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Handling of Fallout Processes from Nuclear Explosions - in Severe Nuclear Accident Program (SNAP)

by

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Summary

SNAP is met.no's operational real-time dispersion model for decision support use by the National Nuclear Preparedness Organization ('Kriseutvalget') in case of nuclear accidents. A new operational version of SNAP has been developed at met.no in 2003. This version includes new parameterization of important physical and meteorological processes for real-time simulation of atmospheric dispersion, transport and fallout of radioactive particles emitted into the atmosphere as a result of a nuclear explosion.

Concerning source term and initial conditions, we have assumed that the radioactivity is mainly transported as particles of different size. We have considered two shapes of the radioactive cloud shortly after explosion: cylinder and mushroom. In both cases, parameters of initial shape and activity depend on the explosive yield. We have also used data presented in (open) military publications.

The effect of large variation of the particle size in the initial cloud, represented by 10 discrete classes with characteristic particle radius ranging from 2 µm to 200 µm, has been tested with regard to transport distances and deposition patterns.

As an overall conclusion, we have shown that including particles of different size - with their hygroscopic properties, will give quite different deposition pattern compared to what has previously been shown to be of interest in military calculation of the fallout from nuclear detonations.

1. Motivation for this development work

Nowadays, the possibility of terrorist attacks is a serious threat all over the world. Such terrorist acts may even involve nuclear detonations. Taking this fact into account, decision makers need a ‘tool’ (model) able to simulate atmospheric transport/dispersion/deposition of the radioactive debris released as a result of a nuclear detonation. In order to provide the National Nuclear Preparedness Organization (‘Kriseutvalget’) with such a tool, the previous version of the SNAP model has been modified to be able to handle such scenarios.

Calculations of the deposition pattern in connection with attacks/use of nuclear weapons, have for a long time been performed at met.no for military purposes. Different NATO documents give guidance and descriptions of how such calculations should be performed for military use (e.g. STANAG, 1994). From EDM/EDF (Effective Downwind Message/Forecast) further calculations of ‘Fallout Predictions’ are performed, - ending in ‘foot-prints’ or sectors/distances where the maximum fallout is expected to occur. The military use of (and the thinking behind) these products is in war or warlike situations, - methods/thinking developed during the “Cold War”.

‘Kriseutvalget’ have other time horizons for its decisions and is interested in mapping the diffuse outer part of the foot-print pattern, - left out of ‘the military calculations’.
Here we have focused on two aspects:

- a: Particles of different size have a marked effect on the fallout pattern. This is not properly taken care of in the military version of these calculations.
- b: Particles can have hygroscopic properties and can easily be incorporated into rain/cloud processes. This can lead to concentrated depositions at locations far away from the foot-print calculated based on gravitational fallout processes only.

2. Short description of the SNAP model and its applications

The first version of SNAP 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 accidents, applicable to scenarios of the Chernobyl type; continuous emissions into the lower part of the troposphere - over a relatively long time period.

The model’s governing equation is solved in the Lagrangian framework by releasing a large number of particles (approximately 105). A ‘particle’ in the SNAP model is not a ‘physical particle’, but rather symbolizing a parcel of the air carrying a large number of physical particles containing the radioactivity.

met.no has since 1994 participated in a number of projects where SNAP has been the main tool. For each new application, adaptation/modification of SNAP has been performed, but the basic structure of the model has remained the same:

- Participation in RTMOD and ETEX experiments, with many European institutions involved, including WMO and EU.
- Participation in the ENSEMBLE project, with 17 participants from Europe, USA and Canada.
- Kola Project, with NRPA. Analysis of the consequences of worst case scenario.
- Chernobyl recalculated, with NRPA.
- Participation in NKS project, with NLH.
- Participation in NKS project, with Nordic meteorological institutes as partners.

3. Modifications of SNAP related to nuclear explosions

SNAP was modified in 2001 as a response to the 11.09. terrorist attacks in the US (Saltbones, 2001). However, the physical processes in this version were very crudely treated and there was an urgent need for improvement of these processes.

The spatial resolution of meteorological input data has been significantly improved in 2003; - a new version of HIRLAM was implemented for operational use at met.no. The new version of HIRLAM operate in a 20 km grid (instead of 50 km), and the number of vertical layers were increased from 31 to 41. (HIRLAM High Resolution Limited Area Model).

We have considered two shapes of the radioactive clouds shortly after the explosion: cylinder (Persson et al., 2000) and mushroom shape (Sofiev et al., 2004). In both cases parameters of initial shape and activity depend on the explosive yield. The large variation of the particle size in the initial cloud is represented by 10 discrete size classes with characteristic particle radius, ranging from 2 μm to 200 μm. We assumed equal share of activity (10%) to each size class.

In the ‘bomb’ version of SNAP, new positions of the particles are computed for each time step (advection). Random walk approach is used for parameterization of horizontal and vertical diffusion processes with different coefficients below and above the mixing height. New parameterization of dry deposition takes into account aerodynamic resistance, surface resistance and gravitational settling. For the relatively large particle classes released during the nuclear explosion, gravitational settling is the dominant process, determining the effectiveness of the dry deposition process. The effectiveness of the wet deposition process is a function of particle size and precipitation intensity in the new parameterization in the ‘bomb’ version.
(PS: Troposphere/stratosphere exchange still needs refinement).

4. Source term parameterization and initial conditions

We consider three classes of explosive yield. Following Persson et al. (2000), parameters for the cylinder shape and activities are given in Table 1. In our approach, the mushroom shape consists of two cylinders; the lower describing the stem and the upper 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.

Table1. Parameters for the cylinder, for the radioactive cloud shortly after the explosion and activities for 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	1×10^{22}

Table2. 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

The 'activity' given in Table 1, refers to the total activity at H+1, i.e. the non-decayed activity valid one hour after the detonation. This is the common way for radiologists to present activity originating from nuclear weapons. (The expected activity at a certain time after H+1 is often assumed to decay according to A(t)=A(1)* t -1.2 , where A is the activity and t is the time in hours after the explosion).

We assume that the spectrum of particles is represented by 10 discrete size classes. Particle size and distribution of activity in the SNAP model, (the same as in the MATCH model (Persson et al. 2000)), are shown in Table 3 - together with corresponding activity share, characteristic gravitational settling velocity and particle radius - calculated for this particle size. Density of the particles in Table 3 is assumed to be 2.88 g cm-3.

Table3. 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 (cm/s)	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	-

For most size classes in Table 3, gravitational settling is the dominant process responsible for removing particles from the air in dry conditions. We note that in the military calculations of fallout after a nuclear detonation, a fallout velocity of about 1 ms-1 is assumed for all radioactive debris. This means that all the radioactive fallout is assembled in the size classes 7 or 8 in our notation, as shown in Table 3. (Note: The gravitational velocity in Table 3, relates to conditions in the lower part of the troposphere, close to the ground).

Comparison of the two assumed initial cloud shapes shortly (H+1) after explosion for three classes of explosive yield, is shown in Figure 1.

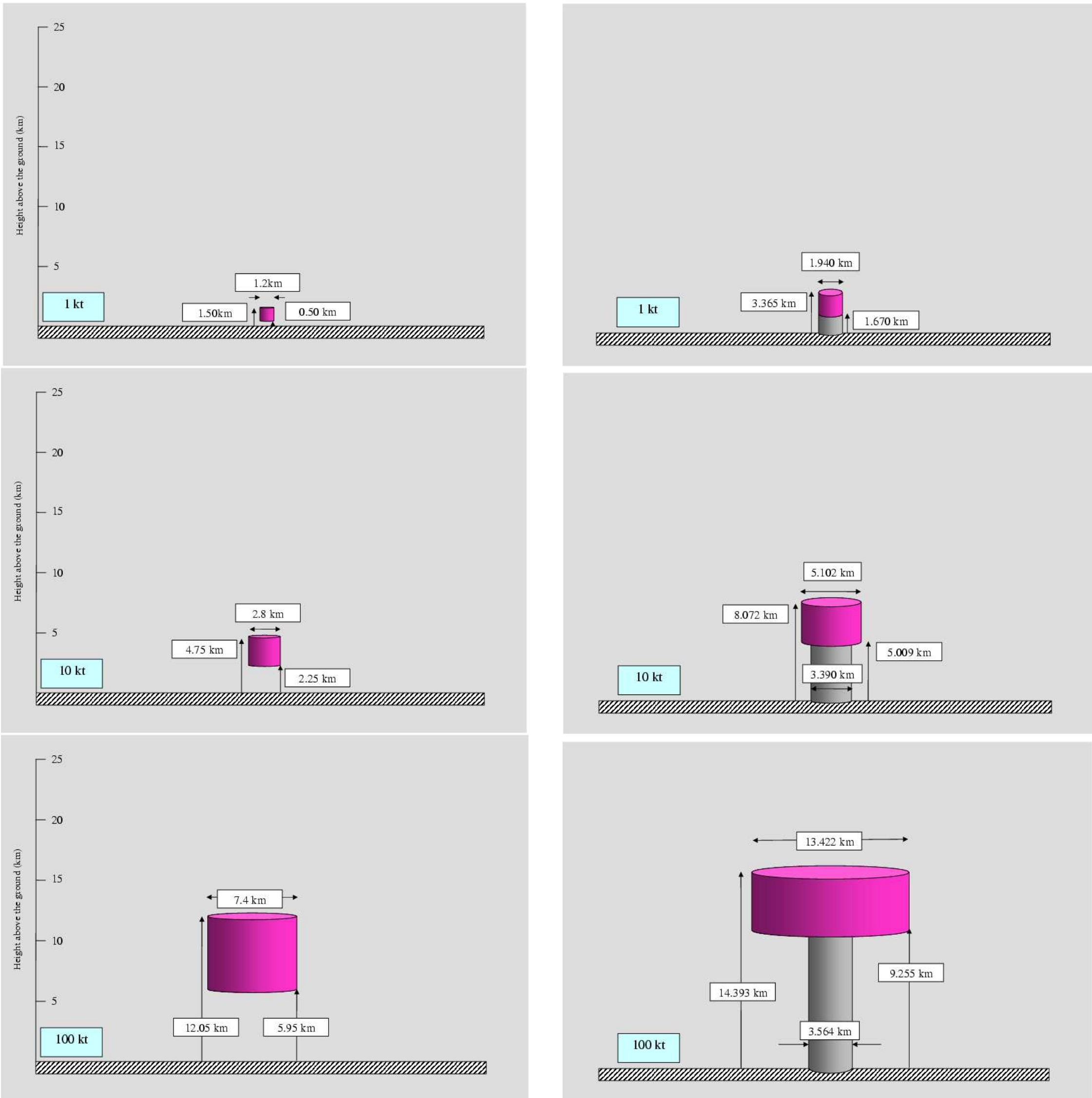


Figure 1. Initial shapes of the radioactive cloud shortly after explosion for 1, 10 and 100 kt yield.   Cylindrical form to the left, mushroom to the right.

5. Parameterization of 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.

Diffusion is the transfer of particles by the wind, on scales that can not be resolved by the SNAP grid system (turbulent motion). A “random walk” approach is used for describing the diffusion process. The “random walk” technique is described in detail in Physic and Maryon (1995). (For a more complete description, see met.no report no 157/2003).

6. Parameterization of dry and wet deposition

For relatively large particles (see Table 2), dry deposition is dominated by gravitational settling. However, for the small particles with the radius 0 - 3 µm, other processes are more important in the removal of particles from the air, - see Seinfeld, (1986) and Zannetti, (1990).

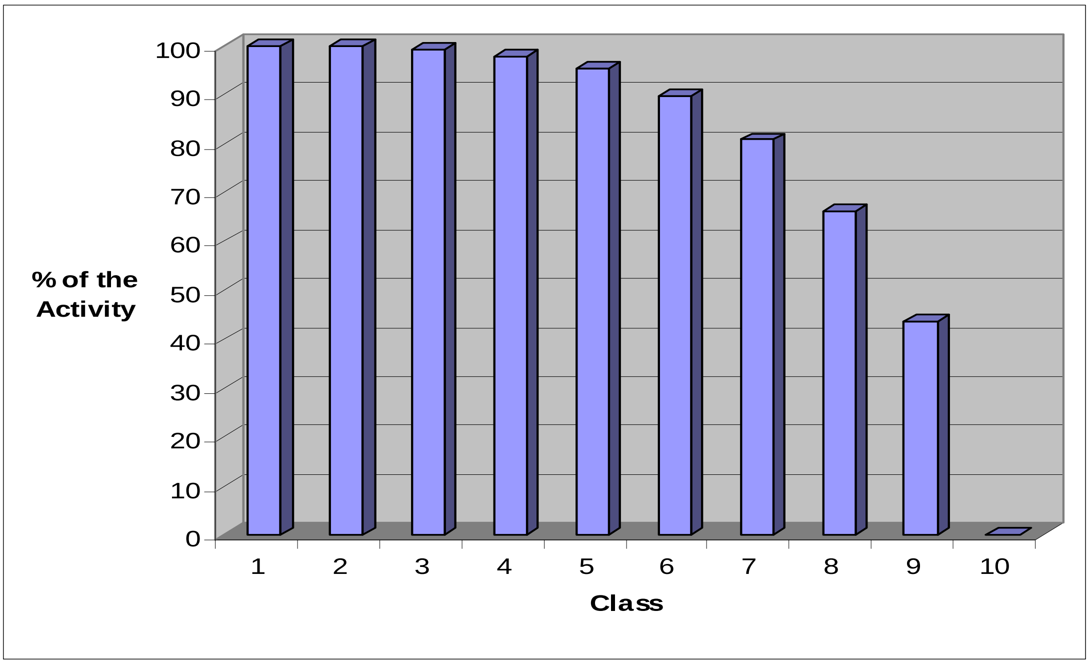


Figure 2. Percent of activity remaining in the model particle after one model time step (Δt=5min) for each of the 10 particle size classes , - when only the dry deposition process is activated.

The dry deposition process removes less than 1 % of the activity in one model time step for the three smallest size classes, - radius range 0 11.5 µm. However, dry deposition process becomes very effective for larger particles. In one model time step, dry deposition remove 56 % of the initial activity in the class 9 - particle radius range 120 250 µm.

Small particles are most effectively removed from the atmosphere by wet deposition. This process includes absorption of particles into the droplets in the clouds and small droplets removed by precipitation, - see Baklanov and Sorensen (2001).

Figure 3 shows the activity remaining in the particles (in percent of initial value) after one model time step when only the wet deposition process is activated, - for the four smallest particle size classes. The remaining activity is significantly smaller for particles with the larger radius - and it quickly decreases with the precipitation intensity for all particle sizes.

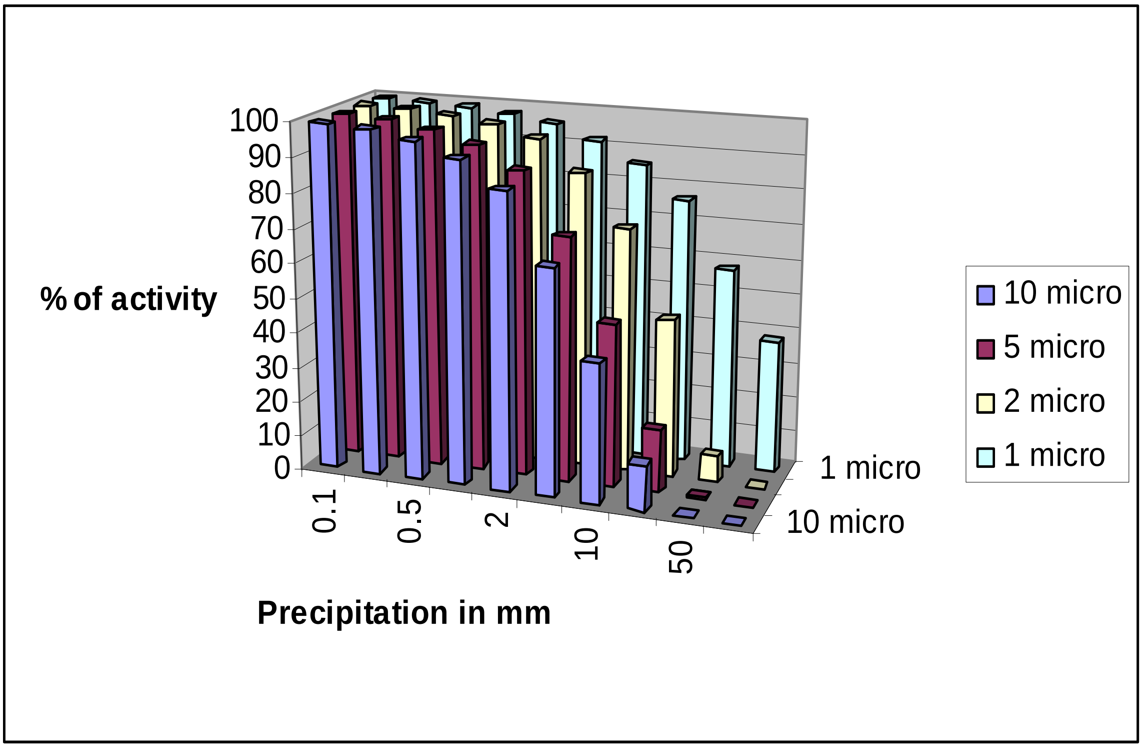


Figure 3. Percent of activity remaining in the particle after one model time step (Δt=5min) when only the wet deposition process is activated, - for four particle size classes.

7. Example of simulation

As an example, the new version of SNAP has been used to simulate a hypothetical nuclear explosion (100 kt yield) north of Scotland at 00 UTC on the 17th of December 2003. The meteorological data (wind, MSLP and precipitation from HIRLAM-20km) 3 hours after the explosion, - shown in Figure 4, - indicate transport to the east for the radioactive debris, - passing over Southern Norway.

The forecasted movement of the radioactive cloud after the explosion is shown in Figure 5, - as total activity at ground level. Total means - the sum of activity in all particles size classes. Approximately 12 hours after the explosion, the cloud is located just west of Southern Norway. After 60 hours, the cloud looks ‘patchy’ and its centre is located at the cost of Black Sea.

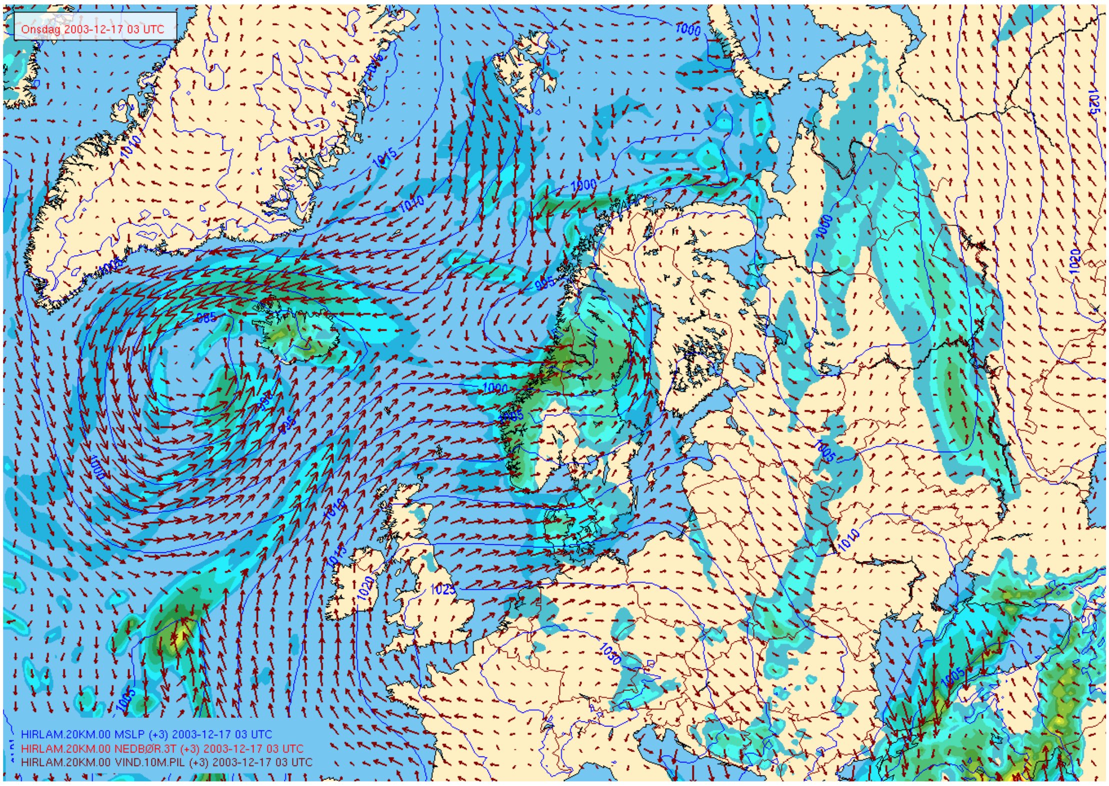


Figure 4. Meteorological situation, 3 hrs after the explosion. MSLP, wind at 10m level and precipitation are shown.

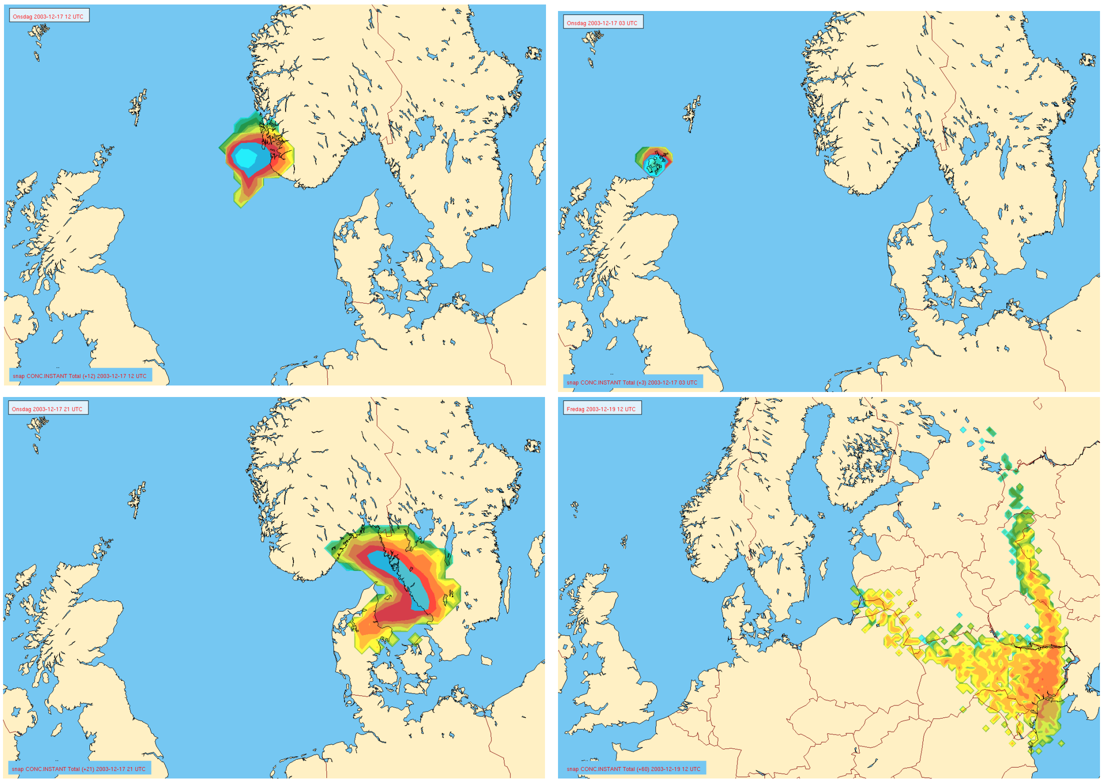
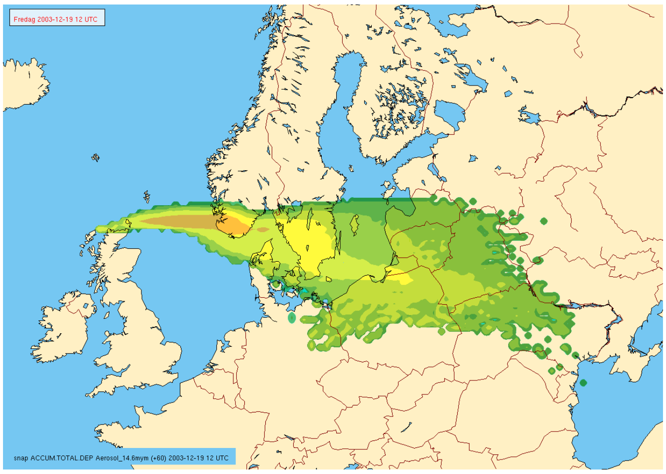
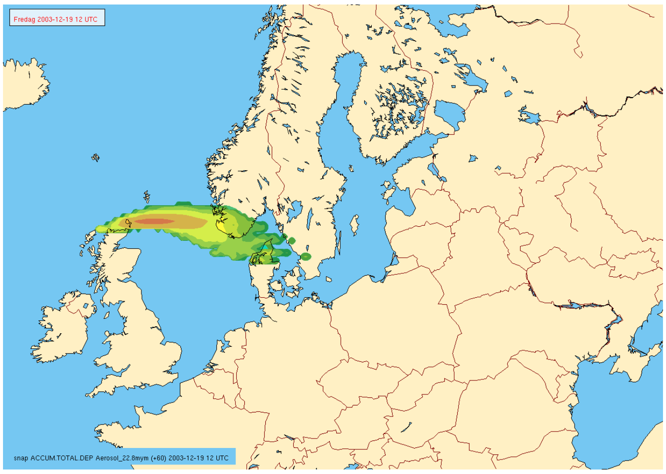


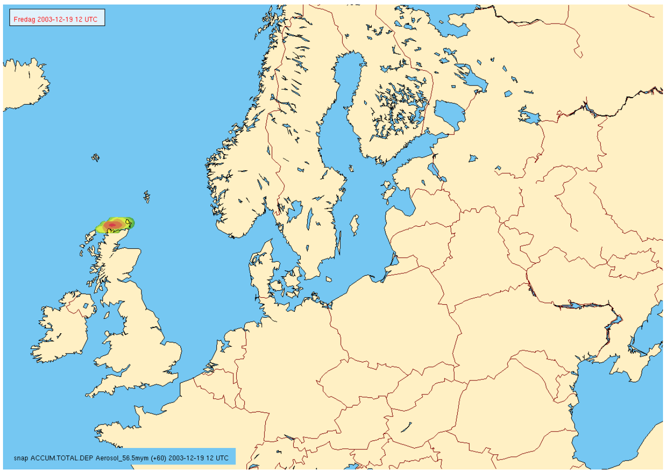
Figure 5. Movement of the radioactive cloud (instantaneous activity close to the surface) after 3, 12, 21 and 60 hours after explosion. Maximum activity 3 hours after the explosion is 106 Bq m-3 close to the site of detonation.



Class 4: Particle radius 14.6 μm



Class 5: Particle radius 22.8 μm

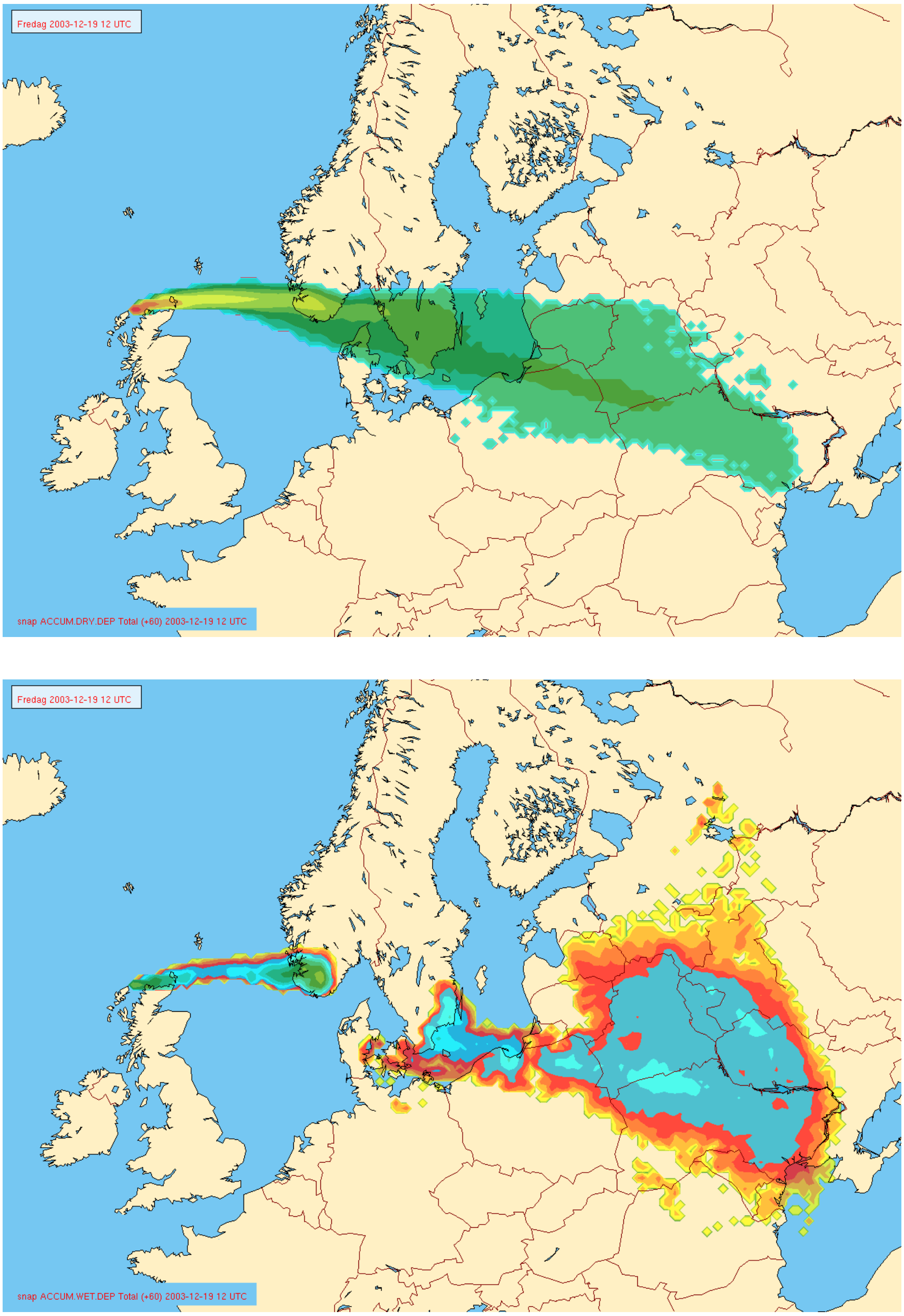


Class 7: Particle radius 56.5 μm

Figure 6. Accumulated total deposition for some of the size classes, 60 hours after explosion.

Forecasted accumulated total deposition 60 hours after the detonation - for some particle size classes - are shown in Figure 6. Only particles with radius smaller than about 20 μm are arriving to - or passing Southern Norway. Larger particles are deposited closer to the site of detonation.

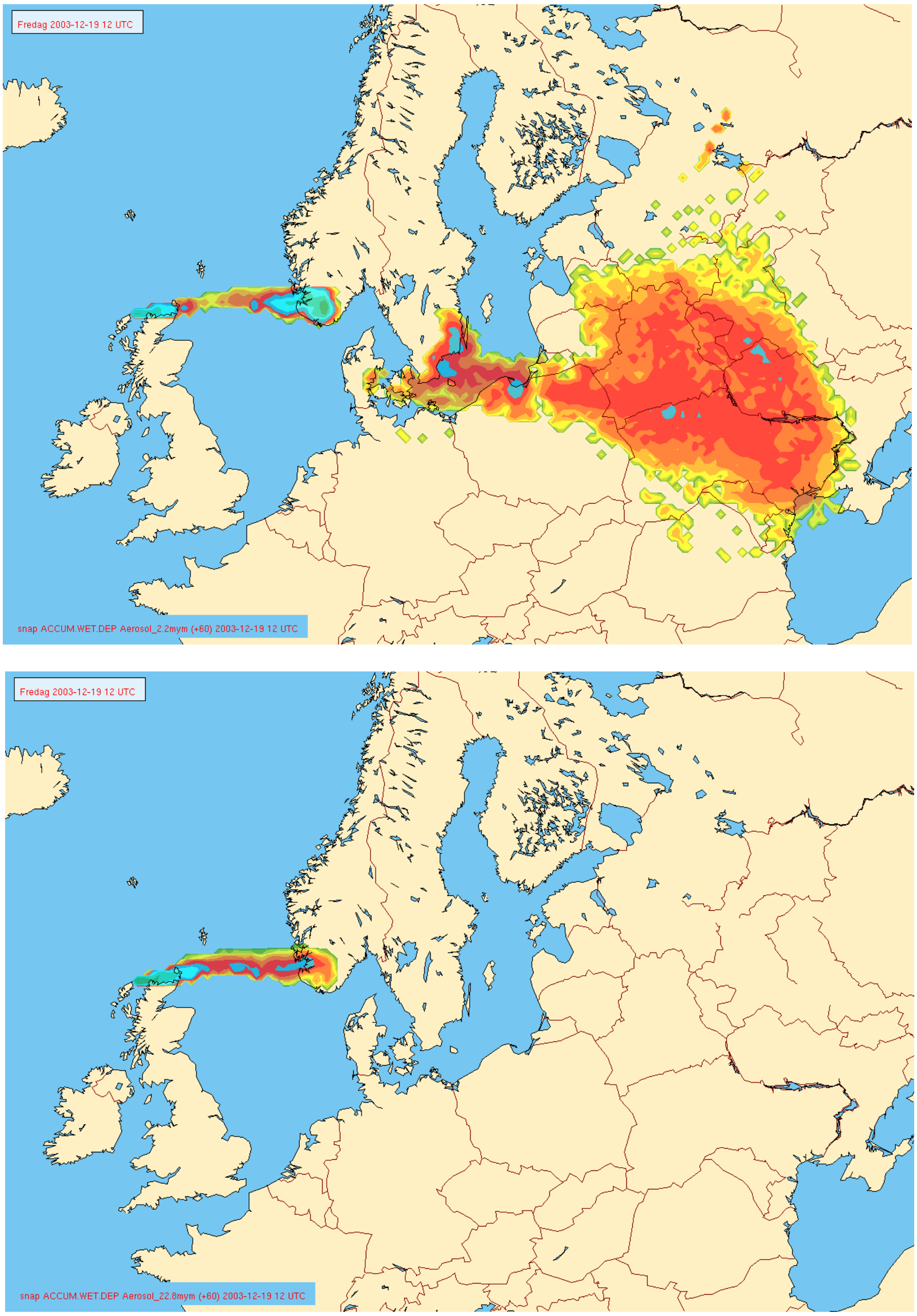
Dry and wet accumulated depositions after 60 hours are shown in Figure 7. The pattern of accumulated dry deposition has a regular and continuous form, whereas the pattern of wet deposition is rather irregular - with scattered local maxima due to irregularity in the precipitation pattern. Note that there is no wet deposition in the Skagerak in the lee of Norwegian mountains.



dry

wet

Figure 7. Accumulated dry and wet deposition 60 hours after explosion. Maximum of dry deposition 1010 Bq m-2 close to the site of detonation. Maximum of wet deposition 108 Bq m-2 occurs in Southern Norway.



Class1

Class 5

Figure 8. Accumulated wet deposition for class 1 (radius 2.2 μm) and for class 5 (radius 22.8 μm) 60 hours after the explosion. Maximum for class 1, - more then 107 Bq m-2 occurs Southern Norway. Maximum for class 5, - also more then 107 Bq m-2 is located near the site of the detonation.

9. Conclusions

A new version of the SNAP model has been developed at the Norwegian Meteorological Institute. This preliminary version is already working reasonably well and according to expectations.

The main conclusions from this development work are summarized below:

- New parameterization of vertical diffusion is kept relatively simple, mainly because of a desire to keep the computational time for the model runs reasonably short.
- In the new parameterization of dry deposition, this process removes less than one percent of the activity (in one model time step) for the three smallest size classes, - particles with radius range 0 11.5 µm. However, the dry deposition process becomes very effective for larger particles.
- The new parameterization of wet deposition, works most effectively for the large particles, - and as precipitation intensity increases, the rate of removal increases for all particle sizes.
- In the first example of model runs, the new version of SNAP was used to simulate a hypothetical nuclear explosion (100 kt yield) north of Scotland at 00 UTC on 17th of December 2003. Concerning different size classes, only particles with radius smaller than about 20 µm arrived to - or past - Southern Norway. Larger particles were deposited closer to the site of explosion. The pattern of accumulated dry deposition (after 60 hours) has a regular and continuous form, whereas the pattern of wet deposition is more irregular with scattered local maxima due to irregularity in the precipitation intensity. Accumulated deposition for class 1 (radius 2.2 µm) and class 5 (radius 22.8 µm) were compared 60 hours after the explosion. The deposition pattern for class 5 ends in Southern Norway, but for class 1 it extends much further to the southeast (see Figures 8).
- As a second example, (not shown in this shortened paper), the new version of SNAP has been used to simulate nuclear explosions of different yields and different initial shape of the radioactive cloud: There were small differences in the results due to different initial shape of the cloud - (cylinder and mushroom). However, there were significant differences in the results for different yields (10 kt and 1000 kt).
- As expected, the different size classes of particles gave quite different deposition patterns. The small particle fraction can be shown to be transported/deposited to distances of continental scale, while the courser fraction will be deposited close to the site of detonation.
- Comparison with military fallout calculations, (not shown in this shortened paper), shows that only the coarse fractions (size class 7 and larger) seems to be of military interest. This compares to the situation shown in example 1, Figure 6, where we see the footprint after the detonation as a local ‘blob’. For sure, here we will find the most concentrated deposition, which is the subject of main concern in tactical military thinking.

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