ATMOSPHERIC DISPERSION OF RADIOACTIVE DEBRIS RELEASED IN CASE OF NUCLEAR EXPLOSION USING THE NORWEGIAN SNAP MODEL

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Abstract: Severe Nuclear Accident Program (SNAP) has been developed at the Norwegian Meteorological Institute (met.no) for modelling dispersion of radioactive debris in case of nuclear accidents. The model has been tested based on the data available from the Chernobyl accident as well as from the ETEX experiments. The main user of model results is the Norwegian Radiation Protection Authority (NRPA) which is responsible for calculating doses in case of a real accident. The model is fully operational for NRPA as well as for met.no. Following a request from NRPA, the SNAP model was modified in such a way that not only dispersion from nuclear accidents can be simulated, but dispersion from nuclear explosions as well. The source term for the model run in case of nuclear explosion has been developed based on cooperation among Scandinavian countries. The source term includes mainly particles of different size and density, which are subject to dry and wet deposition during atmospheric transport. Description of the model and examples of the simulations related to hypothetical nuclear explosions are presented and discussed.

Key words: *Atmospheric dispersion, nuclear explosions, accidental releases, radioactive debris.*

1. INTRODUCTION

Nowadays, the possibility of terrorist attacks is a realistic threat all over the world, including Norway. In the worst case, such terrorist acts may even involve nuclear detonation. Therefore, the decision makers need a tool (model) able to simulate atmospheric transport/dispersion of the radioactive debris released during the nuclear detonation. In order to provide the Norwegian Crisis Committee with such a tool, the (Severe Nuclear Accident Program) SNAP model has been modified to be able to handle scenarios dealing with the nuclear detonations. This work has been done in the frame of co-operation between the Norwegian Meteorological Institute (met.no) and the Norwegian Radiation Protection Authority (NRPA).

Calculations of the deposition pattern (foot-print) after a nuclear detonation have in the past been performed for military purposes. Different NATO documents give guidance and descriptions on how such calculations should be performed for military use (e.g. STANG, 1994). From met.no's point of view, the sections describing "Effective Downwind Message/Forecasts" (EDM/EDF) in the report are highly relevant. These procedures and calculations are performed by met.no to provide Norwegian Military Authorities with updated meteorological information on a routine basis: every 12 hour – based on the most updated runs of met.no's operative Numerical Weather Prediction (NWP) models.

However, for civilian use, these calculations are not directly applicable. The military use of these products (foot-prints) is in war or warlike situations and was developed during the "Cold War". The Norwegian Crisis Committee must have other time horizons for its decisions and is also interested in mapping the more diffuse outer part of the foot-print pattern which is left out of the military part. This was the motivation for developing the bomb version of the SNAP model.

2. BOMB VERSION OF THE SNAP MODEL

The first version of the SNAP model was developed at the Norwegian Meteorological Institute in 1994 (Saltbones et al., 1994) as a Lagrangian particle model, based on cooperation with the UK Meteorological Office and their model NAME (Maryon *et al.*, 1991). The basic processes taken into account in this first version were: emission, transport/dispersion and deposition of the radioactive debris from nuclear accident, applicable to scenarios of the Chernobyl type, with continues emissions over a relatively long time period. In all versions of SNAP, the model's governing equation is solved in the Lagrangian framework by releasing a large number (approximately 10^5) of particles. A 'particle' in the SNAP model is not a real particle, but is representing a parcel of the air carrying a large number of real physical particles containing the radioactivity.

The SNAP model has been improved since 1994 (Saltbones et al. 2000, 2002; Bartnicki et al. 2003) and the first bomb version was ready in 2003 (Saltbones et al., 2003). This version was to a large extent based on the information available from the Nordic partners in the METNET project. Since than, the bomb version has been further modified and improved, but its basic structure has remained unchanged. The details of the bomb version of the SNAP model are given in (Saltbones et al., 2003) and only a brief description of model parameterizations is presented below.

Source term parameterization

We have assumed that the radioactivity is transported as particles of different size. We have considered two shapes of the radioactive clouds shortly after the explosion: a cylinder and a mushroom shape. The large variation of the particle size in the initial cloud is represented by 10 discrete classes with characteristic particle radius ranging from 2 μm to 200 μm. We have assumed an equal activity (10%) in each size class. Parameters of both initial cloud shapes, as well as the activities depend on the explosive yield and we consider four classes of the explosive yield. Following Persson at al. (2000), parameters for the cylinder shape and activities are given in Table 1.

Table 1. Parameters for the cylinder shape of the cloud shortly after the explosion and activities for different explosive yield classes. Single cylinder cloud shape.

Explosive yield (ktonnes)	Base of the Cylinder (km)	Top of the cylinder (km)	Radius of the cylinder (km)	Activity (Bq)
1	0.50	1.50	0.6	2×10^{19}
10	2.25	4.75	1.4	2×10^{20}
100	5.95	12.05	3.2	2×10^{21}
1000	10.00	25.00	8.5	2×10^{22}

In our approach, the mushroom consists of two cylinders, the lower one describing the stem and the upper one describing the hat of the mushroom. Following Sofiev et al. (2004), parameters for the two cylinders of the mushroom are given in Table 2, for the same four yield classes as in Table 1.

Table 2. Parameters for two cylinders for the radioactive cloud shortly after explosion. Mushroom cloud shape. Activities are the same as in Table 1.

Explosive yield (ktonnes)	Base of the upper cylinder (km)	Top of the upper cylinder (km)	Radius of the lower cylinder (km)	Radius of the upper cylinder (km
1	1.67	3.365	0.97	0.97
10	5.009	8.072	1.695	2.551
100	9.255	14.393	1.782	6.711
1000	13.347	21.635	2.648	17.651

There is large variation in the size of the particles in the radioactive cloud after the explosion. In the SNAP model we assume that the particle size spectrum is represented by 10 discrete classes. The total activity is the sum of all ten classes. This is based on the assumption that the activity is uniformly distributed in the mass of the bomb material and that each particle size class gets an equal part of the original bomb material. This implies that a factor of 10 in difference in particle radius for two classes will result in a factor of 10^3 in the number of particles in two classes. In this way we attribute 10% of the original activity in each particle class.

Particle size classes and distribution of activity, in the SNAP model, are the same as in the MATCH model (Persson et al. 2000) and are shown in Table 3 together with corresponding activity share, characteristic gravitational settling velocity and particle radius assumed to calculate this velocity. Density of the particles in Table 3 is assumed to be 3 g cm^{-3}. In case of a detonation close to the ground, particles of soil origin will be excited and drown into the updraft. This fraction of the material has lower density than the original 'bomb' material and also the activity attached to this mass fraction will be quite different in composition. We are unsure how much of this extra activity is included in the numbers presented in Table 1 (Persson et al. 2000). These numbers must therefore be treated with caution.

Table 3. Particle size classes and corresponding parameters used in the SNAP model calculations. Note: we have assumed an equal share of the activity to each size class.

Class No.	Range of the particle radius (μm)	Activity share (%)	Gravitational settling velocity (cms^{-1})	Radius (μm) used for estimation of sedimentation velocity
1	0 - 3	10	0.2	2.2
2	3 -6.5	10	0.7	4.4
3	6.5 – 11.5	10	2.5	8.6
4	11.5 - 18.5	10	6.9	14.6
5	18.5 - 29	10	15.9	22.8
6	29 - 45	10	35.6	36.1
7	45 - 71	10	71.2	56.5
8	71 - 120	10	137.0	92.3
9	120 - 250	10	277.3	173.2
10	≥ 250	10	direct deposition	-

Parameterization of advection and diffusion

Two processes are involved in the atmospheric transport of particles: advection and diffusion. Advection is the transport of particles by the wind, on scales that can be resolved by the wind fields described in the grid system used by SNAP (organized motion). To calculate the advection, three-dimensional wind fields are used, available for the entire model domain. Diffusion is the process of transfer of particles by the wind, on the scales that can not be resolved by the SNAP grid system (turbulent motion). A "random walk" approach is used for describing the diffusion process in SNAP, based on Physic and Marion (1995).

The displacement of each particle is calculated for each model time step using three dimensional velocity fields from met.no's operational Numerical Weather Prediction (NWP) model HIRLAM. For these calculations, the velocity is interpolated to particle position from the eight nearest nodes of the NWP model grid. Bilinear interpolation in space is applied to the horizontal components of the velocity field and linear interpolation to the vertical component. In addition, linear interpolation in time is applied between three-hourly meteorological input fields.

In the model calculations, the advection process is immediately followed by the diffusion process. A random walk approach is used to parameterize horizontal and vertical diffusion. Horizontal diffusion in SNAP is depends on the horizontal length scale which is proportional to the wind speed. Horizontal diffusion is parameterized in the same way for the particles within the Atmospheric Boundary Layer (ABL) and for those above, but the value of the coefficient of the proportionality is different for the two regions. Parameterization of vertical diffusion in the bomb version of SNAP is relatively simple, because for the large particles, vertical diffusion process is dominated by the gravitational settling. The advantage of this simplification is better performance of the model in terms of computational time.

Parameterization of dry deposition

Many particles of different size are released into the atmosphere after a nuclear explosion. For the relatively large particles (see Tab. 2), the dry deposition process is dominated by the gravitational settling. However, for the relatively small particles with the radius 0–3 µm, other processes are more important for removal of particles from the air. Therefore, not only gravitational settling, but also other surface related processes are included in the parameterization of dry deposition.

A key parameter in the dry deposition process is the dry deposition velocity, which is calculated based on the resistance analogy (Seinfeld 1986).. For conditions when Stokes law is valid, gravitational settling velocity with spherical shape of particles is a function of particle size, particle density and air density (Zannetti, 1990). In the case of the larger particle classes, correction to account for high Reynolds numbers is necessary. Such a correction was introduced in the SNAP model (Bartnicki et al., 2003) leading to the set of nonlinear equations which has to be solved at each model time step for each particle. Such a numerical solution may significantly slow down model performance, if it is applied to each individual particle. However, in the 'bomb' version of SNAP, we have used constant values of gravitational settling velocities for each of the selected classes (see Tab. 2), so that application of these equations did not significantly reduced the model performance.

The dry deposition process removes less than one percent of the activity (in one model time step) for the first three classes of particle size with the radius range 0–11.5 µm. However, dry deposition process becomes very effective for larger particles. For example, after one model time step with dry deposition, only 44% of the initial activity remains in the class 9 with particle radius range 120–250 µm. By definition, all particles in class 10 (radius above 250 µm) are deposited at the source location.

Parameterization of wet deposition

Removal of small particles from the atmosphere is mostly caused by wet deposition process. This process includes absorption of particles into the droplets in the clouds and then droplet removal by precipitation. Wet deposition process depends on many complicated factors, which are difficult to take into account, like for example occult deposition related to fog, scavenging by snow, effect of convective precipitation and orographic effects.

In the bomb version of the model, wet deposition is a function of particle radius and precipitation intensity (Baklanov and Sørensen, 2001). The activity remaining in the model particle after one model time step with wet deposition is significantly smaller for particles with the large diameter than for smaller particles, and it quickly decreases with the precipitation intensity for all particle sizes.

RESULTS OF THE MODEL SIMULATIONS

In the first test presented here, the bomb version of the SNAP model has been used to simulate a hypothetical nuclear explosion (10 ktonnes) north of Scotland on 17 December 2003 at 00 UTC. The forecasted meteorological situation indicated transport of radioactive debris to the east passing southern Norway. Approximately 12 hours after explosion, the radioactive cloud is located south of Norway. After 60 hours the cloud is more patchy and is located over Ukraine. The distribution of total activity close to the ground 18 hours after explosion is shown in Figure 1.

The forecasted accumulated total depositions for selected particle classes are shown in Fig. 2. Only particles with radius smaller than 20 µm are arriving to, or passing Norway. Larger particles are deposited closer to the site of explosion.

In the second example shown, the bomb version of the SNAP model has been used to simulate a hypothetical nuclear explosion, taking place near Jan Mayen. The main goal of this simulation was a comparison of the results for two different initial shapes of the radioactive cloud: cylinder and a mushroom shape. This comparison was performed for two bomb yields: 10 ktonnes and 1000 ktonnes. The results are shown in Figures 3 and 4, respectively. There is not much difference in the results due to different initial shape of the radioactive cloud, as indicated by the similar upper and lower rows in Figures 3 and 4. However, there are significant differences in the results for different yields. Radioactive debris from the 10 ktonnes detonation is transported to very different direction compared to the debris from the 1000 ktonnes detonation.

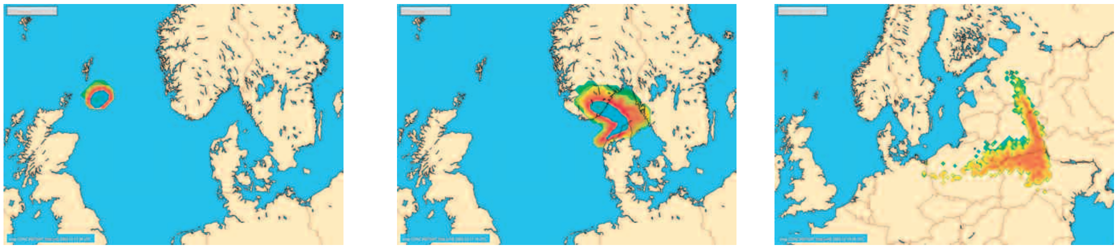

Figure 1. Total activity at the ground: 6 hrs (left), 18 hrs (middle) and 60 hrs (right) after explosion.

Figure 2. Accumulated total deposition for class 4 (left), 5 (middle) and 6 (right) of the particle radius, 60 hours after explosion.

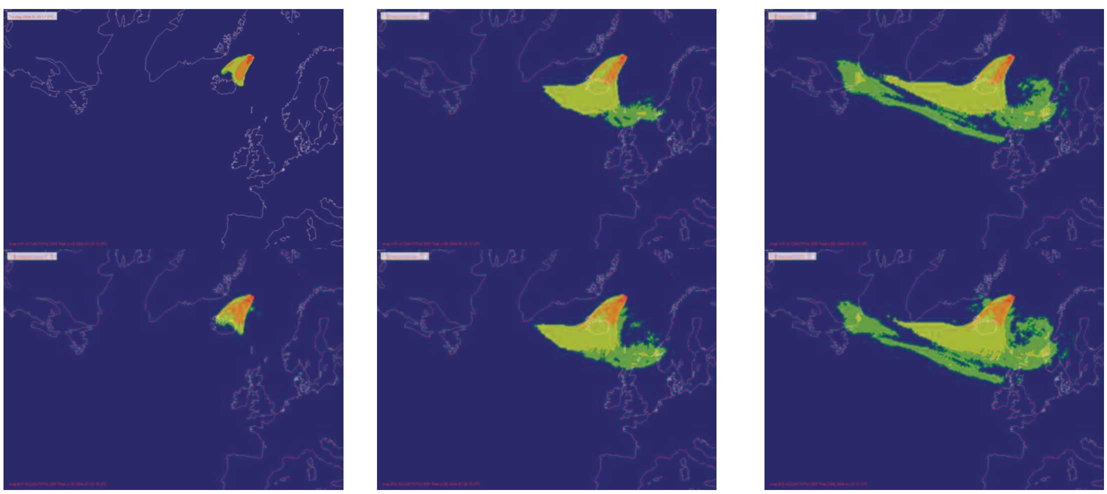

Figure 3. Comparison of accumulated total deposition for cylinder (upper) and mushroom (lower) initial shapes for the radioactive cloud: 12, 36, and 60 hrs after the explosion. The location of explosion is Jan Mayen and the yield is 10 ktonnes.

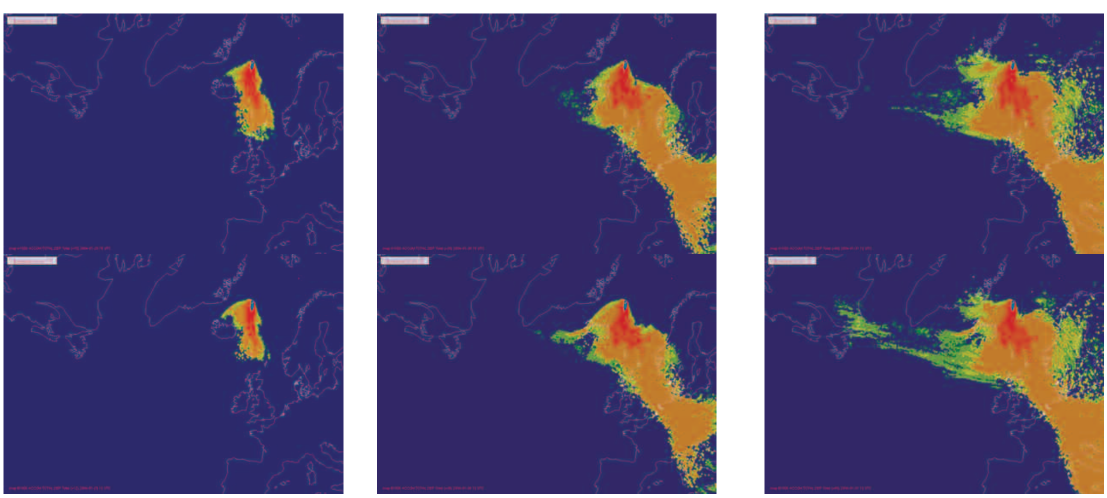

Figure 4. Comparison of accumulated total deposition for cylinder (upper) and mushroom (lower) initial shapes for the radioactive cloud: 12, 36, and 60 hrs after the explosion. The location of explosion is Jan Mayen and the yield is 1000 ktonnes.

3. CONCLUSIONS

In the first, out of two examples of the model run, the bomb version of SNAP has been used to simulate a hypothetical nuclear explosion, which took place north of Scotland on 17 December 2003 at 00 UTC. Presented maps with total activity of all particles from 10 classes indicate that approximately 12 hours after explosion; the cloud is located south of Norway. After 60 hours the cloud is more patchy and had already arrived at the cost of Black Sea. Concerning different classes, only particles with radius smaller than 20 µm are arriving to, or passing Norway. Larger particles are deposited closer to the site of explosion.

In the second example of the simulation, the bomb version of the SNAP model has been used to simulate a hypothetical nuclear explosion, which took place near Jan Mayen. The main goal of this simulation was a comparison of the results for two different initial shapes of the radioactive cloud. This comparison was performed for two bomb yields: 10 ktonnes and 1000 ktonnes. There is not much difference in the results due to different initial shape of the radioactive cloud, however, there are significant differences in the results for different yields. Radioactive debris from the 10 ktonnes detonation is transported to very different direction compared to the debris from the 1000 ktonnes detonation.

REFERENCES

Baklanov, A. and J. H. Sorensen, 2001: Parameterization of radionuclide deposition in atmospheric long-range transport modeling. *Physics of the Chemistry of the Earth (B),* **26**(10), 787-799.

Bartnicki, J., B. Salbu, J. Saltbones, A. Foss and O. Ch. Lind, 2003: Long-range transport of large particles in case of nuclear accident or explosion. Preprints of 26th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application, 26-30 May 2003. Istanbul Technical University, Istanbul – Turkey, 53-60.

Maryon, R.H., Smith J.B. Conway B.J. and D.M. Goddard, 1991: The United Kingdom Nuclear Accident Model. *Prog. Nucl. Energy*, **26,** 85-104.

Persson, Ch., Robertson L. and Thaning L., 2000: Model Simulation of Air and Ground Contamination Associated with Nuclear Weapons. An Emergency Preparedness Model. SMHI report No 95. Swedish Meteorological and Hydrological Institute. Norrkoping, Sweden.

Physic, W. L. and R. H. Maryon, 1995: Near-source turbulence parameterization in the NAME model. Met O(APR) TDN No. 218. UK Meteorological Office.

Saltbones, J., Foss and J. Bartnicki, 1994: SNAP: Severe Nuclear Accident Program. Technical Description. *Research Report* No. **15**. Norwegian Meteorological Institute. Oslo, Norway.

Saltbones, J., Foss A. and J. Bartnicki J., 2000: Threat to Norway from potential accidents at the Kola nuclear power plant. Climatological trajectory analysis and episode studies. *Atmospheric Environment,* **34**, 407-418.

Saltbones, J., Foss A. and J. Bartnicki, :2002: Intercomparison of real time dispersion model results, supporting decision making in case of nuclear accident and focusing on quantification of uncertainty. In; *Eighth International Conference on Harmonisation Within Atmospheric Dispersion Modelling for Regulatory Purpose. Sofia, Bulgaria, 14-17 October 2002.* E. Batcharova and D. Syrakow (Eds.), 92-96.

Saltbones, J., Bartnicki J. and A. Foss, 2003: Handling of Fallout Processes from Nuclear Explosions in Severe Nuclear Accident Program – SNAP. Research Report No. 157. Norwegian Meteorological Institute. Oslo, Norway.

Seinfeld, J.H., 1986: Atmospheric Chemistry and Physics of Air Pollution. John Wiley and Sons. New York. 738 pp.

Sofiev, M., Valkama I., Ilvonen M. and P. Siljamo, 2004: Finish Emergency Modelling Framework SILAM. Part 1. Model Description. Submitted to *Atmospheric Environment.*

STANAG, 1994: STANAG 2103, ATP-45 Vol I/II, 'Reporting Nuclear Detonations, Biological and Chemical Attacks, and Predicting and Warnings of Associated Hazards and Hazard Areas', (NATO Declassified), June 1994.

Zannetti, P., 1990: Air Pollution Modeling – Theories, Computational Methods and Available Software. Southampton: Computational Mechanics.