UDC 504.064.2.001.18

AIRBORNE RISK, REGIONAL VULNERABILITY AND POSSIBLE ACCIDENTAL CONSEQUENCES FROM NUCLEAR SITES IN THE EUROPEAN ARCTIC AND SUB-ARCTIC

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The paper presents achievements of the previous "Arctic Risk" project: "Atmospheric transport pathways, vulnerability and possible accidental consequences from the nuclear risk sites in the European Arctic (multidisciplinary network studies)" of the Nordic Arctic Research Programme (NARP) and several following research initiatives and projects. The main results include the development and testing of a methodology for complex nuclear risk assessment and vulnerability evaluation.

Keywords: *environmental contamination and risk modelling, atmospheric transport, nuclear risk sites, multidisciplinary nuclear risk and vulnerability assessments*

Introduction. A number of dangerous nuclear risk sites (nuclear reactors, weapons and radioactive wastes) were located in the Arctic, especially in the Euro-Arctic region and adjacent areas. For example, in the Northwest Russia, there were about 90 nuclear reactors in operation, and more than 200 reactors are under – or waiting for decommission [9]. Furthermore, there are more than 10 storage sites for radioactive waste (RW), some of which contain large amounts of spent nuclear fuel (SNF). The large number of nuclear reactors (about 1/5 of all nuclear reactors in the world), presented on and along the Kola Peninsula, exceeds by far their concentration in any other region of the world [8].

Radioactive problems and the energy production in the Arctic and Sub-Arctic region are closely linked with nuclear reactors and their nuclear wastes, including commercial nuclear power plants (NPPs) and vessel nuclear power reactors.

There are two NPPs in the Arctic: the Kola NPP in the Murmansk county and the Bilibino NPP in the Chukotka autonomy region, both in the Russian Federation. Within 1000 km of the Arctic Circle there are additional 7 NPPs: one in Russia (Leningrad NPP close to St.-Petersburg), two in Finland (Loviisa and Olkiluoto NPPs), four in Sweden (Barsebæck, Forsmark, Oskarshamn and Ringhals NPPs). The main northern sites with vessel nuclear power reactors situated on the Kola peninsula ('Atomflot' with 10 nuclear icebreakers and five ships with RW and SNF), the Northern Navy bases along the Kola coast), shipyards in Severodvinsk of the Archangelsk region, the Far-East Navy bases on the Kamchatka Peninsula, US Navy bases with nuclear submarines and weapons (e.g., the Thule base on Greenland), as well as the nuclear powered icebreakers and other ships with SNF, transporting by the Northern Sea Way, and submarines patrolled in the Arctic Ocean and northern seas.

Mining activity in the Arctic includes exploring of radioactive ore and minerals with radioactive elements. There are one uranium mining operation at Baker Lake in Canada, the Lovozero and Kovdor mining and refinery factories on the Kola Peninsula, where some mined ores, e.g. loparite, contain radioactive elements. Besides, there are several uranium and thorium deposits of a potential mining [19]. In the northern regions of Russia, 41 peaceful underground nuclear explosions (PUNEs) have been detonated, mostly in Siberia. The main application of the PUNEs was for mining and construction purposes. Three high-yield underground nuclear explosions have been done in Amchitka Island, Alaska, USA for seismic studies and warhead development between 1965 and 1971 [1].

However, the radiological environmental impact of these mining activity and PUNEs is very limited and has purely a local scale [1,16]. So, Chambers *et al.* [10] showed that the long-term population doses due to radon from uranium mill tailings were almost negligible.

Although there are a number of nuclear sites in the Arctic and Sub-Arctic, the existing radioactive contamination of the environment from these nuclear sites is not considerable for the regional scale [8,1,2]. For example, the Barents and Kara seas with about 2/3 of the world dumped nuclear wastes are some of the clearest seas in the world. Thus, the existing radionuclides there are mostly due to the releases from Sellafield (UK) and atmospheric nuclear tests. Monitoring systems around main NPPs under normal conditions show radioactivity levels comparable with the background level of radiation [1].

So, the main and most important radiological problem is the risk of potential severe accidents on nuclear reactors in the Arctic and the surrounding regions. The evaluation and classification of issues of high priority, given by Bergman and Baklanov [8], are mainly based on two risk categories regarding radiological consequences: I) those for which release is known to have occurred or for which a significant probability for release has been confidently estimated, and II) those expected to constitute a risk for considerable release provided the outcome of further analysis of certain steps in the event chain. Cases definitely known to belong to a "high risk" category, may comprise links needed to be more closely analysed in order to yield a satisfactory basis for the assessment process.

I. *Known or probable risk*. Among different objects and situations considered in the Known or probable risk, the Kola and Bilibino nuclear power plants, icebreakers and submarines at refuelling are classified as high risk objects.

II. *Potential risk*. The known and frequent incidence of accidents leading to criticality in reactors on submarines in operation, as well as during refuelling, give evidence of the prevalent risk for future scenarios with high risk of exposure of nearby populations, particularly to airborne releases. This accentuates a general concern for the high number of submarines present along the Kola and Kamchatka coasts. The final event chain for decommissioned nuclear submarines leading to complete scrapping involves certain steps of potential radiological concern. The stages 'Submarines to be decommissioned' and 'Scrapping of nuclear submarines' are identified as two of the most important cases in the risk category 'Potential risk'. Furthermore, subsequent steps dealing with acute storage problems for nuclear fuel, as well as radioactive waste in general also involve potential high risk.

Thus, analysis of published investigations, made within the bounds of the pilot KAS-project shows [8], that, although the main risk of radioactive contamination in the region is attributed to terrestrial nuclear objects, a majority of the existing projects of radiological research in the northern region are directed to estimation of radioactive contamination in seas and radiation risk from the sunken nuclear reactors or radioactive waste.

Although the radiological impact of RW dumping in northern seas may be significant on a local scale, the modelling results and the site specific observations [8,2,17] indicate that dispersion of potentially released radionuclides in seas on regional and global scales would be of minor radiological importance. Calculations based on worst case scenarios for the nuclear reactors dumped in the Kara Sea show [11,18] that on the regional scale an instantaneous release of 1 PBq of ^{137}Cs (the estimated present inventory from all the reactors) would result in a maximum individual dose below 5 μSv/y delivered to a fish eater. On a global scale the radiological impact is negligible, with a collective effective dose commitment from seafood ingestion of about 10 man Sv.

So, the main focus of this study should be directed to estimation of possible consequences from the most important and poorly investigated terrestrial objects of radiation risk: nuclear reactors in European Arctic and adjacent areas.

The risks for radioactive contamination and significant radiological consequences connected with sources in this or adjacent areas, in some cases predominantly affect the conditions at local and regional levels, yet in others appear to be far reaching, and of considerable concern for the whole Arctic region. Thus, it is of particular interest to expound on issues such as:

- *Which sources appear to be the most dangerous now or in the nearest future for those living close to and far from these sites?*
- *Which regions are at the highest risk from hypothetical accidental releases in the Arctic and Sub-Arctic?*

Frequent temperature inversions, together with low wind speed and high-pressure systems, during the Arctic winter allow pollutants to accumulate in the atmosphere of high latitude regions. “The State of the Arctic Environment” report of the Arctic Monitoring and Assessment Programme [1] has emphasised: “there are considerable shortcomings in the analysis available to the AMAP radioactivity assessment group that allow conclusions to be drawn about the probability and consequences of potential accidents in the nuclear power plants in the Arctic”. The final AMAP report [1] gives the following recommendation. “More authoritative and comprehensive evaluations should be made for the risk posed to human health and the environment by accidents in nuclear power installations. Assessments of the risk of releases of radionuclides and the radiological consequences for humans and the environment should be performed for all existing nuclear installations in, and near the Arctic”. From the point of view of the influence of physical and chemical processes on contaminant transport in the Arctic it was recommended [1]: through evaluation of pathways to determine 1) ‘contaminant focusing zones’ or 2) ‘zones of influence’ of known source regions. As one of most important area was emphasised the Murman (Kola) area, where the long-range zone of influence is not well known, despite having large industrial and municipal atmospheric emissions.

For estimation of the potential nuclear risk and vulnerability levels, and for regional planning of radiological environmental monitoring networks and emergency preparedness systems, for dangerous nuclear risk sites (NRSs) it is very important to determine:

- probability of an accident of a certain severity;
- geographical regions most likely to be impacted;
- probability and transport time to different geographical regions;
- probability and effects of the precipitation factor contribution by atmospheric layers;
- probability of the fast transport (i.e. in one day and less) when the impact of the short-lived radionuclides is of the most concern;
- yearly, seasonal and monthly variability of these parameters;
- choice of worst meteorological scenarios for case studies;
- possible contamination and effects on the population in case of an accident;
- site-sensitive hazards of potential airborne radioactive release;

- vulnerability to a radioactive deposition concerning its persistence in the northern latitude ecosystems with a focus on the transfer of certain radionuclides into food-chains and considering risk for different geographical areas and especially for native population;
- analyses of the risk, socio-economical and geographical consequences for different geographical areas and population groups applying available demographic databases and GIS-technology.

Previously, several studies [17,3,6,7,13,14,15] discussed some possible approaches and elements, and preliminarily investigated some of the above mentioned important issues. Most of the studies were done for certain meteorological situations / worst-case scenarios, so the results can be considered as case studies. For the Kola and Bilibino Nuclear Power Plants, possible impacts on the environment and population were considered for the local and regional scales, also based on the probabilistic approach.

However, it is very important to do such kind of study for the whole Arctic region from the main different nuclear risk objects (in particular, nuclear reactors). Different geographical areas and population groups, especially the native people, have different sensitivity, and this should be taken into account when considering geographical, social and economical consequences.

Methodology. The methodological approach for multidisciplinary nuclear risk and vulnerability assessments was suggested for estimation of nuclear risk to the population in the Nordic countries in case of a severe accident at nuclear risk sites (NRSs) (Fig.1). The main focus was on the evaluation of the atmospheric transport and deposition of radioactive pollutants from NRSs. The method developed was derived from a probabilistic point of view. The main question addressed was: *What is the probability for radionuclide atmospheric transport, deposition and impact to different neighbouring regions and countries in case of an accident at a risk site?*

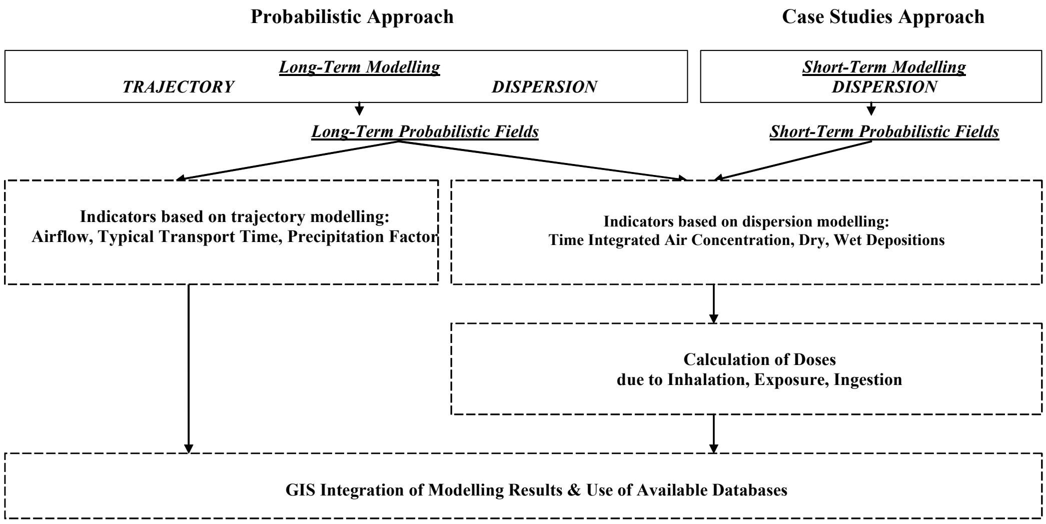


Fig. 1. General scheme of probabilistic assessment of risk sites' impact.

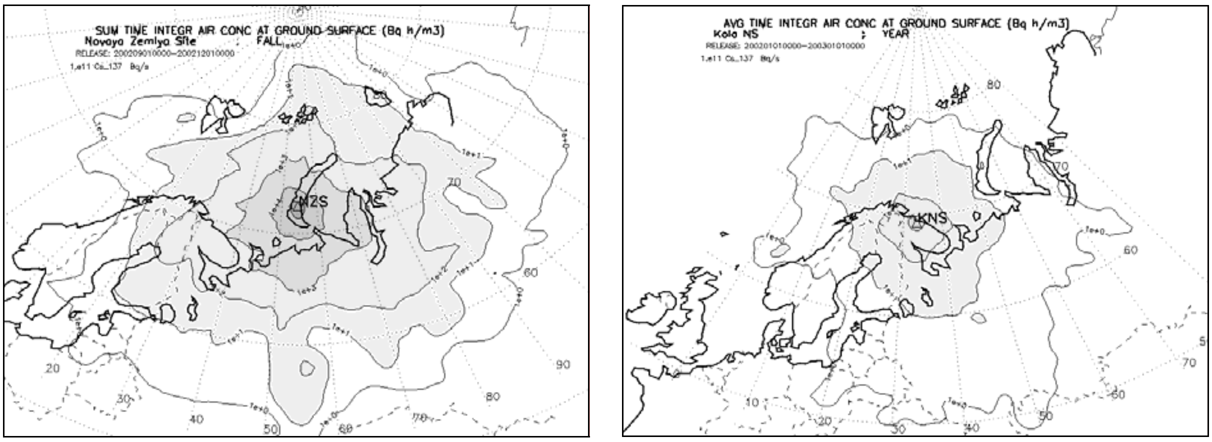
To answer this question a set of different tools was tested and applied:

(i) *Trajectory Modelling* - to calculate multiyear forward trajectories originating over the locations of selected risk sites; (ii) *Dispersion Modelling* - for long-term simulation and case studies of radionuclide transport from hypothetical accidental releases at sites; (iii) *Cluster Analysis* - to identify atmospheric transport pathways from sites and their temporal variability; (iv) *Probability Fields Analysis* - to construct annual, monthly, and seasonal NRS impact indicators to identify the most impacted and sensitive geographical regions;

(v) *Specific Case Studies* - to estimate consequences for the environment and population after a hypothetical accident; (vi) *Vulnerability Evaluation to Radioactive Deposition* - to describe its persistence in the ecosystems with a focus to the transfer of certain radionuclides into the food chains of key importance for the intake and exposure for a whole population and certain population groups; (vii) *Risk Evaluation and Mapping* - to analyse environmental, social, economical, etc. consequences for different geographical areas and various population groups taking into account social-geophysical factors and probabilities, and using demographic databases based on GIS analysis.

This methodology was tested on examples of 24 risk sites located in Arctic, Sub-Arctic, and Northern Europe. The sites included the nuclear power plants' reactors, nuclear reprocessing plant, nuclear submarine, decommissioning site, and former nuclear weapons testing site.

Results and discussions. The focus further is on application of long-term dispersion modelling results for assessment of risk site impact [3,6,7,13–15]. The **D**anish **E**mergency **R**esponse **M**odel for **A**tmosphere (DERMA) [20] was used to simulate long-term (2001-2003) atmospheric transport, dispersion, and deposition of radionuclides from selected NRSs. As input meteorological data, DERMA used: **N**umerical **W**eather **P**rediction (NWP) model data from different operational versions of DMI-HIRLAM and ECMWF global model data.

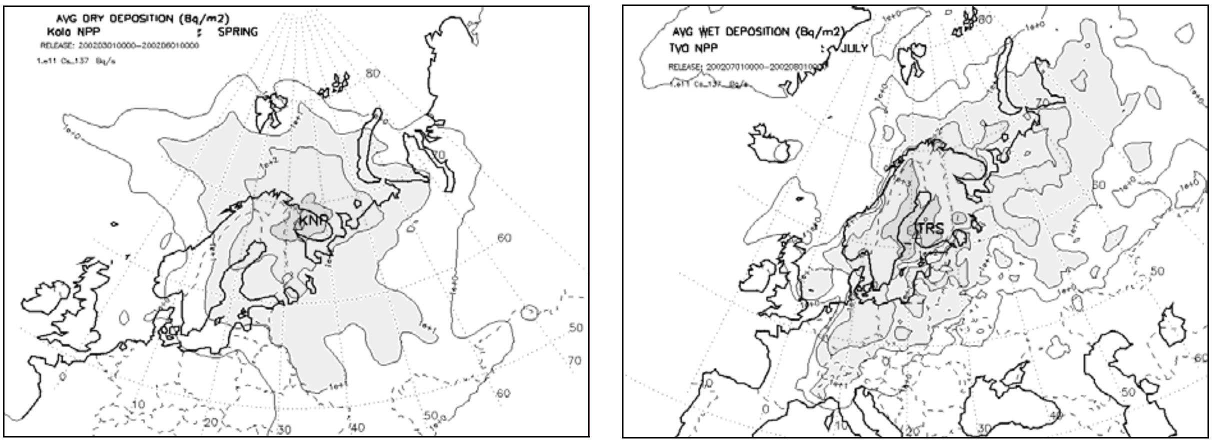


(a) (b)

Fig. 2. Time integrated air concentration – (a) fall summary and (b) annual average – fields resulting from a hypothetical accidental release at the (a) Novaya Zemlay Archipelago, Russia and (b) Kola Repairmen Shipment Yard, Kola Peninsula, Russia.

The following variables (for a daily continuous **d**iscrete **u**nit **h**ypothetical **r**elease (DUHR) of ^{137}Cs at risk sites at rate of 10^{11}Bq/s) were calculated: 1) air concentration (Bq/m^3) in the surface layer; 2) time integrated air concentration, TIAC (Bq·h/m^3); 3) dry deposition, DD (Bq/m^2), and 4) wet deposition, WD (Bq/m^2) fields. Then, these fields were interpolated into a gridded domain (30-89°N and 60°W-135°E) with a resolution of 0.5°latitude vs. 0.5°longitude, and these fields were limited by 5 days of atmospheric transport of radioactive matter after release ended at risk sites.

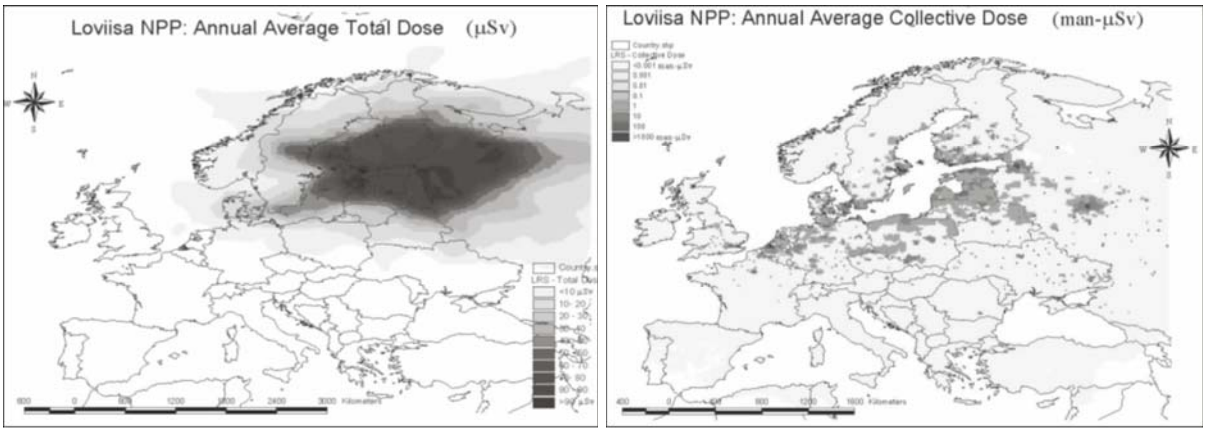
Then, the dispersion modelling results can be analysed in a similar manner as for trajectory modelling [5,12]. Two approaches were considered to construct probability fields for the TIAC, DD, and WD patterns. The first approach (based on the results of dispersion modelling) considers the distribution of the total sum of daily continuous DUHR of radioactivity at the site during the time period of interest (month, season, or year), and field is called the summary field (as shown in Fig. 2a). The second approach is simply based on calculating the average value from the summary field obtained in the first approach, and field is called the average field (as shown in Fig. 2b,3).



(a) (b)

Fig. 3. Average (a) spring dry deposition and (b) July wet deposition fields resulting from the hypothetical accidental release at the (a) Kola plant, Russia and (b) Olkiluoto plant, Finland.

Further, different food chains and exposure approaches for Northern Europe (see overview by *Baklanov et al.,* [4]) and the "Gridded Population of the World" database (ftp://ftp.ciesin.org/pub/gpw/europe/) were used to estimate doses. The calculated concentration and deposition fields for each site were integrated into GIS. All fields were represented by multiple thematic layers converted into gridded domains of similar sizes, and these were interpolated to corresponding grids for further estimation of doses (individual/or total and collective on an annual and seasonal basis) resulting from DUHR at sites.



(a) (b)

Fig. 4. Annual average (a) total/ individual and (b) collective doses resulting from a hypothetical accidental release at the Loviisa plant, Finland.

The doses can be evaluated by averaging on a scale of countries' boundaries, or regions, counties, administrative units, etc. Fig. 3a shows the annual average total (or individual) dose resulting from DUHR at the Loviisa plant. In general, the structure of the calculated dose' field is similar to the total deposition pattern. Fig. 3b shows the annual average collective doses at the same plant. These are strongly depending on the population density. Therefore, the higher collective doses are characteristic for the urbanized and populated regions of the European countries where for such releases it can be more than 100 man-μSv. The northern (less populated) as well as the remotest territories with respect to the site show the lower doses of less than 0.001 man-μSv. The annual and seasonal variability of the average individual and collective doses for other NRSs selected in the Arctic Risk project is shown in *(Baklanov et al.,* [4]*)*.

Conclusions. The proposed approaches, methods, and results can be used by national and international organisations, programmes, etc. performing monitoring and control of the pollution situation; nuclear emergency response, administrative, decision-making, etc. services. It can be used for assessment of monitoring networks and environmental quality, efficiency of environmental protection measures; estimation of potential risk and vulnerability of regions, consequence analysis, probabilistic assessment of local-, regional-, and long-range transport of pollution resulting from short-term accidental or continuous routine releases or discharges of pollution from NCB (nuclear, chemical, biological) and natural hazard sites; during evaluation and decision-making process for construction of a new facility or complex of enterprises posing potential risk of NCB contamination for neighbouring regions, environment, and population; improvement in planning the emergency response and decision-making to potential accidental releases from risk sites of nuclear, chemical, and biological danger.

Acknowledgments. Grants of the Nordic Arctic Research Programme and Nordisk Forskerutdanningsakademi and the RF SOL No 11.G34.31.0078 grant are gratefully acknowledged.

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Екологічний ризик забруднення атмосферного повітря, регіональна уразливість та можливі наслідки від об'єктів радіаційного ризику в Європейській Антарктиці та Субарктиці.

Олександр Бакланов та інш.

Стаття представляє результати, отримані в рамках проекту "Arctic Risk": „Шляхи перенесення в атмосфері, уразливість та можливі випадкові наслідки від ядерних зон ризику в Європейській Арктиці (міждисциплінарне сітьове дослідження)" та подальших наукових проектів. Головні результати включають розробку та перевірку методології для комплексної оцінки радіаційного ризику та регіональної уразливості.

Ключові слова: *забруднення навколишнього середовища та моделювання ризику, атмосферні переноси, зони ядерної небезпеки, оцінка уразливості*

Экологический риск загрязнения атмосферного воздуха, региональная уязвимость и возможные последствия от объектов радиационного риска в Европейской Арктике и Субарктике.

Александр Бакланов и др.

Статья представляет результаты, полученные в рамках проекта "Arctic Risk": "Пути переноса в атмосфере, уязвимость и возможные случайные последствия от ядерных зон риска в Европейской Арктике (междисциплинарное сетевое исследование)" и последующих научных проектов. Главные результаты включают разработку и проверку методологии для комплексной оценки радиационного риска и региональной уязвимости.

Ключевые слова: *загрязнение окружающей среды и моделирование риска, атмосферные переносы, зоны ядерной опасности, оценка уязвимости*