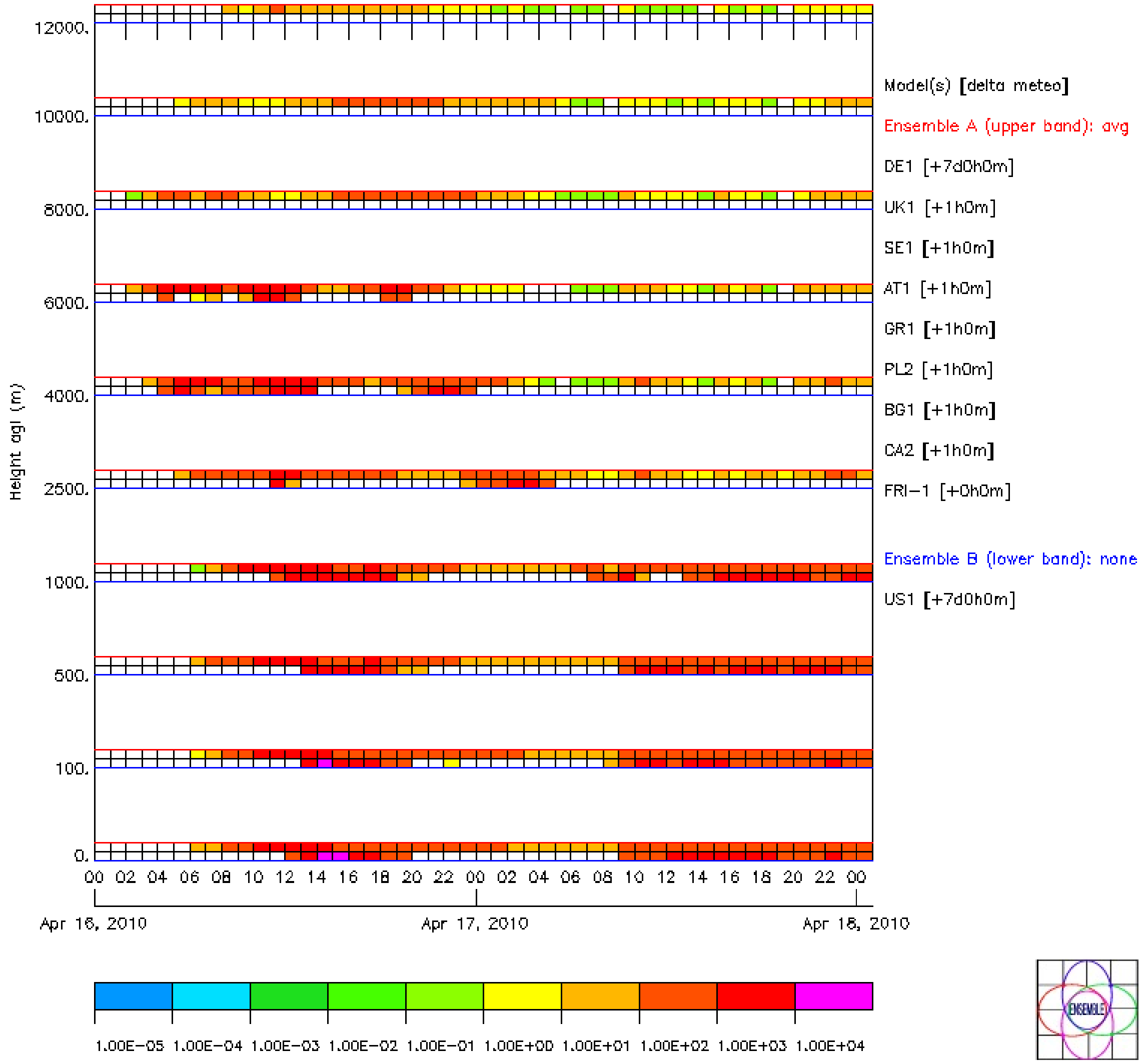


**Figure 6: Time series of vertical profiles of concentration (μg/m3) at Berlin, Germany for a two-day period spanning 00 UTC, April 16 and 00 UTC, April 18. For each level, the top band is an ensemble average of nine European models, while the bottom band is the SRNL result. Each box represents concentration for a given hour. Color-coding at the bottom indicates the intensity.**

restrictions and uncertainty involved in the prediction of ash transport. This eruption provided a useful exercise of the European ENSEMBLE program, coordinated by the Joint Research Centre (JRC) in Ispra, Italy. Model results for a given assumed source are discussed here, showing a variety of different tools available to the modeler. Much like recent efforts at predicting meteorology using an ensemble of meteorological results, the information gained by considering at ensemble of *transport* model results (ten members for the examples illustrated here) leads to a measure of uncertainty in model output. In turn, this can be useful for a DM tasked with making decisions affecting many people covering numerous countries. It should be stressed that if the agencies are running their models in an operational mode, and forecasts uploaded to the ENSEMBLE website in a timely manner, then results such as these are available almost instantaneously through the use of the JRC ENSEMBLE website. This is an extremely valuable asset when compared with the situation of the late 1980's after Chernobyl, when such comparisons would take months to generate.

As time permits, comparison of these results with measurements will be possible. A recent paper[9] describes preliminary efforts to characterize air quality during the Iceland volcanic event in Europe. Maps of daily averaged PM10 concentrations are also given by Colette et al. (2011) across France during April 17 to 20. Measurements indicate the highest concentrations in the northeast part of France on April 18 and 19, which is in qualitative agreement with the spatial plots shown in Figure 1. Of course, quantitative comparisons would require much stricter agreement on the assumed source term, itself a large uncertainty, as discussed in Colette et al. (2011).

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