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ATMOSPHERIC PROGNOSTIC AND DISPERSION MODEL DESIGN FOR USE IN THE EUROPEAN ENSEMBLE MODELING EXERCISES

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1. INTRODUCTION

The Savannah River Technology Center (SRTC) 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. The SRS utilizes an automated, real-time capability for consequence assessment during emergency response to local releases. The emphasis during these situations is to provide accurate guidance as quickly as possible. Consequently, atmospheric transport and dispersion models of a simple physical nature (such as Gaussian plume models) have typically been used in an effort to provide timely responses. However, use of one or two-dimensional (steady-state) winds are inadequate in conditions of high spatial and temporal variability (such as during frontal passage). Increased computing capabilities have led to the use of more sophisticated three-dimensional prognostic models that may capture some of these higher resolution phenomena.

In an ideal situation, the decision-maker (DM) would want to use the "best" model each time an accident occurred. Unfortunately, due to the non-unique nature of solutions to the nonlinear equations governing the atmosphere, model "A" may perform better than models "B" and "C" in one type of weather scenario, and worse during a different situation. Therefore, it is not always possible to distinguish which model is "best", especially during a forecast situation. The use of an ensemble approach of averaging results from a variety of model solutions is beneficial to the modeler in providing the DM guidance on model uncertainties.

Meteorological forecasts generated by numerical models provide individual realizations of the atmosphere. The resulting wind and turbulence fields are then used to drive atmospheric dispersion (transport and diffusion) models. Although many modeling agencies utilize ensemble-modeling techniques to determine atmospheric model sensitivities of prognostic fields (i.e. wind, temperature, radiation, etc.), the European Union has conducted two programs that are the first to examine atmospheric dispersion model output using an ensemble approach. The research discussed in this report is the result of participation in the latest of these two programs, ENSEMBLE (Galmarini et al. 2001).

There have been fifteen modeling agencies that have participated in the ENSEMBLE exercises conducted from 2001 to 2003. For each exercise, participants are asked to provide dispersion results for a given source in the form of instantaneous concentration at various levels above ground, integrated surface concentration, wet and dry deposition, and cumulative precipitation over a large domain covering Europe for forecast periods up to 72 hours. The results are sent in a format for ingestion into a web-based site that is readily available to all participants. This paper discusses the model design used by SRTC to provide input to the European ENSEMBLE program. This includes the use of a prognostic numerical model, the Regional Atmospheric Modeling System (RAMS), and a stochastic Lagrangian-based dispersion model (LPDM). Results are presented relative to other modeling agencies and a discussion of the benefits provided.

2. ENSEMBLE BACKGROUND

The ENSEMBLE program is an extension of previous multi-national modeling efforts conducted in Europe following the Chernobyl accident in an effort to better understand short and long-range transport and dispersion effects in the event of a hazardous atmospheric release. These efforts are the Atmospheric Transport Model Evaluation Study (ATMES, Klug et al. 1992), the European Tracer Experiment (ETEX, Girardi et al. 1998), and the Real Time Model Evaluation (RTMOD, Bellasio et al. 1999). In ENSEMBLE, a web-based system has been implemented to allow for easy dissemination of model results.

During the entire ENSEMBLE program, SRTC participated in 11 planned exercises. In addition, there was a special exercise recreating the first release during ETEX. The following variables are required at the conclusion of each exercise: 'instantaneous' concentration [$Bq\,m^{-3}$] as averaged over the previous hour at five different

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levels above ground (0, 200, 500, 1300, and 3000 m), cumulative surface concentration [$Bq\,m^{-3}$], integrated wet and dry deposition [$Bq\,m^{-2}$], and cumulative precipitation [mm]. This output is required at 0.5° intervals for a domain covering over 5000 km in both latitude and longitude (covering all of Europe, as well as parts of Eastern Asia and Northern Africa) at 3-hr intervals for the duration of the exercise. The specific spatial range is 15°W ≤ LON ≤ 60°E and 30°N ≤ LAT ≤ 75°N and the typical forecast horizon is 60 hours. Typically, notification to participants of an exercise is given several weeks in advance. An alert is sent out within 30 hours of a hypothetical release. Notification occurs via email and fax.

3. MODEL BACKGROUND

A. Prognostic Numerical Model

The prognostic model used in this study is the Regional Atmospheric Modeling System (RAMS, version 3a, Pielke et al. 1992). RAMS is a three-dimensional, finite-difference numerical model used to study a wide variety of atmospheric motions ranging in size from synoptic scale phenomena such as cyclones and hurricanes, to large eddy simulations. Basic features of the model include the use of non-hydrostatic, quasi-compressible equations and a terrain-following coordinate system with variable vertical resolution. The prognostic model is used routinely at the SRS to provide forecasts on both regional and local scales. The RAMS model is capable of simulating a wide range of atmospheric motions due to the use of a nested grid system. Incorporation of topographic features occurs through the use of a terrain-following vertical coordinate system. Other features are discussed in detail in Pielke et al. (1992).

Larger-scale data are available in real time from a variety of sources, although the data used in this application is from the National Oceanic and Atmospheric Administration (NOAA). These larger-scale data are used to generate initialization files in RAMS containing the three-dimensional larger-scale observational data (horizontal velocity components, potential temperature, pressure, and moisture) interpolated to the RAMS (polar-stereographic) model grid. This interpolation is performed on isentropic and terrain-following coordinate surfaces (Pielke et al., 1992). 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. Lateral boundary conditions are also provided at various time increments using a Newtonian relaxation scheme to drive (nudge) the prognostic variables toward the forecasted large-scale values using linear interpolation in time (Davies, 1976).

The actual simulation covers a span of 84 hours, but the first 12 hours are purposely set aside while the model is 'spinning up' a realistic boundary layer. Simulations are nominally generated using analyzed dynamic meteorological fields generated by NOAA's larger-scale Global Forecast System model (GFS, a combination of the Medium Range Forecast (MRF) and Aviation model) at ~190 km grid spacing. Forecast information for the lateral boundary conditions is available at 6-hr increments.

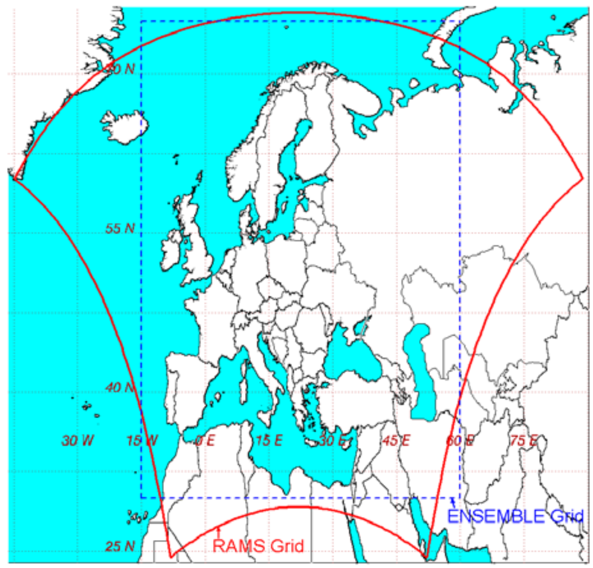

Figure 1: ENSEMBLE domain and SRTC RAMS grid.

The grid used in RAMS (Δx = 75 km) is chosen as a compromise between covering as much of the ENSEMBLE domain as possible and still allowing for the simulations (meteorological and dispersion) to be completed in a short time-span. Ideally, it would be better to use a nested grid system to avoid the contamination at the lateral boundaries that occurs using the nudging scheme (Warner et al., 1997). The RAMS grid is on a polar-stereographic projection, which makes it difficult to cover the regularly spaced grid required in ENSEMBLE. Figure 1 shows the differences between the two systems, revealing that the RAMS grid does not cover parts of the intended ENSEMBLE domain.

B. Stochastic Transport Model

The stochastic transport model used in this study is the Lagrangian particle dispersion model

(LPDM, McNider et al., 1988, Uliasz 1993). Three-dimensional winds and turbulence (Gaussian) fields from RAMS are used as input for LPDM. A large number of particles may be released and their positions tracked by numerically solving the Langevin stochastic differential equation for subgrid-scale turbulent velocites (Gifford 1982) and tracking the particle positions.

Each particle represents a discrete element of pollutant mass that may be used in the calculation of concentration and is assigned varying attributes, including location, turbulent velocity fluctuation, and age. It is important to note that in LPDM, a collection of virtual 'particles' makes up the mass of pollutant released into the atmosphere. A particle released in LPDM should not be confused with aerosols whose characteristics (i.e. diameter, settling velocity, etc.) may be totally different. Concentrations are estimated using the "cell" method, whereby the mass of individual particles in a physical cell is summed. The initial mass of each particle released into the atmosphere is determined from a user-defined mass release rate. This is a discrete method in which the concentration estimate is assumed to be constant throughout the sampling volume. The initial mass of each released particle is assumed to be the same for a given source location and species. The mass of each of the particles may be reduced through radioactive decay by specification of the half-life of the material. Recently, deposition removal mechanisms were added to LPDM (Buckley 2000).

The mass of each released particle is reduced by dry deposition if it is transported near the surface (lowest model level), and by wet deposition if it encounters a column of air in which precipitation has occurred in the latest meteorological data set used to transport the particles.

Cumulative deposition values are continuously summed after each time-step and the mass of each LPDM particle is then updated after this entire process by subtracting out the previously determined mass losses (this mass loss also includes radioactive decay). In this manner, the mass of each particle is depleted according to various physical mechanisms, and deposition values are formulated according to this change in particle mass. The total mass remaining within each cell is then used to determine the concentrations.

For these applications, the concentration grid cell spacing is 37.5 km (half the RAMS grid spacing), while the vertical spacing is the same as in RAMS. The results are interpolated to the $0.5^\circ \times 0.5^\circ$ ENSEMBLE grid where available. Points not covered by the RAMS grid are assigned missing values. In all of the regular ENSEMBLE exercises (except #11), Cs^{137} is released. For Cs^{137}, the material is assumed to be particulate in nature with a particle diameter distribution $0.2 \le d_p(\mu m) \le 10.0$, a half-life of 30.17 years, and a density of 1880 $[kg\,m^{-3}]$. For Exercise 11, Pu^{241} was assumed, with the same particle diameter distribution, but with a half-life of 13.2 years, and a density of 19800 $[kg\,m^{-3}]$.

Table 1: Summary of the ENSEMBLE Exercises

Ex.	Location	Lat (°N)	Lon (°E)	Release Time
1	Lerwick, Shetland Isles	60.15	-1.17	1200 UTC, 18 Apr. 2001
2	Carcassonne, France	43.22	2.33	1200 UTC, 28 Sep. 2001
3	London, England	51.55	0.00	1200 UTC, 21 Nov. 2001
4	Nantes, France	47.22	-1.55	1145 UTC, 05 Feb. 2002
5	Stockholm, Sweden	59.33	18.07	1200 UTC, 16 Apr. 2002
6	Dublin, Ireland	53.87	-6.27	1200 UTC, 25 Jun. 2002
7	Glasgow, Scotland	55.88	-4.23	0700 UTC, 04 Oct. 2002
8	Mochovche, Slovakia	48.27	18.47	1200 UTC, 03 Dec. 2002
9	Bratislava, Slovakia	48.15	17.13	1200 UTC, 12 Feb. 2003
10	London, England	51.55	0.00	1200 UTC, 11 Jun. 2003
11*	London, England	51.55	0.00	1200 UTC, 11 Jun. 2003

**Exercises 10 and 11 differed only in the source material. For Exercise 10, the released material was Cs^{137}, while for Exercise 11 is was assumed to be Pu^{241}. Note that UTC is five hours ahead of Eastern Standard Time (EST).*

4. RESULTS

There were eleven experiments conducted during the ENSEMBLE program (not including the special re-creation of ETEX experiment 1). These are described in Table 1.

The first three exercises required simple sources from a single location of a uniform strength over a specified period of time. However, starting with Exercise 4, the source specifications became more complex. Line source emissions of uniform or varying strength were used in Exercises 4 and 7, while time-varying sources were used in Exercises 5, 8, and 9. Exercises 10 and 11 actually used the same meteorology, but two distinct instantaneous releases were assumed from the same location and at the same time: Cs^{137} and Pu^{241}. This was done in an effort to simulate a ‘dirty bomb’. It should be noted that LPDM in its current configuration could simulate the above scenario in one exercise, but two separate runs were performed in accordance with the ENSEMBLE needs.

As indicated in a previous section, the ENSEMBLE web page provides the user with a variety of ways to examine the results of the simulations, either on an individual model basis, or as an ensemble with user-selected models. For the sake of brevity, results depicting only the agreement of integrated surface concentration (for a low threshold of 1.0 $[\mathrm{Bq\,m^{-3}}]$) for Exercise 7 are shown in Fig. 2 for sixteen different models. Any shaded area indicates that at least one model predicted concentration would exceed 1.0 $[\mathrm{Bq\,m^{-3}}]$ over the simulation period. The chosen model simulations all use analysis meteorology that is at or before the hypothetical release (i.e. what would be available to the modeler in a real emergency situation). The darker the shading, the more agreement among the models exists, while the lighter shading along the periphery of the footprint is simulated by only one or two of the models.

A line source release from Glasgow, Scotland of uniform strength of 1.0×10^{15} [Bq hr^{-1}] from 0 to 500 m above ground was assumed over a four-hour period beginning 0700 UTC, 04 October 2002 (Table 1). Agreement of integrated concentration at 18 UTC, 06 October is shown for a number of models (DK1, PL1, DK2, etc.) in comparison with the SRTC simulation (US1, crosshatched). Figure 2 shows a ‘plume’ headed easterly over the North Sea before turning south and impacting both Scandinavia and northern European mainland. Most models confine the plume at this concentration level to latitudes west of 10ºE, while relatively few models predict the plume traversing east into Poland, Slovakia, and Hungary. The US simulation is contained within the envelope defined by the ensemble of the other models.

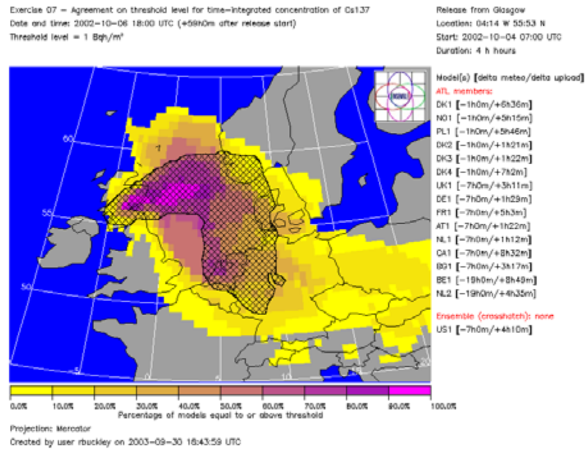

Figure 2: Experiment 7 results showing agreement on integrated surface concentration at 18 UTC, 06 October 2002 for a release from Glasgow, Scotland beginning 07 UTC, 04 October.

5. DISCUSSION/CONCLUSION

A prognostic atmospheric numerical model (RAMS) has been used to create meteorology with more detail than typically available from the national weather services. These data are used in a Lagrangian particle dispersion model to simulate the long-term effects from hypothetical releases in Europe as part of the European Union’s ENSEMBLE modeling program.

Differences between model results stem from the use of different background model physics and numerics, as well as different meteorological input. Most of the European participants use the European Center for Medium Range Weather Forecasts (ECMWF) model for meteorological conditions, while SRTC uses a product generated by NOAA to drive RAMS. A person tasked with giving advice to a decision maker regarding recommended actions in the event of an atmospheric release would find the plot given in Fig. 2 valuable, with the knowledge that multiple simulations using different input and/or physical characteristics provide similar results. In other words, the user would have much more confidence in the ensemble of the results as opposed to an individual simulation.

The SRTC results utilize a relatively coarse model grid, which is quite adequate for long term consequences. However, transport analysis very near the source is not expected to be particularly useful. More powerful computing hardware now allows for the use of finer grid resolution than was available to SRTC at the inception of the ENSEMBLE program. Combined with the parallel processing capabilities of a newer version of RAMS, grid resolutions nearly an order of magnitude better than previously utilized are now possible for use in generating detailed meteorology.

Thus, the ENSEMBLE program has been beneficial to the SRTC atmospheric modeling program in several ways. It has enabled the implementation of more complexity in the atmospheric and transport models. The RAMS model has not only been established for simulations in Europe (thus allowing for modeling of a number of potential accident scenarios in this region of the world), it also has been a test-bed for running a parallel version of the numerical model. In addition, running the code in an automated fashion through a series of shell and script commands is valuable to work performed in other areas of operations at the SRS. The transport model has been improved by incorporating dry and wet deposition removal mechanisms. This particular feature was valuable in subsequent development of a version of LPDM for calculating ingestion and dose from a number of isotopes during graded emergency response exercises at SRS.

The ENSEMBLE program also allows the modeling capabilities at SRTC to be more thoroughly evaluated against other models currently in use. The RAMS model has been evaluated in a number of studies, including comparison with local SRS tower data, and regional NWS surface and upper air observations. However, ENSEMBLE allows for a model inter-comparison not previously performed at offsite locations. Finally, participation in the ENSEMBLE program has provided SRTC scientists the opportunity to network with many European scientists, and to learn more about the modeling program of these different agencies.

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