Atmospheric Transport and Deposition of Particles from Nuclear Detonations

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Content

• Background and short history

• SNAP (Severe Nuclear Accident Program) model concept

• Model applications

• Simulations of nuclear explosions

• Future plans
Background

• Chernobyl accident in 1986
• Contamination of Norwegian territory
• Lack of operational dispersion models (early phase)
• Threats from other potential sources (e.g. Kola)
• Numerical Weather Prediction Models at DNMI
• Cooperation with NRPA, Nordic partners and EU
Main questions in case of an accident (outside Norway):

- Will the radioactive cloud reach Norway?
- If yes, when will the cloud reach Norway?
- What will be concentrations and depositions?

Tools to answer:

- Meteorological analysis e.g. trajectories
- National, operational dispersion model SNAP
- ENSEMBLE (backup + uncertainty)
- Measurements (later phase)
SNAP model - general

- Main ideas from UK NAME model
- Lagrangian particle model
- Gases, noble gases, particles of different size and density
- Advection and diffusion (Random Walk)
- Dry deposition (gravitational settling velocity for particles)
- Wet deposition (function of size and precipitation for particles)
- Meteorological input from HIRLAM 20 and from ECMWF
Applications

- Simulations of Chernobyl accident
- ETEX I and II
- Operational applications (met.no + NRPA)
- METNET project
- ENSEMBLE project
- BOMB version
- HELSINKI scenario (local scale)
Parameters for the cylinder, for the radioactive cloud shortly after the explosion and activities for explosive yield classes. Single cylinder cloud shape (from Person et al., 2000)

<table>
<thead>
<tr>
<th>Explosive yield (ktonnes)</th>
<th>Base of the Cylinder (km)</th>
<th>Top of the cylinder (km)</th>
<th>Radius of the cylinder (km)</th>
<th>Activity (Bq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.50</td>
<td>1.50</td>
<td>0.6</td>
<td>$2 \times 10^{19}$</td>
</tr>
<tr>
<td>10</td>
<td>2.25</td>
<td>4.75</td>
<td>1.4</td>
<td>$2 \times 10^{20}$</td>
</tr>
<tr>
<td>100</td>
<td>5.95</td>
<td>12.05</td>
<td>3.2</td>
<td>$2 \times 10^{21}$</td>
</tr>
<tr>
<td>1000</td>
<td>10.00</td>
<td>25.00</td>
<td>8.5</td>
<td>$1 \times 10^{22}$</td>
</tr>
</tbody>
</table>
Parameters for two cylinders for the radioactive cloud shortly after explosion. **Mushroom** cloud shape. Activities are the same as in previous Table (from Sofiev et al., 2004)

<table>
<thead>
<tr>
<th>Explosive yield (ktonnes)</th>
<th>Base of the upper cylinder (km)</th>
<th>Top of the upper cylinder (km)</th>
<th>Radius of the lower cylinder (km)</th>
<th>Radius of the upper cylinder (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.67</td>
<td>3.365</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>10</td>
<td>5.009</td>
<td>8.072</td>
<td>1.695</td>
<td>2.551</td>
</tr>
<tr>
<td>100</td>
<td>9.255</td>
<td>14.393</td>
<td>1.782</td>
<td>6.711</td>
</tr>
<tr>
<td>1000</td>
<td>13.347</td>
<td>21.635</td>
<td>2.648</td>
<td>17.651</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Class No.</th>
<th>Range of the particle radius (μm)</th>
<th>Activity share (%)</th>
<th>Gravitational settling velocity (cm/s)</th>
<th>Radius (μm) used for estimation of sedimentation velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 3</td>
<td>10</td>
<td>0.2</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>3 - 6.5</td>
<td>10</td>
<td>0.7</td>
<td>4.4</td>
</tr>
<tr>
<td>3</td>
<td>6.5 – 11.5</td>
<td>10</td>
<td>2.5</td>
<td>8.6</td>
</tr>
<tr>
<td>4</td>
<td>11.5 - 18.5</td>
<td>10</td>
<td>6.9</td>
<td>14.6</td>
</tr>
<tr>
<td>5</td>
<td>18.5 - 29</td>
<td>10</td>
<td>15.9</td>
<td>22.8</td>
</tr>
<tr>
<td>6</td>
<td>29 - 45</td>
<td>10</td>
<td>35.6</td>
<td>36.1</td>
</tr>
<tr>
<td>7</td>
<td>45 - 71</td>
<td>10</td>
<td>71.2</td>
<td>56.5</td>
</tr>
<tr>
<td>8</td>
<td>71 - 120</td>
<td>10</td>
<td>137.0</td>
<td>92.3</td>
</tr>
<tr>
<td>9</td>
<td>120 - 250</td>
<td>10</td>
<td>277.3</td>
<td>173.2</td>
</tr>
<tr>
<td>10</td>
<td>≥ 250</td>
<td>10</td>
<td>direct deposition</td>
<td>-</td>
</tr>
</tbody>
</table>
Initial shapes of the radioactive cloud shortly after explosion for 1, 10, 100 and 1000 ktonnes yield. Cylinder type on the left, mushroom on the right.
Vertical coordinate

The hybrid \( \eta \) terrain-following co-ordinate, related to pressure, is the vertical coordinate both in the HIRLAM model and in the SNAP model:

\[
\eta = \frac{p}{p_s} + A \left( 1 - \frac{p_o}{p_s} \right)
\]

Here \( p_s \) is the model surface pressure, \( p_o \) is the reference pressure taken as 1000 hPa, and \( A \) is a specified function of height. The lowest model surface follows the topography, smoothed out in such a way that it fits the horizontal grid resolution. For this surface, the value of \( A \) is zero. Further up in the atmosphere, \( A \) varies with height until \( \eta=A \) at the top of the model atmosphere. The \( \eta \) values belong to the interval \([0,1]\). At the upper model boundary \( \eta=0 \) for \( p=0 \) and at the surface \( \eta=1 \) for \( p=p_s \).
The displacement of each particle is calculated, for one time step, according to the following equation:

\[ x'_{t+\Delta t} = x'_t + \nu (x'_t) \Delta t \]

- \( x'_t = (x, y, \eta) \) - position of the particle before advection
- \( \nu = (u, v, \dot{\eta}) \) - velocity field at time \( t \)
- \( x'_{t+\Delta t} \) - position of the particle after the advection
A random walk approach is used to parameterize horizontal and vertical diffusion. The new particle position after diffusion is calculated as:

\[ x'' = x' + r_x l \]
\[ y'' = y' + r_y l \]
\[ \eta'' = \eta' + r_\eta l_\eta \]

\[ x''_{t+\Delta t} = (x'', y'', \eta'') \] - vector of particle position after application of diffusion

\[ r_x, r_y, r_\eta \] - randomly sampled values from the range (-0.5, +0.5), generated from a uniform distribution

\[ l, l_\eta \] - the length scale parameters for horizontal and vertical turbulent motion
We assume a horizontal length-scale for the turbulent motion, defining horizontal diffusion:

\[ l = ax^b \]

\[ x = |\vec{v}| \Delta t \quad \text{- displacement of particle} \]

\[ |\vec{v}| = \sqrt{u^2 + v^2} \quad \text{- wind speed} \]

\[ b = 0.875 \]

\[ a = 0.5 \quad \text{- below ABL} \]

\[ a = 0.25 \quad \text{- above ABL} \]
Vertical diffusion

The scale of vertical diffusion is different within ABL and above the boundary layer. Parameterization of vertical diffusion in the bomb version of SNAP is relatively simple, because of the large particles low sensitivity to vertical diffusion process compared to gravitational settling. The advantage of this simplification is a better performance of the model concerning computational time.

\[ l_\eta = 0.08 \quad \text{- below ABL} \]

\[ l_\eta = 0.04 \quad \text{- above ABL} \]
Dry deposition (1)

A key parameter in the dry deposition process is the dry deposition velocity, which can be calculated based on the resistance analogy (Seinfeld 1986). For particles of arbitrary size:

\[
\nu_d = \left( r_a + r_s + r_a r_s \nu_s \right)^{-1} + \nu_s
\]

- \( r_a \) - the aerodynamic resistance, accounts for turbulent diffusion from the free atmosphere to surface laminar sub-layer

- \( r_s \) - the surface layer resistance, related to diffusion through a laminar sub-layer

- \( \nu_s \) - the gravitational settling velocity, a dominating dry deposition process for large particles
For conditions when the 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):

\[ v_s = \frac{d_p^2 \cdot g \cdot (\rho_p - \rho_a) \cdot C(d_p)}{18 \nu} \]

- \( d_p \) - particle diameter
- \( g = 9.81 \) - acceleration of gravity (m s\(^{-2}\))
- \( \rho_p \) - density of particle
- \( \rho_a = \rho_a(p, T) \) - density of the air
- \( C(d_p) \) - Cunningham correction factor
- \( \nu = \nu(T) \) - dynamic molecular viscosity of the air
Gravitational settling velocity (2)

The density of the air is calculated from the equation of state

\[ \rho_a = \frac{p}{R \cdot T} \]

- \( p \) - atmospheric pressure
- \( T \) - absolute air temperature
- \( R \) - gas constant for dry air (J kg\(^{-1}\) K\(^{-1}\))

Viscosity of the air is a function of temperature (RAFF, 1999):

\[ \nu = 1.72 \times 10^{-5} \cdot \frac{393}{T + 120} \cdot \left( \frac{T}{273} \right)^{\frac{3}{2}} \]

Cunningham correction factor for small particles is calculated as (Zannetti, 1990; Seinfeld, 1986):

\[ C(d_p) = 1 + \frac{2\lambda}{d_p} \cdot \left( 1.257 + 0.4e^{-0.55 \frac{d_p}{\lambda}} \right) \]

\[ \lambda = 6.53 \times 10^{-8} \] - mean free path of air molecules (m)
Gravitational settling velocity (3)

Stokes equation is not valid for particles with the radius larger than 10 – 15 μm. 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 following equations (Seinfeld, 1986):

\[
\nu_s \left(1 + \frac{3}{16} \text{Re} + \frac{9}{160} \text{Re}^2 \ln(2 \text{Re})\right) = \frac{d_p^2 \cdot g \cdot (\rho_p - \rho_a) \cdot C(d_p)}{18\nu} \quad 0.1 < \text{Re} \leq 2
\]

\[
\nu_s \left(1 + 0.15 \text{Re}^{0.678}\right) = \frac{d_p^2 \cdot g \cdot (\rho_p - \rho_a) \cdot C(d_p)}{18\nu} \quad 2 < \text{Re} \leq 500
\]

\[
\text{Re} = \frac{\nu_s d_p \rho_a}{\nu} \quad \text{- Reynolds Number}
\]

Above equations are non-linear and require numerical solution, which is slowing down model performance. In the operational ‘bomb’ version of SNAP, we have used constant values of gravitational settling velocities for each of the selected classes, so that application of these equations did not significantly reduced the model performance.
Dry deposition (2)

In the model equations we have assumed that model particles located above the mixing height level are not affected by the dry deposition process. Reduction of activity $A$, for each model particle located within the mixing height, due to dry deposition after time $\Delta t$ can be calculated as:

$$A(t + \Delta t) = A(t) \cdot e^{-k_d \cdot \Delta t}$$

$$k_d = \frac{v_d}{h}$$

Percent of activity remaining in the model particle after one model time step (min.) with dry deposition only, for each of 10 particle size classes.
Wet deposition (1)

\[ A(t + \Delta t) = A(t) \cdot e^{-k_w \cdot \Delta t} \]

The coefficient of wet deposition \( k_w \) is a function of the particle radius \( r \) and the precipitation intensity \( q \) (Baklanov and Sørensen, 2001):

- \( r \leq 1.4 \mu m \)
  \[ k_w = a_0 \cdot q^{0.79} \]
- \( 1.4 \mu m < r \leq 10 \mu m \)
  \[ k_w = (b_0 + b_1 \cdot r + b_2 \cdot r^2 + b_3 \cdot r^3) \cdot f(q) \]
- \( r \geq 10 \mu m \)
  \[ k_w = f(q) \]

\[ f(q) = a_1 \cdot q + a_2 \cdot q^2 \]

- \( a_0 = 8.4 \cdot 10^{-5} \)
- \( a_1 = 2.7 \cdot 10^{-4} \)
- \( a_2 = -3.618 \cdot 10^{-6} \)
- \( b_0 = -0.1483 \)
- \( b_1 = -3.220133 \)
- \( b_2 = -3.0062 \cdot 10^{-2} \)
- \( b_3 = 9.34458 \cdot 10^{-4} \)
Percent of activity remaining in the particle after one model time step with wet deposition only, for four particle classes.
Simulations

(1) In the first example, the SNAP model has been used to simulate a hypothetical nuclear explosion north of Scotland on 17 December 2003 at 00 UTC. Forecasted meteorological situation (wind, MSLP and precipitation) indicated transport of radioactive debris to the east passing southern Norway.

(2) In the second example of simulation, 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.
Simulation (1) – meteorology

Meteorological situation, 3 hrs and 60 hrs after explosion. MSLP, wind at 10m level and precipitation are shown.
Simulation (1) – results

Movement of the radioactive cloud (instantaneous activity at the ground) up to 60 hours after explosion with 3 hours interval. Maximum of the activity – 106 Bq m\(^{-2}\) near the detonation site
Simulation (1) – results

Class 1: Particle radius 2.2 μm
Class 2: Particle radius 4.4 μm
Class 3: Particle radius 8.6 μm

Class 4: Particle radius 14.6 μm
Class 5: Particle radius 22.8 μm
Class 6: Particle radius 36.1 μm

Class 7: Particle radius 56.5 μm
Class 8: Particle radius 92.3 μm
Class 9: Particle radius 173.2 μm

Accumulated total deposition for different classes particles, 60 hours after explosion.
Accumulated total dry and total wet deposition 60 hours after explosion. Maximum of dry deposition – 1010 Bq m\(^{-2}\) close to the detonation site. Maximum of wet deposition – 108 Bq m\(^{-2}\) occurs in the south of Norway.
Accumulated total deposition (sum from all particle classes) 60 hours after explosion.
Comparison of accumulated total deposition for cylinder and mushroom initial shapes for the radioactive cloud: 12, 24, 36, 48 and 60 hrs after the explosion. The location of explosion is Jan Mayen and the yield is 10 ktonnes.
Comparison of accumulated total deposition for cylinder and mushroom initial shapes for the radioactive cloud: 12, 24, 36, 48 and 60 hrs after the explosion. The location of explosion is Jan Mayen and the yield is 1000 ktonnes.
Future

- Bomb/particle operational with HIRLAM 10
- High resolution model (1 km) which can be applied in the accident area
- New parameterizations (e.g. dirty bombs)
- Explanations of past events e.g. Bomb detonations in late 50-ties and 60-ties
Thank you for attention

We hope that in the future SNAP model will be used for hypothetical and historical cases, ONLY!