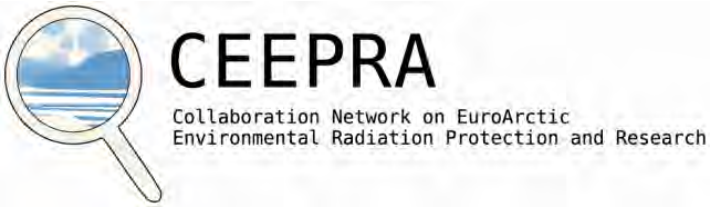
Traces of Fukushima nuclear power plant accident observed in the EuroArctic region

Ari Leppänen[1], Nadezhda Kasatkina[2], Bredo Møller[3] and Anna Nalbandyan[3]

[1] – Radiation and Nuclear Safety Authority, Finland (STUK)
[2] - Murmansk Marine Biological Institute (MMBI)
[3] - Norwegian Radiation Protection Authority (NRPA)



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1. Introduction

The Great East Japan Earthquake on March 11th, 2011 at magnitude 9 generated a series of large tsunami waves that struck the east coast of Japan, the highest being 38 m at Aneyoshi, Miyako (EERI, 2011). The tsunami waves hit the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) causing a loss of backup electric generation. The FDNPP had executed an emergency shutdown during the earthquake. However, in the tsunami event the emergency power generators were lost and the reactors left without cooling. Without cooling, the reactor cores overheated due to the decay heat in the nuclear fuel. Radioactive emissions into the atmosphere from the damaged reactors of the FDNPP started on March 12th, 2011. Despite the rescue efforts, large quantities of radioactive nuclides were emitted into the atmosphere and sea. The estimates of the released activity vary between different sources. According to the IAEA June 2012 Fukushima Dai-ichi status report, approximately 150 PBq of ^{131}I and 8.2 PBq of ^{137}Cs were released into the atmosphere (IAEA, 2012). Of the total radioactivity released, about 20 % came from Unit 1, 40 % from Unit 2 (peak on March 15th) and 40% from Unit 3 (peak on March 16th) (Thakur et al., 2013). The atmospheric radioactive release was transported across the Pacific to North America (Bowyer et al., 2011 and Diaz et al., 2011), to Europe (Masson et al., 2011) and to Central Asia (Bolsunovsky and Dementyev, 2011). By day 15 after the initial releases of radioacytivity, traces fission products from FDNPP were detectable all across the Northern hemisphere (Thakur et al., 2013). Among the various radionuclides released in large amounts, iodine-131 (^{131}I; $T_{1/2}$ = 8.0 d), cesium-134 (^{134}Cs; $T_{1/2}$ = 2.1 yr) and cesium-137 (^{137}Cs; $T_{1/2}$ = 30.1 yr) were easily detectable and of major interest for health impact assessments. Other short-lived radionuclides including tellurium-132 (^{132}Te; $T_{1/2}$ = 3.2 d), tellurium-129 (^{129}Te; $T_{1/2}$ = 1.2 hr), tellurium-129 in meta-stable state (^{129m}Te; $T_{1/2}$ = 33.6 d), iodine- 132 (^{132}I; $T_{1/2}$ = 2.3 h), and cesium-136 (^{136}Cs; $T_{1/2}$ = 13.16 d) were detected at trace levels. Outside Japan, the released radioactivity did not pose a health risk.

After the Chernobyl accident, the importance of both the short- and long-term effects of radioactive contamination were recognized. The detailed knowledge of temporal trends in activity concentrations of different fission products will offer an opportunity to test atmospheric transport, reactor core simulation and biological models.

2. Releases observed in the surface air

2.1 High Arctic

In the simulations of the Fukushima release a small branch of the plume travels across the Arctic region while the main plume travelled across the Pacific, North America, Atlantic and then to Kolarctic region. One of the stations to observe atmospheric radioactivity concentrations in the European High Arctic is located at Mount Zeppelin at Ny-Ålesund in Svalbard. The monitoring station observes airborne radioactivities in aerosol form. The station in run by Finnish Meteorological Institute (FMI). FMI is one of the partners in the Collaboration Network on EuroArctic Environmental Radiation Protection and Research (CEEPRA) project. The figure 1 shows the time series of ^{134}Cs and ^{137}Cs activity concentrations and the ^{134}Cs/^{137}Cs ratio in aerosol form observed at Mt. Zeppelin after the accident at Fukushima Dai-ichi NPP. The first observations where done on April, 25th- April, 28th. Highest concentrations of ^{134}Cs, ^{137}Cs and ^{131}I where observed during April 1st- April 4th, 2011. The figure 2 shows the atmospheric total beta and concentrations of ^{131}I as a function of time. The figure 3 shows the comparison between observed ^{131}I concentrations and SILAM (System for Integrated modeLling of Atmospheric coMposition) dispersion model calculations. As it can be seen from the figure the computer model underestimates the ^{131}I concentrations but succeeds well in the timing of the release plume (Figure 3 was adopted from Paatero et al., 2012).

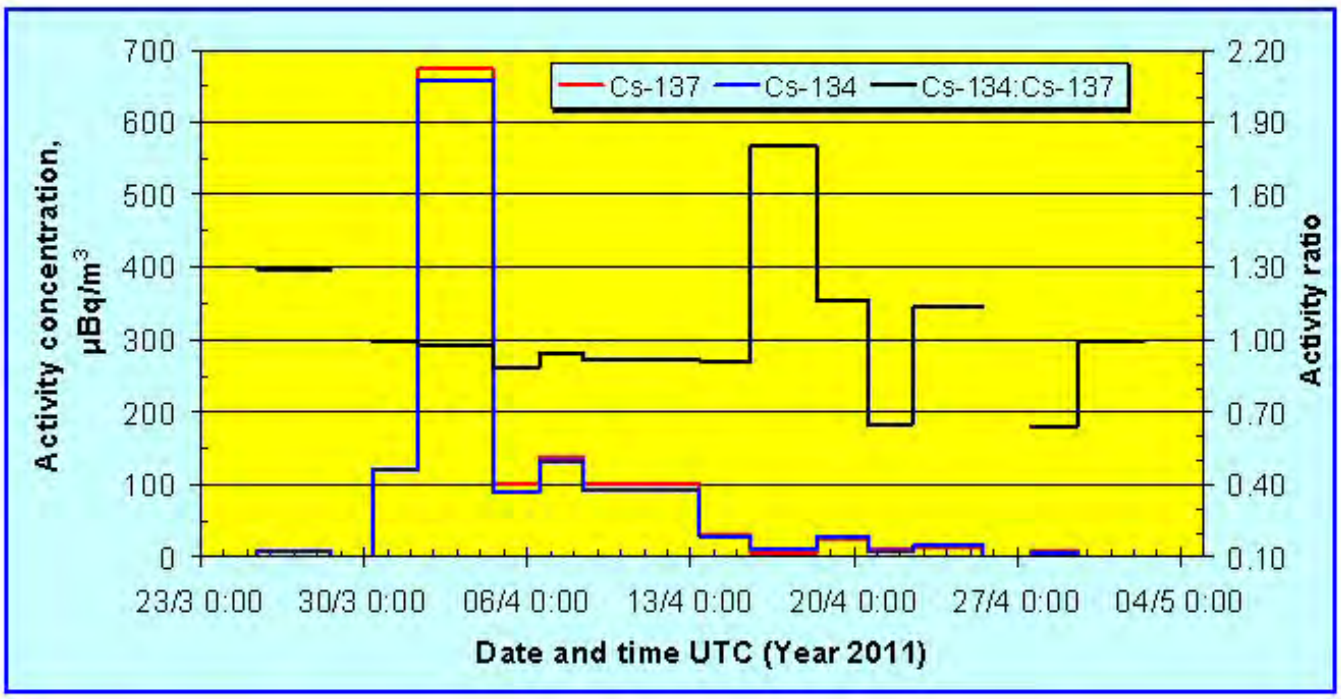

Figure 1. Activity concentrations of ^{134}Cs and ^{137}Cs observed at Mt. Zeppelin in Longyearbyen, Svalbard (Figure adopted from Paatero et al., 2012).

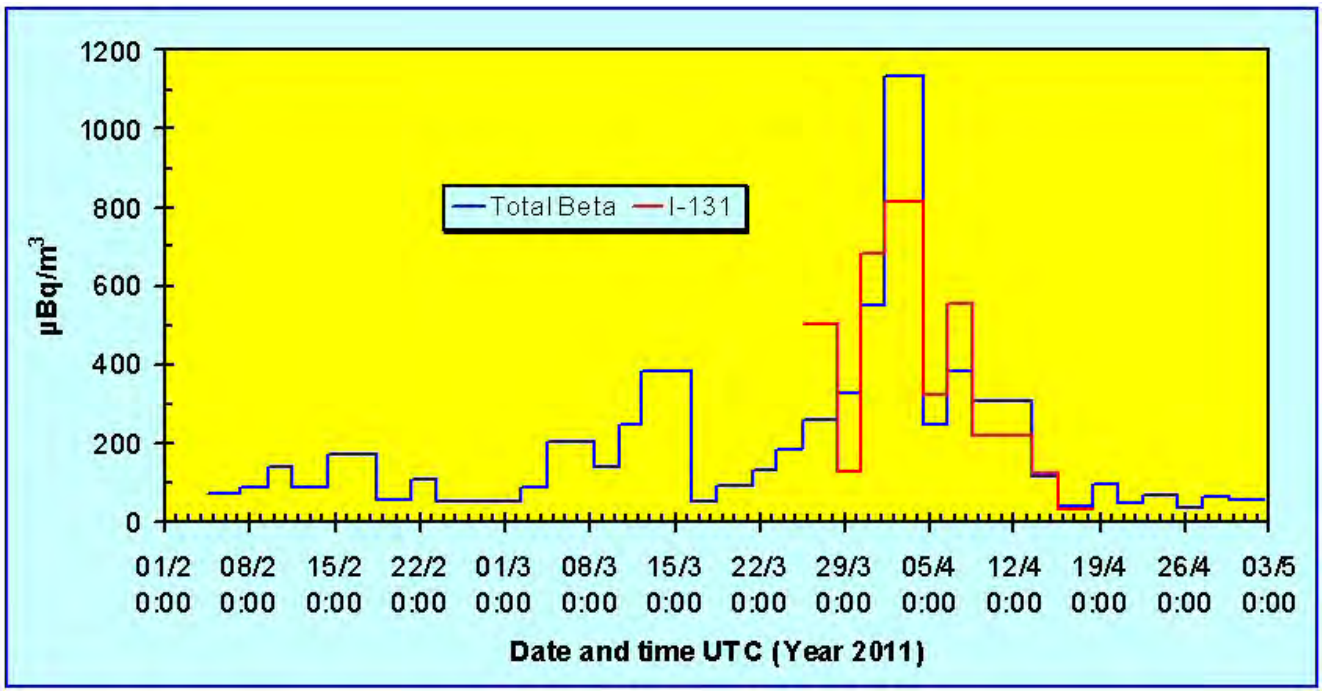

Figure 2. Total beta and ^{131}I concentrations observed at Mt. Zeppelin in Longyearbyen, Svalbard (Figure adopted from Paatero et al., 2012).

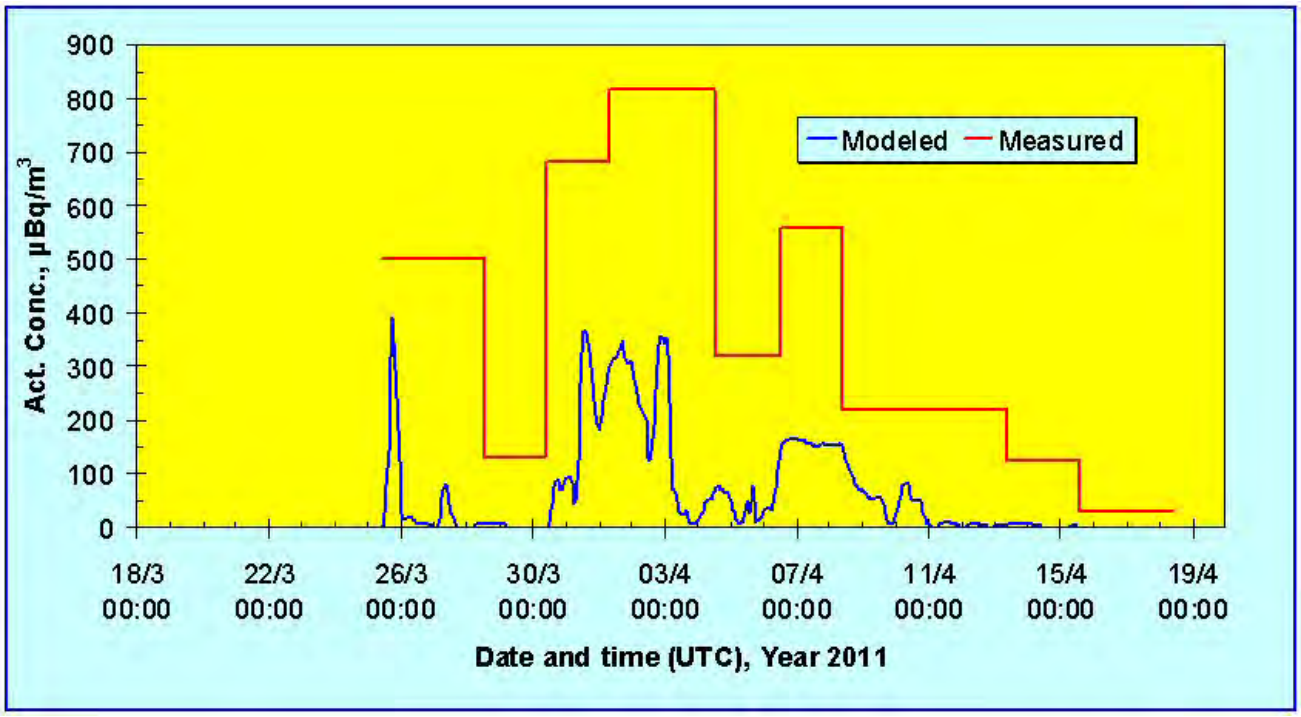

Figure 3. Comparison between observed ^{131}I concentrations and results of SILAM dispersion model.

Another air monitoring station located at Longyearbyen in Svalbard is being operated by the Norwegian Radiation Protection Authority (NRPA) - partner in the CEEPRA project. This station is a part of the global monitoring CTBTO network (Comprehensive Nuclear-Test-Ban Treaty Organization). After the accident at the Fukushima Dai-ichi NPP, the results of measurements were provided to the Norwegian Meteorological Institute (MET – associated partner in the CEEPRA project) for modelling and assessment. Using data on activity concentrations of ^{137}Cs in the air, MET performed analogical comparison as FMI to see the difference between the calculated by atmospheric dispersion and observed concentrations.(Klein H. and Bartnicki J., 2014).

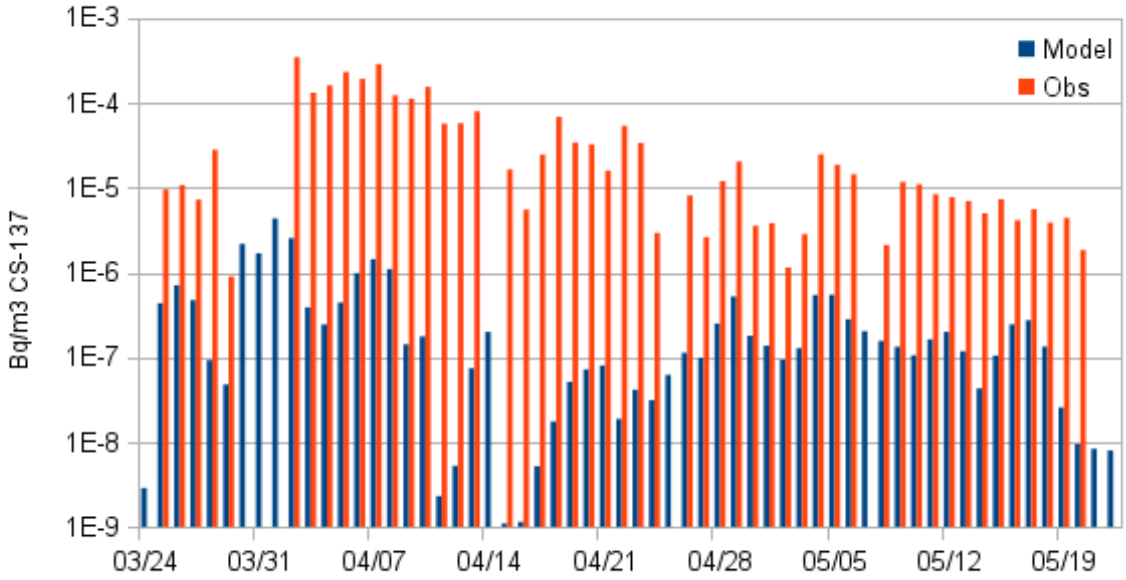

Figure 4. Comparison between observed ^{137}Cs concentrations and results of EEMEP dispersion model (MET, unpublished study).

For simulations Norwegian experts used the Eulerian EEMEP global-scale model developed as a modification of the EMEP MSC-W model in the framework of the European Monitoring and Assessment Program (EMEP) (Simpson, D. et. all, 2012a; 2012b). At present the EEMEP model is partly operational at MET while it is still under going testing and development.

As seen from Fig. 4, there is a good agreement between measured and calculated arrival times, but calculated concentrations are at least one order of magnitude too low compared to measurements (Klein H. and Bartnicki J., 2014). Thus, as in the case with modeling of ^{131}I concentrations with Finnish SILAM, the model used in Norway also underestimated ^{137}Cs concentrations, but succeeded well in the arrival time of the release plume. However, this is only a preliminary comparison of the model results with measurements at this stage.

2.2 Kolarctic Region

2.2.1. Norway (Finnmark and Troms)

The Norwegian Radiation Protection Authority (NRPA) has three sampling stations to monitor airborne radioactivities in the Kolartic region. The stations are located in Svanhovd in the Pasvikdalen, in Skibotn in the municipality of Storfjord in Troms county and in Viksjøfjell east of Kirkenes near Russian border. During the Fukushima accident the monitoring stations were collecting aerosol samples in different intervals which can be seen in the figure 5. The concentrations in the figures 5-7 are expressed in the units of μBq/m^3. The figure 5. panel A shows the concentrations of ^{131}I in surface observed in Norwegian Kolarctic stations. The sampler located in Svanhovd was sampling not only ^{131}I in particle phase, but also sampling ^{131}I in gaseous phase. The samplers located in Skibotn and in Viksjøfjell where not equipped with this capacity. Figure 5 panel B shows the concentrations of ^{134,136,137}Cs isotopes in surface air and the panel C concentrations of ^{129m,132}Te isotopes and ^{132}I which is the daughter nucleus of ^{132}Te in the above mentioned stations. The ^{131}I in gaseous form was observed by far in highest concentrations thus underlining the importance of this isotope. The highest concentrations in Norwegian stations were observed in the samples collected during April 1st-April 2nd. In the figure 5 the mid-point of the sampling

period is used as a reference which is indicated by the different color and shape symbols. In total 7 different anthropogenic radioactive isotopes from Fukushima NPP accident were observed in Northern Finland.

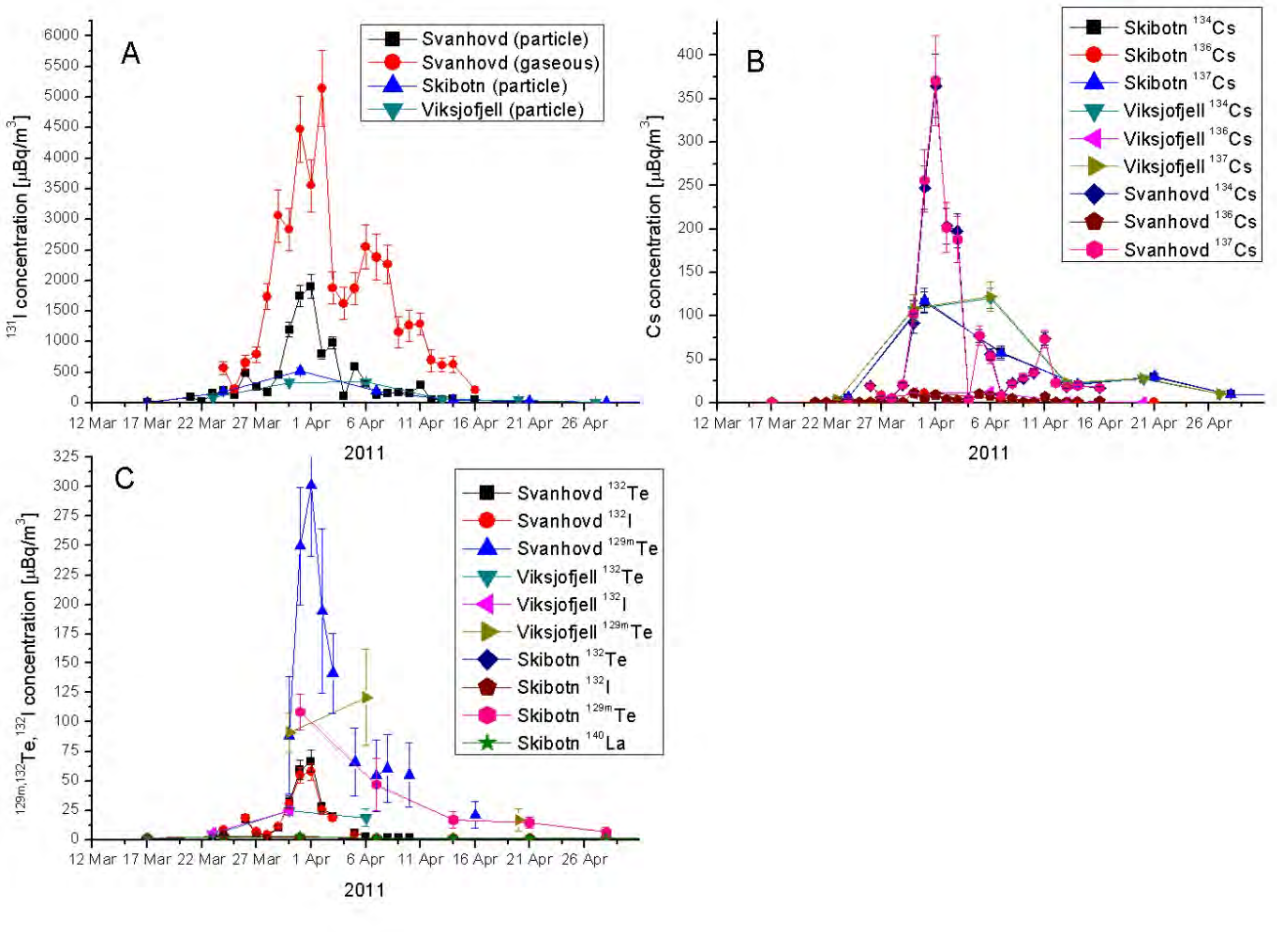

Figure 5. Concentrations of ^{131}I originating from Fukushima observed in Norwegian Kolartic sampling stations in March-April, 2011 (Masson et al., NRPA, unpublished data).

2.2.2 Finland (Lapland)

In Finland, the Radiation and Nuclear Safety Authority (STUK) has three sampling stations located in the Kolarctic region one at the Arctic Circle at Rovaniemi, one at Sodankylä in the Central Lapland and one at Ivalo in the municipality of Inari. During the accident all stations were able to samples radioactive nuclides as aerosols and in gaseous form. During the accident Rovaniemi station was collecting samples daily while Sodankylä and Ivalo stations were sampling on bi-weekly basis. The first observations of Fukushima plume was observed from the samples collected during March 18th – March 21st. Highest concentrations were observed from the samples collected during April 1st- April 2nd, 2011. The figure 6 panel A shows the ^{131}I concentrations, in both particle and gaseous form, observed in Finnish sampling stations, the panel B shows the concentrations of ^{134,136,137}Cs isotopes and the panel C shows the concentrations of ^{129,129m,132}Te and ^{132}I. In the figure 6 the mid-point of the sampling period is used as a reference which is indicated by the different color and shape symbols. In total 6 different anthropogenic radioactive isotopes from Fukushima NPP accident were observed in Northern Finland.

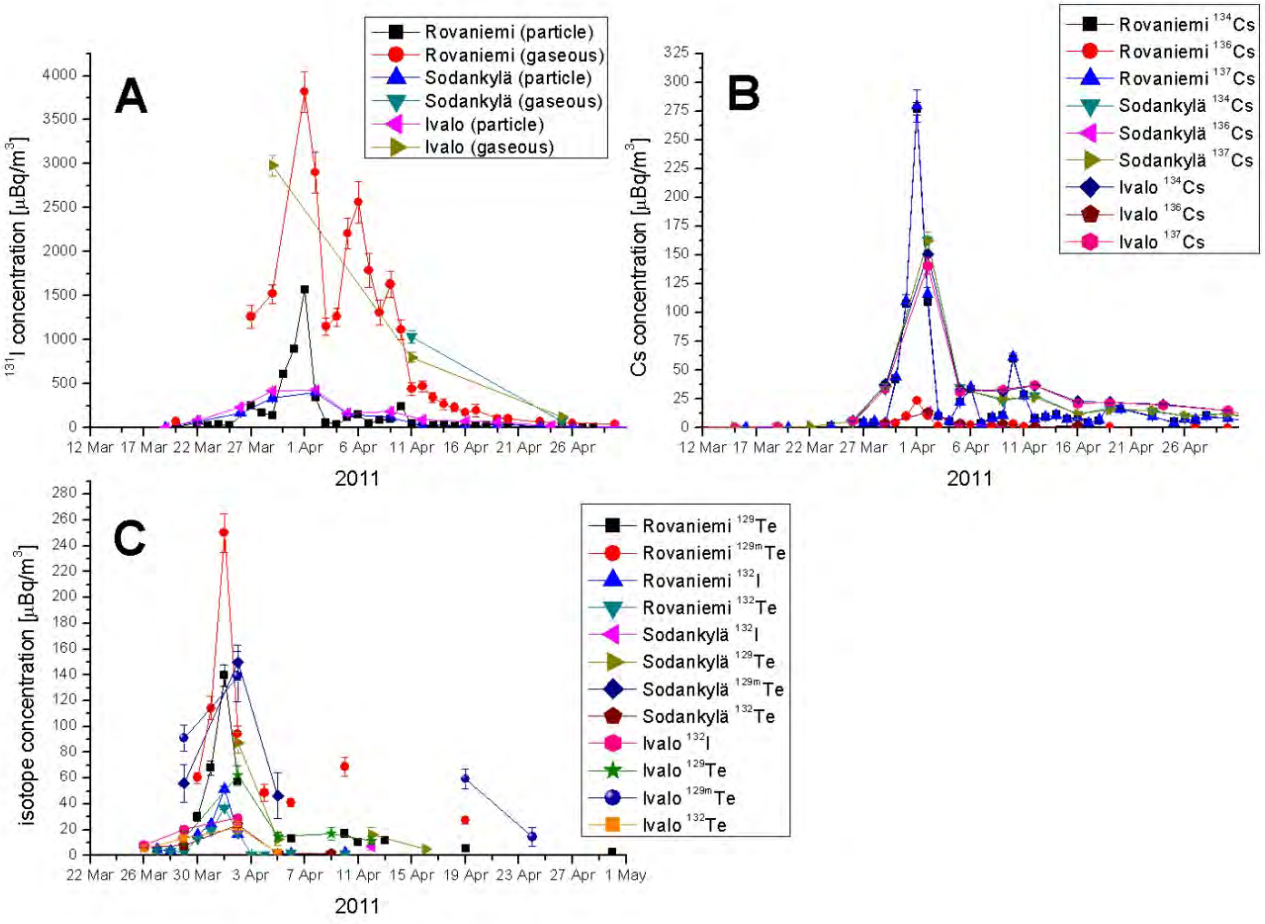

Figure 6. Concentrations of different isotopes in surface air in Finnish Lapland during March-April, 2011. Panel A shows the concentrations of ^{131}I, panel B shows the concentrations of ^{134}Cs, ^{136}Cs and ^{137}Cs and panel C shows the concentrations of ^{129}Te, ^{129m}Te, ^{132}Te and ^{132}I (Leppänen et al., 2013).

2.2.3 Russia (Kola Peninsula)

The Russian Federal Service on Hydrometeorology and Environmental Monitoring (RosHydroMet) monitored airborne radioactivity concentrations in Murmansk in the spring of 2011. Along with the concentrations of anthropogenic radioactive substances dose rate was also monitored. The concentrations of anthropogenic radioisotopes observed in Murmanskc were slightly lower compared to concentrations observed in Norway and in Finland. In all three regions the peak concentratios were observed roughly at the same time.

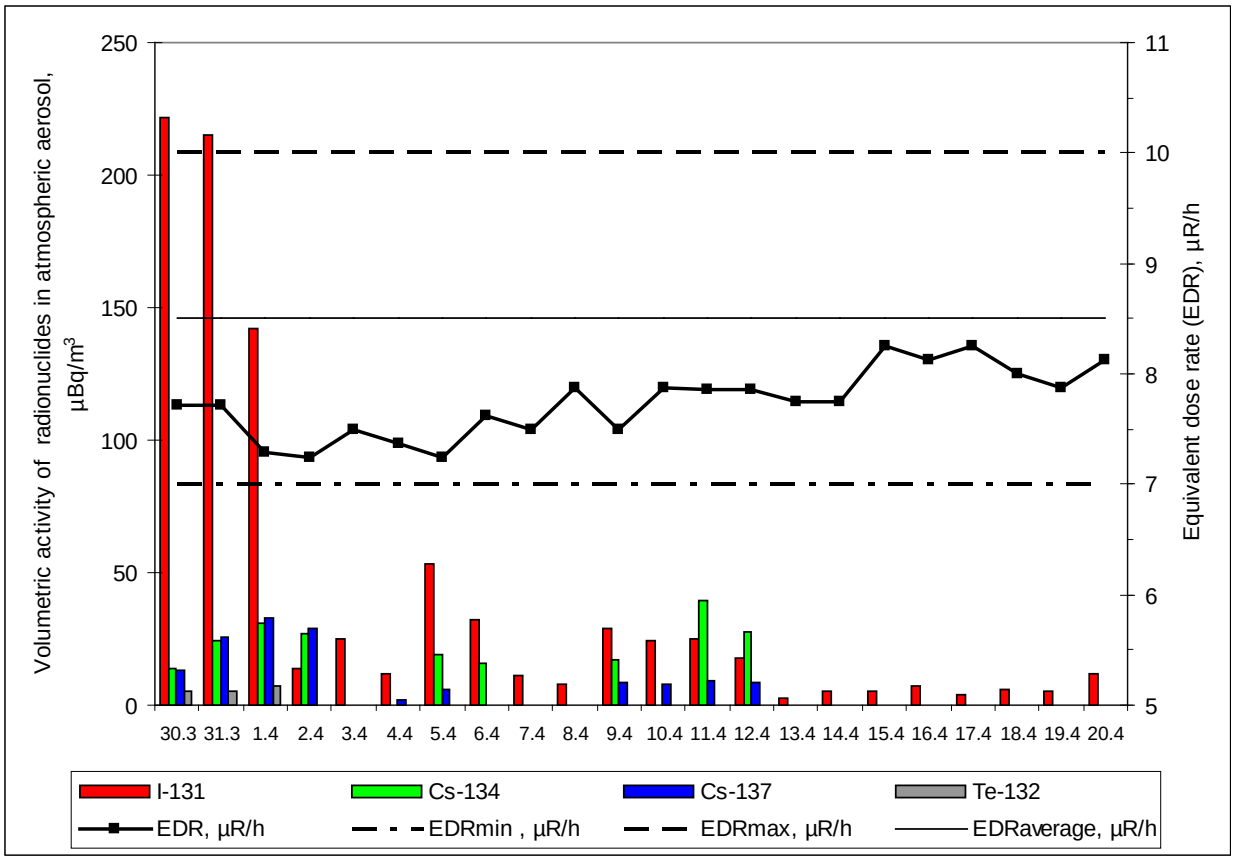

Figure 7. Concentrations of anthropogenic radionuclides originating from Fukushima NPP accident observed at Murmansk, Russia in March-April, 2011. (Murmansk Department on Hydrometeorology and Environmental Monitoring, unpublished data).

3. Deposition

3.1 Deposition in Finnish Lapland

Along with airborne radioactivity fallout samples were also collected. The deposition samples were only collected in three locations Rovaniemi, Sodankylä and Ivalo in the Finnish Lapland. Fallout includes particles that are scavenged by rain and snow (wet deposition) and dust which settles on surfaces (dry deposition). Figure 8 shows the level of ^{137}Cs and ^{90}Sr fallout (Bq/m^2 per 3 months) measured at Rovaniemi from 1972 until 2012. In the 1970s and early 1980s there are minor peaks in the spectrum which are possibly caused by the Chinese atmospheric nuclear weapons tests while the fallout from Chernobyl is indicated as sharp peak in 1986. The fallout from Fukushima NPP accident is also indicated in the figure 8. The table 1 shows the amount of deposition observed in different monitoring stations in Finnish Lapland. According to the table 1 the fallout from Fukushima derived ^{134}Cs and ^{137}Cs varied between 0.3-0.7 Bq/m^2 for both isotopes depending on location. Higher deposition values were observed at Rovaniemi than in most Northern station at Ivalo.

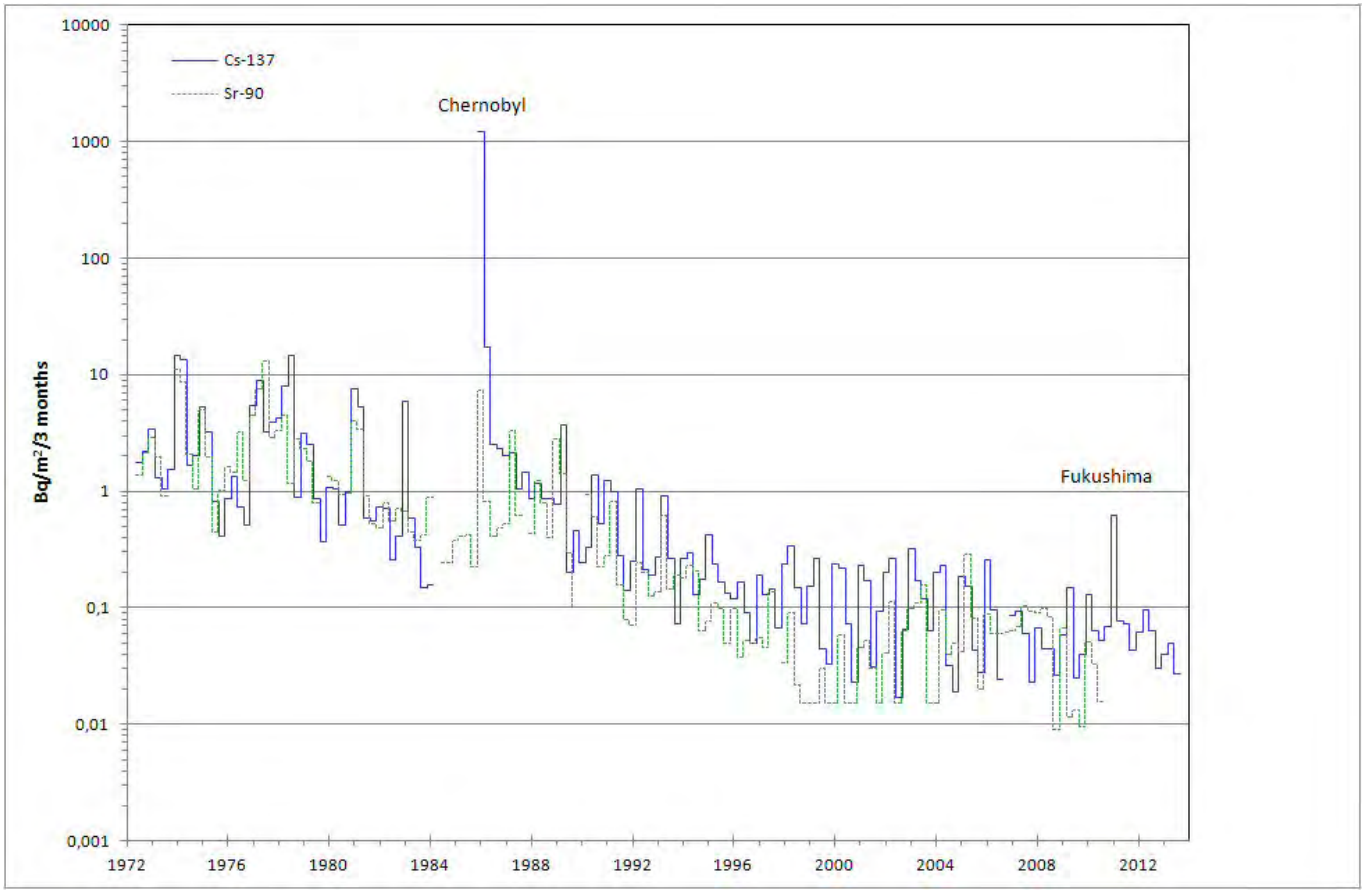

Figure 8. Time series of Cs-137 and Sr-90 in fallout collected at Rovaniemi, Finland (STUK, 2012).

Table 1. Anthropogenic radioactivities detected in cumulative deposition during the first, second and third quarters of 2011. The results are expressed in the units of Bq/m² with an uncertainty of 2σ. (Leppänen et al., 2013)

	January-March		April-June				July-September		
Location	^{134}Cs	^{137}Cs	^{134}Cs	^{137}Cs	^{131}I	^{134}Cs/^{137}Cs	^{134}Cs	^{137}Cs	^{134}Cs/^{137}Cs
Ivalo	<0.10	<0.10	0.21 ± 0.05	0.28 ± 0.08		0.75 ± 0.28	0.07 ± 0.06	0.06 ± 0.06	1.17 ± 1.54
Sodankylä	<0.15	<0.15	0.32 ± 0.08	0.53 ± 0.11		0.60 ± 0.20	0.06 ± 0.05	0.09 ± 0.07	0.67 ± 0.78
Rovaniemi	<0.15	<0.15	0.57 ± 0.08	0.62 ± 0.10	8.5± 2.9	0.92 ± 0.20	0.06 ± 0.04	0.08 ± 0.04	0.83 ± 0.62

3.2 Deposition in Murmansk oblast, Russia

In Murmansk oblast in Russia, the Russian Federal Service on Hydrometeorology and Environmental Monitoring (Murmansk Department) is responsible for collection and analyses of the aerosol and fallout measurements. The over all responsibility of compiling the nationwide report is on Research and Production Association ”Typhoon”. In 2011 the annual atmospheric fallout of ^{137}Cs in the territory of Murmansk oblast was 1.12 Bq/m² in average which is 3.5 times higher than the annual deposition 0.32 Bq/m² measured during 2010 (Typhoon, 2012). Thus the estimated contribution of Fukushima accident in deposition in Murmansk was approximately 0.8 Bq/m². This value is similar to the deposition value of 0.3-0.7 Bq/m² observed in Lapland in Finland (see table 1).

4. Biota samples

The institutes participating in the CEEEPRA project collected various environmental samples during 2011-2013. Some of these samples contained ^{134}Cs which is relatively short lived cesium isotope, having a half-life of 2.06 years. ^{134}Cs was released into nature from the Chernobyl accident and from the Fukushima accident. In Finland ^{134}Cs was observed in various environmental samples until the end of 1990's and the begining of 2000. After that enough time had passed from the Chernobyl accident allowing ^{134}Cs to decay away. This can be seen from figure 9 which shows the time series of ^{134}Cs concentrations in *Cladonia Stellaris* lichen collected from Finnish Lapland. The trend line shows how ^{134}Cs from Chernobyl decayed away. The concentrations observed during 2011-2013 are clearly above this trend line and can thus be considered to originate from Fukushima NPP accident. The $^{134}Cs/^{137}Cs$ ratio found in Fukushima release was approximately 1 (Masson et al., 2011, Leppänen et al., 2013). This ratio can also be found in figure 1 and in table 1 of this report.

Thus by using the $^{134}Cs/^{137}Cs$ ratio of 1 and measuring the ^{134}Cs and ^{137}Cs concentrations the contribution of Fukushima accident to the environment of the Kolarctic region can be estimated. By using the $^{134}Cs/^{137}Cs$ ratio of 1 the measured ^{134}Cs value also indicates the addition of ^{137}Cs whereas the measured ^{137}Cs represents the sum of ^{137}Cs concentrations where also ^{137}Cs originating from nuclear weapons test in the 1950-1960's and the Chernobyl accident is included The sections below show the concentrations of ^{134}Cs in biota samples originating from Fukushima accident. It should be noted that these in addition to these samples a number of similar biota samples were collected but the concentrations of ^{134}Cs were below detection limit. Hence, the values shown here are not typical but from the higher end. In tables 2 and 3 the terms "dry weight" refers to the weight when sample has been dried and all water has been evaporated whereas "fresh weight" refers to the weight that the sample weight when the sample was collected.

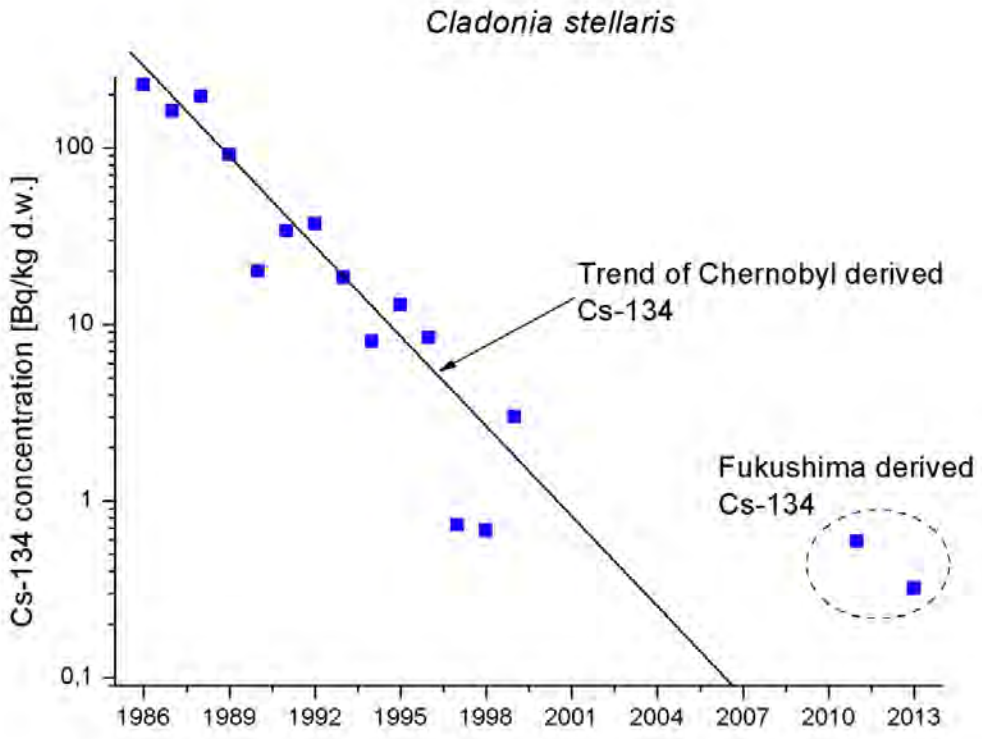

Figure 9. ^{134}Cs concentrations found in *Cladonia Stellaris* lichen in Lapland, Finland (STUK, unpublished data)

4.1 Finland

Radiation and Nuclear Safety Authority (STUK) monitors environmental radioactivity by collecting various environmental samples. After the Fukushima special attention was paid to the detection of ^{134}Cs which would indicate traces of Fukushima derived radionuclicdes in the environment of Lapland. The table 2 shows the summary of the samples where ^{134}Cs was detected during 2011-2013. It should be noted there were also biota samples collected where ^{134}Cs was not observed and thus the values give in table 2 are biased towards higher values. In any case the influence of the Fukushima NPP accident to the levels of radioactivity in Lapland was very small. The increase caused by the Fukushima accident to the ^{137}Cs concentrations was typically less than 1 %.

Table 2. The table shows concentration ranges of ^{134}Cs and ^{137}Cs and the increase caused by the Fukushima accident to the ^{137}Cs concentrations. N refers to the number of samples (STUK, unpublished data).

sample type	^{134}Cs conc. range [Bq/kg]	^{134}Cs conc. median [Bq/kg]	^{137}Cs conc. range [Bq/kg]	^{137}Cs conc. median [Bq/kg]	increase [%]		N
mushrooms	0.02-2.1	0.58	23-3650	310	0.12	dry weight	30
beard lichens	0.2-5.6	0.57	3.7-50	13	5.6	dry weight	30
lichens	0.2-7.6	0.82	20-200	57	0.82	dry weight	16
reindeer	0.3-43	1.5	8.7-910	370	0.39	dry weight	21
fish	0.02-0.28	0.07	5.0-46	12	0.61	fresh weight	20
wolf	0.2-1.2	0.74	145-375	178	0.41	fresh weight	10
cloud berry	0.02		63		0.03	fresh weight	1
moose	0.02-0.03	0.02	14-17	16	0.15	fresh weight	2

4.2 Norway

The Norwegian Radiation Protection Authority (NRPA) have analysed a number of environmental samples. The table 3 shows the samples where ^{134}Cs was detected. The levels are similar that of observed in Finnish Lapland showing only very minor increases in cesium concentrations. The contribution of Fukushima accident to the anthropogenic radioactivity concentrations was very small of the order of few percent.

Table 3. Summary of the biota samples where ^{134}Cs was observed collected from Finnmark and Troms, Norway during 2012-2013 (NRPA, unpublished data).

sample type	^{134}Cs conc. range [Bq/kg]	^{134}Cs conc. median [Bq/kg]	^{137}Cs conc. range [Bq/kg]	^{137}Cs conc. median [Bq/kg]	increase [%]		N
mushrooms	0.5-7.1	2.3	600-1340	810	0.2	dry weight	6
lichens	1.4-3.9	2.6	65-96	80	3.3	dry weight	2
reindeer	0.35-0.41	0.38	86-87	87	0.4	fresh weight	2
red fox	0.21-0.78	0.38	13-71	25	1.5	fresh weight	17

4.3 Russia

In the CEEPRA project Murmanks Marine Biological Institute (MMBI) collected and analyzed environmental samples from Murmansk oblast during 2011-2012. Due to the very low deposition value of approximately 0.8 Bq/m^2 of the Fukushima release in the Murmansk region (section 3.2) the observations of the Fukushima derived ^{134}Cs was scarse. The Fukushima release was only observed in one sample of star reindeer lichen (*Cladonia Stellaris*). The sample was collected from outside the town of Apatity not far away from kola NPP on October 18th, 2011. The ^{134}Cs concentration in this sample was 1.9 ± 1.0 Bq/kg while the ^{137}Cs concentration was 33 ± 8 Bq/kg. Thus the contribution of the Fukushima accident to the environmental ^{137}Cs level which existed in the nature before the accident was estimated to be approximately 2-6 %. This increase is comparable to the increase observed in lichen samples in Northern Norway.

5. Summary

The atmospheric concentrations from Fukushima accident were very small. This was due to the dilution in the atmospheric due to the long distance between Kolartic region and Japan. This lead to very small deposition of ^{134}Cs and ^{137}Cs at the level of 0.3-0.8 Bq/m^2. In the Chernobyl accident large quantaties of ^{134}Cs and ^{137}Cs were emitted and deposited in the Kolartic region. The ^{137}Cs deposition from Chernobyl accident was few thousand Bq/m^2 and the ^{134}Cs less than one thousand Bq/m^2. Despite large deposition of ^{134}Cs 25 years had passed since the accident and ^{134}Cs had decayed away leaving. No ^{134}Cs had been observed in the environmental ion Kolartic region since the turn of the millenium. This means that any observation of ^{134}Cs in environmental samples originates from Fukushima. Very small traces of ^{134}Cs in environmental samples have been observed in Norway, Finland and Russia after the accident. The levels were typically of the order of few Bq/kg or below. The influence of Fukushima accident to the Kolartic environment was observable but insignificant and it has no effects on human health or to the state of the environment.

References

Bolsunovsky, A., Dementyev, D., 2011. Evidence of the radioactive fallout in the center of Asia (Russia) following the Fukushima nuclear accident, J. Environ. Radioact., 102, 1062–1064

Bowyer, T.W., Biegalski, S.R. , Cooper, M., Eslinger, P.W., Haas, D. , Hayes, J.C., Miley, H.S., Strom, D.J. , Woods, V., 2011. Elevated radioxenon detected remotely following the Fukushima nuclear accident, J. Environ. Radioact., 102 (7), 681–687

Diaz, L.J., Jaffe, D.A., Kaspar, J., Knecht, A., Miller, M.L., Robertson, R.G.H., Schubert, A.G.,
Arrival time and magnitude of airborne fission products from the Fukushima, Japan, reactor incident as measured in Seattle, WA, USA, 2011. J. Environ. Radioact., 102 (11), 1032–1038

EERI (Earthquake Engineering Research Institute). Special Earthquake Report — November 2011.
http://www.eqclearinghouse.org/2011-03-11-sendai/files/2011/11/Japan-eq-report-tsunami2.pdf

IAEA, Fukushima Daiichi status report, June 28, 2012.
http://www.iaea.org/newscenter/focus/fukushima/statusreport280612.pdf

Klein H. and Bartnicki J., 2014. Development of the EEMEP model for applications in the ARGOS system. Report no. 4/2014, Air Pollution, Oslo, 2014. 65 pp. ISSN: 0332-9879 (publishing in progress).

Leppänen, A.-P., Mattila, A., Kettunen, M., Kontro, R., 2013. Artificial Radionuclides in Surface Air in Finland Following the Fukushima Dai-ichi Nuclear Power Plant Accident, J. Environ.Rad., 126, 273-283.

Masson, O., Baeza, A., Bieringer, J., Brudecki, K., Bucci, S., Cappai, M., Carvalho, F.P., Connan, O., Cosma, C., Dalheimerc, A., Didier, D., Depuydt, G., De Geer, L.E., De Vismes, A., Gini, L., Groppi, F., Gudnason, K., Gurriaran, R., Hainz, D., Halldrsson, O., Hammond, D., Hanley, O., Hole, K., Homoki, Zs., Ioannidou, A., Isajenko, K., Jankovic, M., Katzlberger, C., Kettunen, M., Kierepko, R., Kontro, R., Kwakman, P.J.M., Lecomte, M., Leon Vintro, L., Leppänen, A.-P., Lind, B., Lujaniene, G., Mc Ginnity, P., Mc Mahon, C., Malá, H., Manenti, S., Manolopoulou, M., Mattila, A., Mauring, A., Mietelski, J.W., Møller, B., Nielsen, S.P., Nikolic, J., Overwater, R.M.W., Pálsson, S.E., Papastefanou, C., Penev, I., Pham, M.K., Povinec, P.P., Ramebäck, H., Reis, M.C., Ringer, W., Rodriguez, A., Rulík, P., Saey, P.R.J., Samsonov, V., Schlosser, C., Sgorbati, G., Silobritiene, B.V., Söderström, C., Sogni, R., Solier, L., Sonck, M., Steinhauser, G., Steinkopff, T., Steinmann, P., Stoulos, S., Sýkora, I., Todorovic, D., Tooloutalaie, N., Tositti, L., Tschiersch, J., Ugron, A., Vagena, E., Vargas, A., Wershofen, H., and Zhukova, O., 2011. Tracking of Airborne Radionuclides from the Damaged Fukushima Dai-Ichi Nuclear Reactors by European Networks, Environ. Sci. Technol., 45 (18), 7670–7677.
Simpson, D., Benedictow, A., Berge, H., Bergstr¨om, R., Emberson, L. D., Fagerli, H., Hayman, G. D., Gauss,M., Jonson, J. E., Jenkin,M. E., NyA˜ ri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, A., and Wind, P. (2012a) The EMEP MSCW chemical transport model - Part 1: Model description, Atmos. Chem. Phys. Discuss., 12, 3781-3874, doi:10.5194/acpd-12-3781-2012.

Simpson, D., A. Benedictow, H. Berge , R. Bergstr˜A{m, L. D. Emberson, H. Fagerli, C. R. Flechard, G. D. Hayman, M. Gauss, J. E. Jonson , M. E. Jenkin, A. NyA˜ ri , C. Richter, V. S. Semeena, S. Tsyro , J.-P. Tuovinen, A. Valdebenito, and P. Wind (2012b) The EMEP MSC-W chemical transport model - technical description Atmos. Chem. Phys., 12 (16), 7825-7865.

STUK B-159, Surveillance of Environmental Radiation. Annual report 2012, Raimo Mustonen (ed.), pp. 34-35, Helsinki, Finland. ISBN 979-952-479-931-1.

Paatero J., Vira, J., Siitari-Kauppi, M., Hatakka, J., Holmén, K., Viisanen, Y., 2012. Airborne fission products in the high Arctic after the Fukushima nuclear accident. J. Environ. Radioact., 114, 41-47.

Typhoon (2012). Radiation situation on the territory of Russia and the adjacent states in 2011. Annual report, RPA "Typhoon", Obninsk, editor - S.M. Vakulovsky, 2012, 298 p. (In Russian). http://www.typhoon.obninsk.ru/rus/ipm/lab3/ezhegodniki_ro.htm

Thakur, P., Ballard, S., Nelson, R., 2013. An overview of Fukushima radionuclides measured in the northern hemisphere. Sci. Tot.Env., 458-460, 577-613.