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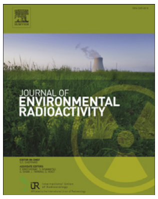

Atmospheric transport of radioactive debris to Norway in case of a hypothetical accident related to the recovery of the Russian submarine K-27

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ABSTRACT

The Russian nuclear submarine K-27 suffered a loss of coolant accident in 1968 and with nuclear fuel in both reactors it was scuttled in 1981 in the outer part of Stepovogo Bay located on the eastern coast of Novaya Zemlya. The inventory of spent nuclear fuel on board the submarine is of concern because it represents a potential source of radioactive contamination of the Kara Sea and a criticality accident with potential for long-range atmospheric transport of radioactive particles cannot be ruled out. To address these concerns and to provide a better basis for evaluating possible radiological impacts of potential releases in case a salvage operation is initiated, we assessed the atmospheric transport of radionuclides and deposition in Norway from a hypothetical criticality accident on board the K-27. To achieve this, a long term (33 years) meteorological database has been prepared and used for selection of the worst case meteorological scenarios for each of three selected locations of the potential accident. Next, the dispersion model SNAP was run with the source term for the worst-case accident scenario and selected meteorological scenarios. The results showed predictions to be very sensitive to the estimation of the source term for the worst-case accident and especially to the sizes and densities of released radioactive particles. The results indicated that a large area of Norway could be affected, but that the deposition in Northern Norway would be considerably higher than in other areas of the country. The simulations showed that deposition from the worst-case scenario of a hypothetical K-27 accident would be at least two orders of magnitude lower than the deposition observed in Norway following the Chernobyl accident.

1. Introduction

In September 1981, the nuclear submarine K-27 was scuttled in very shallow waters (depth of just 30 m) in the outer part of Stepovogo Bay on the eastern coast of Novaya Zemlya (72°31′N, 55°30′E) where it lies today. The submarine K-27 is one of several objects with spent nuclear fuel (SNF) which have been dumped in the Kara Sea over time. K-27 contains two liquid metal reactors (LMRs) of 70 MW maximum thermal power each, which used Pb–Bi as a coolant. The reactors were loaded with 180 kg of U-235. Concerns have been expressed by various parties with regards to the radiological consequences of potential radionuclide releases from the submarine and in particular potential releases if a salvage operation is initiated.

There are four scenarios that have been envisaged which could result in potential releases from the submarine when subjected to different, hypothetical management options and/or handling stages. These include: (i) potential leakage or accident associated with the so called "zero alternative", when no action is taken. The

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submarine remains at its current location and any release would occur at a depth of 20–30 m below the sea surface. In this case most of the available radionuclides would be released directly into the water, (ii) a potential accident during the lifting of the submarine to the surface. Depending on the depth, the major part of the available radionuclides would be released either into the water or directly into the air. (iii) an accident during transportation of the submarine from Novaya Zemlya to its probable final destination at Gremikha Bay – one of the sites where radioactive wastes related to the Russian Northern Fleet activities have been accumulated. (iv) a potential accident at the final destination at Gremikha Bay. The hypothetical accidents in alternatives (iii) and (iv) have the potential to occur on the water surface or on shore with most of the radionuclides released directly into the air.

In our study, we only take into account the last three scenarios as all of these involve direct releases of radionuclides into the air. There is also a possibility for an accident to occur under water. At locations close to the surface, this would create a secondary release of radionuclides into the air, but the magnitude of such a release is assumed to be much lower than in the case of a direct release into the air.

For all the alternatives mentioned above, a risk of an accident as a consequence of an uncontrolled chain reaction event cannot be ruled out. Such a hypothetical accident might pose a risk of contamination occurring over Norwegian territory and thus, should be analysed from different perspectives. Here, we focus on the worst case meteorological scenario for Norway as a receptor, but the same approach can be applied for other receptors e.g. Scandinavian countries and Russia. The main goal of this study was to analyse atmospheric transport to and deposition of radionuclides over Norwegian territory, in case of a nuclear accident related to lifting and transporting the K-27 submarine. Preliminary results of the study have been described in Bartnicki et al. (2013). Here we present the final results.

2. Material and methods

The SNAP (Severe Nuclear Accident Program) model (Bartnicki et al., 2011) was the main tool for all dispersion simulations presented here. This Lagrangian particle dispersion model is currently operational at the Norwegian Meteorological Institute, MET, for emergency situations.

The estimation of the atmospheric transport to and deposition of radionuclides over Norway released in a hypothetical K-27 accident has been performed in six steps. The first step was a preparation of a large database with meteorological data required as input for the SNAP model, for a period of 33 years (1980–2012). This meteorological database is available for a domain covering an area of 4400 km × 2200 km which includes both the entire Norwegian territory and the region of Novaya Zemlya where the K-27 submarine is currently located.

The second step involved the development of a preliminary source term for potential accidents which could be used by the dispersion model. Three locations for potential accidents with resultant releases of radioactivity to the environment were assumed: 1) in the present location of K-27 at Novaya Zemlya, 2) on the way to Murmansk and 3) in Gremikha Bay as the final destination.

In the third step, the SNAP model was run with the preliminary source term starting twice a day for the entire 33 years period with meteorological data. As a result of the model simulations, surface concentration fields and deposition fields were calculated for selected radioactive particles for the entire model area.

Based on these results, in the fourth step, the worst case meteorological scenarios were selected for potential accidents in each of the three locations. They were selected based on the highest levels of deposition on Norwegian territory. In addition, statistical analysis was performed for the 33-year period in this step. This analysis included calculation and discussion of the probability of arrival to an arbitrary place in Norway and the calculation of the shortest arrival time.

The fifth step focussed on development of the final source term corresponding to the K-27 accident scenario involving a hypothetical uncontrolled chain reaction with 10^{20} fissions and the most recent estimates of residual activities for the reactors on board the nuclear submarine K-27 (NRPA, in preparation). The final source term was estimated based on experiences from the Chernobyl accident and includes different categories (groups) of radioactive particles and iodine gases. Particle densities were calculated from physical data given in Lide (2005) and under the assumption of a UO_2Be composition of the reactor fuel (IAEA, 1997).

In the sixth and final step of the study, the SNAP model was run with the final source term for selected worst case meteorological scenarios for all three locations of the potential accident. The results of these runs are presented and discussed here.

2.1. SNAP model

The SNAP model is a Lagrangian particle model and has been developed at MET for simulating atmospheric dispersion of radioactive debris, first from nuclear accidents and then from nuclear explosions. As is the case for many other models, the development of SNAP started after the Chernobyl accident which occurred in April 1986. The first, preliminary version of SNAP was developed in 1994 and became fully operational at MET in December 1995 (Saltbones, 1995). It was tested against tracer measurements in the European Tracer Experiment (ETEX) (Saltbones et al., 1996) and then improved (Bartnicki and Saltbones, 1996). The SNAP model was compared with other models (Maryon et al., 1996) and tested on measurements available from the tracer experiment – ATMES (Saltbones et al., 1998).

The basic concept of a Lagrangian particle model is rather simple in principle. The emitted mass of radioactive debris is distributed among a large number of model particles. After the release, each model particle carries a given mass of selected pollutant which can be in the form of gas, aerosol or particulate matter. A model particle, in this approach, is given an abstract mathematical definition, rather than providing a definition for a physical air parcel containing a given pollutant. The model particle is used in SNAP as a vehicle to carry the information about the pollutant emitted from the source. It is not given a definite size and cannot be subdivided or split into parts. On the other hand, the mass carried by the particle can be subdivided and partly removed during the transport.

The plume rise in the SNAP model is not explicitly calculated, because for long range atmospheric transport it is assumed that the plume rise effect is already included in the initial distribution of the radioactive cloud after the accident or explosion and especially in the vertical range. This is a typical approach for most of the long range transport models.

In the early versions of the SNAP model, only aerosols (diameter below 1 μm particles) were taken into account in the model equations. However, measurements performed by the Norwegian University of Life Sciences after the Chernobyl accident, showed that large particles (mm) to fragments were deposited close to the site, while much smaller radioactive particles (in the order of 1–20 μm), so called 'hot particles', could also be transported for long distances and end up in Norway 2000 km from the release site (Salbu et al., 2001). Later, it has been observed that radioactive particles are released following all types of severe nuclear events (Salbu and Skipperud, 2009; Salbu and Lind, 2011; Wendel et al., 2013). Therefore, parameterization of particle properties (arbitrary diameter, composition and density) was introduced into the SNAP model and this model version was applied to re-simulate the Chernobyl accident (Bartnicki et al., 2003). This version was also applied for simulating the potential release from Kola, focussing on the release of radioactive particles of different size and density (Bartnicki et al., 2005).

Introduction of arbitrary particles into the SNAP equations made it possible to create a model version for nuclear explosions (Saltbones et al., 2003). In the current model version (Bartnicki et al., 2011), atmospheric dispersion from both nuclear accidents and nuclear explosions can be simulated, as well as, atmospheric transport and deposition of radioactive particles of arbitrary size and density. This model version has been used for all the computations presented and discussed here.

2.2. Meteorological database

The European Medium Range Weather Forecast Centre (ECMWF) in Reading, UK, is a valuable source of not only meteorological forecasts, but of long term historical meteorological data as well. For the specific Norwegian needs, a historical meteorological database NORA10 was developed first (Reistad et al., 2011) based on ERA40 – a historical database developed at ECMWF (Uppala et al., 2005). For the present study, a new improved meteorological database called NORA10-EI has been prepared and used. The database NORA10-EI has been produced by dynamical downscaling of the ERA-Interim (Dee et al., 2011) reanalysis with the HIRLAM numerical weather prediction model (Undén et al., 2002). Its domain includes the north-eastern North Atlantic and the Nordic countries. The horizontal resolution is approximately 11 km. Surface fields are stored every hour, while model level fields are stored every third hour. This database covers the period January 1980 and up to December 2012. It has been used as a meteorological input for all SNAP runs in this study.

2.3. Selection procedure

It is difficult to formulate a set of objective criteria for selecting the worst case meteorological scenario for the atmospheric transport of radionuclides to Norway. Considering the problem from the environmental perspective, maximum deposition over Norwegian territory has been used as the main criterion in selecting the worst case scenario.

Three locations of a hypothetical K-27 accident were taken into account: 1) the initial – present location of K-27, 2) the location on the way to Murmansk region and 3) the final location corresponding to a reception point at Gremikha Bay. A map with all three locations of the potential accidents is shown in Fig. 1.

The selection of the worst case meteorological scenario was made by performing SNAP model runs for a given accident scenario for the entire considered period. The transport of the recovered K-27 over the Barents Sea would be possible only during a two-month window (August and September) because of difficult meteorological conditions and extensive presence of sea ice in the remaining months of the year. Therefore, for the accidents at all locations, SNAP was run twice a day, but only for August and September, each year.

The source-term of the worst case accidents at the different locations is highly uncertain. To separate the meteorological variability from the source term uncertainties, a simplified source term has been selected for the identification of the worst meteorological case. This simplified source-term defined in Table 1 assumed release of ^{137}Cs particles with diameter 0.55 μm and density 2.3 g cm^{-3}. The size and density are taken from ARGOS database (Hoe et al., 2002; Bartnicki et al., 2011). ARGOS is a decision support system used by radiation protection authorities in Scandinavian countries: Norway, Denmark Sweden and Finland.

The deposition of ^{137}Cs to Norwegian territory has been used as a pre-selection criterion for the worst cases for each accident location. The top cases of the pre-selection were then inspected visually for the final selection of the worst case meteorological scenarios.

2.4. Worst case source term for K-27 accident

The simplified preliminary source term was only used for the model runs in the selection procedure. A more advanced and complicated source term was developed for the final SNAP runs with the selected worst case meteorological scenarios. This source term was based on the inventory which has been developed through considering, among other things, the reactor design and its existing barriers (furfural, bitumen).

For the compilation of the potential source term it is necessary to estimate the residual activities in the reactor of the submarine located in different places within the vessel and related to different radionuclides. There are several estimates available from the past (IAEA, 1997; Lavkovsky, 1999), but in the present work we have used the most updated estimates of residual activities for the K-27 reactor by 2013, as shown in Table 2. More details concerning this source term are provided in NRPA (in preparation).

Degradation of the reactors with time may lead to an event involving a Spontaneous Chain Reaction (SCR). There are two possible conditions for an SCR to occur: (1) water penetration into the core, and (2) relative displacement of fuel resulting in reduction in the compensation capacity of the Control and Protection System (CPS) operating elements. The reactor compartment of K-27 was sealed before dumping to reduce risk of releases of radionuclides in the marine environment. In addition, measures were taken to prevent displacement of fuel and infiltration of water through injection of preservatives (e.g. furfural, bitumen) into the free spaces of the reactor compartments.

The specification of the source term for the final model runs was developed with all the above facts in mind. In the final model runs, utilizing the worst case meteorological scenarios, the same source term was used for all three locations of the potential accident. Activities for the present study were calculated at the time of release assuming various release fractions as considered by NRPA (in preparation), plus the activity generated during a potential criticality event.

Four particle classes with different densities and sizes and iodine gas were taken into account in determining the source term for the final model runs. Specification of the source term for four classes of particles and for iodine gas is shown in Table 3.

In the SNAP model, the properties of radioactive particles (U matrix) and gases are included in the so-called “model particles” explained in Section 2.1. The number of model particles for simulating the source term, described in Table 3, can be reduced, mainly because of similarities between different groups of radioactive particles. The specification of the model particles used in the SNAP runs for the worst case scenarios is presented in Table 4.

Altogether, 30 model particles were used in the SNAP runs with the final source term. These model particles represent the real particles listed in Table 3. We assumed a release time of 1 h and a release height in the range of 0–100 m for this accident.

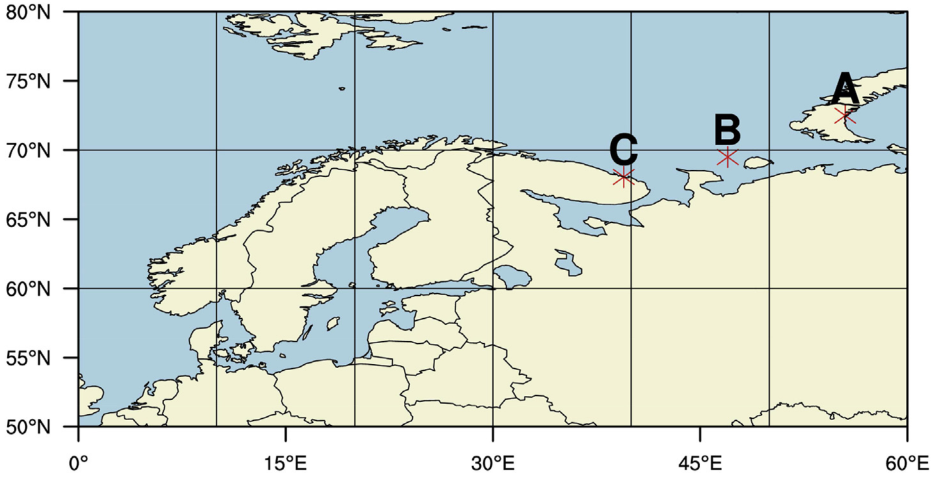


Fig. 1. Three accident locations which have been taken into account in the selection procedure: A) the initial – present location of K-27, B) the location on the way to Murmansk region and C) the final location at Gremikha Bay.

3. Results and discussion

The extensive meteorological database which was established within this study has been used for the selection of the worst case meteorological scenarios and statistical analysis of the results and especially for the probability maps of arrival to Norway (see Section 3.2).

3.1. Selection of the worst case meteorological scenarios

An important element of the selection procedure is the choice of the criterion or criteria for the worst case. This is a challenging problem which can be approached from different perspectives.

Under normal conditions, wet deposition is the most effective mechanism for significant deposition, even at substantial distances from the original source (Wright et al., 1997). Therefore, wet meteorological situations need to be accounted for and especially for those situations involving long-distance atmospheric transport without precipitation on route followed by heavy precipitation at the arrival point.

In this study focus has been placed upon the potential for environmental impacts, including impacts on food-chains leading to man. Thus, average deposition over Norwegian territory was chosen as the worst case criterion in the selection procedure. Only ^{137}Cs particles were released in the preliminary source term. These particles are among the smallest and lightest, being subject to moderate wet-deposition. The ^{137}Cs is also a well-studied isotope and has been observed to undergo long-range atmospheric transport.

From all model runs we selected those contributing to non-zero deposition to Norwegian territory. By dividing the number of contributing runs by the number of total runs we could calculate the percentage of meteorological situations with transport to Norway from the accident locations. The number of cases with deposition above zero decreased with the distance between the release location and Norway. For releases at the initial location, during the transport and at the final destination, the probabilities

Table 1
Specification of the preliminary source term used for the selection procedure.

Parameter	Value
Initial location	72.5N 55.5E
Intermediate location	69.5N, 47.0E
Final location	68.04N, 39.33E
Radionuclide	Cs-137 in the particle form
Particle size	0.55 μm
Particle density	2.3 g cm^{-3}
Release rate	2.0×10^{11} Bq s^{-1}
Release period	12 h
Vertical range	0–500 m

Table 2
The most recent estimates of residual activities for the reactors on board the nuclear submarine K-27. Reference year 2013.

Activity source	Main radionuclides	Activity (TBq)
Fission products	^{137}Cs + ^{137m}Ba, ^{90}SR + ^{90}Y	270
Control rods	^{152}Eu, ^{154}Eu	40
Reactor shell constructions	^{63}Ni, ^{60}Co	11
Actinides	^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am	4.6
Tritium	^{3}H	34

Table 3
Source term for the worst case accident scenario for K-27 submarine which includes a hypothetical SCR event.

Component	Half-life	Total release (Bq)
UO$_2$Be, density = 2.1 g cm^{-3}, size classes: 0.1, 0.5, 1.0, 5.0, 10.0, 20.0, 50.0, 100.0 μm		
^{137}Cs	30.17 years	7.1×10^{12}
^{90}Sr	28.8 years	6.2×10^{12}
^{238}Pu	No decay	1.6×10^{11}
Bitumen, density = 1 g cm^{-3}, size classes: 0.1, 0.5, 1.0, 5.0, 10.0, 20.0, 50.0, 100.0 μm		
^{137}Cs	30.17 years	4.4×10^{11}
^{90}Sr	28.8 years	3.9×10^{11}
^{238}Pu + ^{240}Pu	No decay	1.0×10^{10}
^{131}I	8.04 days	1.4×10^{11}
Metal coolant, density = 10.5 g cm^{-3}, size classes: 0.1, 0.5, 1.0, 5.0, 10.0, 20.0, 50.0, 100.0 μm		
^{137}Cs	30.17 years	4.4×10^{11}
^{90}Sr	28.8 years	3.9×10^{11}
^{238}Pu	no decay	1.0×10^{10}
Ru-106, density = 3.3 g cm^{-3}, size classes: 0.1, 0.5, 1.0, 5.0, 10.0, 20.0 μm		
^{106}Ru	1.02 years	1.9×10^{9}
I-131, gas, density = 0.0113 g cm^{-3}		
^{131}I	8.04 days	1.4×10^{11}
^{133}I	20.04 h	5.2×10^{12}

Table 4
Specification of the model particles representing the real particles and gases for the worst case SNAP model runs. The symbol "●" indicates the type of the model particle used in the simulations. Decay means assumed decay half-life.

Group	Density (g cm^{-3})	Radius (μm)								Release (Bq)	Decay (h)
		0.1	0.5	1.0	5.0	10	20	50	100		
UO_2Be	2.1	●	●	●	●	●	●	●	●	1.35×10^{13}	No
Bitumen	1.0	●	●	●	●	●	●	●	●	9.8×10^{11}	No
Metal	10.5	●	●	●	●	●	●			8.4×10^{11}	No
^{106}Ru	3.3	●	●	●	●	●	●			1.9×10^{9}	No
^{131}I	0.0113	●								1.4×10^{11}	192.96
^{133}I	0.0113	●								5.2×10^{12}	20.04

of reaching Norwegian territory were 17%, 25% and 37%, respectively. Also, the average deposition over Norway was clearly dependent upon the distance from the release location, with the largest depositions occurring for the source located at the final destination.

The worst meteorological cases for hypothetical accidents are presented as maps of total ^{137}Cs deposition in Fig. 2. For the hypothetical accident at the initial location, the worst case meteorological scenario was found for a release starting on 26th August 1998 at 00 UTC. For the hypothetical accident during transport and at the final destination, the worst case meteorological scenario was found for a release starting on 7th September 1986 at 12 UTC and on 22nd September 2004 at 12 UTC, respectively. These selected meteorological situations were used for SNAP runs with the worst case accident scenario discussed in Section 3.3.

The deposition pattern is similar for initial and final accident locations and also similar, but with some small differences, for the accident location during transport or 'on the way'. In all three cases, there is a clear initial transport of radionuclides to the west, before the plume trajectory turns to the south and even to the east during the late stage of transport. The main difference for the accident location 'on the way' is the visible addition of direct transport to the east from the source.

For all accident locations, a relatively high deposition level can be noticed in the most northern part of Norway. Elevated depositions can be also observed in central Norway. Deposition levels in southern Norway are much lower than those in northern Norway.

The selected meteorological situations described above were used for the model runs with the realistic, worst case accident scenario discussed in Section 3.3.

3.2. Probability maps

The probability of arrival is an important piece of information for risk estimation. The probability of arrival to a given model grid was calculated as the ratio of model runs with non-zero deposition in a given grid to the total number of model runs. The maps of probability of arrival to each model grid are shown in Fig. 3 for all three accident locations.

The probability of arrival to Norway is clearly higher for the hypothetical accident at the final destination in Gremikha Bay than for accidents at the two other locations. The probability of arrival has a maximum in the very northern part of Norway falling within the ranges 10–15%, 15–25% (but closer to 15%) and 15–25% (but closer to 25%) for the accident in the initial location, 'on the way' and at the final destination, respectively. These probabilities are much lower in the model grids located in southern Norway, below 1% for the accident at the initial location and below 3% for the accident at the remaining locations.

3.3. Worst case scenarios with the final source term

The SNAP model was run with the source term for the realistic, worst-case accident scenario described in Section 2.4 and for all three selected worst case meteorological scenarios.

Limited information was available in relation to a realistic radionuclide distribution among different particle size classes and a particle distribution pattern for the worst case source term. Therefore, an equal distribution was assumed for each of the size classes used in the SNAP runs. This assumption could lead to an overestimation of the contribution of large particles to the deposition, while this potential overestimation will be limited to short range transport only.

The heat generated during an explosion would have the potential to lift radioactive pollutants into the air. Usually the upper limit for vertical distribution of pollutants in such cases is the top of the mixing layer. For the chosen locations and the time of the year when the potential accidents could occur, a typical height of the mixing layer would be about 100 m. Therefore, we have assumed the release to be in the range of 0–100 m, corresponding to a typical mixing layer with a height of 100 m.

The horizontal spread of radionuclides during the release was assumed to occur in a cylinder with a radius of 25 m. There is some uncertainty in this assumption, but for a long range transport, as exemplified by our case, the calculated levels of deposition are rather insensitive to this parameter.

The results of the model simulations for the worst case accident scenario and worst case meteorological scenarios are shown in Fig. 4 for all three locations of the hypothetical accident. This figure shows the total deposition after 96 h from the accident start. Total refers to the sum of wet and dry deposition from all considered particle classes.

In case of the accident at the initial location, two regions situated in the northern part of Norway would be affected. The absolute maximum values of total deposition for this scenario were seen in the northern part of Finnmark, falling in the range of 10–30 Bq m^{-2}. The range of total deposition in the region between Nordland and Troms was slightly lower: 3–10 Bq m^{-2}. The rest of Norway was practically unaffected by radioactive contamination in this scenario.

The shape of the total deposition was predicted to be slightly different in the case of an accident location 'on the way', but also, in this case, the absolute maximum was observed in northern Norway. However, the maximum of total deposition in the northern part of Finnmark was close to 300 Bq m^{-2}, much higher than in the previous case. Also in this scenario, the central and southern parts of Norway were not affected by the accident.

The Norwegian area covered by the deposition in case of the accident location in Gremikha Bay was predicted to be significantly larger than in the two previous cases. The local maxima of total deposition were visible again in the north, affecting the three

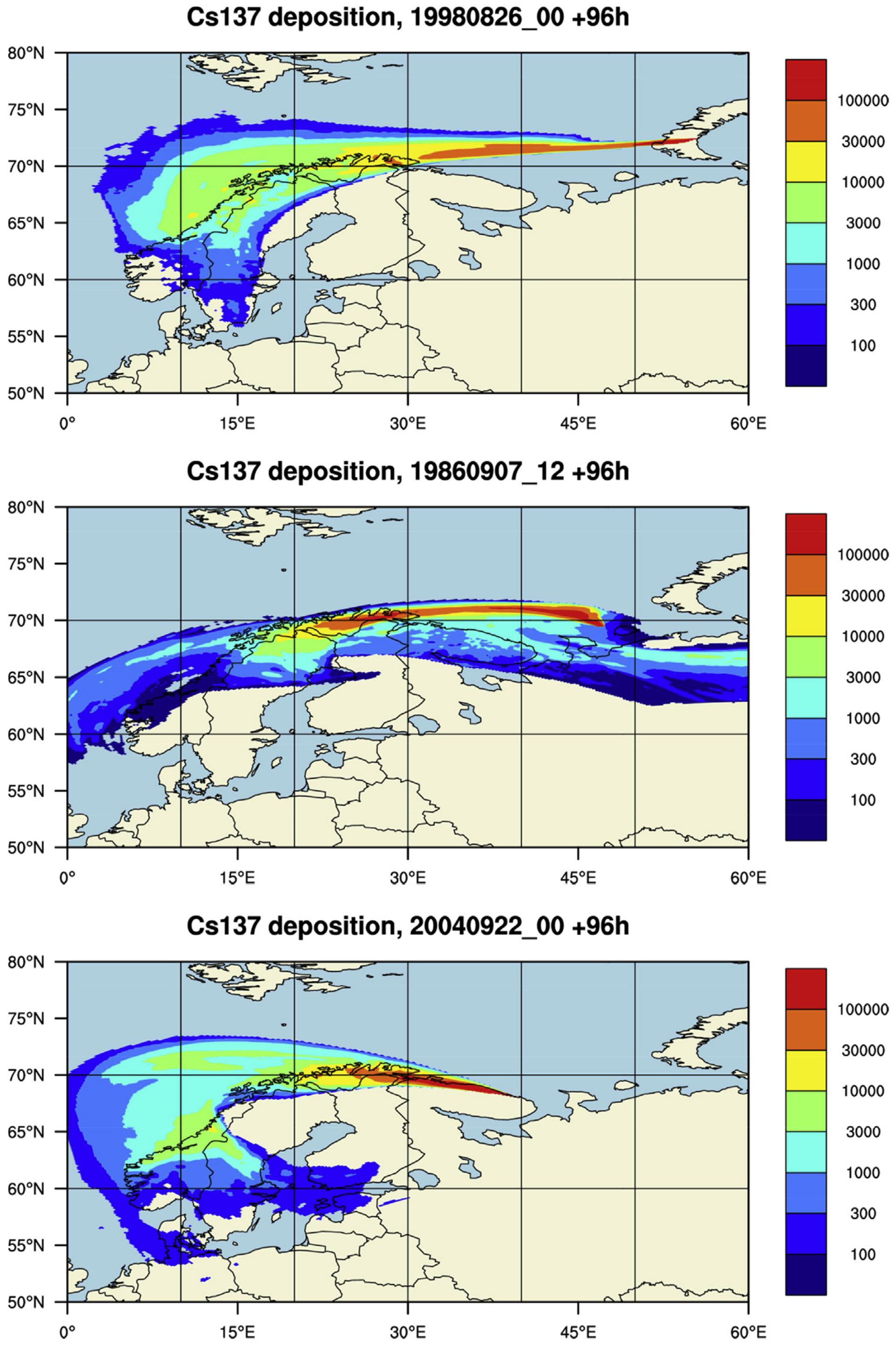


Fig. 2. Maps of total deposition of ^{137}Cs in the worst case meteorological scenarios, 96 h after the accident start. Accident at initial location – top, accident on the way – middle and accident at the final destination – bottom. Units: Bq m^{-2}.

counties: Finnmark, Troms and Nordland. In addition, several counties in central Norway (Nord-Trøndelag, Sør-Trøndelag, Møre and Romsdal, Oppland and Hedmark) were also affected. The levels of local maxima of total deposition were 100–300 Bq m^{-2} in the north and 10–30 Bq m^{-2} in central Norway. This was the worst case of combined meteorological and accident scenario among the three locations of a potential accident.

Comparison of three deposition maps shown in Fig. 4 clearly indicates that in any case it is the very northern part of Norway that would receive the highest deposition.

3.4. Dry versus wet deposition

In general, wet deposition is much more effective in removing elements from the air than dry deposition, conditional, of course,

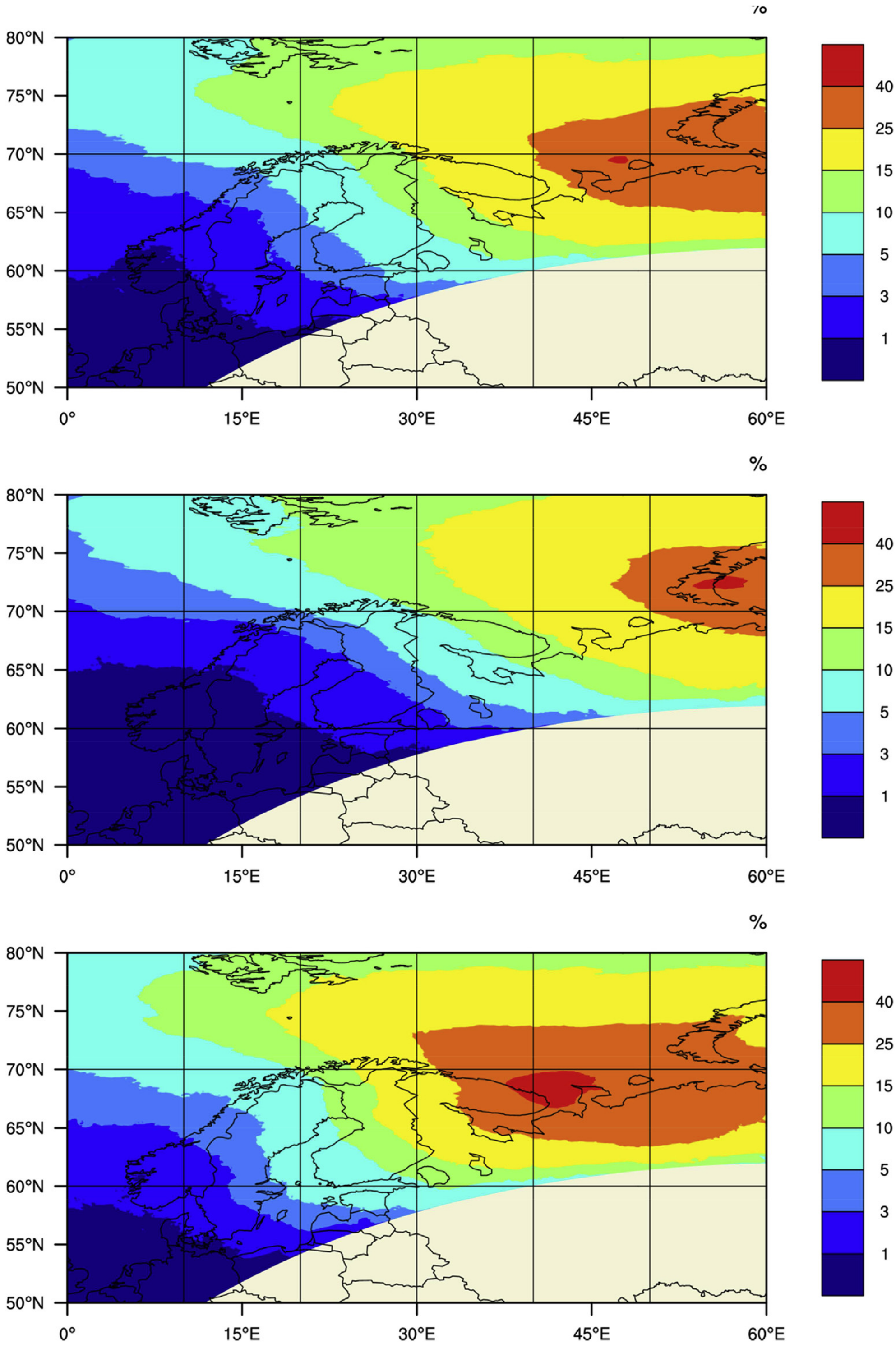


Fig. 3. Maps of probability of arrival (in %) to each model grid from releases: at initial location – top, on the way to Gremikha Bay – in the middle and at the final destination – bottom.

on there being precipitation during transport from the source to the receptor. The wet deposition parameterization developed by Baklanov and Sørensen (2001) is implemented in the SNAP model. In this parameterization washout coefficients are dependent on the particle size, precipitation intensity and precipitation type. A comparison of dry and wet deposition after 96 h from the accident start, for the worst case meteorological scenario with Gremikha as the accident location, and final source term is shown in Fig. 5. Except for a small area on the North Sea, wet deposition dominated over dry deposition everywhere, especially in northern and central Norway.

3.5. Depositions from individual components

Total deposition from all components together was presented and discussed in the previous section. Here we will discuss the

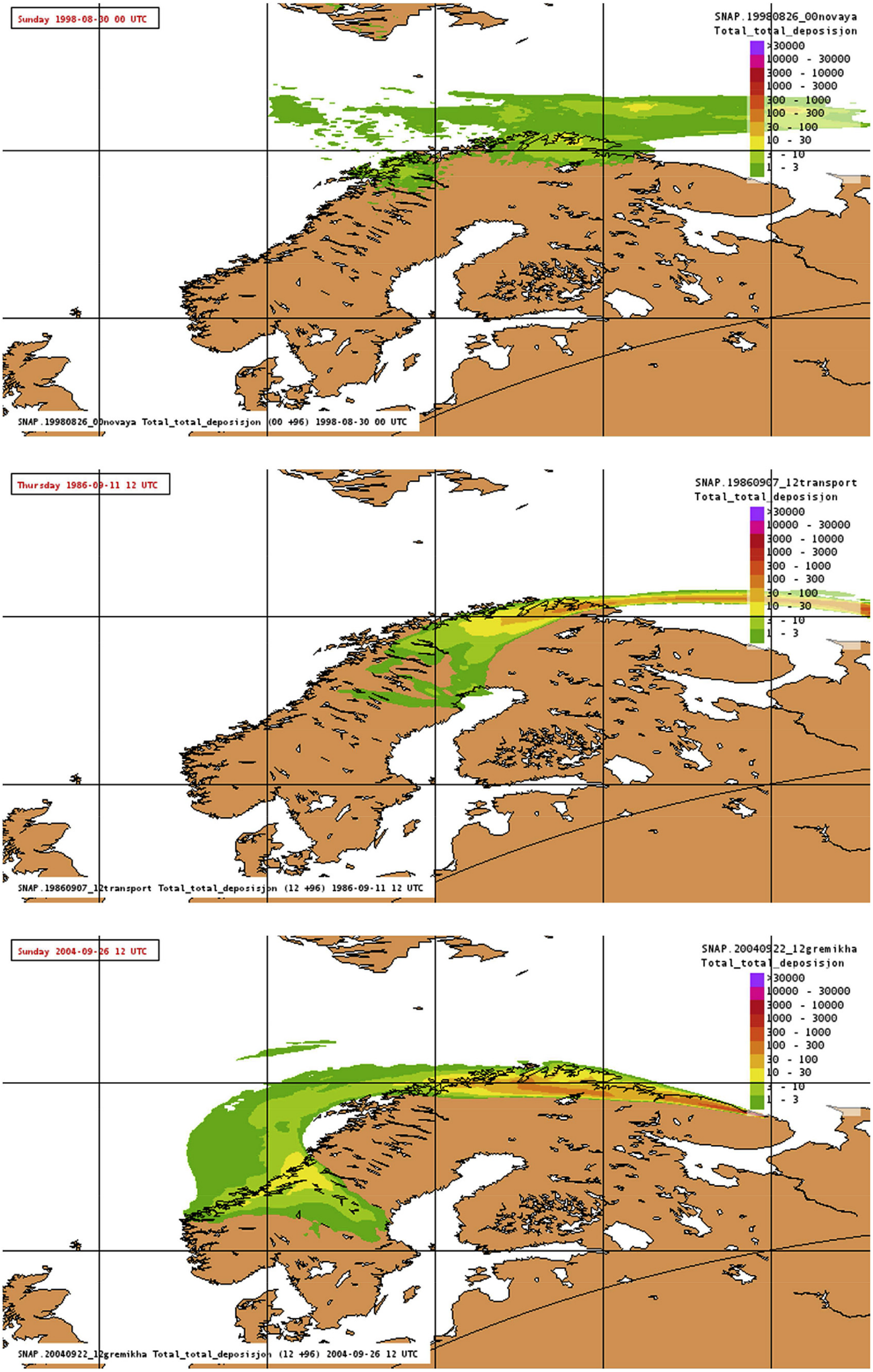


Fig. 4. Maps of total deposition (wet + dry and from all components) from SNAP runs with the final source term specified in Table 4 and worst case meteorological scenario for accident at the initial destination (top), on the way (middle) and at the final destination (bottom). Units: Bq m^{-2}.

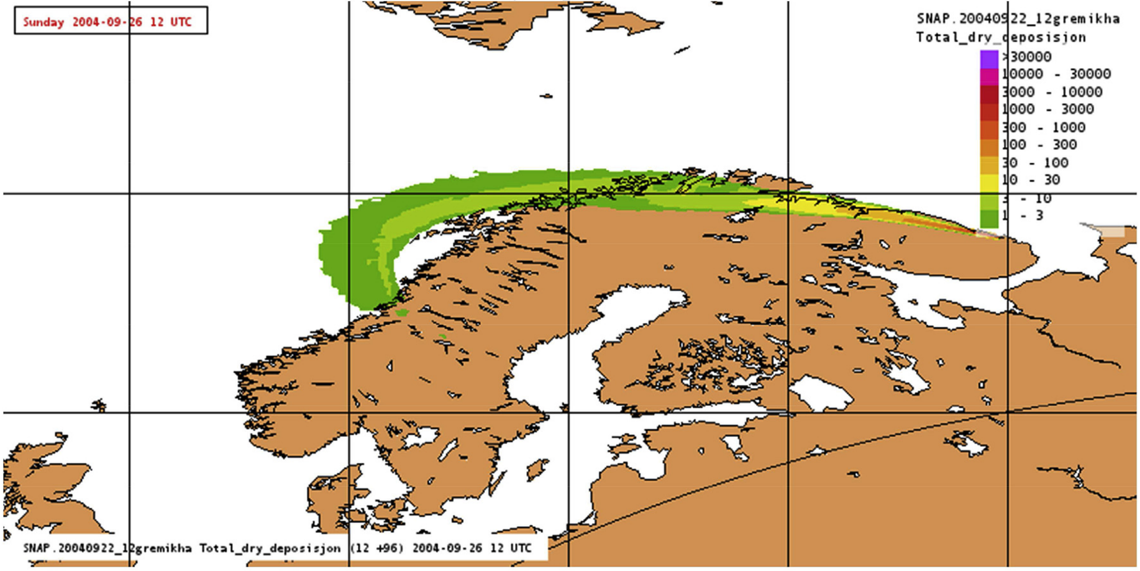
individual impact of all 30 model components included in Table 4. The complete results of the model run for all individual components are not shown due to limited space, but can be found in Bartnicki et al. (2013).

Among the four groups of particles which were included in the SNAP run for the worst case scenario, the total release was highest for the UO_2Be group, falling two orders of magnitude above the releases for the two next groups (Bitumen and Metal). The total release of the last group (^{106}Ru) was again much lower, more than four orders of magnitude lower than the UO_2Be group. The total releases of iodine gases were one and two orders of magnitude lower, for ^{133}I and ^{131}I, respectively.

These differences in total releases for the groups are clearly reflected in the deposition maps available in Bartnicki et al. (2013). Also, differences in particle sizes for individual components within each group were quite significant and probably the most important in terms of deposition levels in Norway. Deposition from UO_2Be components was higher than deposition from the Bitumen group and slightly lower than the deposition from the Metal group (Bartnicki et al., 2013). The main reason for lower deposition of the Metal group, despite very similar levels of release, was the higher density of particles in the metal group compared to the Bitumen group. The difference in total release was so large that deposition from the last group, ^{106}Ru, was hardly visible on the maps and could only be seen close to the source (Bartnicki et al., 2013).

There are some similarities for all groups of particles. Namely, long range transport is most effective when the particle size is below 1 μm. For the UO_2Be group, deposition fields were very similar for particles with sizes 0.1, 0.2 and 1.0 μm. Above 1 μm, the transport range rapidly decreased and for particles with sizes above 20 μm (50 and 100 μm) only local areas, close to the source, were subject to deposition. To illustrate this fact, four maps for

Dry deposition



Wet deposition

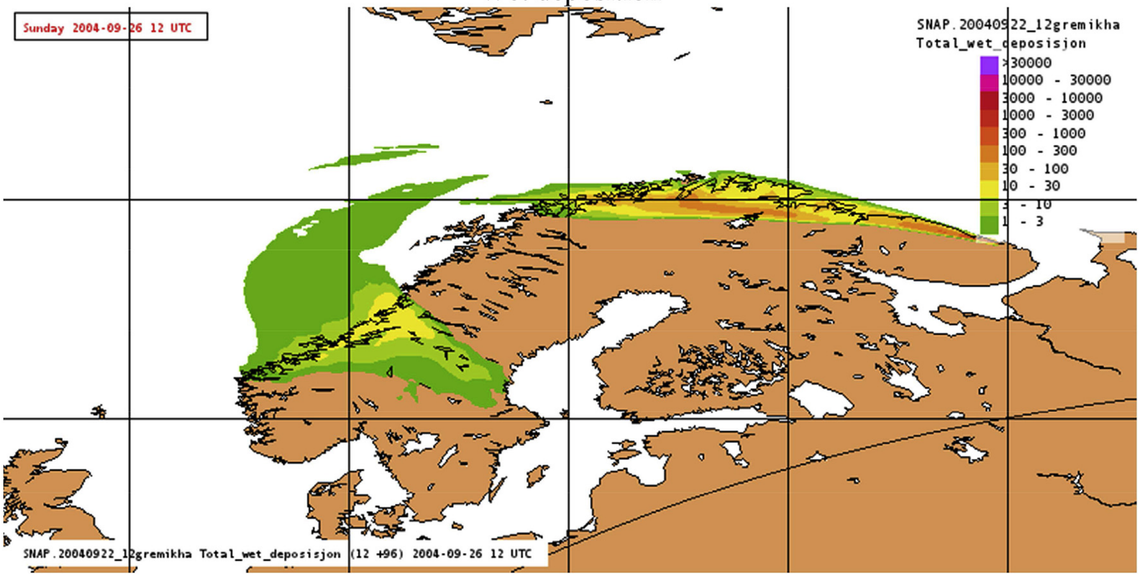


Fig. 5. Comparison of dry (top) and wet (bottom) deposition maps from SNAP runs with the final source term specified in Table 4 and worst case meteorological scenario for accident at the final destination. Both wet and dry deposition is the sum of depositions from all 30 components. Units: Bq m^{-2}.

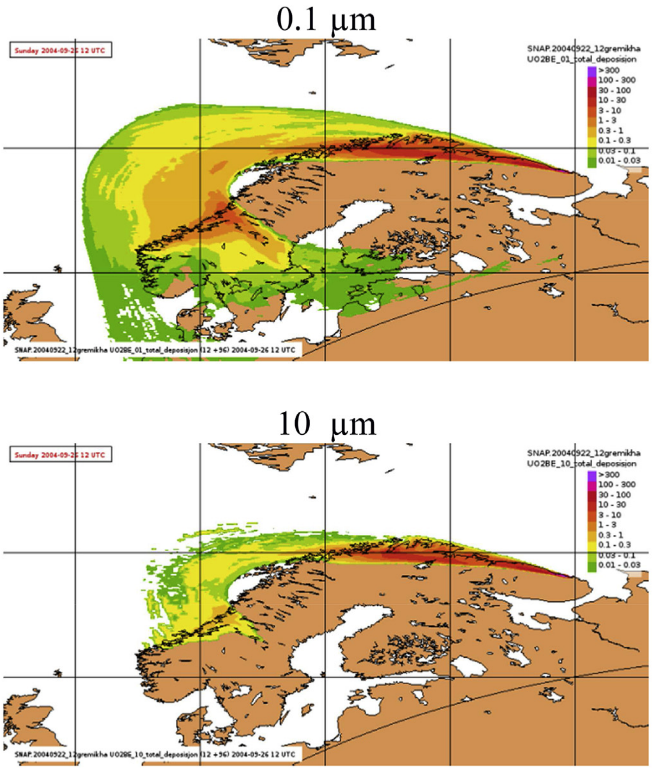


Fig. 6. Deposition maps from SNAP runs with individual UO_2Be particles with the radius 0.1, 1.0, 10.0 and 20.0 μm. Total (dry + wet) deposition is shown after 96 h from the accident start in Gremikha Bay. Units: Bq m^{-2}.

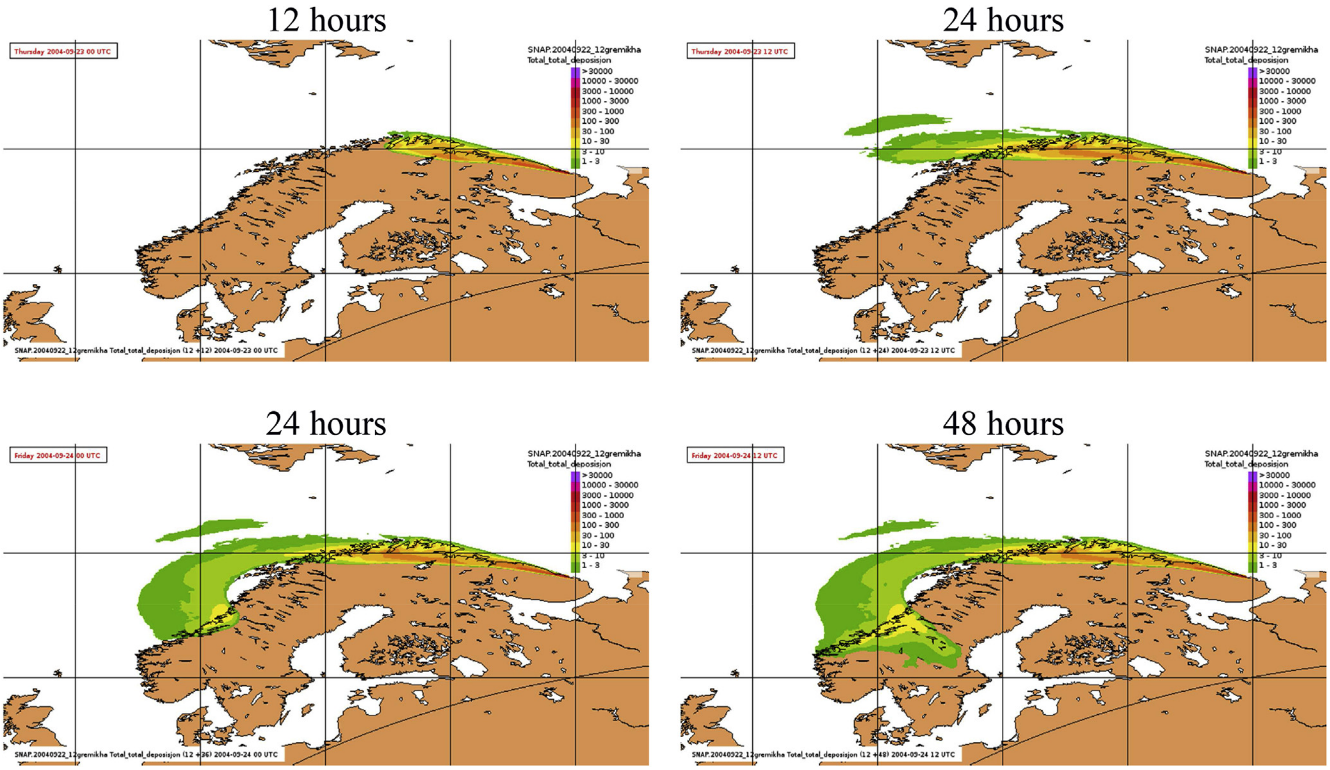


Fig. 7. Maps of total (sum of depositions from all 30 components) from SNAP runs with the final source term specified in Table 4 and worst case meteorological scenario for accident at the final destination after 12, 24, 48 and 96 h from the accident start. Units: Bq m^{-2}.

individual UO_2Be particles with different sizes are presented in Fig 6.

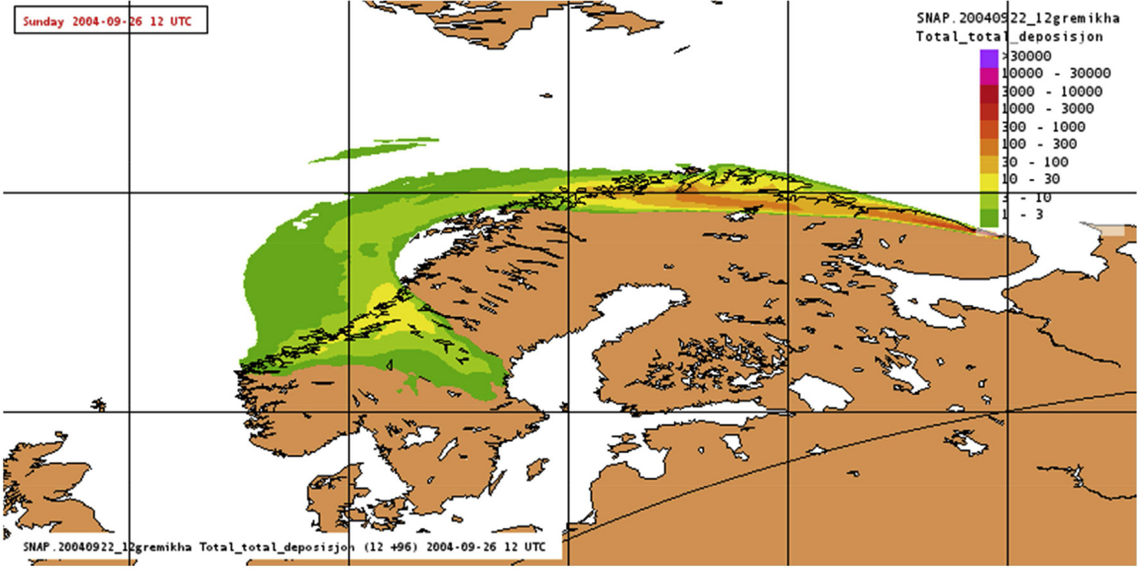
Deposition fields for radioisotopes of Iodine and especially for ^{133}I were similar to the deposition fields of particles with a radius below 1 μm.

3.6. *Dynamics of the transport*

The radioactive cloud resulting from the potential accident scenario where K-27 is located in Gremikha Bay has the potential to be transported rapidly towards Norway. The evolution in time was analysed by inspection of the total deposition maps for the worst case meteorological scenario and a potential accident at this final destination location for the submarine. The maps were calculated for the period of 96 h with 3 h intervals and the same scale is used for all of them. Here, we only present four maps in Fig. 7, as examples. For the complete set of these maps we refer to Bartnicki et al. (2013).

Already after 8–9 h after the initial accident, the Norwegian cities such as Vadsø, Vardø and Kirkenes would be contaminated with radioactive fallout. In the next 1–2 h contamination would extend to the towns of Mehamn and Hammerfest. After 18–20 h of transport, the city of Tromsø would also be affected by deposition. Subsequently, in the next 15–16 h, deposition from the radioactive cloud would only expand over the sea. Approximately 35–36 h from the accident start, Namsos and Steinkjer would be affected by the deposition and slightly later, after the next 9 h, Trondheim would also be affected. In the next stage, the radioactive cloud was predicted to travel to Sweden reaching the Baltic Sea after a transport time of 51 h. Because of the deposition scale used, Oslo

Total deposition – K-27



Total deposition – Chernobyl

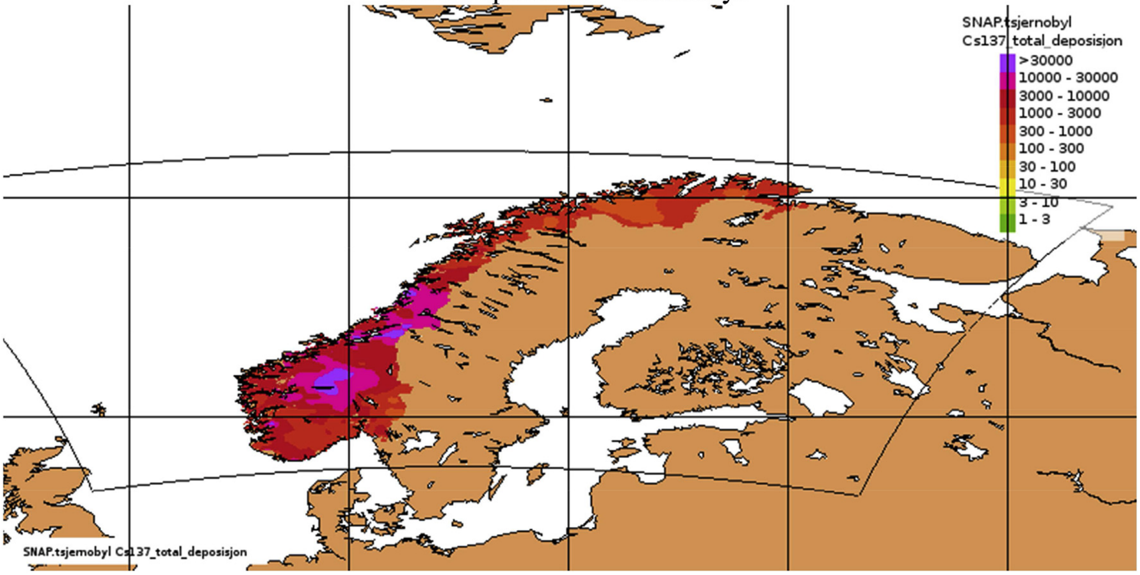


Fig. 8. Comparison of total deposition map from the worst case K-27 scenario (top) with total deposition map from the Chernobyl accident (bottom). The same scale is used on both maps. Deposition data for Norway from Chernobyl accident were provided by NRPA (Backe et al., 1986).

was not covered by the deposition, however with a source term involving a higher release than the one considered here for a potential K-27 accident, we would expect radionuclides to be deposited in the Oslo area as well. Under such circumstances, the estimated travel time would be 40–45 h after the start of the accident.

3.7. Comparison with Chernobyl accident

The total deposition over Norway from the potential K-27 accident was compared with the deposition from the Chernobyl accident in the same domain, as shown in Fig. 8.

The deposition data after the Chernobyl accident was based on soil measurements of ^{137}Cs in municipalities in Norway (Backe et al., 1986). The data have been gridded using regularized splines with tension interpolation (Mitasova and Hofierka, 1993). Subsequently, the results have been smoothed to compensate for local extremes, and to provide maps which might be more easily compared with modelled depositions.

After the Chernobyl accident, central Norway and especially some mountain regions were affected by relatively high levels of ^{137}Cs deposition. The maximum, above 50 kBq m^{-2} ^{137}Cs, was observed in the Valdres and Jotunheimen areas. The helicopter measurements made in 2011 over Jotunheimen have revealed that the deposition in 1986 was above 200 kBq m^{-2} in the most contaminated areas (Baranwal et al., 2011; Skuterud et al., 2014). The maximum deposition from the potential K-27 accident would be at least two orders of magnitude lower (100–300 Bq m^{-2}) than the maximum deposition attributable to Chernobyl and largely restricted to northern Norway. The deposition in southern Norway associated with the potential release from K-27 will be two to three orders of magnitude lower than the maximum levels associated with the Chernobyl accident.

4. Conclusions

The main conclusions from this study with regards to a hypothetical accident at submarine K-27 situated at Novaya Zemlya and transported to a final destination in Gremikha, are:

- The number of cases with deposition above zero over Norwegian territory decreases with the distance between the release location and Norway. For releases at the initial location (Stepovogo Fjord), during transport and at the final destination (Gremikha Bay) of the submarine, the probabilities of deposition events occurring over Norwegian territory are 17%, 25% and 37%, respectively. This relationship was also reflected in the maps showing the probability of arrival to Norway. The worst case meteorological scenarios were selected for the dates: 26 August 1998, 7 September 1986 and 22 September 2004, for hypothetical accident locations corresponding to the initial destination, during transport and at the final destination, respectively. The worst meteorological case among all destinations is the one at Gremikha Bay.
- Model simulations with a source term corresponding to the worst case accident scenario showed that for all locations of the potential accident, the northern part of Norway would be affected. Central Norway could also be affected by contamination, in addition to northern Norway, if the potential accident occurred in K-27 when located at Gremikha Bay. In all computations, the contribution of wet deposition to total deposition was much higher than the contribution from dry deposition.
- The differences in total release for individual particle groups are clearly visible in calculated depositions. Long range transport was most effective when the particle radius was below 1 μm. For particles with a radius of 50 μm and above only local areas, close to the sources, were subject to radioactive particle inputs.
- The radioactive cloud resulting from the K-27 potential accident when situated in Gremikha Bay was transported rapidly towards Norway in the worst case scenario. Already after 8–9 h from the start of the accident, a large part of northern Norway would be contaminated. Approximately 35–36 h from the accident start, a large part of central Norway would also be affected.
- Compared to the Chernobyl accident, the maximum deposition level from K-27 accident is predicted to be at least 100 times lower than the maximum deposition in Norway from the Chernobyl accident. Also the area of Norway affected is different in both cases. Primarily northern Norway would be affected from the K-27 accident whereas mostly central Norway was affected by fallout from the Chernobyl accident.

There are two general conclusions from this study: (1) Assuming that the source term for the worst case K-27 accident scenario is reasonable, there are no substantial radiological consequences for Norway. Even the maximum predicted levels would be much lower than in case of Chernobyl accident. (2) Calculated depositions are very sensitive to the magnitude of the source term used. Therefore, for estimation of the radiological risk to Norway, it is very important to develop as accurate as possible estimations of the source term in case of a potential accident involving the K-27 submarine. For this reason, much effort has been expended on precisely this task in preparation for the simulations presented in this paper.

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