A REAL TIME DISPERSION MODEL FOR SEVERE NUCLEAR ACCIDENTS

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ABSTRACT

The model: Severe Nuclear Accident Program (SNAP) has been developed at the Norwegian Meteorological Institute (DNMI) in Oslo to provide decision makers and Government officials with a real-time tool for simulating large accidental releases of radioactivity from nuclear power plants or other sources. The model has been developed as a part of DNMI's contribution to the EUREKA project - MEMbrain (EU-904-1).

SNAP is developed in the Lagrangian framework in which atmospheric transport of radioactive pollutants is simulated by emitting a large number of particles from the source. SNAP can be used to predict the transport and deposition of a radioactive cloud or to analyze the behavior of the cloud in the near past. It is also possible to run the model in the mixed mode (partly analyses and partly forecasts).

SNAP is fully operational, which means that it can be run by the meteorologist on duty at any time. Updated meteorological input to the model is provided by DNMI's operational Numerical Weather Prediction model HIRLAM. The output from SNAP has two forms: First on the maps of Europe, or selected parts of Europe, individual particles are shown on the screen during the simulation period. Then, immediately after the simulation, concentration/deposition fields can be shown every three hours of the simulation period as isoline or color shading maps. In addition, model output is stored on a public accessible disk for further processing by the user of the Norwegian Application of MEMbrain - the Norwegian Nuclear Emergency Preparedness Organization.

INTRODUCTION

In case of a nuclear accident it is very important to know the time and space pattern of the radioactive cloud released to the atmosphere. Real-time dispersion models were developed in many different countries in order to simulate atmospheric transport and deposition of radionuclides, being emitted in case of a nuclear accident. The output of such models is of great value to decision makers responsible for handling the emergency situation. Discussion of the requirements for a real-time dispersion model for application in Norway is given by Saltbones [11]. Such a model has been developed at the Norwegian Meteorological Institute (DNMI); 'Severe Nuclear Accident Program (SNAP)'.

The first version of SNAP was developed at DNMI [11], [12], [13], [14] based on the same theoretical assumptions and basic architecture as the NAME model, [10], designed and developed at the UK Meteorological Office. Although the first version of SNAP was in operational use at DNMI already in 1994, a fully operational version was implemented last year as part of DNMI's contribution to the Norwegian Application of the Major Emergency Management (MEMbrain) Project, which is a part of the EUREKA (EU-904) activity. MEMbrain is a computer based decision support system for emergency management in case of large accidents. A/S Quasar Consultants has been project leader for the Norwegian part of MEMbrain, with the support from five norwegian research institutions. The user of the system is a Norwegian Radiation Protection Authority (NRPA) in its function as secretariat for the Nuclear Emergency Preparedness Organization. The development of the system have been given a financial support from EKSPOMIL and Norwegian State Authorities.

The main objective of SNAP is to provide decision makers and Government officials with a real-time tool for simulation of large accidental releases of radioactivity to the atmosphere in case of a nuclear accident. SNAP is now fully operational at DNMI, which means the meteorologist on duty, on request from the NRPA, can start a simulation at any time - day and night.

Since the Chernobyl accident in 1986, many operational dispersion models with real-time simulation capabilities, similar to SNAP, have been developed for use by the national weather services in Europe. As examples, we can list: NAME of the UK Meteorological Office [10]; MATCH of the Swedish Meteorological and Hydrological Institute (SMHI) [9] ; Lagrangian Particle model of the German Weather Service [3] . Many of these models, including SNAP, have been tested in the European Tracer Experiment (ETEX) [2], [6], [7] . In this real-time modelling exercise, participants from 28 research institutions in 21 countries in Europe, North America and Japan could compare their model results with air samples of the released tracer PFC, perfluoromethylcyklohexane.

In this paper, we describe the operational version of SNAP which is currently installed at DNMI.

SNAP MODEL

SNAP is developed in the Lagrangian framework, in which atmospheric transport of radioactive pollutants is simulated by emitting a large number of particles from the source. The main advantage of the Lagrangian approach is a possibility of precise parameterization of advection processes. After release, each particle carries a given mass of radioactive nuclides, which can be in the form of gas or aerosol. During the atmospheric transport, the radioactive mass of each particle is reduced by dry and wet deposition and radioactive decay. SNAP can be used to predict the transport and deposition of a radioactive cloud (up to 48 hours, in the present version) or to analyze the transport/diffusion behavior of the cloud in the near past. It is also possible to run the model in the mixed mode (partly analyses and partly forecasts).

Model Domain

Simulation with the SNAP model can be performed in different grid systems. The system most frequently used is shown in Figure 1. This is the grid system used by HIRLAM (High Resolution Limited Area Model), currently DNMI's main operational weather prediction model [5] , [8] .

The vertical structure of SNAP is made compatible with the one used by HIRLAM, using data from a subset (14 layers, 7 layers below 1800m) of the vertical layers available. This choice is determined by the meteorological data available from HIRLAM as input to SNAP simulations. Concentration and deposition fields computed by SNAP are stored/presented in the same grid as shown in Figure 1.

There are two classes of meteorological input data for SNAP. The first is produced directly by HIRLAM and includes: wind, temperature and precipitation. The second is the mixing height, which defines the height of the Atmospheric Boundary Layer (ABL). The mixing height is computed from NWP model output (HIRLAM), but it stands out as a separate class; both due to its importance for SNAP as input, but also because the procedure to determine the mixing height is so sensitive for the outcome of the simulation. This procedure is described in detail in [15] and [10].

The most important meteorological elements provided by HIRLAM model are:

- horizontal wind (u,v) - in 14 layers
- vertical velocity $\dot{\eta}$ - in 14 layers
- temperature - in 14 layers
- precipitation - at the ground
- pressure - at the ground

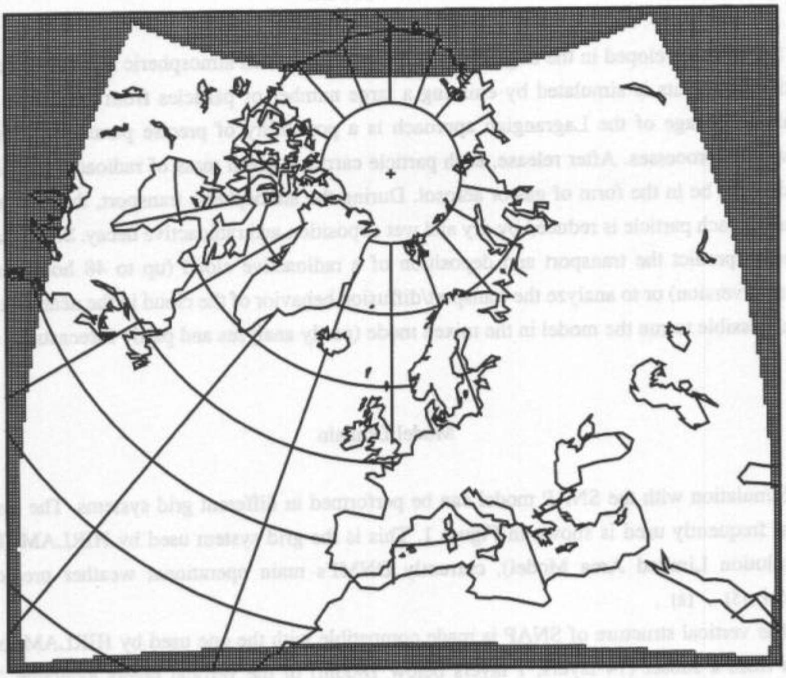

Figure 1: Model domain most frequently used for SNAP computations.

Source-Term Specification in SNAP

Three groups of substances are taken into account in the source-term specification in SNAP: Aerosols (A), Noble Gases (NG) and other gases (G). All groups are in most cases assumed to be emitted into the atmospheric boundary layer (ABL). Only in case of an explosion, a certain fraction of the emission may reach the atmosphere above the ABL as a direct injection in the emission process.

During the model simulation we use a unit emission rate ($1\ g\ s^{-1}$) for each group. Since the basic model equations of SNAP are linear in relation to emission, concentration and deposition (mass), the results of a 'run' using '*unit emission rate*' can be easily scaled by multiplying output concentration and deposition according to 'corrected' emission rates. In this way, unit output fields are very convenient for the model user, because the transport of arbitrary isotope can be taken into account by scaling the results after the model run is completed. An additional advantage of this approach gives a possibility of performing "off-line" modeling of the radioactive decay. These features give the user more flexibility in testing different emission scenarios with different radioactive species. However, we have to mention that there are some restrictions for scaling SNAP results and this problem is discussed in more detail in Saltbones [15].

Advection of Particles

Emission of radionuclides into the atmosphere is simulated by the release of a large number of particles. Usually, we use 900 particles for each timestep (typically 15 min.). These particles are advected by wind at different levels of the atmosphere.

The displacement of each particle is calculated for every model time step. In this calculation, three-dimensional velocity is interpolated to particle position from the eight nearest nodes in the model grid. Bilinear interpolation in space is applied to the components of the velocity field, and linear interpolation in time is applied between six-hourly meteorological input fields provided by HIRLAM. The displacement of each particle in one time step is calculated according to the following equation:

$$\vec{x}'_{t+\Delta t} = \vec{x}_t + \vec{v}\left(\vec{x}_t\right)\Delta t \tag{1}$$

where $\vec{x}_t = (x, y, \eta)$ is the position of the particle and $\vec{v}_t = (u, v, \dot{\eta})$ is the velocity field at time t. The intermediate position of the particle after advection procedure is denoted by the vector $\vec{x}'_{t+\Delta t}$.

Horizontal and Vertical Diffusion of Particles

In the model computations, the processes - advection and diffusion - are separated so that advection is first performed, then followed by the diffusion process in a stepwise manner. A 'random walk' approach is used to parameterize horizontal and vertical diffusion. The sequence of steps for the parameterization of the process is described below, see also Maryon *et al.* [10]. Slightly different parameterization is used for particles located within the ABL and for those above, but it can be described by the same equations. The new particle position is calculated as:

$$
\begin{aligned}
x'' &= x' + r_x l \\
y'' &= y' + r_y l \\
\eta'' &= \eta' + r_\eta l_\eta
\end{aligned}
\tag{2}
$$

where $\vec{x}''_{t+\Delta t} = (x'', y'', \eta'')$ is the vector of particle position for $t + \Delta t$ after application of the horizontal diffusion operator, r_x, r_y and r_η are the randomly sampled values from the range <-0.5, +0.5>, generated from a uniform distribution; l and l_η are the length scale parameters for horizontal and vertical turbulent motion.

In the case of vertical diffusion, parameterization is different within the ABL and above. The timestep of 15 minutes (900 s) corresponds to the turn-over time of a large eddy within the ABL: $\Delta t \approx z_i / w_c \approx 900s$, where z_i is the ABL height and w_c is a characteristic convective velocity. This means that after approximately 15 min., a particle does not 'remember' its previous position within the ABL. Therefore, vertical diffusion in this region is parameterized as a random relocation of particles between surface and z_i, applied after each timestep. To allow a vertical exchange of particles between the ABL and a free atmosphere, the mixing zone is extended above the ABL from z_i to $z_i + \Delta z_i$. In the η-coordinates, vertical diffusion including the exchange mechanism is described by the following equation:

$$\eta'' = 1 - (1 - \eta_H - \Delta\eta)\,(r_\eta + 0.5) \tag{3}$$

where η_H is the vertical position of the ABL top (in η-coordinates) and $\Delta\eta = 0.005$. Above the ABL, vertical diffusion is parameterized by Equation (2) with $l_\eta = 0.04$.

Dry Deposition

A particle carry an initial mass - $M_p(t_0)$ - from the source. The initial mass can be interpreted as the mass associated with one of the emission classes: - noble gasses, ordinary gas class or the aerosol class. The mass in each of these classes is treated somewhat differently for each depletion process. The mass $M_p(t_0)$ is sub-divided into smaller units. Particles located above the atmospheric boundary layer, are not subject to the dry deposition process. For particles in the boundary layer, the situation is different. Assume that the boundary layer consists of - n - 'fictitious layers' or $n=z_b$, where z_b is the number of 'meters' of the boundary layer thickness. The particle is randomly 'assigned' a number - n_p - from the number set $<z_b>$. A number n_{crit} has been prescribed, being an element in the lower part of the number set $<z_p>$. If $n_p > n_{crit}$, no mass is lost by this particle. If $n_p \leq n_{crit}$, a certain fraction of the particle's mass - ΔM_{pd} - is deposited onto the ground.

The 'adjustable' probabilistic parameters for the process, are given numerical values corresponding to a rate of efficiency that can be compared with the more commonly used parameterization of the process, for example, the concept 'dry deposition velocity'. The values of the 'key' parameters n_{crit} and ΔM_{pd} determine the efficiency of the dry deposition process.

Parameterization of Wet Deposition

In the parameterization of the wet deposition process, we use 'probability curves'. A 'probability curve' can be explained as follows: If we choose an arbitrary point (x, y, t) in a 'grid-volume' (Δx, Δy, Δt), a 'probability curve' will tell us: "What is the probability for 'real' precipitation to occur in this specific point in space and time, - given we have access to the amount of precipitation (Prec) predicted by DNMI's operational NWP model". These ideas and concepts have been developed and used in the models describing transport/deposition of acidifying substances at DNMI [1].

For Prec = 0, no wet process acts on the particles. For Prec > 0, we define a two-step process. First step: We read from the 'probability curve' for the precipitation amount in question, what the probability is for 'real' precipitation to occur at the 'space-time' point in question.

$$P_w = Prob(Prec) \tag{4}$$

Next step: We randomly assign '0' or '1' to each particle. The '1' value is chosen with a probability P_w, and '0' value with a probability $(1 - P_w)$. This means, if the total number of particles is N in the grid-volume in question, then P_w N particles are affected by the wet deposition in a timestep Δt, and a certain fraction of the 'wet' particles' mass is deposited to the ground.

The 'adjustable' probabilistic parameters for the process, are given numerical values corresponding to a rate of efficiency that can be compared with the more common parameterization of wet deposition, for example, the 'scavenging ratio' concept. The 'probability curves' will be the 'key' in determining the efficiency of the process. The 'probability curve' worked out by P.E. Haga [4] is shown in Figure 3.

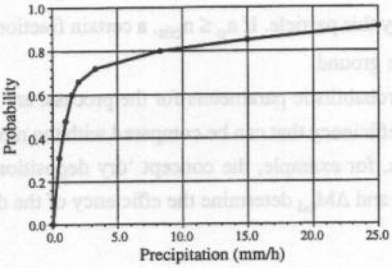

Figure 2. The probability curve for precipitation used in SNAP, taken from Haga [4] .

APPLICATIONS OF SNAP

The main application of SNAP are real-time simulations of the transport of radionuclides released during a nuclear accident (operational application). In addition SNAP can be used to simulate events from the past, for which meteorological data are available in archives, and special events related to model intercomparisons and tests.

Operational Application

SNAP is fully operational which means that it can be run by the meteorologist on duty at any time. During the simulation of a nuclear accident, SNAP produces different types of output. Part of this output is graphically displayed directly on the screen during the simulation. Another part is stored in files for further processing, like for example; creating off-line graphics, producing files with time series of the activity ('Becquerelograms') for different locations and storing results on public-accessible discs.

On-line graphics on screen: When we start a simulation using SNAP, a new window with the map of Europe appears on the computer screen in which different fields can be displayed during the model run. For example, on Figure 3, individual particles are shown after 72 hours of the simulation of a continuous release from a point source located in England. In the upper-left corner of the window (Figure 3), three numbers are always displayed: current date, time (utc) and number of particles inside the model domain (displayed in parenthesis). In addition, there is a line at the top which indicates how much of the simulation has been completed.

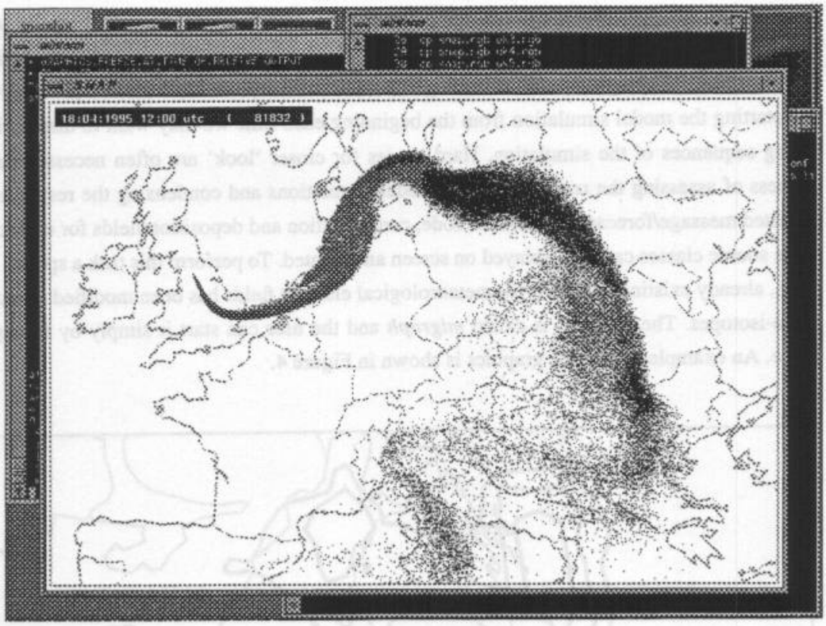

Figure 3. On-line display of the particles in SNAP simulation.

During a model run, the user can graphically display on-line the following fields:

- particles effected by precipitation - individual locations
- particles not effected by precipitation - individual locations
- particles in the ABL - individual locations
- particles above the ABL - individual locations
- all particles in the atmosphere - individual locations
- precipitation amount for the last three hours - isolines
- concentration of mass/activity in the ABL - isolines
- accumulated wet deposition - isolines
- accumulated dry deposition - isolines
- accumulated total (wet + dry) deposition - isolines

Off-line display and printing of the model results: When the simulation is finished, the fields listed in the previous paragraph (except particles) can repeatedly be displayed on the screen with better resolution (zooming) and hard copies of these fields can be printed. This option is very useful. Close inspection of interesting features can be repeated and studied in detail without starting the model simulation from the beginning each time we may want to display interesting sequences of the simulation. Hard copies for closer 'look' are often necessary in the process of assessing the results from the model simulations and condensing the results into a digested message/forecast. In off-line mode, concentration and deposition fields for each of the three source classes can be displayed on screen and printed. To perform this task a special software, already existing at DNMI for meteorological element fields has been modified to include radio-isotopes. The program is called *migraph* and the user can start it simply by typing the name. An example of off-line graphics is shown in Figure 4.

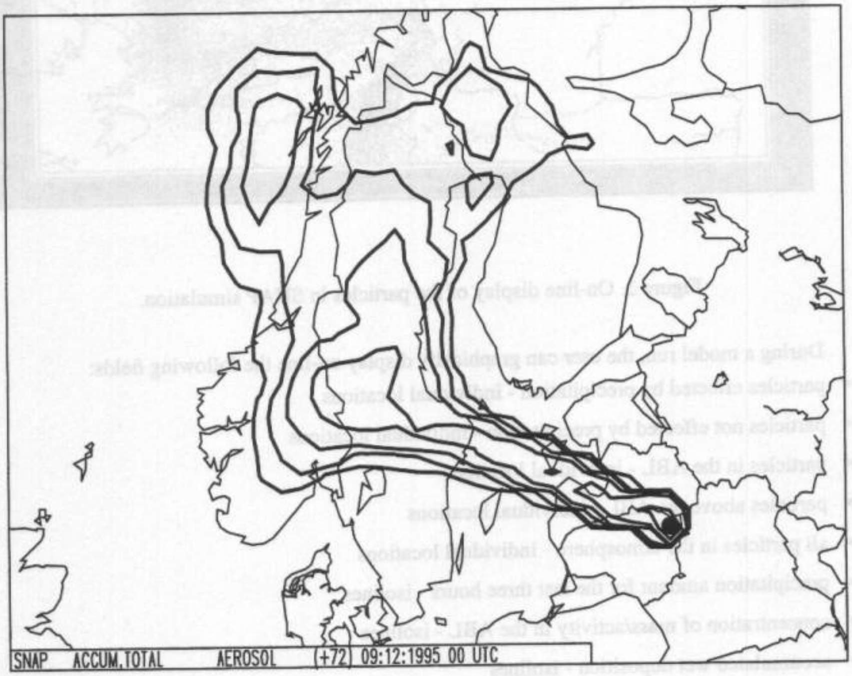

Figure 4. Isolines of total accumulated deposition for the aerosol group shown after 72 hours of the simulation. Units: $10^{-12}\ g\ m^{-2}$ (first isoline).

Public-accessible files: Accesses to the output files from the SNAP simulations as well as to meteorological data are restricted to DNMI staff. However, the users of the MEMbrain system, (NRPA) will also have remote access to the results from SNAP simulations. For this purpose, the output files are written in agreed format on a special disc at DNMI which is available for the outside users.

Other Applications

Besides the operational applications, SNAP is often used for special tasks. For example, SNAP was used in the ETEX experiment [15] , in which model results were compared with the measurements, as well as with the results produced by other models. Also, the Chernobyl accident in April 1986 has been simulated using SNAP model [11] . In this simulation, special attention was paid to atmospheric transport of radionuclides to Norway. The results from SNAP have also been compared with other Scandinavian models in the frame of Nordic collaboration in functional exercises. However, despite all these additional activities, the operational applications of the model are the most important. The future development of SNAP, will mainly be directed towards these operational aspects.

CONCLUSIONS

The SNAP model in its present stage of development is fully operational and can be used for the simulation of nuclear accidents anywhere in Europe, in real time. However, the model is still under development with the main focus on improveing of the parameterization of the physical processes during the release and transport of radioactive material. The main effort in the future model development will go towards:

better parameterization of the source-term

improved description of wet deposition

more user-friendly set-up for operational services at DNMI

The above tasks will be performed as an extension of the MEMbrain project.

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