ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

RAPORTTEJA
RAPPORTER
REPORTS
2014:8

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No. 2014:8 UDC 551.510.7

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Ilmatieteen laitos
Meteorologiska institutet
Finnish Meteorological Institute
Helsinki 2014

ISBN 978-951-697-837-9 (paperback)
ISBN 978-951-697-838-6 (pdf)
ISSN 0782-6079

Unigrafia Oy
Helsinki 2014

FINNISH METEOROLOGICAL INSTITUTE

Series title, number and report code of publication

Published by Finnish Meteorological Institute
(Erik Palménin aukio 1) , P.O. Box 503
FIN-00101 Helsinki, Finland

Reports 2014:8

Date March 2014

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Project

CEEPRA

Title

ATMOSPHERIC TRANSPORT OF RADIONUCLIDES FOLLOWING HYPOTHETICAL REACTOR ACCIDENTS

Abstract

In this work two reactor accident scenarios were studied using the SILAM dispersion model developed in the Finnish Meteorological Institute. The accident scenarios were the planned nuclear power plant at Pyhäjoki, Finland and the planned floating nuclear reactor at the Shtokmann gas field in the Barents Sea. The calculated atmospheric concentration and deposition values were compared to those measured after the atmospheric nuclear tests of the 1950s and the 1960s and the 1986 Chernobyl accident. To obtain data on the atmospheric concentration of radionuclides in the air since the 1960s a set of archived aerosol samples was analysed for radioactivity.

In the case of a hypothetical reactor accident at Pyhäjoki the average cesium-137 deposition would be about the same as the maximum values observed in Finland after the 1986 Chernobyl accident. In Finnish Lapland north of Rovaniemi the exposure would be at its maximum 170 times higher than the exposure in 1986.

The floating reactors planned to the Barents Sea contain relatively low amounts of radioactivity and thus the consequences of a hypothetical reactor accident would remain quite local. For example the deposition of plutonium-241 would be less than 10 Bq/m^2 which is one per cent of the deposition after the atmospheric nuclear tests.

The SILAM results were also compared with the results obtained with the SNAP model operated by the Norwegian Meteorological Institute. In most cases the models gave quite comparable results. The biggest differences are related to the occurrence of precipitation and its effect on the wet deposition.

Publishing unit
Arctic Research

Classification (UDK)
551.510.7

Keywords
Nuclear accidents, atmospheric releases

ISSN and series title
0782-6079 Reports

ISBN

978-951-697-837-9, 978-951-697-838-6 (pdf)

Language
English

Sold by
Finnish Meteorological Institute
P.O.Box 503, FIN-00101 Helsinki
Finland

Pages 30

Price

Note

ILMATIETEEN LAITOS

Julkaisun sarja, numero ja raporttikoodi
Raportteja 2014:8

Julkaisija Ilmatieteen laitos, (Erik Palménin aukio 1)
PL 503, 00101 Helsinki

Julkaisuaika Maaliskuu 2014

Tekijä(t)

Jussi Paatero, Julius Vira, Susanna Salminen-Paatero,
Timo Ryyppö, Jerzy Bartnicki, Heiko Klein & Ari-Pekka Leppänen

Projektin nimi
CEEPRA

Nimeke
RADIONUKLIDIEN KULKEUTUMINEN ILMAKEHÄSSÄ HYPOTEETTISTEN REAKTORIONNETTOMUUKSIEN JÄLKEEN

Tiivistelmä

Tässä työssä Ilmatieteen laitoksella kehitetyllä SILAM-leviämismallilla on tutkittu kahta eri reaktorionnettomuusskenaariota, Pyhäjoelle kaavailtua ydinvoimalaitosta sekä Barentsin merelle Shtokmannin kaasukentälle suunniteltua kelluvaa ydinreaktoria. SILAM-mallilla laskettuja radioaktiivisuuspitoisuuksia pintailmassa sekä laskeumassa on verrattu tasoihin, joita esiintyi Suomessa 1950- ja 1960-luvun ilmakehässä tehtyjen ydinasekokeiden sekä vuoden 1986 Tshernobylin ydinvoimalaitosonnettomuuden takia. Vertailuarvojen saamiseksi on työn aikana analysoitu arkistoituja aerosoli- eli ilmapölynäytteitä, jotka on kerätty Lapissa 1960-luvulta alkaen.

Pyhäjoen onnettomuusskenaariossa cesium-137:n keskimääräinen laskeuma olisi suurimmillaan samaa suuruusluokkaa kuin vuoden 1986 Tshernobylin ydinvoimalaitosonnettomuuden aiheuttama laskeuma Suomessa. Lapissa Rovaniemen pohjoispuolella altistus ilmassa kulkeutuvalle radioaktiivisuudelle olisi 17-170 suurempi kuin vuonna 1986.

Barentsin merelle suunnitellun kelluvan ydinreaktorin sisältämä radioaktiivisuusmäärä on verrattain pieni, joten mahdollisen onnettomuuden sattuessa radioaktiivisen saasteen vaikutukset jäisivät hyvin paikallisiksi. Esimerkiksi plutonium-241:n keskimääräinen laskeuma kaksi vuorokautta päästön jälkeen olisi pahimmillaan noin 10 Bq/m^2, mikä on noin yksi sadasosa 1950- ja 1960-luvun ilmakehässä tehtyjen ydinasekokeiden aiheuttamasta laskeumasta.

Osana työtä SILAM-mallin antamia tuloksia on verrattu Norjan Ilmatieteen laitoksen SNAP-malliin. Useimmissa tapauksissa mallit antavat varsin yhteneväisiä tuloksia. Suurimmat erot johtunevat säämallin tuottamista sateista sekä niiden aiheuttamasta märkälaskeumasta.

Julkaisijayksikkö
Arktinen tutkimus

Luokitus (UDK)
551.510.7

Asiasanat
Ydinonnettomuudet, kulkeutuminen ilmakehässä

ISSN ja avainnimike
0782-6079 Raportteja

ISBN
978-951-697-837-9 (nid.), 978-951-697-838-6 (pdf)

Kieli
englanti

Myynti
Ilmatieteen laitos
PL 503, 00101 Helsinki

Sivumäärä 30

Hinta

Lisätietoja

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INTRODUCTION

Considerable amounts of man-made radioactivity have been transported to the Arctic environment since the start of the nuclear era in 1945. There has been a variety of sources contributing to this: nuclear weapons tests, the 1986 Chernobyl accident, liquid and atmospheric emissions from the nuclear fuel reprocessing plants in Sellafield and Dounreay, the United Kingdom, La Hague, France, operational and accidental liquid and atmospheric emissions from the nuclear weapons production and fuel reprocessing facilities in Russia (Chelyabinsk, Tomsk and Krasnoyarsk), Soviet dumping of nuclear waste and used reactors to the Arctic Ocean. Local contamination has occurred due to accidents involving aircrafts carrying nuclear weapons, nuclear-powered vessels and the handling of their fuel cycle. Especially important of these has been the Novaya Zemlya nuclear test site. The Soviet Union conducted there 91 nuclear tests in the atmosphere, ground surface and water in 1955-1962 including the most powerful atmospheric nuclear test ever ("Tsar Bomba" or "Big Ivan", 50-58 megatons) on 30 October 1961 (Arctic Monitoring and Assessment Programme, 2010). The most recent source of artificial radioactivity transported to the Arctic is the 2011 Fukushima accident (Paatero 2et al., 2012).

Two new nuclear facilities are being planned in or close to the Arctic. A construction of a nuclear power plant to Pyhäjoki, western Finland, is under preparation. The Shtokmann natural gas production field in the Barents Sea could be powered with floating nuclear reactors according to Russian plans. Atmospheric transport modeling was applied to study the potential risks of hypothetical accidents in these plants. The resulting atmospheric concentrations of radioactivity were compared to those that occurred in Finland in the 1960s due to the atmospheric nuclear tests. This work is part of the project "Collaboration Network on EuroArctic Environmental Radiation Protection and Research (CEEPRA)", www.ceepra.eu.

COMPUTATIONAL AND EXPERIMENTAL METHODS

Transport modeling

Dispersion of radionuclides was simulated with the System for Integrated modeLling of Atmospheric coMposition SILAM (Sofiev et al., 2006, 2008). The dynamic core of the model is based on the transport scheme of Galperin (1999, 2000) combined with the extended resistance analogy of Sofiev (2002) for vertical diffusion. The model was driven by ECMWF meterorological forecast data and configured at a horizontal resolution of 0.25 degrees and with 9 vertical levels reaching height of 7700 m.

Wet and dry deposition as well as radioactive decay are included as loss processes. Wet deposition is computed using scavenging coefficients based primarily on the data of

Horn et al. (1987), Smith and Clark (1989) and Jylhä (1991). Dry deposition is modelled using the resistance approach (Hicks et al., 1987; Lindfors et al., 1993).

The assumptions concerning the hypothetical Pyhäjoki and Barents Sea accidents are listed in Tables 1 and 2. Transport and dispersion calculations with the SILAM model were made for every day of the year 2010. Cumulative deposition after 48 hours and 48 hour average activity concentration in the ground-level air of four nuclides, ^{90}Sr, ^{131}I, ^{137}Cs, and ^{241}Pu, were calculated. Based on these calculation average activity concentration and deposition situations were produced. In addition, one reference case for Pyhäjoki with a slightly higher release fraction (2 %) and the atmospheric transport lasting 120 hours was calculated. The accident parameters and source term in the case of Pyhäjoki power reactor were as follows:

- Site Pyhäjoki, Finland 64°32'N, 24°15'E,
- Pressurized water reactor, thermal power 4000 MW,
- End of the refueling interval,
- Instant release after shutdown, and
- Effective release height 200 m above sea level.

The accident parameters and source term in the case of the floating nuclear reactor were as follows:

- Site Shtokmann gas field, Barents Sea 73°N, 44°E,
- Ice breaker reactor,
- Burnup of 466000 MWdays/ T HM,
- Instant release two hours after shutdown,
- Nuclide inventory from Reistad and Ølgaard (2006), and
- Effective release height 100 m above sea level.

Table 1. Source term for the Pyhäjoki accident scenario.

Nuclide	Inventory Bq	Release fraction, %	Release Bq
Sr-90	3.9E17	0.1	3.9E14
I-131	3.9E18	3.0	1.17E17
Cs-137	5.2E17	1.5	7.8E15
Pu-241	6.2E17	0.1	6.2E14

Table 2. Source term for the Shtokmann accident scenario.

Nuclide	Inventory Bq	Release fraction, %	Release Bq
Sr-90	8.68E15	0.2	1.74E13
I-131	4.54E16	1.0	4.54E14
Cs-137	8.83E15	1.0	8.83E13
Pu-241	3.20E14	0.2	6.40E11

Experimental work

Finnish Meteorological Institute has collected weekly aerosol samples at its regional office at the Rovaniemi airport since 1965 (Fig. 1). The samples were measured for long-lived beta activity and then archived for future use. For this project these samples were retrieved from the filter archive. Metadata of the samples, especially air volumes, were collected from station logbooks. The ^{137}Cs content of the samples were measured with semiconductor gamma spectrometry at the Finnish Meteorological Institute and at the Laboratory of Radiochemistry, University of Helsinki. Additional data was obtained from STUK – Radiation and Nuclear Safety Authority, Regional Laboratory in Northern Finland.

Figure 1. Aerosol sampling station at the Rovaniemi airport, regional office of the FMI. The arrow points to the sampling inlet on the roof of the building.

RESULTS AND DISCUSSION

Transport and deposition from the Pyhäjoki site

Prevailing weather conditions have a crucial effect on the dispersion of the atmospheric emissions caused by a nuclear power plant accident. The direction of air flows settles the course of the emission plume. On one hand, the wind speed determines how quickly the emission plume is moving on. On the other hand, the wind speed determines also the vertical and horizontal dispersion of the plume, which affects the concentrations of radioactive substances. In turn, precipitation efficiently scavenges the radioactivity from the atmosphere to the ground, affecting the amount of the radioactive deposition. The 48 hours' average activity concentrations of ^{90}Sr, ^{131}I, ^{137}Cs, and ^{241}Pu in the ground-level air for the Pyhäjoki site are depicted in Figures 2-5. Corresponding deposition maps are depicted in Figures 6-9. On average the activity concentration and deposition values

decrease rapidly as the distance from the accident site increases. However, individual cases differ considerably. Depending on wind conditions and occurrence of rain the radioactive release plume can affect areas from North Atlantic Ocean to Ural mountains. In a calm weather situation, on the other hand, the effects might remain quite local (Figures 10-14).

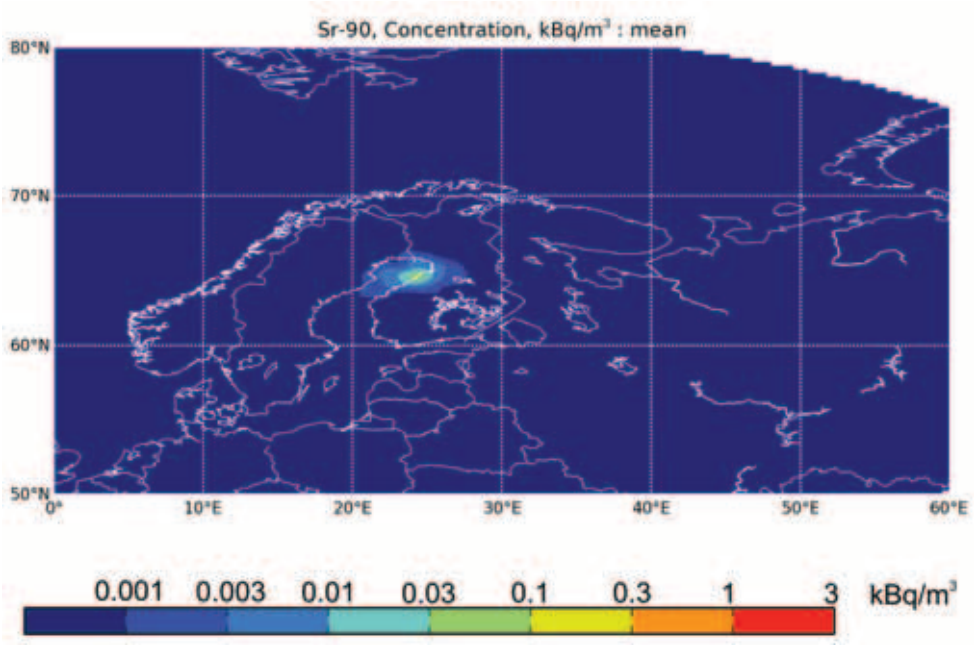

Figure 2. 48 hour average activity concentration of ^{90}Sr in the ground-level air after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

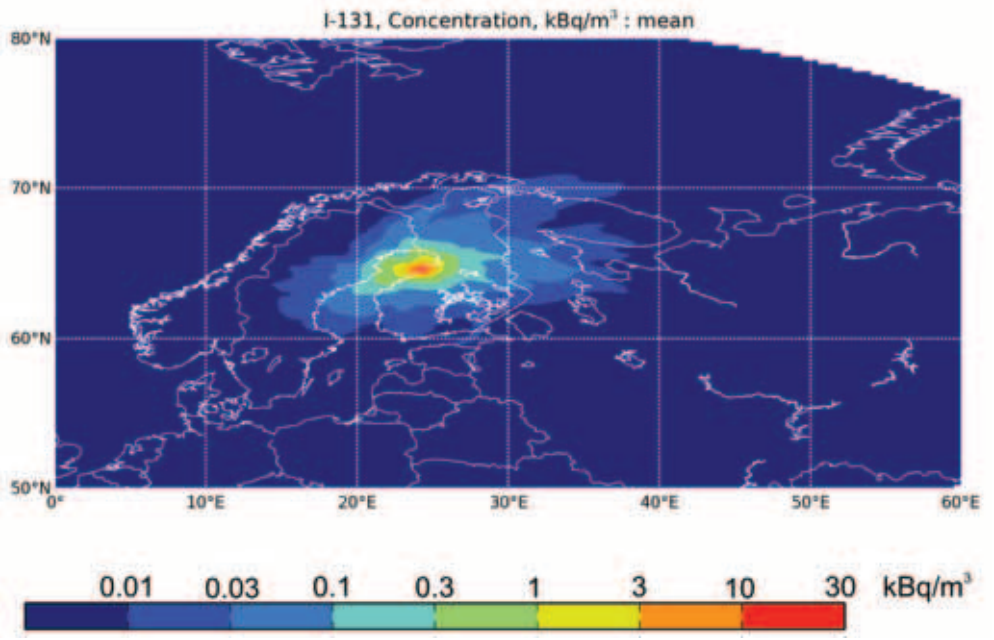

Figure 3. 48 hour average activity concentration of ^{131}I in the ground-level air after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

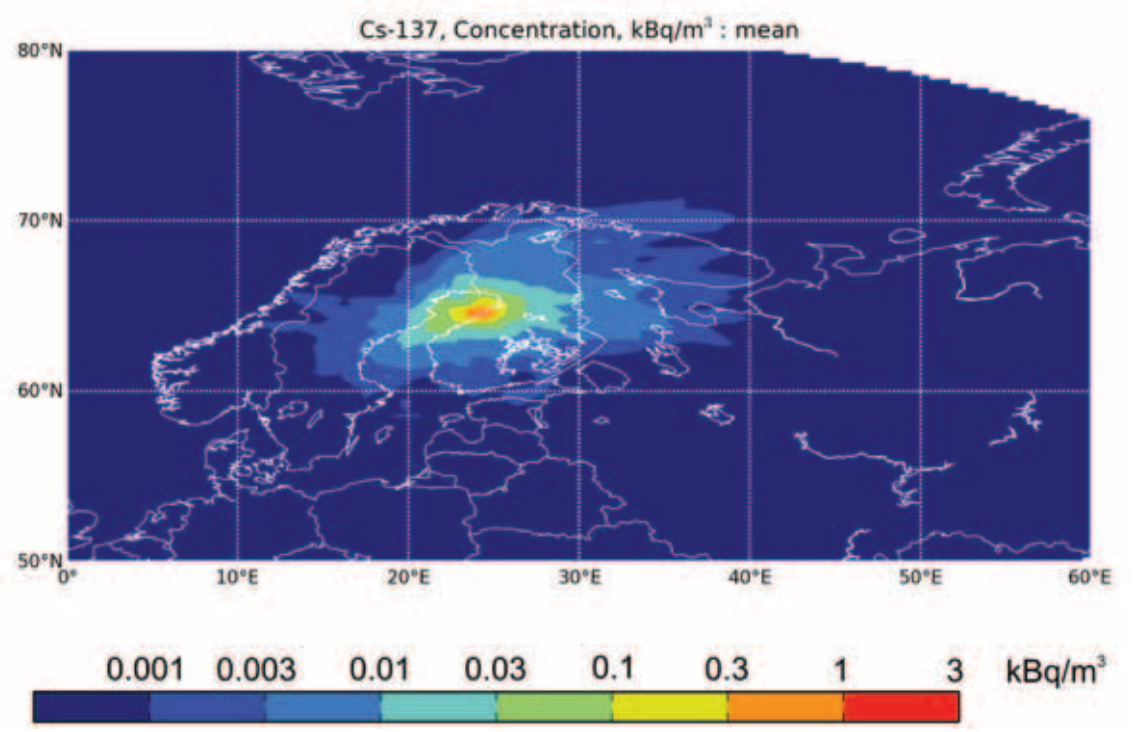

Figure 4. 48 hour average activity concentration of ^{137}Cs in the ground-level air after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

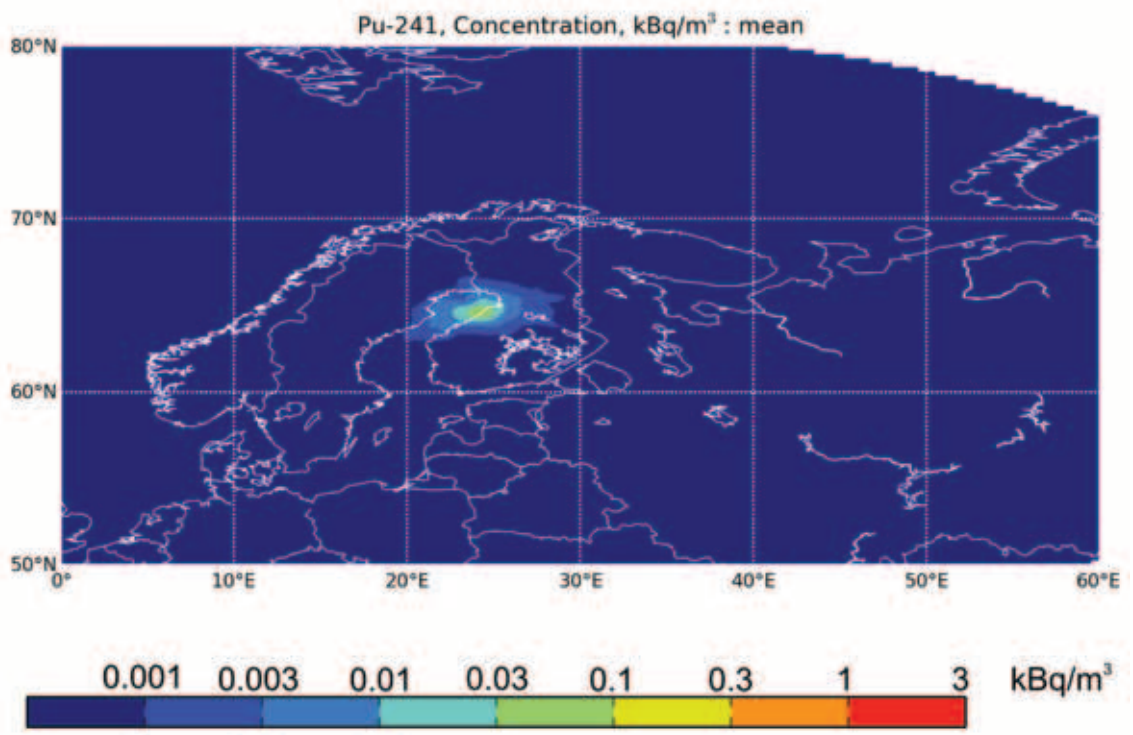

Figure 5. 48 hour average activity concentration of ^{241}Pu in the ground-level air after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

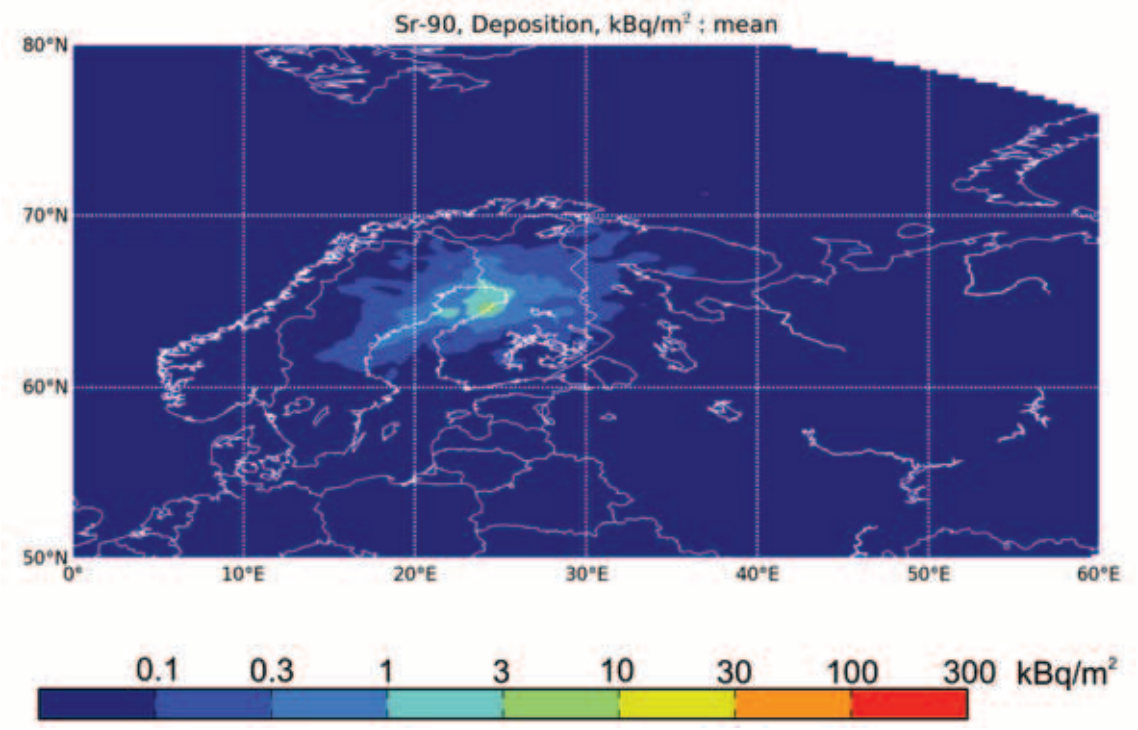

Figure 6. Cumulative deposition of ^{90}Sr 48 hours after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

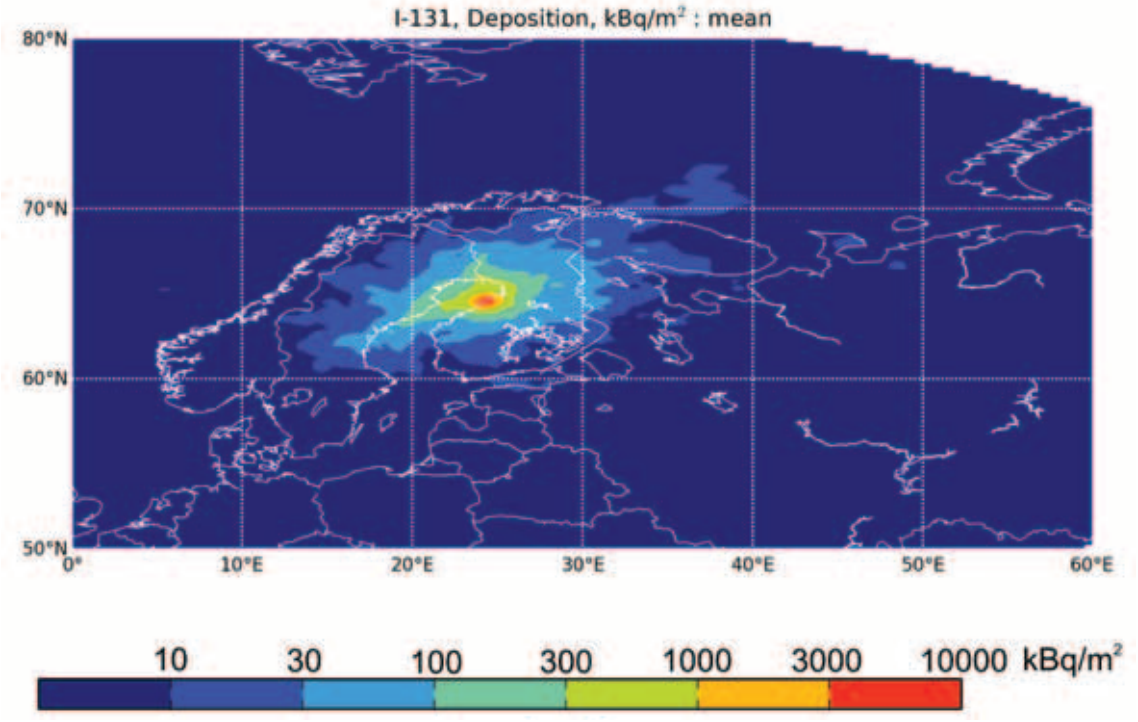

Figure 7. Cumulative deposition of ^{131}I 48 hours after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

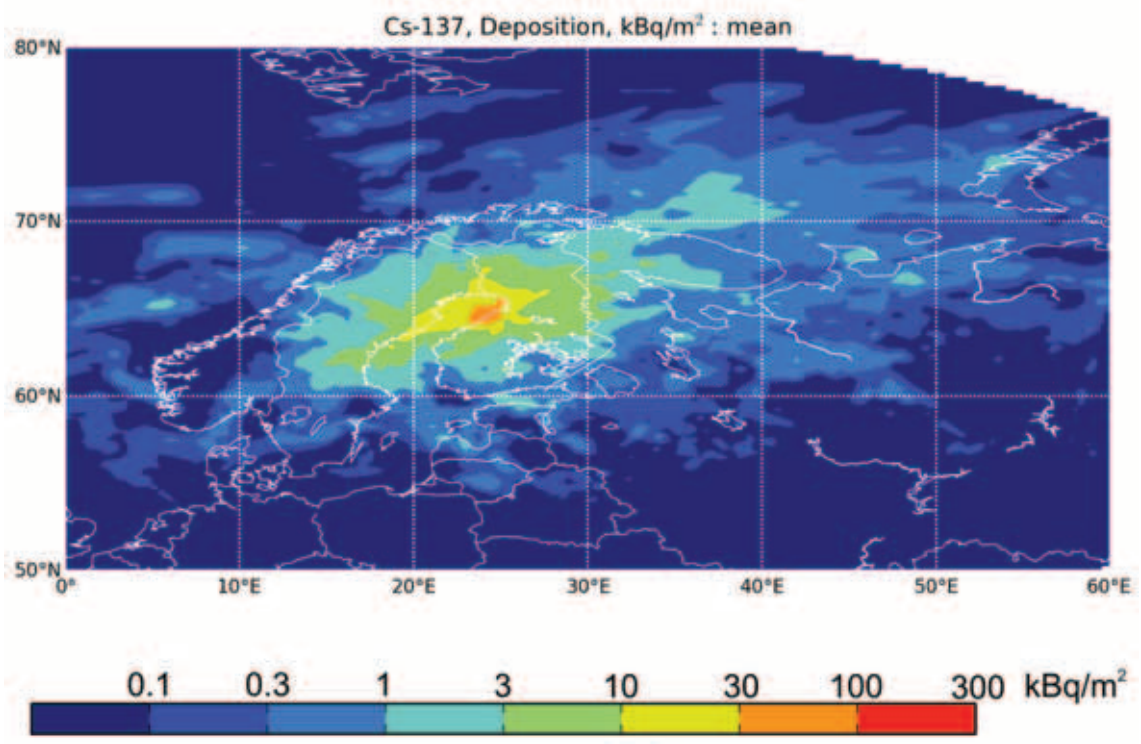

Figure 8. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

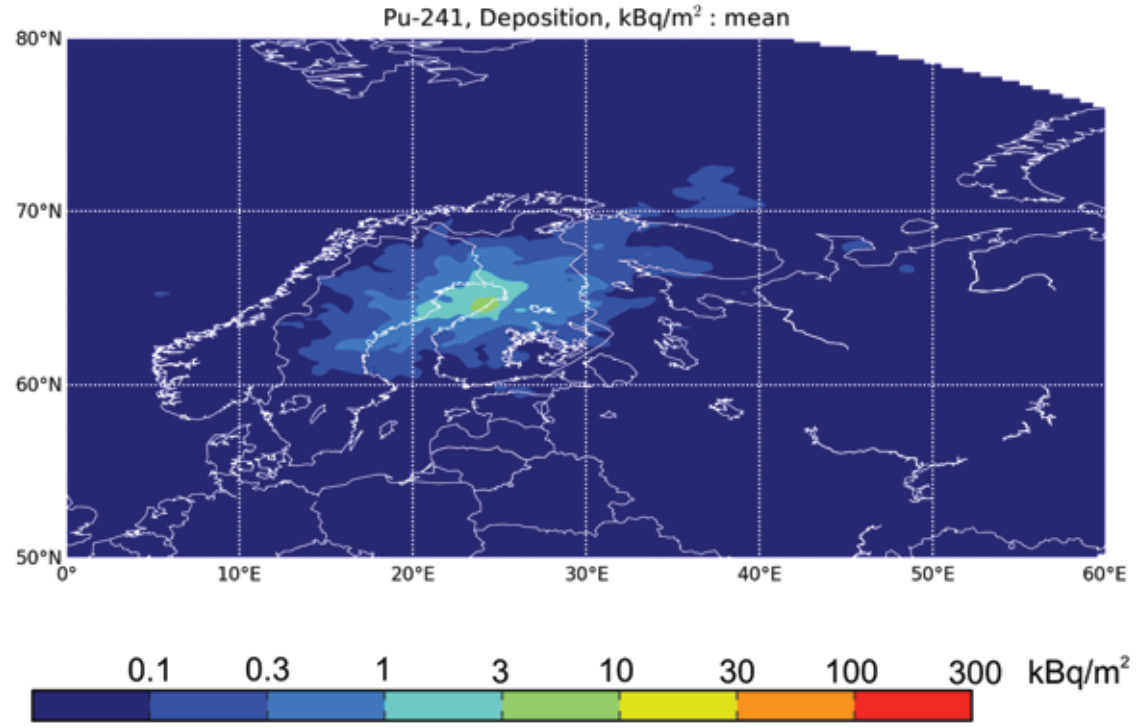

Figure 9. Cumulative deposition of ^{241}Pu 48 hours after a hypothetical reactor accident at Pyhäjoki, average of 365 cases.

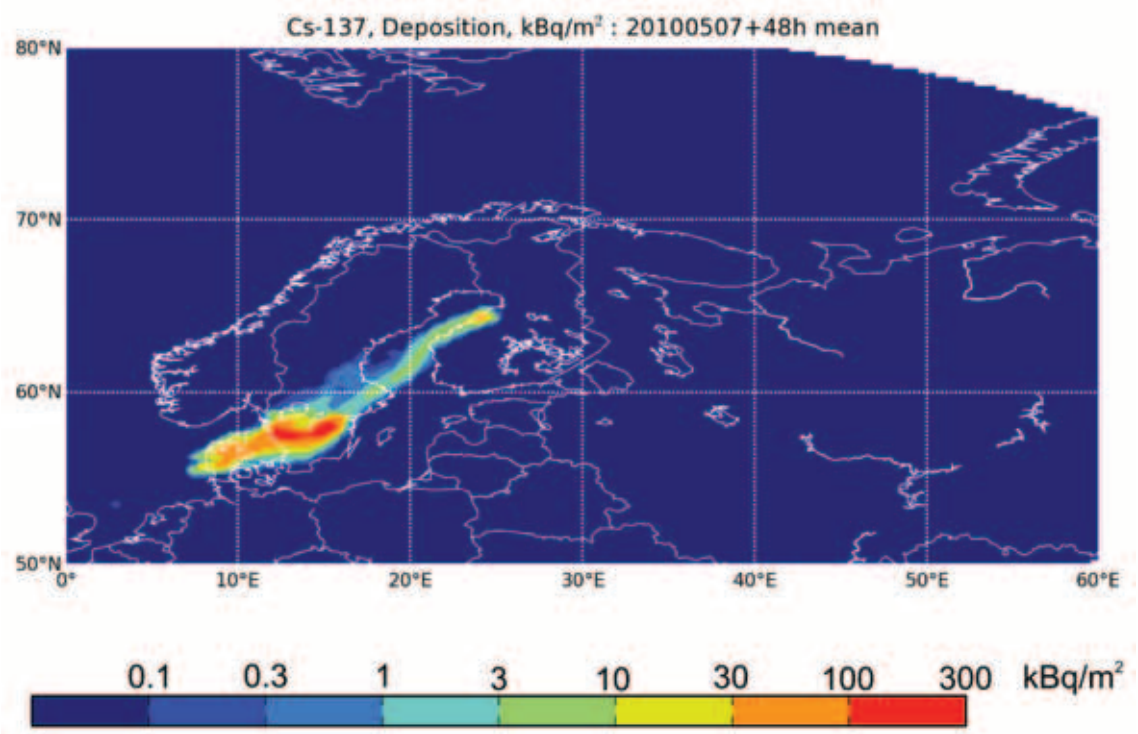

Figure 10. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Pyhäjoki, case 7 May 2010.

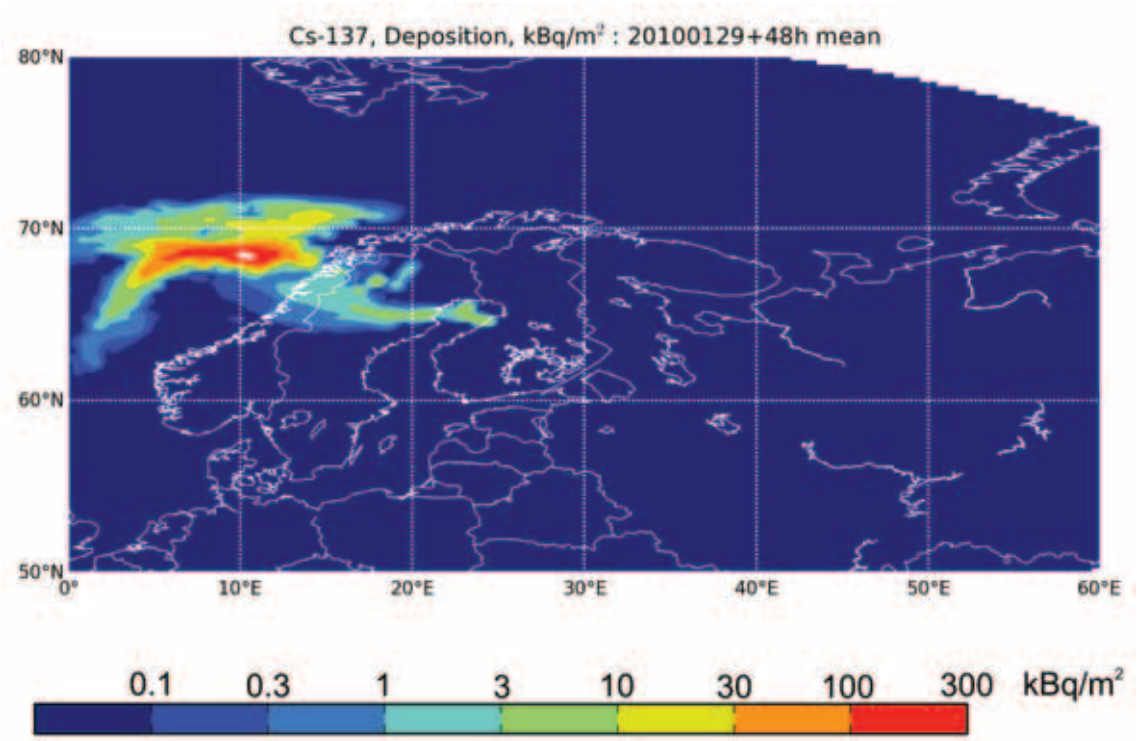

Figure 11. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Pyhäjoki, case 29 January 2010.

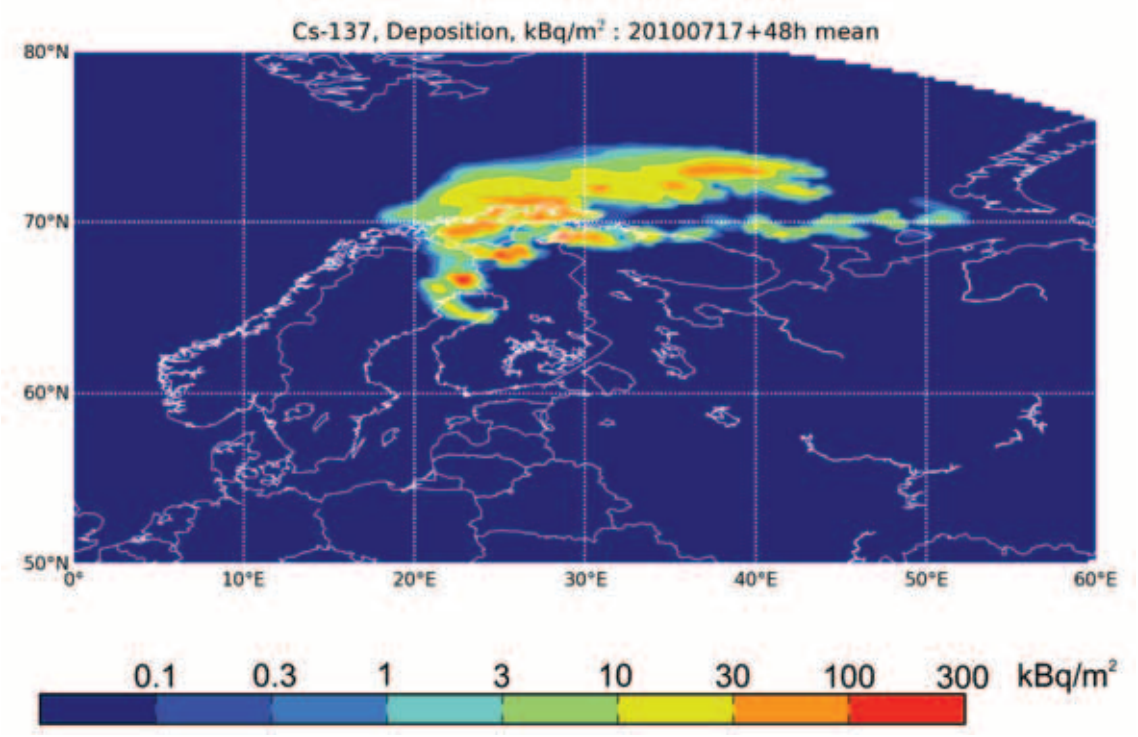

Figure 12. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Pyhäjoki, case 17 July 2010.

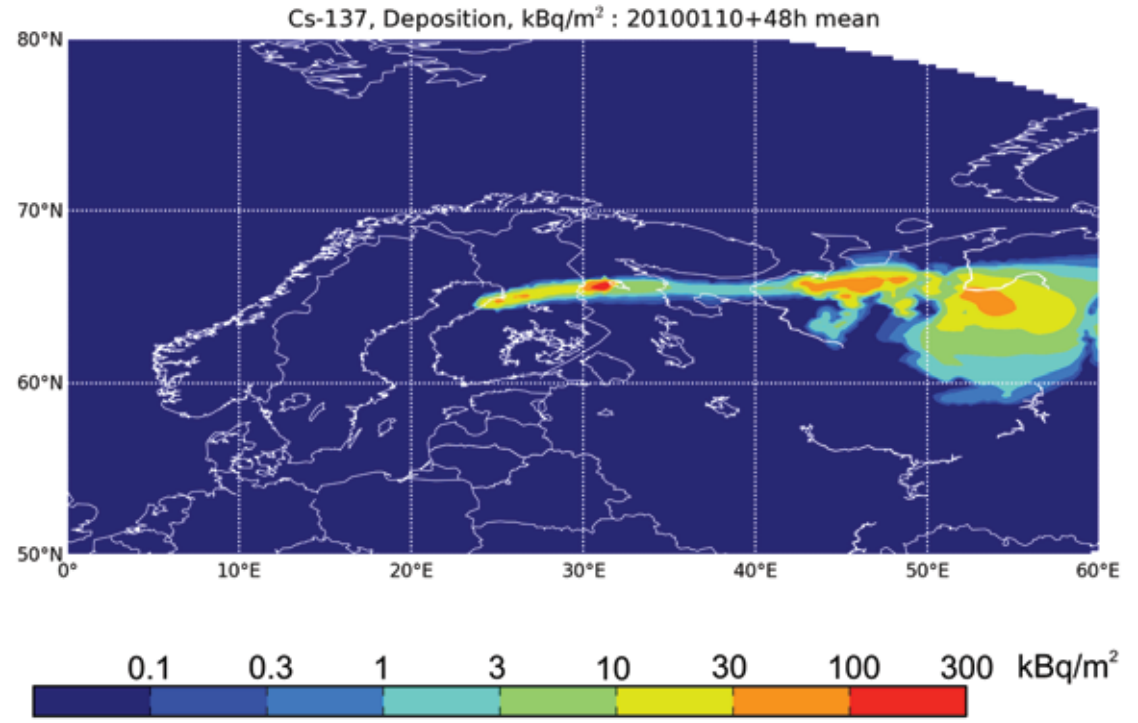

Figure 13. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Pyhäjoki, case 10 January 2010.

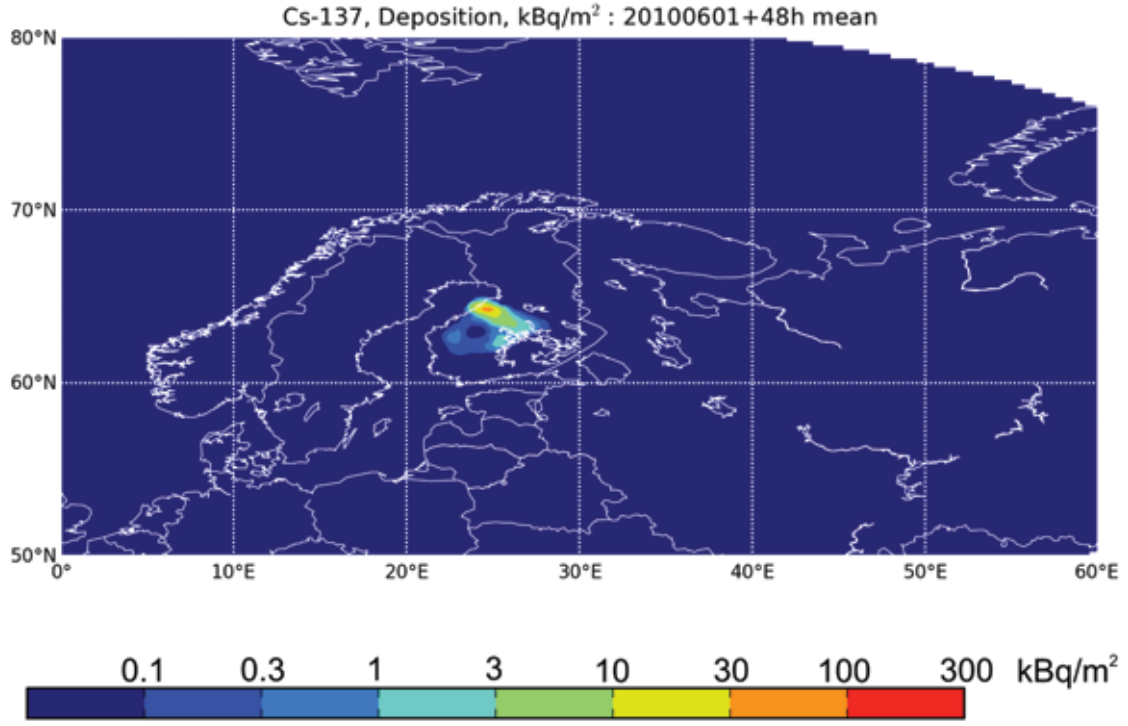

Figure 14. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Pyhäjoki, case 1 June 2010.

Transport and deposition from the Shtokmann site

The average activity concentrations of ^{90}Sr, ^{131}I, ^{137}Cs, and ^{241}Pu in the ground-level air for the floating nuclear reactor are depicted in Figures 15-18. Corresponding deposition maps are depicted in Figures 19-22. Again, the average values decrease quite rapidly as the distance from the release point increases. From the northern Finland point of view even in the worst case the radioactive deposition in northern Finland would remain rather low. With the accident parameters described earlier the ^{90}Sr deposition would be, on average, less than the deposition caused by the atmospheric nuclear tests of the 1950s and the early 1960s (Paatero et al. 2010).

Comparison of SILAM and SNAP model results

The SILAM model results were compared to the SNAP model operated by the Norwegian Meteorological Institute (Bartnicki et al., 2011) using same cases and source terms. Both Pyhäjoki and Barents Sea accidents were analysed. This way the results of both models could be compared and some conclusions formulated, also about the uncertainty of the simulations. Same forecast length was used but the meteorological data used as well as the model domains were different. Also the output from both models is slightly different, but still the most important feature can be compared.

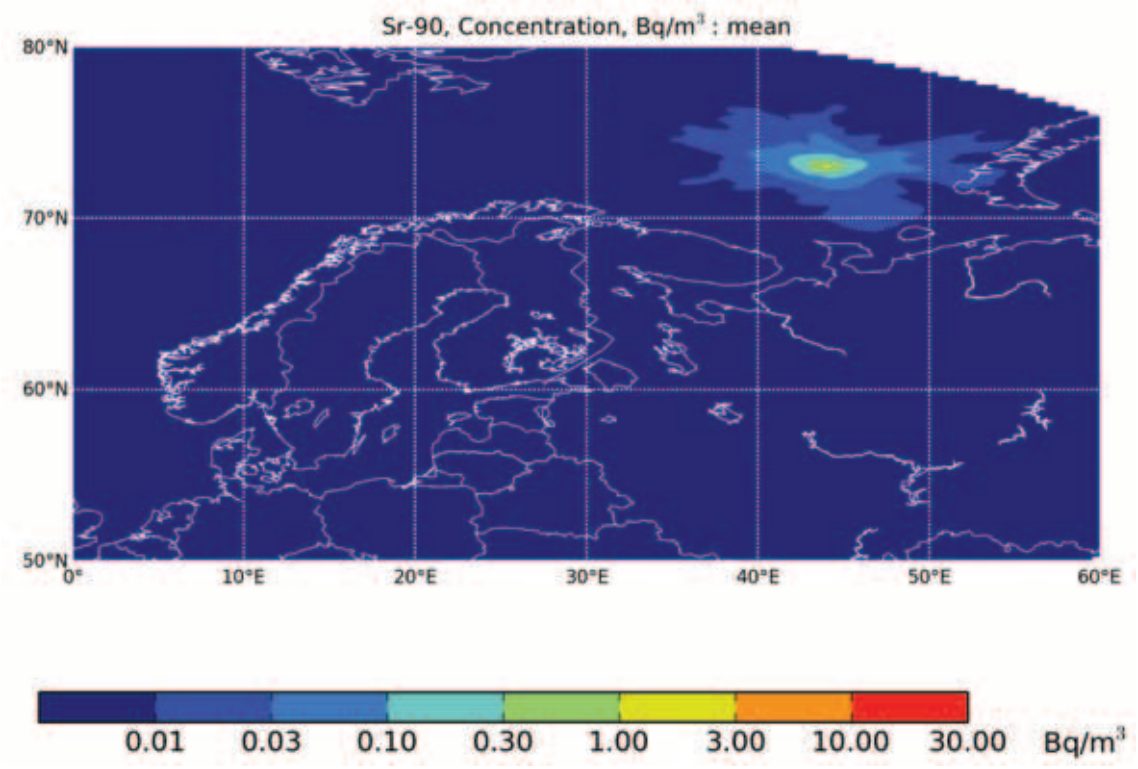

Figure 15. 48 hour average activity concentration of ^{90}Sr in the ground-level air after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

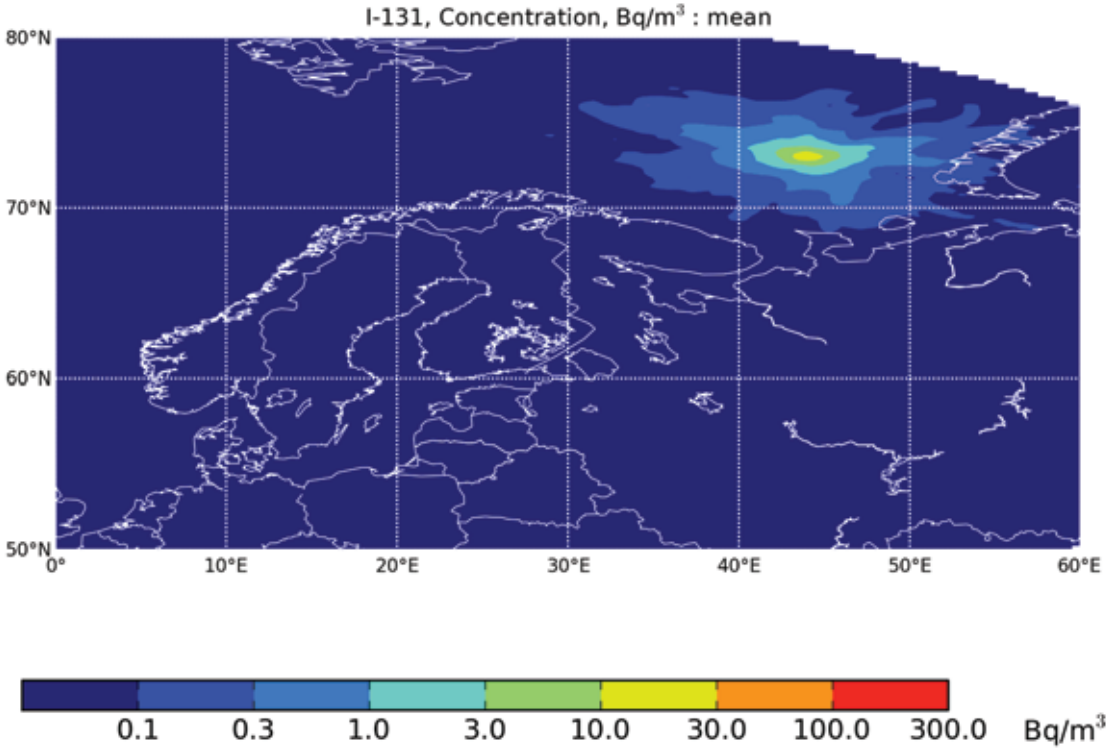

Figure 16. 48 hour average activity concentration of ^{131}I in the ground-level air after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

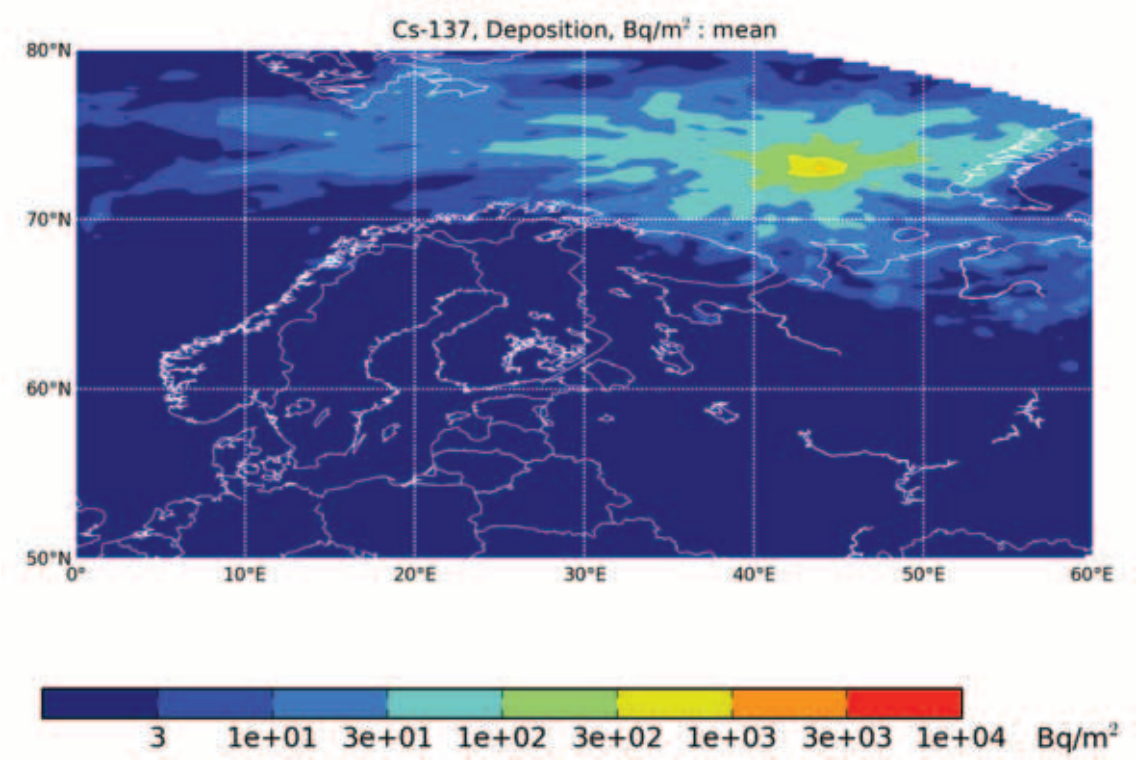

Figure 17. 48 hour average activity concentration of ^{137}Cs in the ground-level air after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

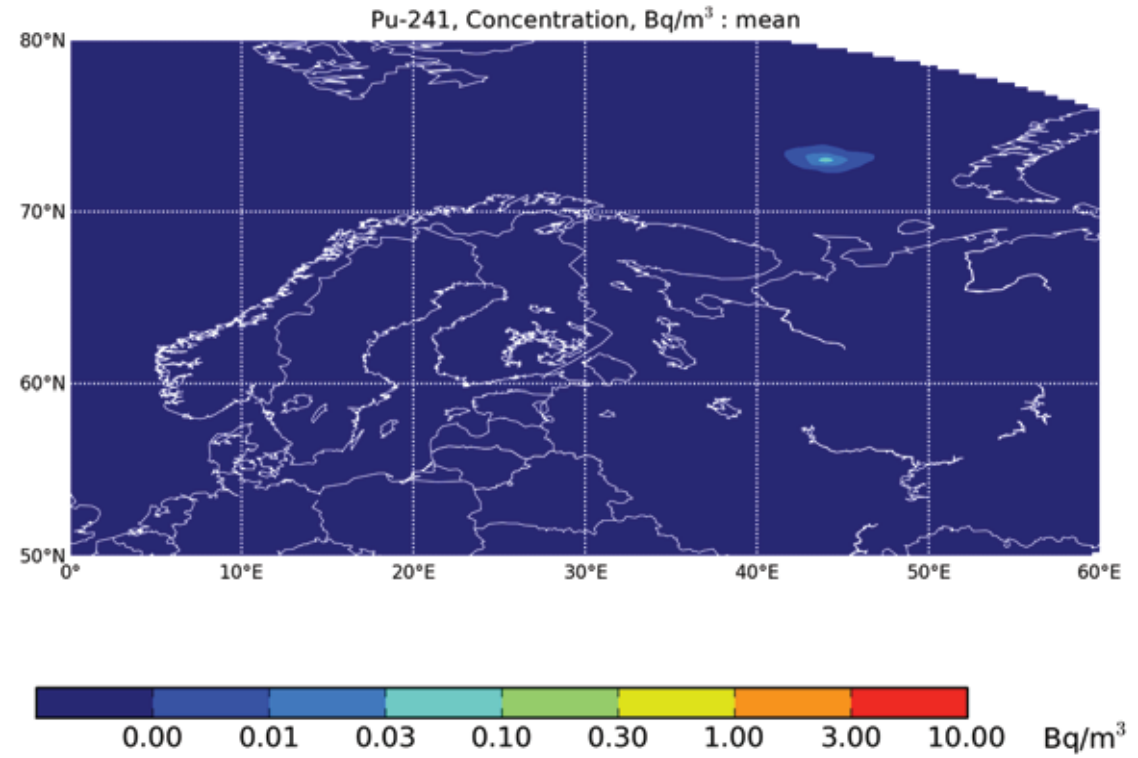

Figure 18. 48 hour average activity concentration of ^{241}Pu in the ground-level air after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

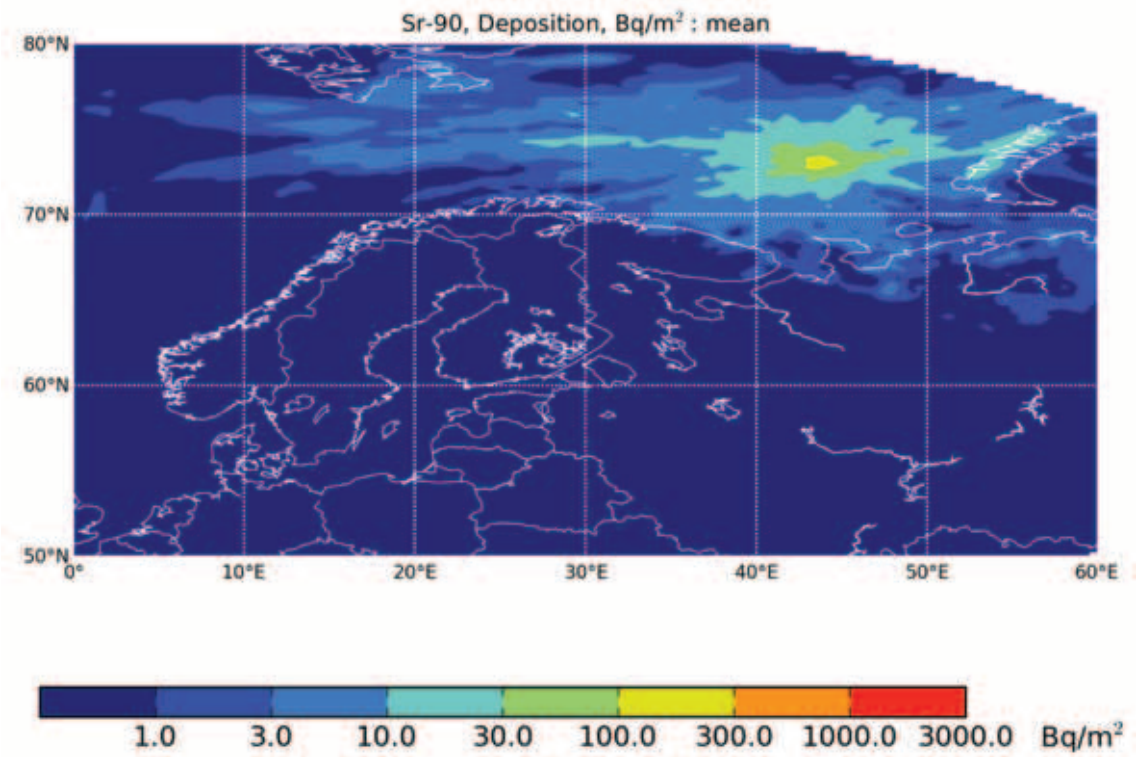

Figure 19. Cumulative deposition of ^{90}Sr 48 hours after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

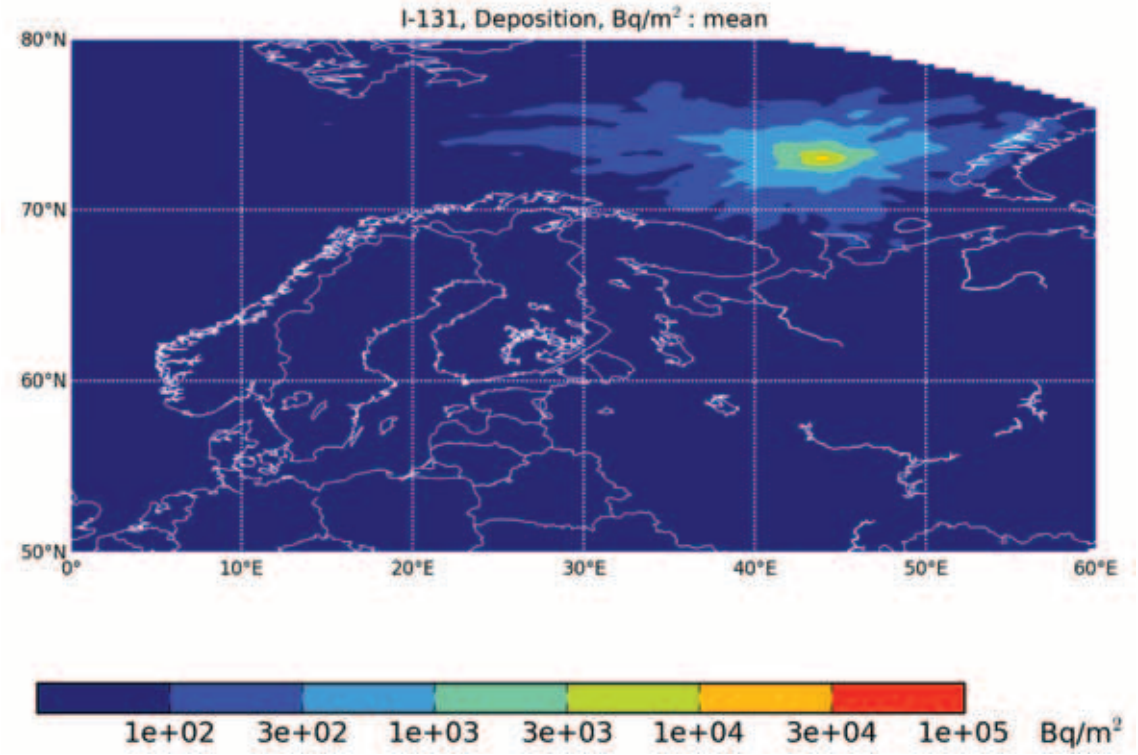

Figure 20. Cumulative deposition of ^{131}I 48 hours after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

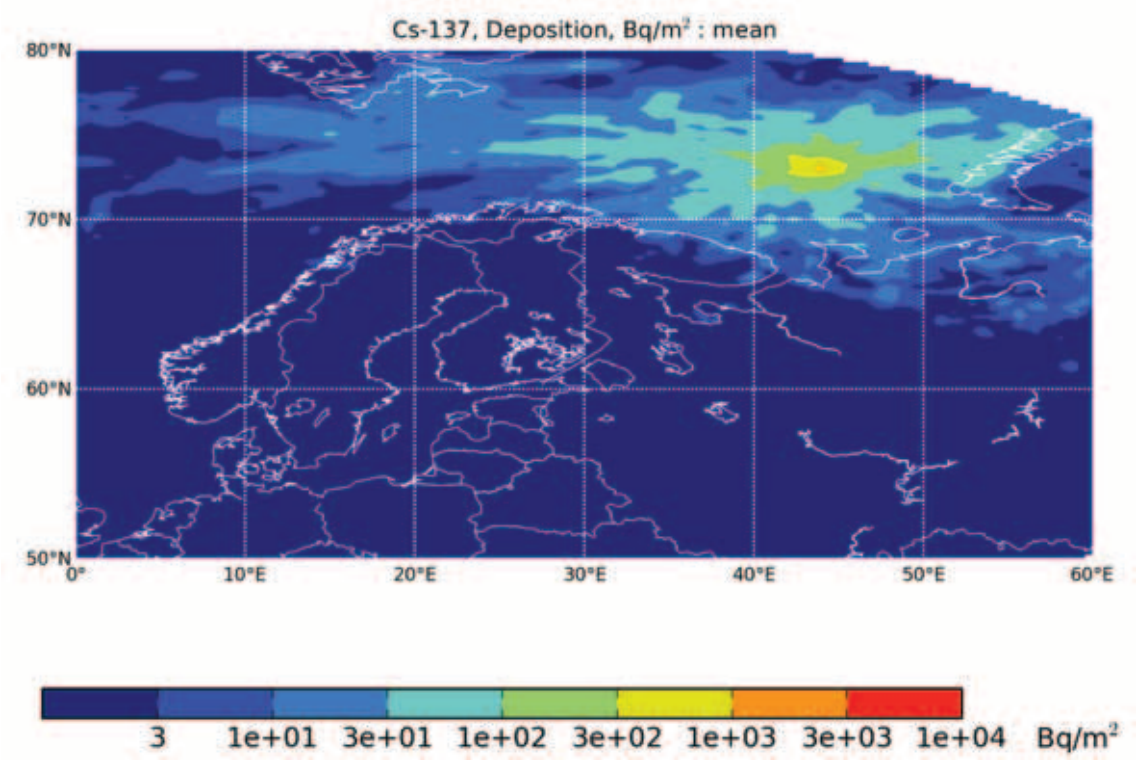

Figure 21. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

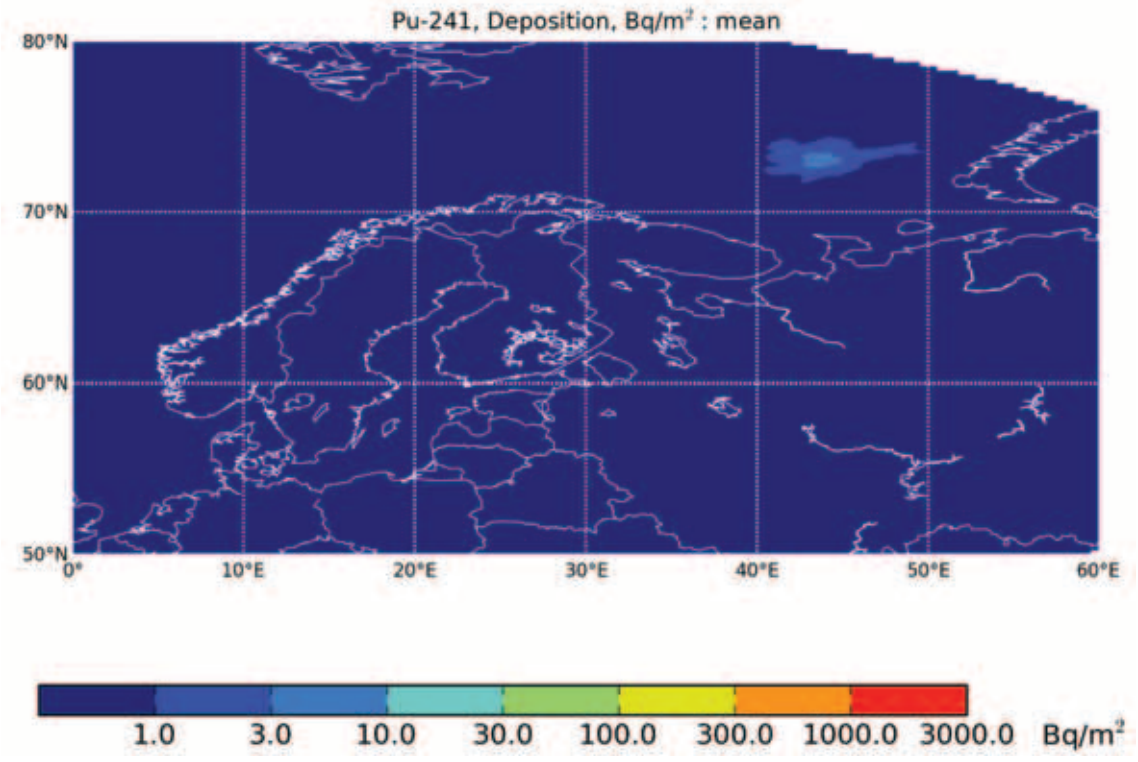

Figure 22. Cumulative deposition of ^{241}Pu 48 hours after a hypothetical reactor accident at Shtokmann gas field, average of 365 cases.

Comparison of the ^{137}Cs deposition from the release at the Pyhäjoki nuclear power plant calculated by the SILAM and SNAP models is shown in Fig. 23. The calculated deposition fields are very similar and especially the spatial pattern of the deposition with the characteristic tongue to the south. The deposition values on the tongue calculated by SNAP are a bit larger than the values calculated by SILAM, probably because of differences in precipitation fields in both models.

Comparison of atmospheric concentrations from the release at the floating nuclear power plant on the Barents Sea, and calculated by the SILAM and SNAP models are shown in Figs. 24-27, for ^{90}Sr, ^{131}I, ^{137}Cs and ^{241}Pu, respectively. The corresponding depositions are shown in Figs. 28-31, for ^{90}Sr, ^{131}I, ^{137}Cs and ^{241}Pu, respectively. There are some common features in the calculated concentrations and deposition fields for all tested nuclides. The spatial patterns of calculated concentrations and depositions, as well as predicted directions of transport are very similar. In the SILAM calculations, there is always a gap in concentrations and depositions over Northern Finland, but not in SNAP calculations. Depositions calculated by SNAP are slightly higher than those calculated by SILAM and there is more lateral spread in the SNAP results in simulations of both accidents, most likely due to differences in precipitation fields.

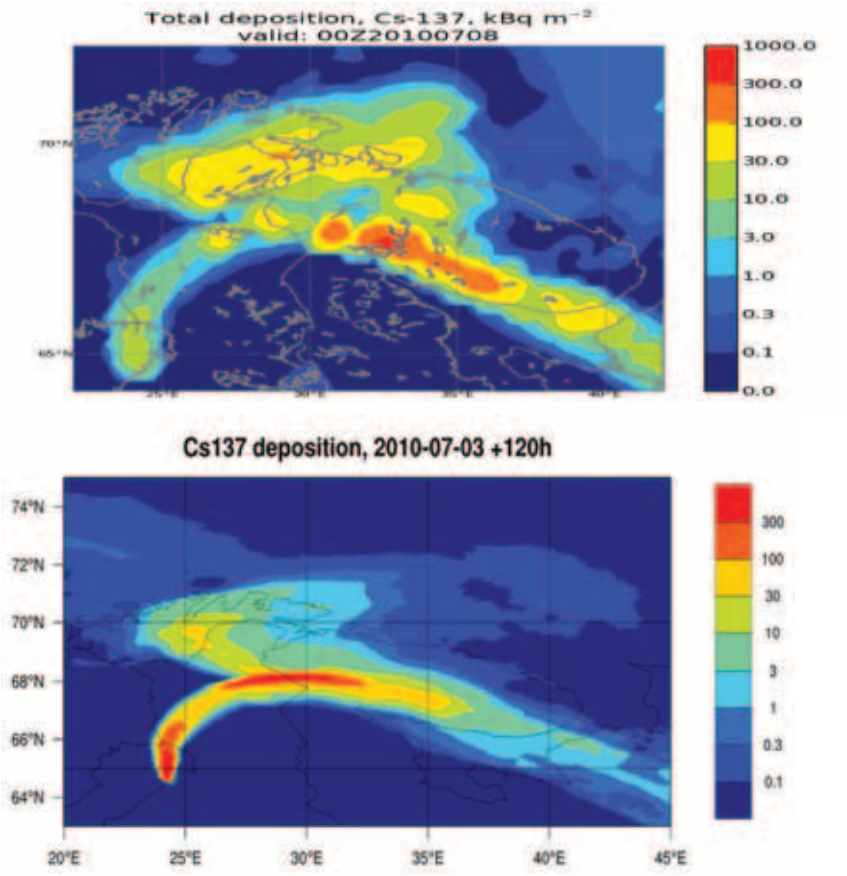

Figure 23. Cumulative deposition of ^{137}Cs 120 hours after a hypothetical reactor accident at Pyhäjoki, case 3 July 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

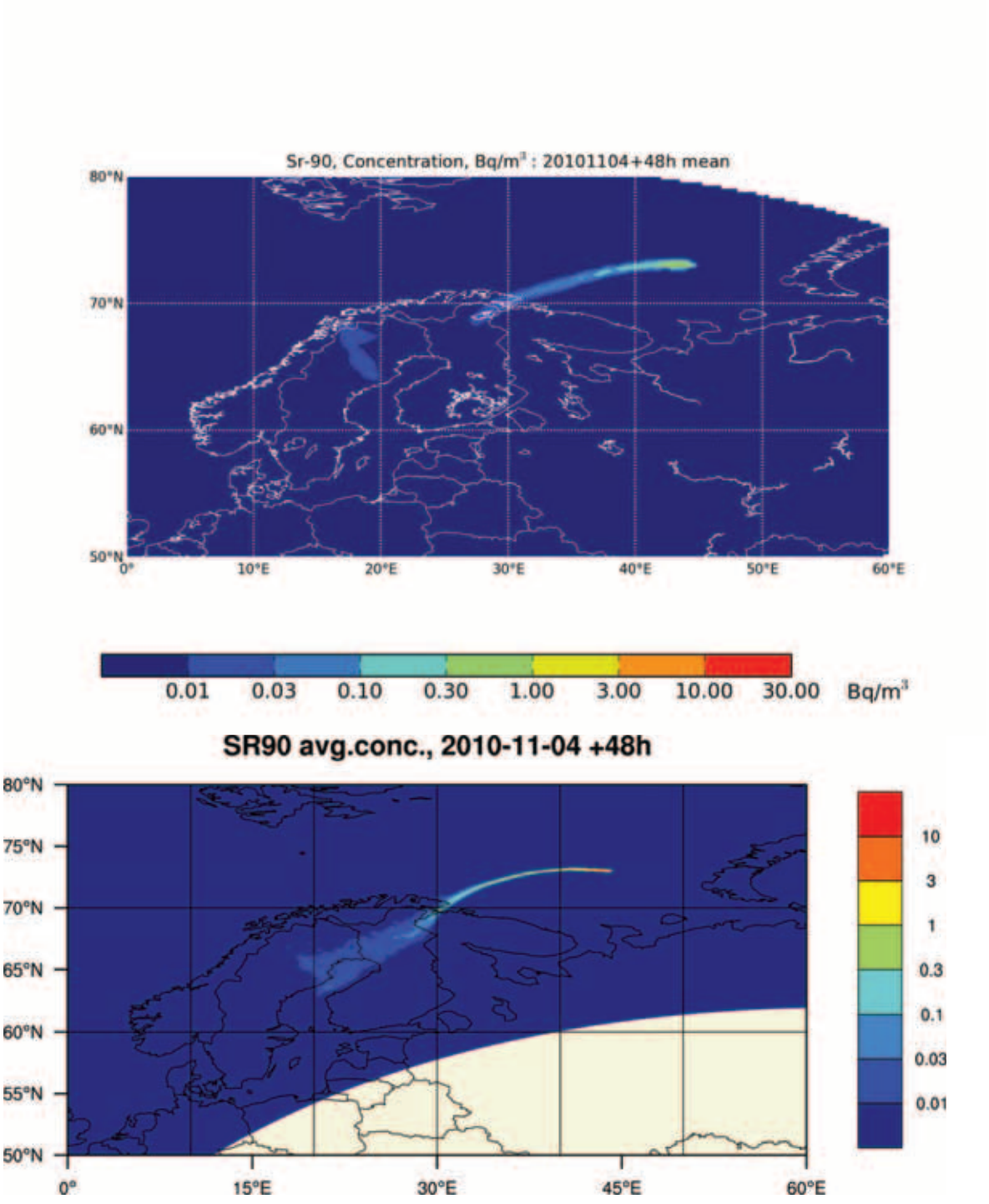

Figure 24. 48 hour average activity concentration of ^{90}Sr after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

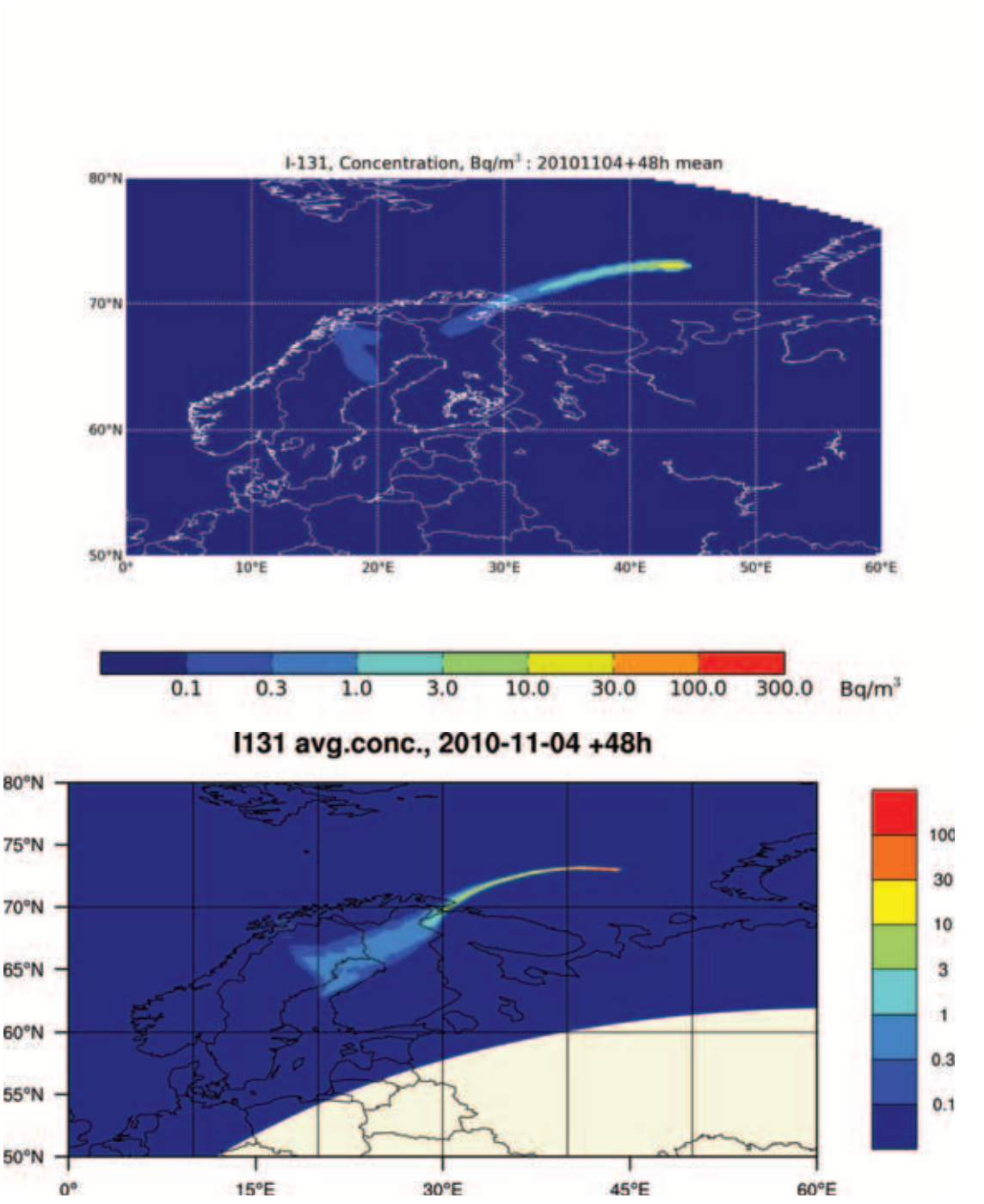

Figure 25. 48 hour average activity concentration of ^{131}I after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

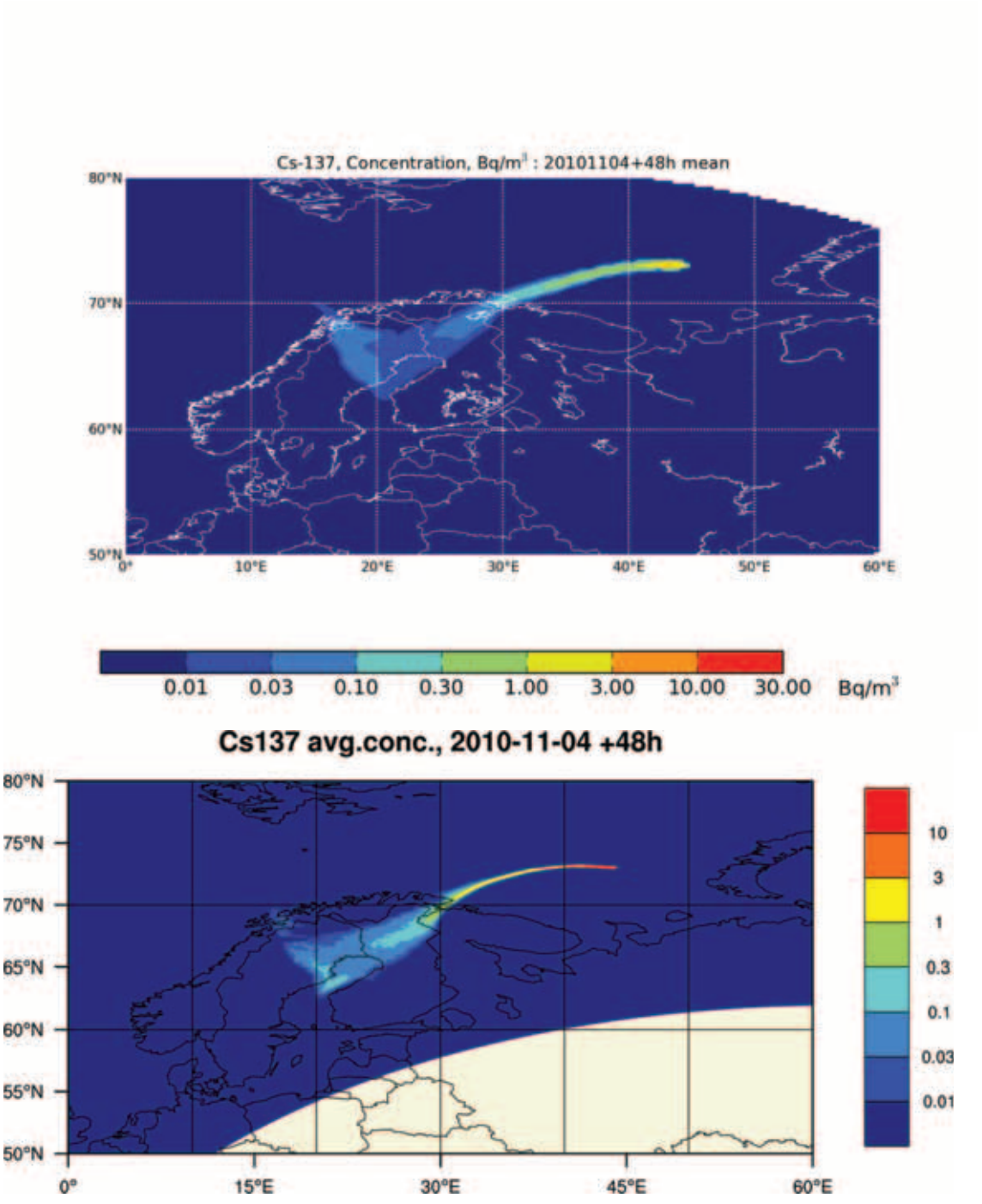

Figure 26. 48 hour average activity concentration of ^{137}Cs after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

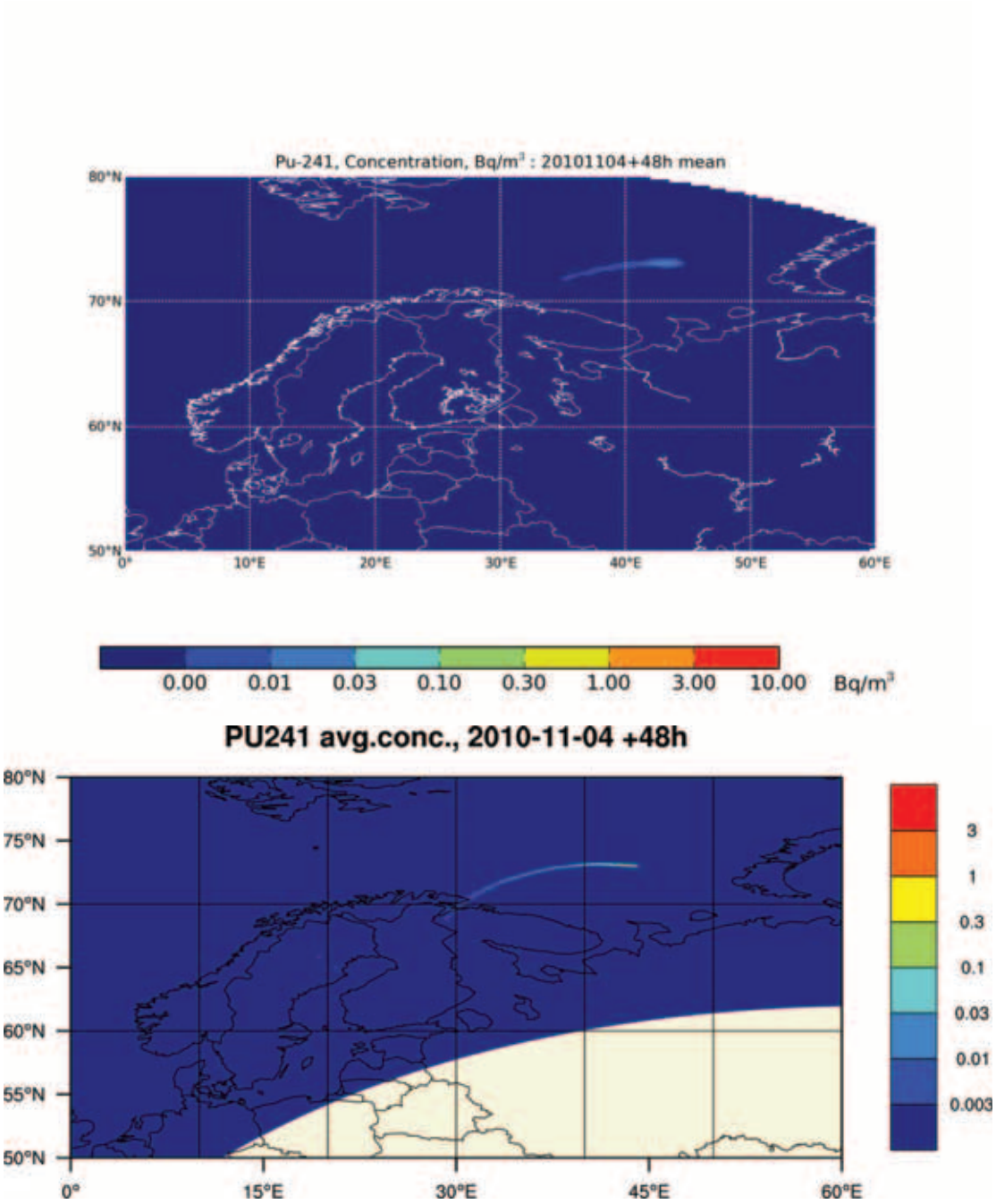

Figure 27. 48 hour average activity concentration of ^{241}Pu after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

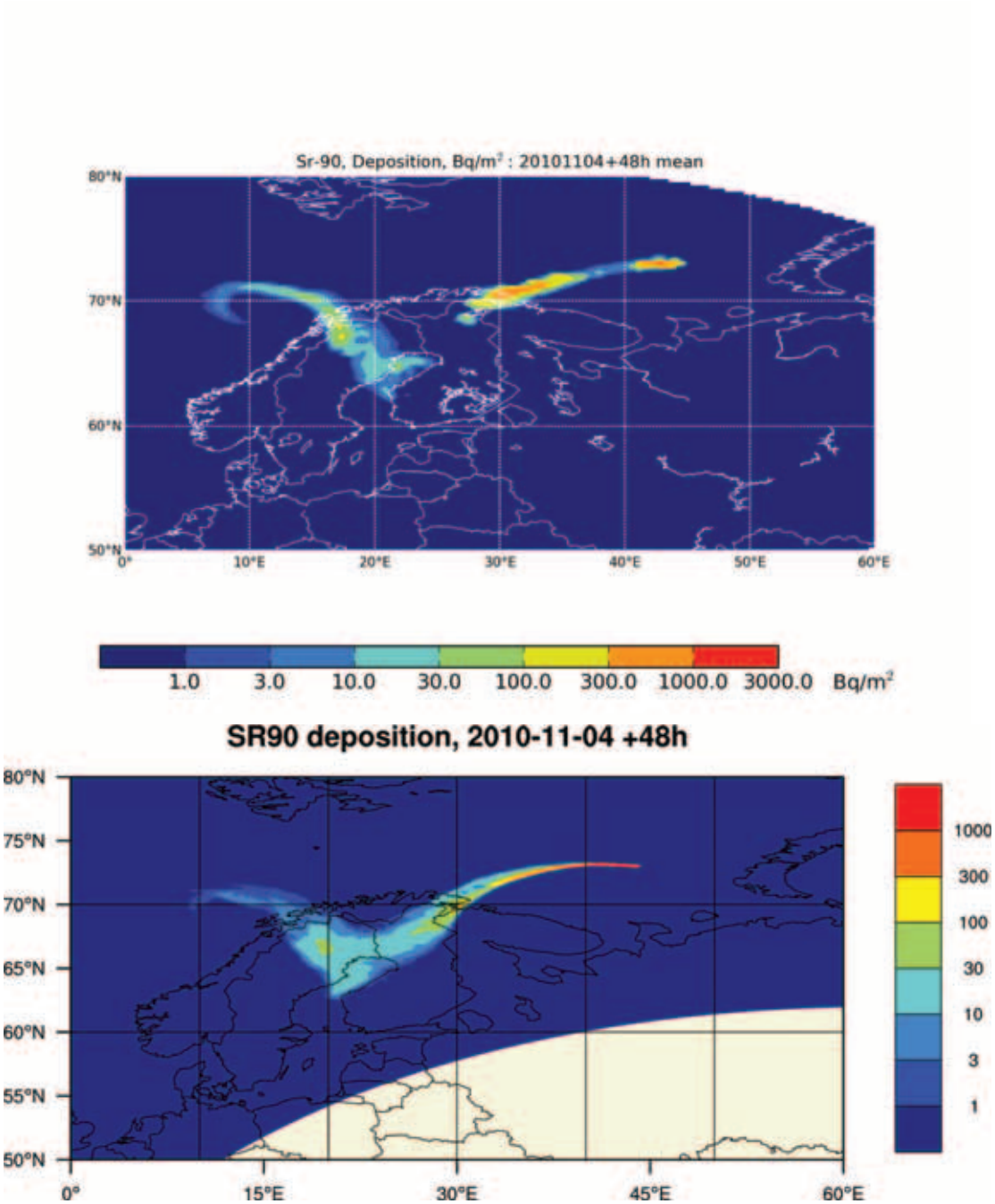

Figure 28. Cumulative deposition of ^{90}Sr 48 hours after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

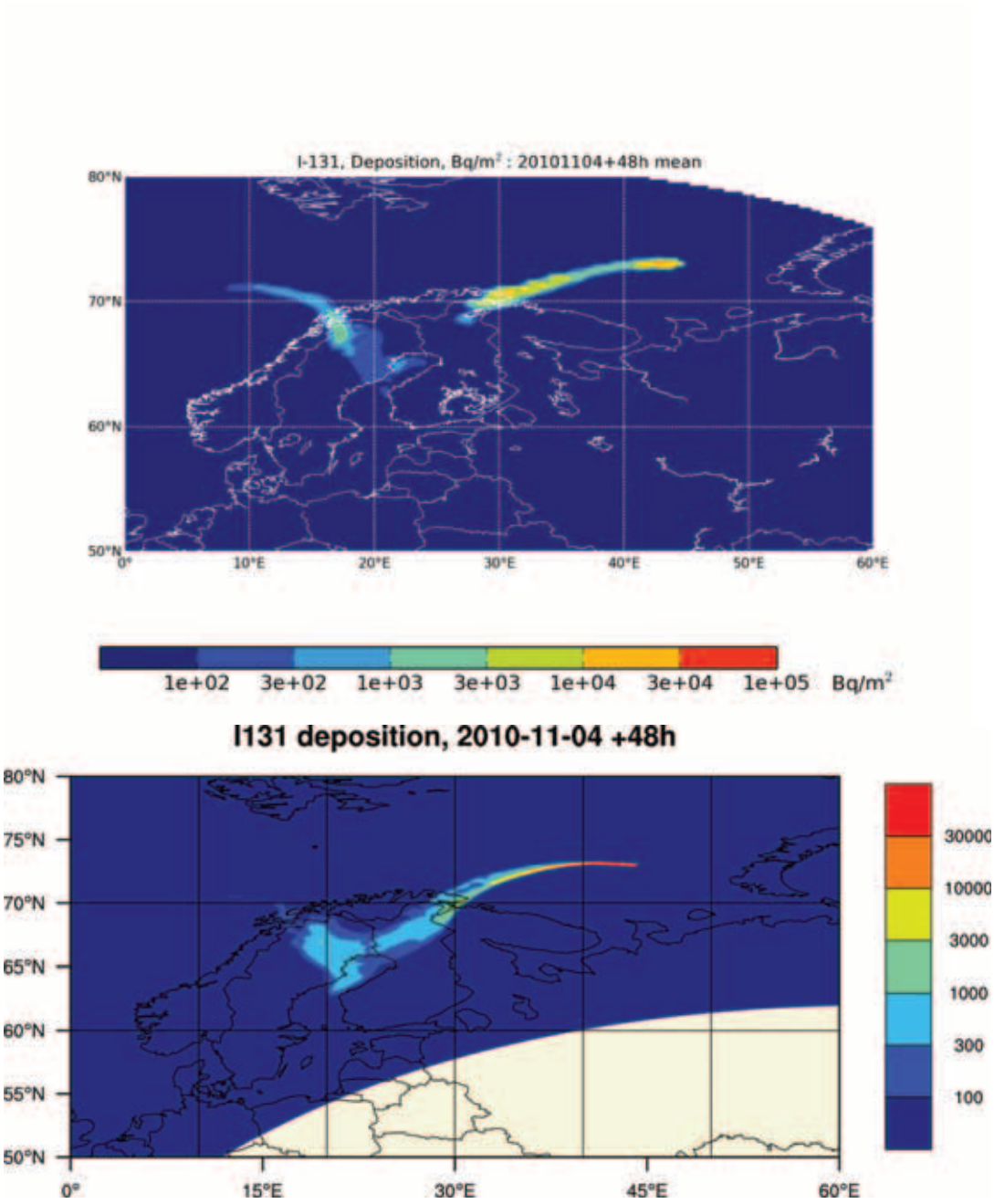

Figure 29. Cumulative deposition of ^{131}I 48 hours after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

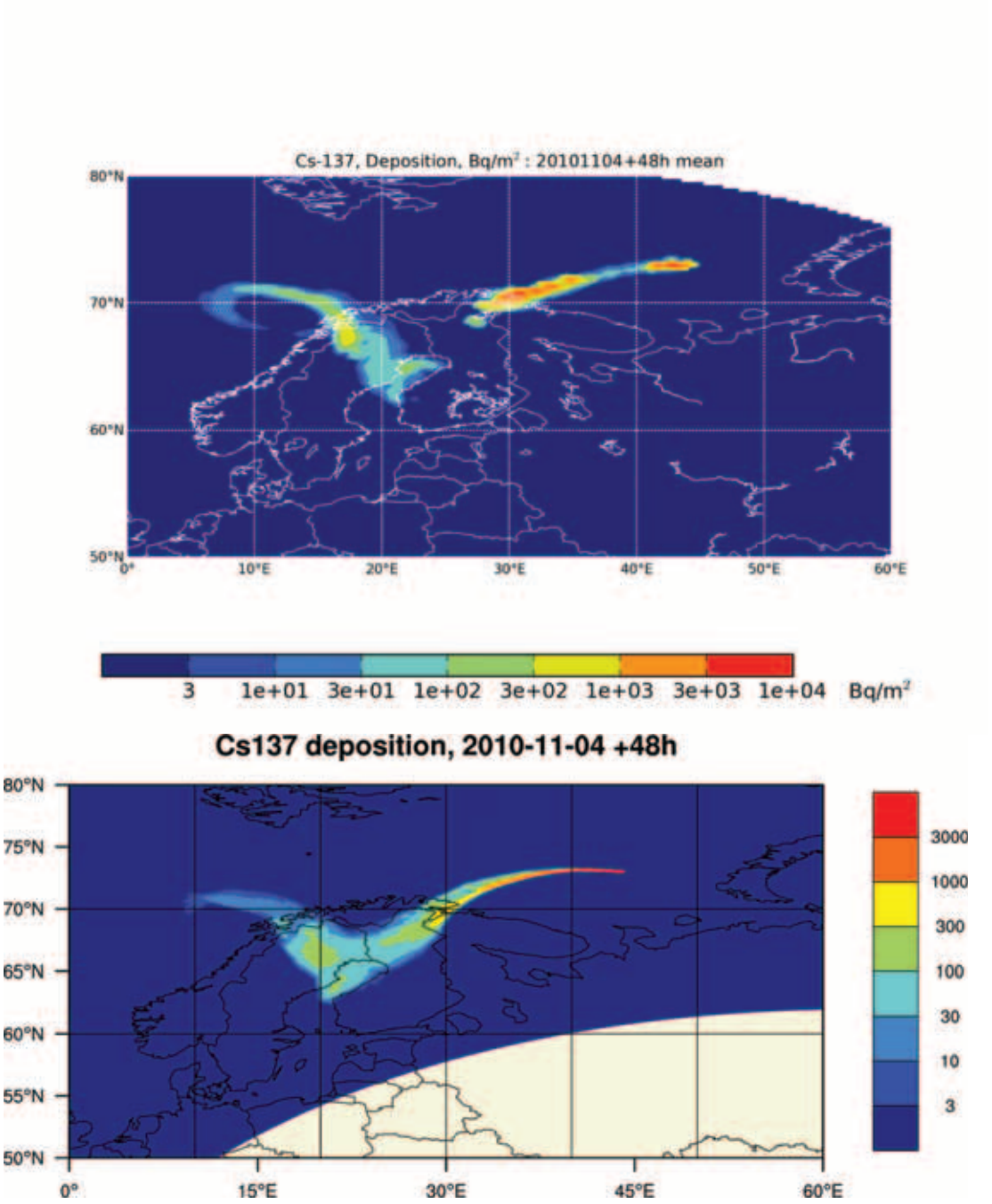

Figure 30. Cumulative deposition of ^{137}Cs 48 hours after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

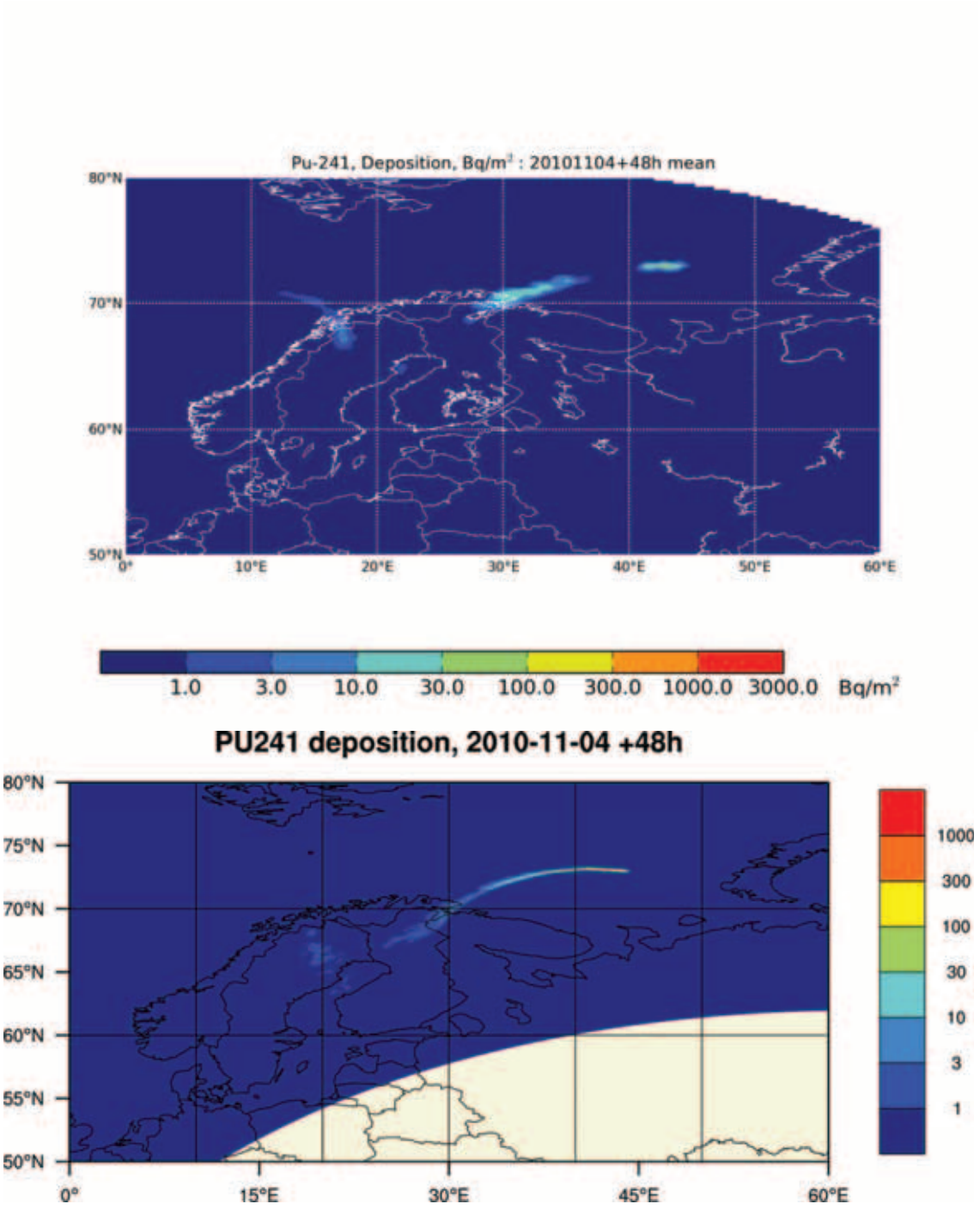

Figure 31. Cumulative deposition of ^{241}Pu 48 hours after a hypothetical reactor accident at Shtokmann gas field, Barents Sea, case 4 November 2010, comparison between SILAM (upper panel) and SNAP models (lower panel).

Comparison of modeled radionuclide concentrations with observations

The annual ^{137}Cs activity concentration in the ground-level air at Rovaniemi is presented in Figure 32. The measured maximum ^{137}Cs activity concentration, 328 µBq/m³, occurred in 1986. We can now make a rough comparison of the observations and model simulations described earlier to assess the levels of these two exposure sources in Finnish Lapland north of Rovaniemi. The annual exposure in 1986 was 328 µBq/m³ multiplied with 365 days = 119720 µBq×d×m^{-3}. To obtain the same exposure in two days an activity concentration of 119720 µBq×d×m^{-3} / 2 d = 59860 µBq×m^{-3} = 0.060 Bq/m^3 would be needed. The exposure of 48 hours activity concentration in the average case of ^{137}Cs from Pyhäjoki (Fig. 4) would be 17-170 times higher than the exposure in 1986 assuming no protective measures were taken. In the case of the Shtokmann site (Fig. 17) the exposure would be 50 times or less higher than the exposure in 1986.

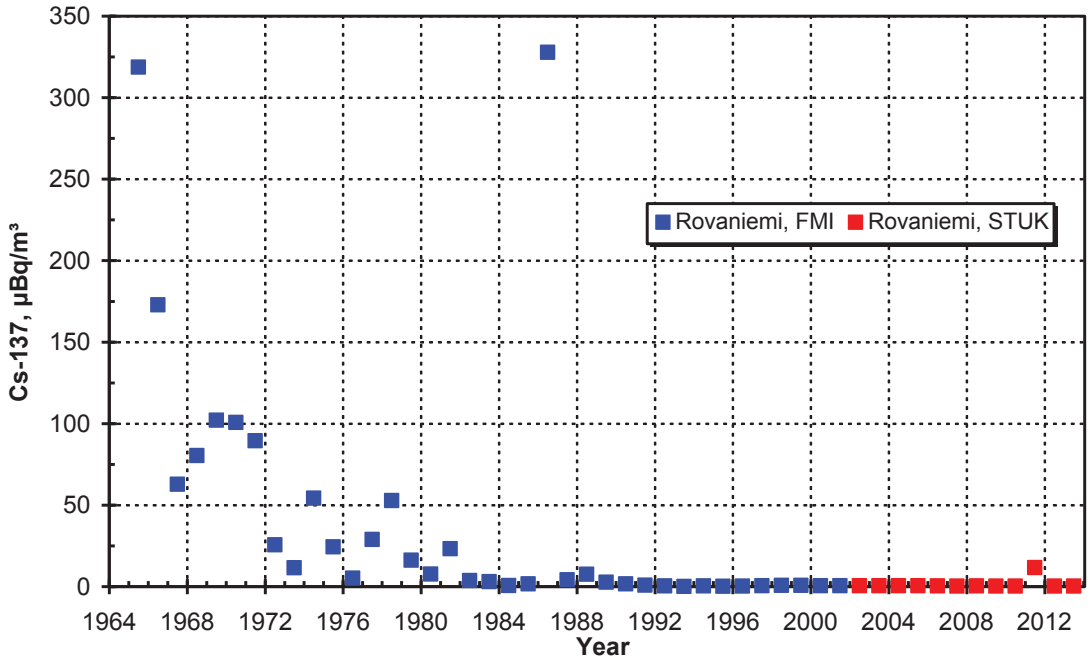

Figure 32. Measured annual average activity concentration of ^{137}Cs in the ground-level air (µBq/m³) at Rovaniemi 1965-2013.

CONCLUSIONS

This work once again shows how prevailing weather conditions are of the utmost importance in a case of an accidental radioactive release into the atmosphere. The direction of air flows settles the course of the emission plume. On one hand, the wind speed determines how quickly the emission plume is transported. On the other hand, the vertical and horizontal dispersion of the plume depends on the wind speed. This affects the concentrations of radioactive substances. Atmospheric radioactivity is removed from

the atmosphere by radioactive decay and by wet and dry deposition. Most radionuclides are bound to atmospheric aerosol particles. Dry deposition is important especially with large particles. Precipitation efficiently scavenges the radioactivity from the atmosphere to the ground, affecting the amount of the radioactive deposition.

The following conclusions can be formulated based on presented results of the comparison between the SILAM and SNAP models:

- Very similar spatial patterns for concentration and deposition for both models and for both examined cases. Directions of the transport are practically the same in the results of both models.
- In case of SILAM simulation of hypothetical accident on the Barents Sea, there is always a gap in concentrations and depositions over Northern Finland, but not in case of SNAP.
- Depositions calculated by SNAP look slightly higher than those calculated by SILAM and there is more lateral spread in the SNAP results in simulations of both accidents.
- Precipitation is the most likely reason for small differences between SILAM and SNAP in calculated concentration and deposition fields.

The calculated exposure to ^{137}Cs in the ground-level air is an overestimation. People spend much of their time indoors and ventilation systems of buildings usually automatically provide some cover against atmospheric radioactivity. In addition, in an emergency situation people would be adviced to stay indoors and enhance the protection provided by their residences by shutting down ventilation systems and sealing doors and windows.

ACKNOWLEDGEMENTS

This work is part of the project "Collaboration Network on EuroArctic Environmental Radiation Protection and Research (CEEPRA)". The project was financed by the EU, Kolarctic ENPI CBC programme managed by the Regional Council of Lapland.

Collaboration Network on EuroArctic Environmental Radiation Protection and Research (CEEPRA)

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ILMATIETEEN LAITOS, RAPORTTEJA 2014:8
ISBN 978-951-697-837-9 (paperback)
ISBN 978-951-697-838-6 (PDF)
ISSN 0782-6079
Unigrafia
Helsinki 2014