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## SCIENTIFIC REPORT

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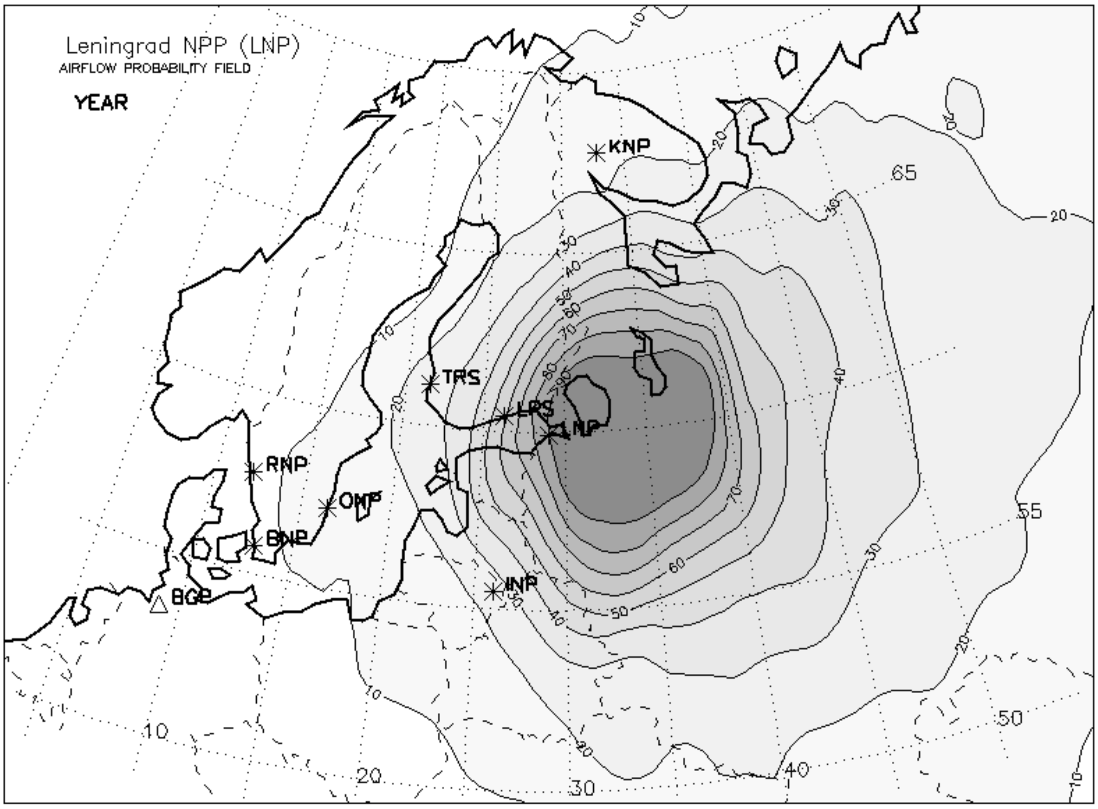
# Atmospheric Transport Pathways, Vulnerability and Possible Accidental Consequences from Nuclear Risk Sites: *Methodology for Probabilistic Atmospheric Studies*

Alexander Baklanov and Alexander Mahura

‘Arctic Risk’ Project of the Nordic Arctic Research Programme



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# SUMMARY

The risks for radioactive contamination and radiological consequences for any studied area are connected with sources in this and adjacent area. In some cases, they predominantly affect geophysical and social conditions at local and regional scales. In other cases, they appear to be far reaching, and of concern for larger territories. Thus, it is of particular interest to study issues such as: *Which sources appear to be the most dangerous now or in the nearest future for people living close and far from these sources? Which geographical territories and countries are at the highest risk from a hypothetical accidental release in a selected area?*

*The main purpose of this multidisciplinary study* is to 1) develop a methodology for a complex nuclear risk and vulnerability assessment, and 2) test methodology by estimation of a nuclear risk to population in the Nordic countries in case of a severe accidents at the nuclear risk sites (**NRSs**), and in particular, – nuclear power plants (**NPPs**).

For assessment of the probabilistic risk and vulnerability, we consider:

***1) social-geophysical factors:***

- proximity to NRSs;
- population density in area;
- presence of critical groups of population;
- ecological vulnerability of area;
- risk perception, preparedness of safety measures, systems for quick response;
- economical and technical means, counteracting consequences of accident;

**2) *probabilities*:**

- probability of an accident of certain severity at NRSs;
- probability of atmospheric transport towards area of interest from NRSs;
- probability of radionuclide removal over area during atmospheric transport.

For estimation of vulnerability/risk for different geographical regions, a risk function was defined as a complex index of risk for different factors.

The main focus of this report is description of the developing methodology for evaluation of the atmospheric transport of radioactive pollutants from the nuclear risk sites and, in particular, from the nuclear power plants. The suggested method is given from the probabilistic point of view. The **main question** we are trying to answer is: *What is the probability for radionuclide atmospheric transport to different neighbouring countries in the case of an hypothetical accidental release at NPPs?*

To answer this question we applied for probabilistic atmospheric studies **two research tools**: (i) isentropic trajectory modelling to calculate forward trajectories originated at NPPs (for a multiyear period), and (ii) statistical analysis tools (exploratory, cluster and probability field analyses) to explore the structure of calculated trajectory data sets seasonally and monthly in order to evaluate atmospheric transport patterns, fast transport, typical transport time, and other indicators.

The **results** of this study are applicable for the further GIS analysis to estimate risk and vulnerability as well as for the emergency response and preparedness measures in the cases of the accidental releases at NPPs.

# I. INTRODUCTION TO THE PROBLEM

The risks for radioactive contamination and significant radiological consequences connected with sources in this or adjacent area, 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 the hypothetical accidental releases in the Euro-Arctic?*

A number of dangerous nuclear risk sites (nuclear reactors, weapons and radioactive wastes) are situated in the European region, Arctic territories and adjacent areas. For example, in the Northwest Russia, there are about 180 nuclear reactors in operation, and about 140 reactors are waiting to be decommissioned (*Nilsen et al., 1994, 1996; IIASA, 1996*). Furthermore, there are more than 10 storage sites for radioactive waste, 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 (*Bergman and Baklanov, 1998*).

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 (*AMAP, 1998*) had 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 (*AMAP, 1998*) 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 (*AMAP, 1998*): 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, it is very important to determine for dangerous nuclear risk sites (NRSs):

- 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 short-lived radionuclides impact is 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 native population;
- the analyses of the risk, socio-economical and geographical consequences for different geographical areas and population groups applying available demographic databases and GIS-technology.

It is very important to develop a methodology for the complex multidisciplinary nuclear risk and vulnerability assessments. Previously, our studies (*Baklanov, 1995; Jaffe et al., 1997a; Thaning & Baklanov, 1997; Mahura et al., 1997; Jaffe et al., 1997b, Bergman et al., 1998; Baklanov et al., 1998; Mahura et al., 1999; Baklanov et al., 1999*) as well as others (*Slaper et al., 1994; Bartnicki & Saltbones, 1997; Saltbones et al., 1997; NACC, 1998, Andreev et al., 1998*) discussed some possible approaches and elements, and preliminarily investigated some of the mentioned above important issues. For example, the Kola and Bilibino Nuclear Power Plants possible impact on environment and population were considered by *Baklanov et al., 1998; Mahura et al., 1999; Baklanov et al., 2001.*

However, it is very important to do such kind of studies for the whole Euro-Arctic region from main different nuclear risk objects (in particular, nuclear reactors). Moreover, the atmospheric transport and residence time of radionuclides within different atmospheric levels can differ widely, and especially for the Arctic territories. Therefore, the probability and transport time for main transport pathways should be studied at different altitudes when the air from the accident area is transported to other geographical regions. Furthermore, different parameterisation of physical atmospheric processes (e.g., precipitation scavenging and mixing height development) and consequences for population are needed to be developed for the Euro-Arctic regions. Finally, different geographical areas and population groups, especially native people, have different sensitivity, which is very important to take into account considering geographical, social and economical consequences. Practically, the considered project is closely connected to the Swedish ÖCB Multidisciplinary Research Program 'Nuclear Risks in the Barents Euro-Arctic Region' (*ÖCB, 2000*) and other activities of the existing research groups in the Nordic countries and Northwest Russia.

The suggested methodology, developed in this study, as we already mentioned, is a logical continuation of several previous our studies in close co-operation with different research groups. Initially, the study of possible regional risk from the Kola Peninsula nuclear risk sites was started at the Kola Science Centre, Russian Academy of Sciences in 1991 in the bounds of the Russian State Programme 'Ecological Safety of Russia' of the Russian Federation Ministry of Environment, according to the Project 'RISK': 'Determination of risk zones and elaboration of scenarios of extreme radiologically dangerous situations in the Northern areas' and projects for the Kola NPP (*Baklanov et al., 1992, 1994; Baklanov, 1995*). This study was continued in 1995-1997 and extended for the Kola-Barents region nuclear risk sites in a series of pilot studies/projects (e.g. the 'Kola Assessment Study') of the International Institute for Applied Systems Analysis (IIASA) and the Swedish Defence Research Establishment (FOA), supported by the Swedish Council for Planning and Coordination of Research (FRN). These studies were based on dispersion modelling, system analysis and ranging of possible risk from different nuclear risk sites in the Kola-Barents region (*Baklanov et al., 1996; IIASA, 1996; Bergman and Baklanov, 1998; Bergman et al., 1998; Baklanov and Bergman, 1999*). Other study was continued in 1996-1997 at the University of

Alaska, Fairbanks for the Bilibino NPP using trajectory modelling and cluster analysis to evaluate atmospheric transport pathways to Alaska in the bounds of UAF-ADEC Joint Project (*Mahura et al., 1997a; Jaffe et al., 1997a; Mahura et al., 1999*). A similar study with a more complex approach for the statistical trajectory analysis and dispersion modelling for several specific cases was realised in 1997 for the Kola NPP in the bounds of the UAF-FOA-BECN Joint Project, sponsored by the Barents Environmental Centres Network (BECN), (*Mahura et al., 1997b; Jaffe et al., 1997b; Baklanov et al., 2001a*).

As the next step for multidisciplinary analysis of nuclear risk in the Barents Euro-Arctic Region the 'Risk and Nuclear Waste in the Barents region' Programme (1998-2000) was initiated by the University of Umeå and FOA (*Baklanov and Bergman, 1998; ÖCB, 2000; Baklanov et al., 2001a; Mahura et al., 2001; Rigina and Baklanov, 1999; Baklanov et al., 2001b*). At the same period the INTAS Project (1998-2000) supplemented the *ÖCB* Project and involved additionally scientific groups from Russia (*Bergman, 1999; INTAS, 2000*). Additionally, a joint study of DMI and Novosibirsk Computing Centre, Russian Academy of Sciences suggested an alternative method for estimation of nuclear risk and vulnerability areas, based on the sensitivity theory and inverse modelling (*Penenko and Baklanov, 2001*).

Therefore, the current 'Arctic Risk' NARP Network Project (*Segerståhl et al., 2001; Baklanov and Mahura, 2001; AR-NARP, 2001*) is a logical continuation and generalisation of our previous studies in this field on the new developed methodological base, suggested in this report.

# II. ARCTIC RISK NARP PROJECT PURPOSES

The '***Arctic Risk'*** Project: 'Atmospheric Transport Pathways, Vulnerability and Possible Accidental Consequences from the Nuclear Risk Sites in the European Arctic*'* (December 2000 – December 2003) is a multidisciplinary networking study project of the Nordic Arctic Research Programme (NARP), involved several research teams from the Nordic countries and coordinated by the Danish Meteorological Institute (Dr. Alexander Baklanov). Recently updated information is available at the project web-site: http://www.dmi.dk/f+u/luft/eng/arctic-risk/main.html.

## 2.1. *PROJECT ITEMS*

The **main purpose** of this project is to develop methodology for complex nuclear risk and vulnerability assessment, and to test methodology by estimating atmospheric transport pathways, airflow patterns and probabilities, region vulnerability and possible consequences for population from the most dangerous Nuclear Risk Sites (NRSs) in areas of the European North.

This includes the following **main objectives**, which could be achieved by using the suggested methodology for:

- the examination of the existing *atmospheric transport patterns* for the main nuclear risk sites, the *contribution of the precipitation factor*, and the *probabilities of the fast transport, airflow, etc.;*
- the estimation of the *possible impact and consequences* in terms of radioactive deposition, and environmental contamination, in different Euro-Arctic regions from hypothetical accidents at different sites in the northern areas;
- the evaluation of the *vulnerability* to a radioactive deposition concerning its persistence in the ecosystems; in particular, with a focus on the transfer of certain radionuclides into food-chains of key importance for the intake and exposure in whole population and certain native groups of the Euro-Arctic regions; and
- the estimation of the risk and socio-economical consequences for different geographical areas and population groups of the Nordic countries, in particular, native Saami and Inuit.

The **goal** of the project will be realised through:

- *building of network*: by co-ordinating activities between existing scientific groups in Denmark, Finland, Norway, Sweden and Northwest Russia, and applying the www-technology to exchange by intermediate and final research results;
- *training and mobility of researchers*: by involving young scientists to choose the career in the area of the Arctic research and to perform research in the Nordic country other than their home country; and
- *presenting and publishing of research results*: by writing and submitting articles for peer-reviewed scientific journals, presenting results of the studies during meeting, workshops and conferences, and publishing a joint report/book and www-information.

The **results** can be used in the event of an accident to estimate the probability of the radionuclide transport from NRSs. It is very important to have a probabilistic assessment of a possible meso-, regional- and long- range transport of pollutants, especially for studies of social and economical consequences of the radioactive risk for the Nordic countries. These results are important for the purposes of the regional emergency planning and decision making, development and improvement of the monitoring systems for the radiation situation.

### 2.2. *STRATEGY FOR PROJECT RISK ASSESSMENT*

Based on the existing studies (*OTA 1995, NACC 1995, IIASA 1996, AMAP 1998, ÖCB 2000; INTAS 2000*) it is reasonable to determine the following sites/areas with a highest concentration of nuclear reactors or weapons and most dangerous Nuclear Risk Sites (NRS) in, and near, the European Arctic:

- the Kola Peninsula with about 300 reactors, storage of nuclear fuel and nuclear weapons sites;
- the Leningrad NPP (Sosnovyy Bor, Sankt-Petersburg county, Russia);
- the Ignalina NPP (Ignalina, Lithuania);
- the nuclear weapons test range on the Novaya Zemlya Archipelago (Russia);
- the NPPs in Finland, Germany, United Kingdom and Sweden.

Several NRSs, of the most importance from the mentioned above list, were chosen for the suggested project (Figure 1). It is necessary to note that in this study we will not focus on the probabilities of

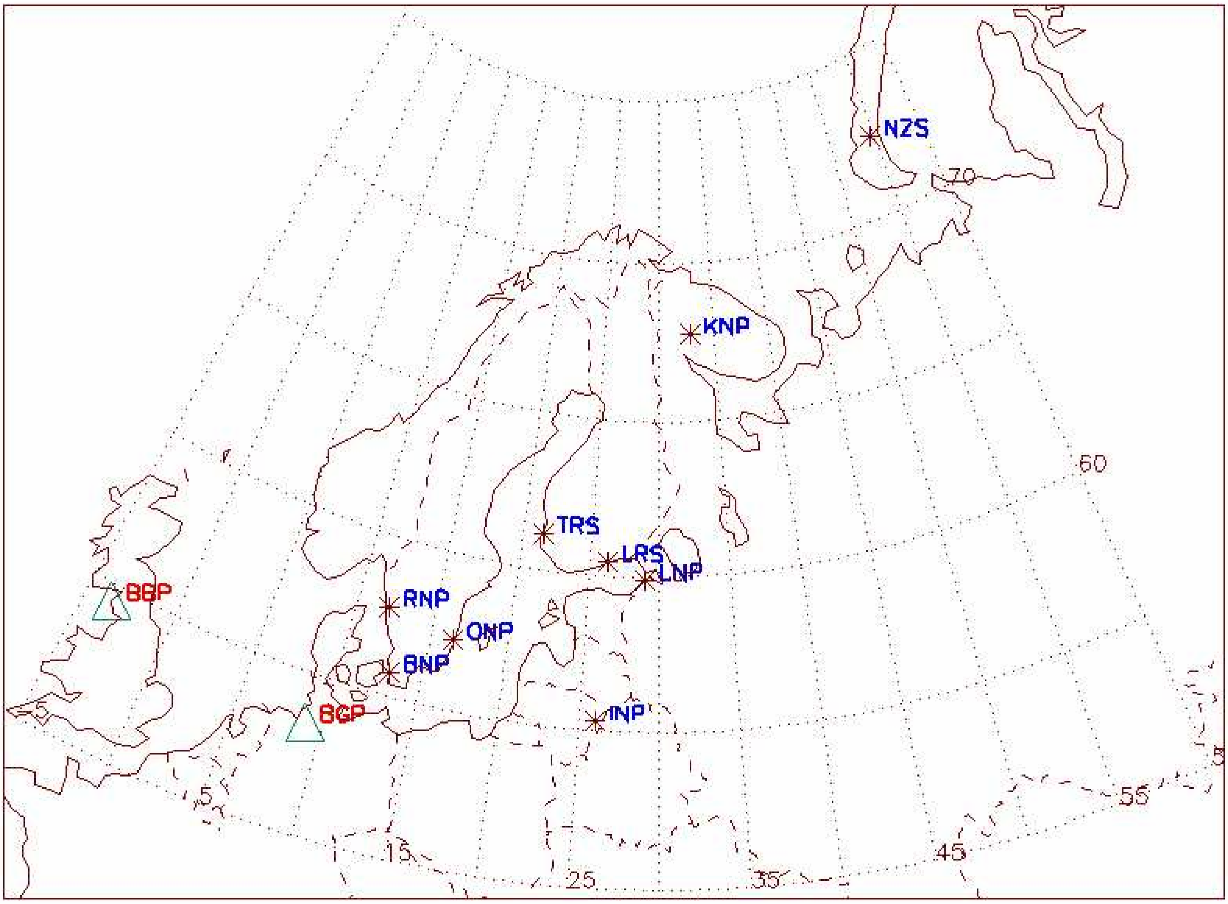


**Figure 1.** Nuclear Risk Sites (LNP - Leningrad NPP, KNP - Kola NPP, INP - Ignalina NPP, BBP - Block of British NPPs, BGP - Block of German NPPs, TRS - Olkiluoto NPP, LRS - Loviisa NPP, BNP - Barsebaeck NPP, ONP - Oskarshamn NPP, RNP - Ringhals NPP, NZS - Novaya Zemlya test site).

nuclear accidents on the NRSs; for the risk assessments it can be an input parameter from other studies (e.g., Probabilistic Safety Assessments, PSA).

In this study, at the **first step,** we calculate forward trajectories for air parcels leaving the chosen NRSs, and then we apply several statistical analysis techniques (exploratory, cluster and probability field analyses) to identify the main transport patterns for each NRS. The analyses focus on the following characteristics:

- probability that air from the NRS will be transported to different Euro-Arctic regions,
- number of days this transport will take;
- effect of precipitation by atmospheric layers;
- probability of the fast transport (in one day and less) when the short-lived radionuclides are the main concern;
- yearly, seasonal, and monthly distribution of the mentioned characteristics.

The geographic regions of particular focus are the whole Arctic region, Northern Europe and Nordic countries. Forward trajectories are calculated starting at three altitudes (500, 1500 and 3000 m above sea level - asl) to reflect atmospheric transport patterns within the boundary layer, in the transition between the boundary layer and free troposphere, and in the free troposphere. Such approach will allow the approximations of a wide range of potential radionuclide release scenarios. The trajectories will be used to estimate the probability of atmospheric transport and probability of each NRS site impact on the most populated geographical areas (*Mahura et al., 1999; Baklanov et al., 2001*). The combination of the probability fields for airflow, fast transport and precipitation factor will underline the geographical areas which are more vulnerable to the NRS impact in the case of accidental release.

At the **second step**, the results of the previous step will be used as input into the impact studies. The efforts at this step will focus on several case studies of potential radionuclide releases including source terms and impacts on population of various geographic areas of the Euro-Arctic region.

For simulation of possible consequences on a regional scale, the DERMA model, developed by the Danish Meteorological Institute (*Sørensen, 1998; Sørensen et al., 1998; Baklanov and Sørensen, 2001*), will be used. This model is a 3-D Lagrangian long-range transport dispersion model, which uses a puff diffusion parameterisation. The DMI-HIRLAM (*Sass et al., 2000*) high-resolution meteorological data (E-version: 0.15° or G-version: 0.45°, see Figure 4) will be used as input data. We should note, that among 27 institutions from the European countries, USA, Canada and Japan, which contributed to model validations based on the ETEX experiment, the DERMA model was emphasised as being a very successful (*Graziani et al., 1998*). DMI's 3D Lagrangian transport model calculates forward and backward trajectories for any point in the area. It can utilise meteorological data from the different versions of DMI-HIRLAM as well as ECMWF's global model.

At the **third step,** an analysis of the risk levels and possible consequences for the population in a whole and different population groups, in particular, native Saami, in the Euro-Arctic region will be carried out. For these purposes, we will use the empirical models and correlation between fallout and doses for humans, which were received on a basis of investigations of the nuclear tests and Chernobyl accident effects on the Nordic countries (*Moberg, 1991; Selnæs and Strand, 1992; Dahlgaard, 1994; Brynildsen et al., 1996; Nielsen, 1998; Bergman and Ågren, 1999; ÖCB, 2000*). An analysis of the risk levels (potential contamination and exposure) and possible consequences for the population in the local/meso-scale will be carried out using models adapted for specific northern nutrition pathways. Some long-term consequences will be estimated also in the regional-scale using empirical models and correlation between fallout and doses for humans.

At the **forth step**, we will apply the GIS-based analyses in integration with mathematical modelling (*Rigina & Baklanov, 1999, 2001; Rigina, 2001*) which give possibilities to develop a common methodological approach for complex assessment of regional vulnerability and risk gathering separate aspects of study (modelling of consequences, probabilistic analysis of pathways, dose estimation, etc.). Available demographic databases and GIS-analysis will allow us to evaluate the social and economical consequences for different geographical areas and population groups, especially native people in the Nordic countries.

The results of these studies will complement each other in assessing the risk of radioactive fallout from the NRS's potential radioactive releases in the Euro-Arctic region. This risk assessment will help in the formulation of the policy regarding to a decision making in the cases of accidental radionuclide releases at NRSs which may impact the population in the Nordic countries.

## 2.3. *MILESTONE CHART FOR THE PROJECT*

**Task I:** ***Network facilities and choice of most important Nuclear Risk Sites for the project***
Organise a kick-off meeting, establish a network facility, and launch a web-site for continuous exchange of intermediate results as a communication link between participants during the project. Analyse risk of severe accidents in potentially dangerous Nuclear Risk Sites (NRSs) in, and near, the Euro-Arctic, and choose the four to six most important sites for the project studies.

**Task IIa:** ***Forward trajectory modelling***
Forward trajectory modelling from each NRS will be performed to assess the most common transport pathways for air parcels. As minimum as seven years of data (1990-1996) from the meteorological archives will be used as the basis for the modelling. This will result in more than 327 thousand trajectories. For further statistical analysis, trajectories (4 trajectories starting at 00 UTC and 4 trajectories at 12 UTC) at altitudes of 500, 1500 and 3000 m asl for each NRS will be selected. Experience shows that the number of valid trajectories (excluding - missing cases in the original meteorological archives, complex trajectories showing strong divergence in flow, and processing problems) is being equal to around 75-90% of the potential trajectories.

**Task IIb:** ***Exploratory and cluster analysis of trajectories***
The resulting valid trajectories will be classified into transport pathways using cluster analysis technique. It will permit to assess the most common transport pathways for NRS sites. The important transport characteristics such as probability, transport time, fast transport, and etc will be calculated on yearly, seasonally and monthly basis to investigate the temporal variability for each site.

**Task IIc:** ***Probability fields and cumulative probability of the NRS impact on geographical areas***
Isentropic trajectories will be used to construct and analyse the probability fields for the airflow, precipitation factor and fast transport for each NRS. A software package database will be build to visualise the probability fields for purposes of the risk analysis and availability for other research studies.

**Task IId:** ***Isentropic trajectory model improvement***
Improvement and integration of the isentropic trajectory model into the WWW environment. Test the applicability of the model for the ECMWF/ NCAR meteorological data archives, for different grid domain resolution and different research goal projects: access the main transport patterns and evaluation of trajectories in the combination with atmospheric pollutants. Test sensitivity of model to a complexity of the arctic meteorology.

**Task III:** ***Radioactive contamination modelling***
Choose several trajectories calculated by isentropic trajectory model as specific cases for analysis which should be related to the atmospheric transport to the most populated areas and reflect the worst meteorological including precipitation. Choose the worst case scenarios and model the radioactive contamination using the DERMA long-range transport model and DMI-HIRLAM high-resolution meteorological data (0.15°or 0.45°).

**Task IV:** ***Workshop and publication***
Organisation of the intermediate workshop to exchange by results between participants and evaluate the progress of the study. Publication of the first year study results. The results of this study will be prepared for submission in a form of a scientific article to a peer-reviewed journal as well as presented at a conference. Other publications may result as time and resources allow (e.g., WWW dissemination).

**Task V:** ***High-resolution trajectory analysis***
High-resolution trajectory analysis based on the DMI trajectory model and meteorological field data from the DMI-HIRLAM NWP archive will be performed for a period up to 1 year. The main purpose is to compare the resulting trajectories with the isentropic trajectory model trajectories for a longer period of time and lower resolution.

**Task VI:** ***Estimation of possible consequences***
Perform an evaluation of the vulnerability to a radioactive deposition concerning its persistence in the ecosystems; in particular, with a focus on the transfer of certain radionuclides into food-chains of key importance for the intake and exposure in whole population and native groups of the Euro-Arctic regions, in particular Saami.

**Task VII:** ***Analysis of social and economical consequences***
Estimate the social and economical consequences for different geographical areas and population groups of the Nordic countries applying the GIS-analysis and using available demographic databases for the Nordic countries.

**Task VIIIa:** ***Integration of the project results into the WWW environment***
Final and intermediate results of most importance will be summarised in the form of the WWW report. Develop visualisation application for presentation of the various probability fields – rapid transport, airflow and precipitation factor - in an interactive regime.

**Task VIIIb:** ***Final publications and workshop***
Results of the study will be prepared for submission to a peer-reviewed journal submission in a form of the scientific article and as a final report for the project or a book. The results will be

presented on a conference/workshop. Other publications may result as time and resources allow (e.g., WWW dissemination).

**Task VIIIc:** ***Maintaining the network, bridging knowledge between the research communities***
It is an intention to keep close relations between the project groups and to maintain the multidisciplinary research network for nuclear risk scientists of the Nordic countries and North-west Russia after the project period.

## 2.4. *NETWORK PARTICIPANTS*

The network project involves the following research teams from the four Nordic countries.

- The Danish Meteorological Institute, DMI (Dr. Alexander Baklanov, Dr. Jens Havskov Sørensen and guest-scientist Alexander Mahura from the Kola Science Centre, Russian Academy of Sciences) has considerable experience in trajectory modelling for NRSs, statistical analysis of the atmospheric transport and different indicators of the NRSs impact as well as meso-, regional and long-range atmospheric transport and deposition modelling for NRS in the Euro-Arctic region.

- The Norwegian Radiation Protection Authority, NRPA (MSc. Tone D. Selnæs Bergan) has a competence in a spatial study on vulnerability of different population groups and development of action load maps for selected food styles. NRPA will also be a link to the ongoing AMP programme and facilitate the modelling of historical nuclear weapons fallout pattern for comparison.

- The Swedish Defence Research Authority, FOI (Dr. Ronny Bergman) can cover assessing of the short and long term sensitivity and vulnerability to radioactive fallout concerning radioactive contamination of important food products from the agricultural and forest landscapes of the Nordic countries.

- The Thule Institute of University of Oulu, Finland (Prof., Dr. Boris Segerståhl) has long experience in studying elucidation in an socio-economic perspective based on the results from the project study with focus on radiological consequences of the radiation legacy.

- The RISØ National Laboratory, Denmark (Dr. Sven Nielsen) has considerable experience in assessing short- and long-term sensitivity and vulnerability to radioactive fallout concerning radioactive contamination of important sea food products from the northern seas.

- The Centre for Regional Science of University of Umeå, CERUM, Sweden (Dr. Lars Westin) can handle multidisciplinary and regional science aspects of the study and linking with the ÖCB Multidisciplinary Research Program ‘Nuclear Risks in the Barents Euro-Arctic Region’.

- The Geographical Institute of Copenhagen University, Denmark (Dr. Olga Rigina) has a competence in the integration of GIS-analysis and mathematical modelling for the radiation risk and vulnerability assessment for the population of the Nordic countries.

The project has two external advisors: 1) Dr. Steen C. Hoe, The Danish Emergency Management Agency (DEMA; in Danish: Beredskabsstyrelsen), which is an institution under the Ministry of the Interior, is responsible for the Danish nuclear emergency preparedness (including Greenland and the Faroe Islands) and 2) Dr. Per Strand, Norwegian Radiation Protection Authority (NRPA), Arctic Monitoring and Assessment Program (AMAP), Norway.

The project has also collaborators from other non-Nordic research centres, e.g. the Kola Science Centre of Russian Academy of Sciences (KSC RAS), Apatity, Murmansk region, Russia; the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, and etc. In particular, in close co-operation with the 'FAR East Coastal Study' (FARECS) of the IIASA's Radiation Safety of the Biosphere Project (RAD) Project, the suggested in this report methodology for the risk studies will be applied for the nuclear risk sites on the Russian Far East.

# III. SUGGESTED METHODOLOGY FOR COMPLEX RISK ANALYSIS

## 3.1. *COMPLEX RISK AND VULNERABILITY ASSESSMENTS*

There could be two approaches – case studies & probabilistic risk analysis - to study the possible consequences and nuclear risk from NRSs (Figure 2). The first approach – case studies - is commonly used for estimation of possible dose for population and proceeds from the physical laws of radioactive matter transport from a nuclear reactor to Man. This method is very useful for the specific case studies to estimate possible consequences of hypothetical accidents for typical or worst case scenarios and weather situations. However, such an approach is very expensive for long-term (e.g. one or several years) simulations and probabilistic assessments and is inconvenient for an analysis of factors of different nature like, for example, geophysical processes of radionuclide transport and social-economical factors. So, alongside with the first method, we are suggesting a simpler and more universal approach, based on a combination of different factors and probabilities of separate processes with appropriate weights.

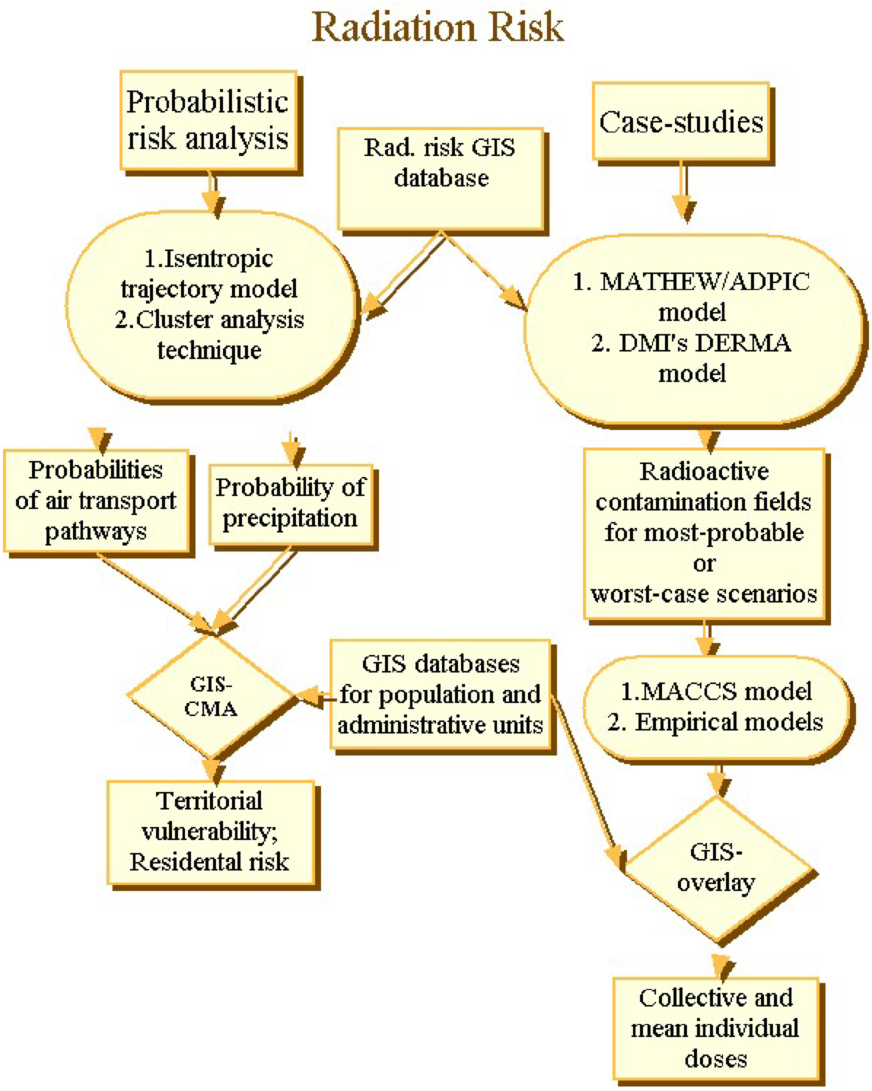


**Figure 2.** Scheme of the assessment of the complex nuclear risk based on the probabilistic risk analysis and case studies (*Rigina 2001*).

The suggested method was demonstrated for several risk sites in the Kola Peninsula, the Russian Arctic for the countries of Northern Europe (*Baklanov et al., 2001; Rigina & Baklanov, 2001*).

Each from the two basic approaches: the probabilistic assessments and the 'cased study' has some possibilities and shortcomings, so it is not enough to one of them for the complex risk assessments. So, we suggest a combination of the both methods, as it is presented in Figure 2: the probabilistic assessment (shown at the left side of Figure 2), and the case study (shown at the right side of Figure 2), this combination gives a quit complex and non-expensive approach.

For assessment of the probabilistic risk and vulnerability, we consider:

***2) social-geophysical factors:***

- ♦ proximity to NRSs;
- ♦ population density in area;
- ♦ presence of critical groups of population;
- ♦ ecological vulnerability of area;
- ♦ risk perception, preparedness of safety measures, systems for quick response;
- ♦ economical and technical means, counteracting consequences of accident;

**2)** ***probabilities*****:**

- ♦ probability of an accident of certain severity at NRSs;
- ♦ probability of atmospheric transport towards area of interest from NRSs;
- ♦ probability of radionuclide removal over area during atmospheric transport.

For estimation of vulnerability/risk for different regions, a risk function was defined as a complex index of probability of risk for different factors. There could be two approaches to define such a function. The first approach is commonly used for estimation of possible dose for population and proceeds from the physical laws of radioactive matter transport from a nuclear reactor to Man. However, such an approach is inconvenient for an analysis of factors of different nature like, for example, geophysical processes of radionuclide transport and social-economical factors. So, alongside with the first method, we are suggesting a simpler and more universal approach, based on a combination of different factors and probabilities of separate processes with appropriate weights.

The following models and approaches are used in the suggested methodology for the probabilistic complex risk and vulnerability studies:

- Trajectory modelling - 3-D isentropic trajectory model (*Merrill et al., 1985*) and 3-D DMI trajectory model (*Sørensen et al., 1994*) - calculate multiyear forward trajectories originated at NRSs;
- Cluster analysis technique (*Jaffe et al., 1997a; Mahura et al., 1999; Baklanov et al., 2001*) - identify atmospheric transport pathways from NRSs;
- Probability fields analysis (*Jaffe et al., 1997b; Baklanov et al., 1998; Mahura et al., 1998*) - construct monthly and seasonally airflow, fast transport, precipitation factor probability fields and other indicators to identify the most impacted geographical regions;
- Long-range transport - DERMA (*Sørensen, 1998; Baklanov and Sørensen, 2001*) and DMI-HIRLAM (*Sass et al., 2000*) models - simulate radionuclide transport for hypothetical accidental releases at NRSs, and compare with results of trajectory modelling;

- Specific case studies - estimation of consequences for environment and population after hypothetical accidents using experimental models based on the Chernobyl effects for the Nordic countries (*Moberg, 1991; Dahlgaard, 1994; Nielsen, 1998; Bergman, 1999; Baklanov et al., 2001*);
- Evaluation of vulnerability to radioactive deposition - concerning its persistence in the ecosystems with focus to transfer of certain radionuclides into food chains of key importance for the intake and exposure in a whole population and certain groups of the Nordic countries (*Bergman, 1999*);
- Complex risk evaluation and mapping - using demographic databases in combination with the GIS-analysis (*Rigina & Baklanov, 1999, 2001; Rigina, 2001*) - to analyse socio-economical consequences for different geographical areas and various population groups taking into account: 1) social-geophysical factors (proximity to NRSs, population density; critical groups of population; ecological vulnerability of area; risk perception, preparedness of safety measures and quick response systems; counteracting economical and technical consequences of accident) and 2) probabilities (accident of certain severity; atmospheric transport from NRSs; removal over area during atmospheric transport).

The method for the complex risk evaluation and mapping is discussed in papers (*Rigina, 2001; Rigina and Baklanov, 2001*). They are devoted to the problems of residential radiation risk and territorial vulnerability with respect to nuclear sites in the Kola Peninsula. The study suggests two approaches, based on an integration of the mathematical modelling and the GIS-analysis, to calculate radiation risk/vulnerability.

First, modelling simulations were done for a number of case-studies, based on real data, such as reactor core inventory and estimations from the known accidents, for a number of typical meteorological conditions and different accidental scenarios. Then, using these simulations and the population database as input data, the GIS-analysis reveals administrative units at the highest risk with respect to the mean individual and collective doses received by the population.

Then, two alternative methods were suggested to assess a probabilistic risk to the population in case of a severe accident on the Kola NPP (as an example) based on social-geophysical factors: proximity to the accident site, population density and presence of critical groups, and the probabilities of wind trajectories and precipitation. The two latter probabilities were predicted by the discussed here statistical methods and trajectory models. The GIS analysis was done for the Nordic countries as an example, because the population data for the Kola Peninsula were out-of-date.

GIS-based spatial analyses integrated with mathematical modelling allow to develop a common methodological approach for complex assessment of regional vulnerability and residential radiation risk, by merging together the separate aspects: modelling of consequences, probabilistic analysis of pathways, dose estimation etc. The approach was capable to create risk/vulnerability maps of the Nordic countries and to reveal the most vulnerable provinces with respect to the radiation risk sites.

In this report we will not consider aspects of the dispersion and deposition modelling and the method for the complex assessment of regional vulnerability and residential radiation risk, based on GIS modelling and analysis. This was preliminary discussed in previous publication (*Rigina, 2001; Rigina and Baklanov, 2001*) and will be a topic for the next project report. The main item/focus of this report is to describe the suggested methodology for the probabilistic atmospheric studies for the risk assessment, namely the four upper blocks at the scheme of the complex risk assessment, presented in Figure 3.

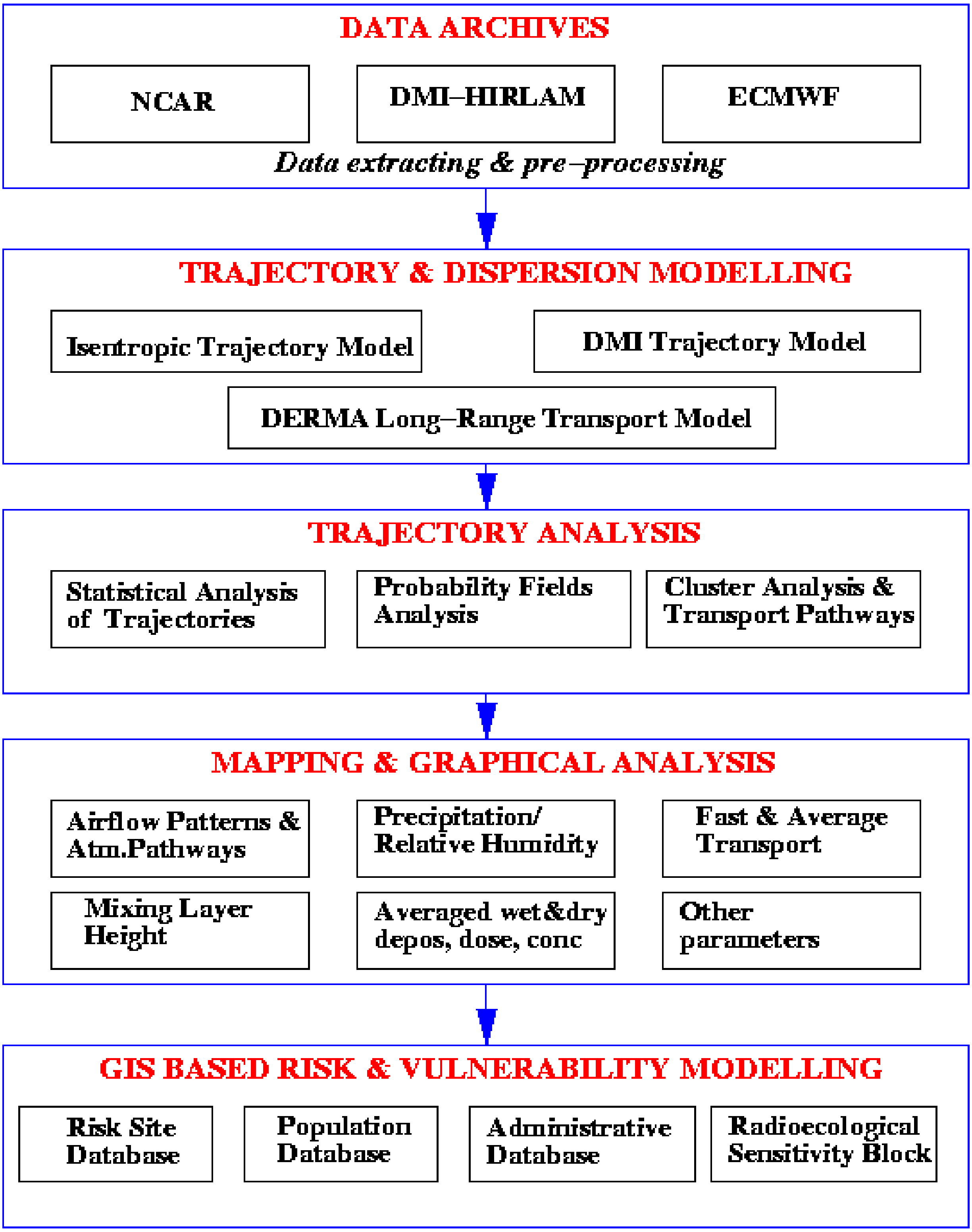


**Figure 3.** Suggested scheme of the complex risk assessment.

## 3.2. *MAIN INDICATORS OF NRS IMPACT*

The following several indicators of the possible NRS impact were developed for the probabilistic atmospheric studies.

### ***1. Airflow and Fast Transport Probability Fields***

Each trajectory, calculated by isentropic trajectory model, contains information about longitude, latitude, altitude, pressure, temperature, relative humidity and other variables at each 12 hours interval. Therefore, using such information we could construct the probabilistic fields for atmospheric patterns.

The first type of probabilistic fields shows the common features in the atmospheric transport patterns from NRS. It could provide a general insight on a possible main direction of the radioactive plume transport as well as the probability that it will reach or pass any geographical area.

The second type of probabilistic fields indicates the probability of the air parcels movement during the first day of atmospheric transport. In particular, these fields are calculated after the first 12 and 24 hours of transport. It is important information, especially, for estimation of the radionuclide impact such as iodine isotopes. These fast transport fields show, which territories may be reached after the first half or day, and which areas are at the most danger due to fast transport.

### ***2. Typical Transport Time Fields***

The indicator - Typical Transport Time (TTT) - fields could show: first, how long it will take for an air parcel to reach a particular geographical area from the NRS location, and second, which areas would be at the highest risk during the first few days of transport after an accidental release at NRS. To visualise TTT fields, at the first step, we constructed a new polar grid domain having 36 sectors (10 deg each) with NRS in the centre. At the second step, in the same way as in the probability field analysis, we counted number of trajectory intersections in each grid cell of new domain. Then, we selected along each sector a grid cell with absolute maximum of trajectory intersections and construct an isoline of TTT for a particular term in days.

### ***3. Maximum Reaching Distance***

The indicator - Maximum Reaching Distance (MRD) - shows the farthest boundaries on the geographical map, which might be reached during the first day, at least, by one trajectory originated over the NRS location . To visualise the MRD indicator we used all endpoints of calculated trajectories during the first day of transport. An isoline of MRD had been drawn through the grid boxes where at least one trajectory intersected with the grid's boundaries. We should note also, that although the likelihood that an air parcel will reach these boundaries is the lowest, it is still a possible case of transport.

### ***4. Maximum Possible Impact Zone***

The indicator - Maximum Possible Impact Zone (MPIZ) - as an integral characteristic, shows areas as well as boundaries with the highest probability of reaching by trajectories during the first day of transport .To visualise MPIZ indicator we accounted also all endpoints of calculated trajectories during the first day of transport. Then, similar approach for construction of the probability fields (as for the fast transport and airflow fields) was used to construct the MPIZ field. An isoline of MPIZ had been drawn through the areas with the highest occurrence of trajectory intersections.

### ***5. Removal or Precipitation Factor***

During the transport of radionuclides, within the atmosphere many different processes may influence the distribution of substances. Wet deposition is the term of most concern. It is highly temporally and spatially dependent. It plays important role in the estimation of the radionuclide surface deposition. Deposition of radionuclides at the surface due to washout might produce a cellular figure as was recorded after the Chernobyl accident. We should note that to analyse the possible contribution of the removal processes during atmospheric transport from the NRSs locations we might apply at least three different approaches, which are briefly described in the next chapter of this report and will be a separate topic for one of the following project reports.

The suggested methodology of probabilistic atmospheric studies and evaluation for each above-mentioned indicators of the NRS impact is shown in Chapter 4.

# IV. METHODOLOGY FOR PROBABILISTIC ATMOSPHERIC STUDY

## 4.1. *METEOROLOGICAL DATA ARCHIVES*

Data analysis is a basic for the atmospheric science research. Data might be represented in different forms and at different temporal and spatial scales. They might be obtained from a variety of different sources such as ground meteorological stations, radars, sounding, satellites, aeroplanes, etc. Models, which rely on intensive usage of the supercomputing resources, can produce gridded arrays for the commonly used basic variables. Atmospheric models can calculate temperature, humidity, wind components, vertical motions and other variables at different levels.

In our study, as input data, we used several gridded datasets, which are described below.

### NCAR Dataset

Dataset DS082.0 - NCEP Global Tropospheric Analyses (from July 1976 till April 1997) is one of the major gridded analyses available at the National Center for Atmospheric Research (NCAR, Boulder, Colorado, USA). It is a part of the operational and gridded analyses performed at the National Center for Environmental Prediction (NCEP; prior to 1995 known as the National Meteorological Center – NMC).

This dataset has a resolution of 2.5° x 2.5° latitude vs. longitude (145 x 37 grids) for both Northern and Southern hemispheres. It consists of the surface, tropospheric, tropopause, and lower stratospheric analyses as well as at the standard levels up to 50 millibars (mb). The main analysed variables are the following: geopotential height, temperature, u-, v-, and w-components of the wind, relative humidity, sea level pressure, surface pressure and temperature, sea surface temperature, snowfall, precipitable water, potential temperature, vertical motion, tropopause pressure and temperature. Analysis has been done on a daily basis at 00 and 12 UTC terms (Universal Coordinated Time).

The dataset is available from the NCAR Mass Storage System (MSS) or from the NCEP/NCAR reanalysis CD-rooms. More detail information about DS082.0 dataset could be found at the www-address http://dss.ucar.edu/datasets/ds082.0/ and in publications by *Baker, 1992; Trenberth & Olson, 1988; Randel, 1992.*

### DMI-HIRLAM Datasets

The DMI-HIRLAM high-resolution meteorological data (D-version: 0.05°, N- and E-versions: 0.15 ° or G-version: 0.45°, see Figure 4; with 1 hour time resolution) are used as input data for high resolution trajectory or dispersion simulations. The vertical model levels (in total 31 levels) are presently located at 33, 106, 188, 308, … meters for a standard atmosphere. The High Resolution Limit Area Model (HIRLAM) numerical weather prediction model (*Källen, 1996*) is run operationally by the Danish Meteorological Institute (www-address - *www.dmi.dk*) for the European territory and for the Arctic region since 1990. DMI's 3-D Lagrangian transport model (*Sørensen et al., 1994*) calculates forward and backward trajectories for any location in the area. It can utilise meteorological data from the different versions of DMI-HIRLAM as well as ECMWF's global model.

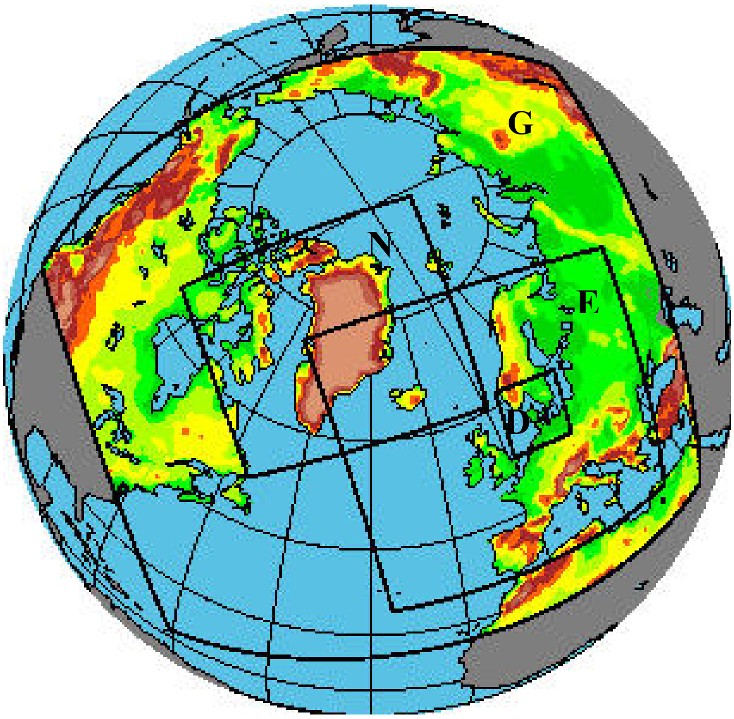


**Figure 4.** The DMI-HIRLAM operational NWP system domains.

The present DMI weather forecasting system is based on an extended version of the HIRLAM 4.7 (*Sass et al., 2000*). The forecast model is a grid point model. The data assimilation is intermittent, and it is based on the 3-D variation data assimilation (3DVAR). The operational system consists of four nested models called DMI-HIRLAM-G, DMI-HIRLAM-N, DMI-HIRLAM-E, and DMI-HIRLAM-D. These models are identical except for horizontal resolutions and integration domains. The model domains are shown in Figure 4. The lateral boundary values for the "G"model are ECMWF forecasts, while those for "N" and "E" are "G" forecasts, and those for the "D"model are "E" forecasts. For some limited periods of time the DMI-HIRLAM system was run for other areas as well, e.g. for a part of China and the surrounding region.

The forecasting system is run on the NEC-SX4 supercomputer with connections to other DMI computers. The produced model level and surface field files are archived on the UNITREE mass storage system. So, the DMI-HIRLAM data can be used in the operational mode or from the archives.

## ECMWF Datasets

The meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK is based on the ECMWF's global model forecast and analysis (http://www.ecmwf.int/services/data/archive/index.html) and it has a resolution up to 0.5° x 0.5° latitude vs. longitude and 3 hours time interval for both Northern and Southern hemispheres. It consists of the geopotential, temperature, vertical velocity, u- and v-components of horizontal wind, relative humidity and specific humidity at each level, etc. Analysis has been done on a daily basis at 00, 06, 12 and 18 UTC terms.

The ECMWF has the following data archives: ECMWF/WCRP level III-A Global Atmospheric Data Archive (TOGA), Operational Atmospheric Model, ERA-15 (ECMWF Re-Analysis 15), ERA- 40 (ECMWF Re-Analysis 40), Wave Model, Ensemble Prediction System (EPS), Seasonal Forecast, and Monthly Means.

The ERA-15 production system generated re-analyses from December 1978 to February 1994. The ERA-15 Archive contains global analyses and short range forecasts of all relevant weather parameters, beginning with 1979, the year of the First GARP Global Experiment (FGGE). The Level III-B archive is subdivided into three classes of data sets: Basic 2.5° x 2.5° Data Sets (17 vertical pressure levels); Full Resolution Data Sets (e.g. 1° x 1°, 31 hybrid model vertical levels); Wave archive.

The data sets are based on quantities analysed or computed within the ERA-15 data assimilation scheme or from forecasts based on these analyses. The Basic Data Sets contain values in a compact form at a coarse resolution. They are particularly suitable for users with limited data processing resources. The Full Resolution Data Sets provide access to most of the data from the ERA-15 atmospheric model archived at ECMWF. These archives have a higher space resolution. They should only be used where high resolution is essential; in this respect they are particularly suited for use in conjunction with case studies and as initial conditions for high-resolution models. This archive includes analysis, forecast accumulation and forecast data. Data are available on the surface, pressure levels and model levels.

The new reanalysis project ERA-40 (*Simmons and Gibson, 2000*) will cover the period from mid-1957 to 2001 overlapping the earlier ECMWF reanalysis, ERA-15, 1979-1993. Analysis and forecast fields will only be made available as complete years and only after validation.

### 4.2. *TRAJECTORY MODELING*

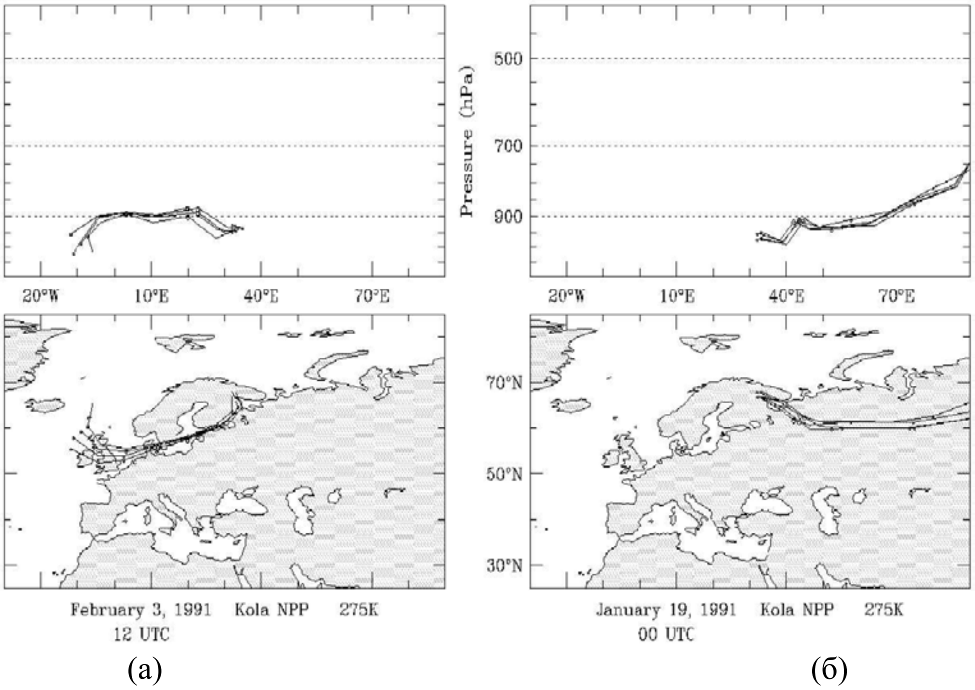
In general, each computed atmospheric trajectory represents a pathway of an air parcel motion in time and space. We consider trajectories as an estimation of the mean motion of a diffusing cloud of some material. There are a few approaches to model atmospheric trajectories. Two of these approaches are commonly used: 1) isobaric and 2) isentropic (*Danielsen, 1961*). For isobaric trajectories it is assumed that air parcels are moving along the surfaces of the constant pressure. For isentropic trajectories it is assumed that air parcels are moving along the surfaces of the constant potential temperature. In general, of course, modelling of more realistic trajectories – "fully 3-D trajectories" - is preferable, but it is complex and requires incorporation into simulation of large number of variables and parameters as well as increases the computational time.

In our study for the long-period statistics we selected the isentropic approach. Although this type of trajectory models uses assumption of adiabatically moving air parcels and neglects various physical effects, it is still a useful research tool for evaluating common airflow patterns within meteorological systems on various scales (*Merrill et al., 1985; Harris & Kahl, 1990; Harris & Kahl, 1994; Jaffe et al., 1997a; Mahura et al., 1997a; Jaffe et al., 1997b; Mahura et al., 1999* and others). Some uncertainties in these models are related to the interpolation of meteorological data, which might be sparsely measured, applicability of the considered horizontal and vertical scales, assumptions of vertical transport, and etc (*Merrill et al., 1986; Draxler, 1987; Kahl, 1996; Stohl, 1998*).

In our study, as input data, we used a gridded dataset - Dataset DS082.0 - NCEP Global Tropospheric Analyses - available at the National Center for Atmospheric Research (NCAR, Boulder, Colorado, USA). We interpolated the original gridded wind fields to potential temperature (isentropic) surfaces. We choose isentropic assumption in our study because isentropic trajectories are a better representation of the air parcels atmospheric transport in comparison with isobaric trajectories because they are more realistic. Additionally we should note that quality of trajectory calculation is highly dependent on the original quality of the NCEP's fields (2.5° x 2.5° latitude vs. longitude), and it may not reflect the contribution of the frontal passages and local terrain phenomena. However, the trajectory errors rising during a single calculation might be smoothed in the further analysis due to the large number of trajectories in the multiyear dataset.

An interpolation procedure has been performed for a period of 7 years, 1990-1996. We applied a technique described by *Merrill et al., 1985*. Then, we used these interpolated wind fields on isentropic surfaces to calculate trajectories in the model domain at various levels within atmosphere. The model grid domain selected for this study covers area between 20°-82.5°N and 60°W-127.5°E. All forward isentropic trajectories from the nuclear risk sites regions were computed twice per day (at 00 and 12 UTC, Universal Co-ordinated Time) at different potential temperature levels. These levels (total 16) ranged from 255°K to 330°K with a step of 5°K. We computed more than 327 thousand trajectories for each NRS. Less than two percent of the trajectories were missing because of the absence of archived meteorological data and processing problems.

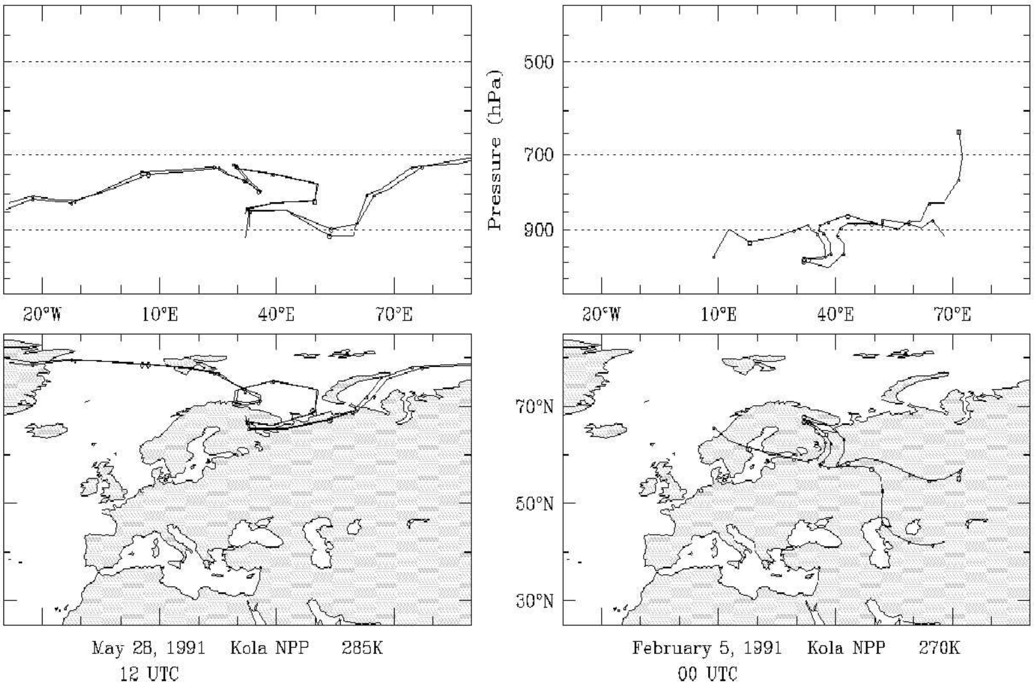
In this study, instead of calculating only one trajectory per each NRS per UTC term, we used for every calculation four trajectories. The initial points of trajectories are located at each corner of a 1°x 1°of latitude vs. longitude box, where NRS is in the centre of the box. Calculation of four trajectories simultaneously allowed us to evaluate a consistency of the wind field in the direction of the atmospheric transport.



(a) (б)

**Figure 5.** Examples of trajectories showing consistent air flow for the Kola NPP.

Although we used all calculated trajectories for the further analysis, we should note that here are differences in the representation of the general flow along trajectories. The flow is considered to be a reasonably consistent along the transport pathway if all four trajectories had shown a similar direction (reflecting convergence of flow) of transport for one time period (as shown in Figure 5). Trajectories, showing a strong divergence of flow, are assigned to a category of the "complex trajectories" (as shown in Figure 6). These trajectories reflect more uncertainties in the air parcel motion. These differences are not so important in evaluation of the general climatological patterns, but they can be significant in, for example, identification of source regions for air pollutants, evaluation of the nature of the specific events with recorded elevated concentration of species, tracking tracers in the atmosphere, and others.



(a) (б)

**Figure 6.** Examples of trajectories showing divergence of flow (complex trajectories) for the Kola NPP.

For all NRS, the most probable release heights would be within the boundary layer, i.e. within the first hundred meters above the ground. Therefore, at the next step, from all isentropic trajectories we selected only those trajectories originating within this layer. So, per each site, we extracted more than 24.4 thousand trajectories (from original more than 327 thousand trajectories). All chosen trajectories for further statistical analysis have duration of 5 days. We decided to use this limitation in duration of trajectories because of 1) quality and accuracy of trajectory calculations after 5 days drops significantly, 2) observing development frames of the synoptic scales systems in the European region, as well as 3) relative proximity of the analysed geographical regions from the sites of interest.

Finally, to study altitudinal variations in the flow patterns (in particular, within the boundary layer and free troposphere), we also considered trajectories originated over the NRS regions at the top of the boundary layer (i.e. we assumed - near 1.5 km above sea level (asl)).
For high-resolution meteorological data, based on the DMI-HIRLAM and ECMWF archives, the trajectory model, developed at DMI (*Sørensen et al., 1994*) will be used.

### 4.3. *TRAJECTORY CLUSTER ANALYSIS*

In general, the cluster analysis is a variety of multivariate statistical analysis techniques, which could be used to explore the existing structure within data sets (*Romesburg, 1984*). The specific purpose of this analysis is to divide a data set into groups (or clusters) of similar variables (or cases). *Miller (1981)* initiated application of the cluster analysis on trajectories. It was used to analyse the general atmospheric transport pathways at the Mauna Loa Observatory (Hawaii) over the North Pacific Ocean. The important output of the study was evaluation of the airflow climatology, in particular, over the long time periods. Then later, cluster analysis techniques on trajectories were used extensively by various researchers in different scientific fields.

In general, output of cluster analysis on trajectories can provide insights in the tracers transport, common atmospheric flow patterns for the sites of interest, identification of the source regions for atmospheric pollutants, and etc. Application of cluster analysis with respect to the nuclear risk sites, and in particular, for the nuclear power plants located in the Murmansk and Chukotka regions of Russia, have been performed by *Jaffe et al. (1997a), Mahura et al. (1997a), Mahura et al. (1997b), Baklanov et al. (1999), Mahura et al. (1999), Baklanov et al. (2001).*

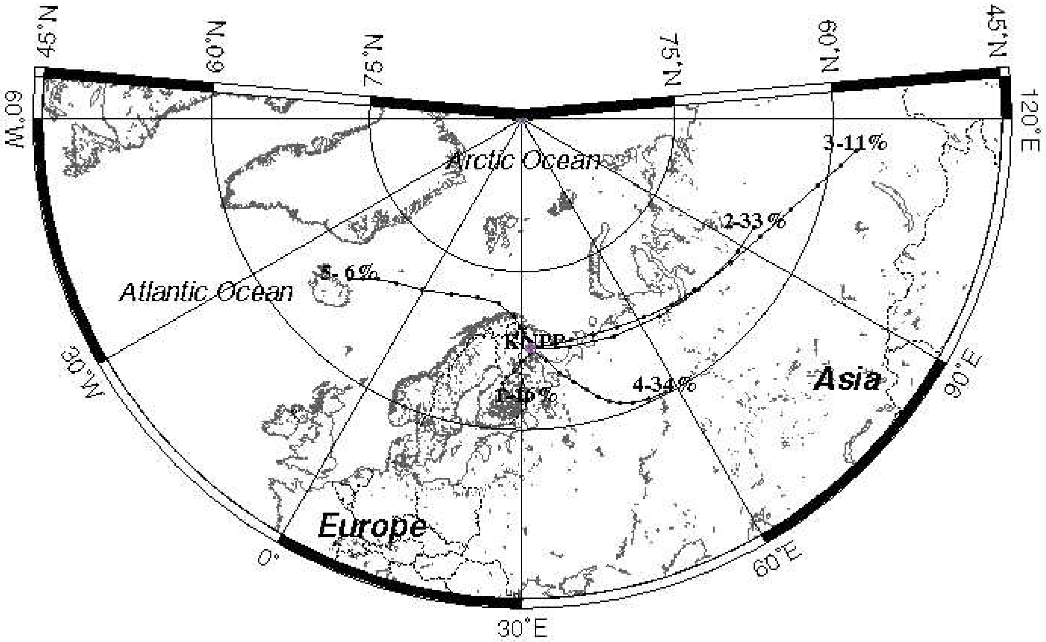


**Figure 7.** Atmospheric transport pathways (cluster mean trajectories) from the Kola NPP region based on the forward trajectories during 1992.

In this study for the simple airflow climatology, we suggest to use the same cluster analysis technique that was applied in *Jaffe et al. (1997a), Jaffe et al. (1998a), Mahura et al. (1999),* and *Baklanov et al. (2001).* The SAS/STAT software package (developed by SAS Institute Inc., http://www.sas.com/) has tools for many types of statistical analysis techniques including various cluster analysis procedures. In our study, we used the FASTCLUS procedure, which performs a disjoint cluster analysis on a basis of the Euclidean distances computed from one or more quantitative variables.

We use cluster analysis to divide calculated trajectories into groups, which represent the major airflow transport regimes. The following criteria were used: latitude and longitude values at each time interval of 12 hours. These represent both direction and velocity of air parcel motion. Similarity among trajectories in each cluster is maximised considering the full length of each 5-day forward trajectory. Within each cluster, individual trajectories can be averaged to obtain the mean cluster trajectory (or transport pathway). Thus, the original large data set of trajectories can be reduced to a small number of mean cluster plots. And further, these plots then could be interpreted, based on common synoptic conditions and features.

One example of the cluster analysis to represent the major atmospheric transport pathways (cluster mean trajectories) from the Kola NPP region based on the forward trajectories during the fall of 1992 is presented in Figure 7. Using cluster analysis technique, we summarise the airflow climatology for selected NRSs regions and can perform the analyses on a seasonally, yearly, and for the multiyear period basis.

### 4.4. *PROBABILITY FIELD ANALYSIS*

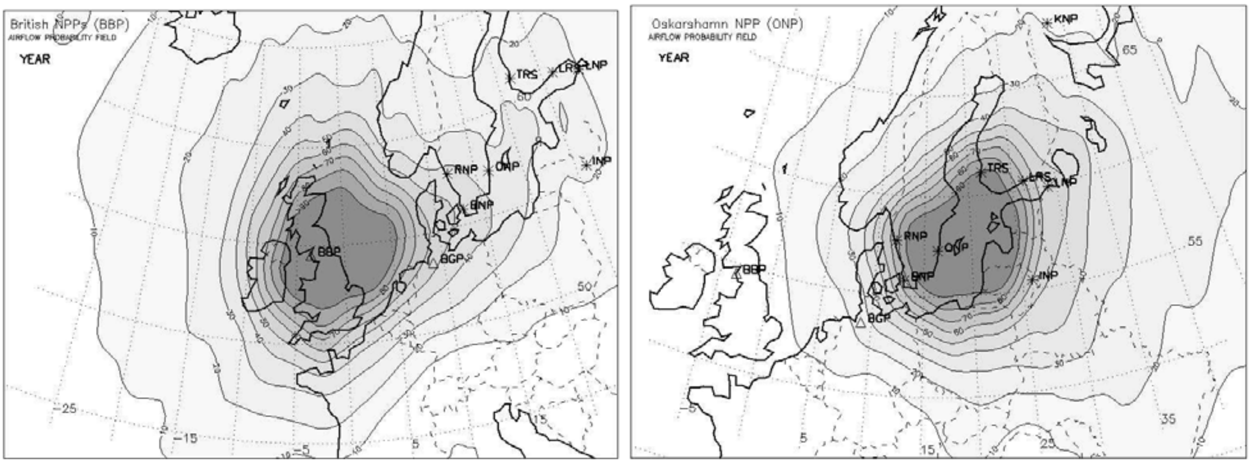
Probabilistic analysis is one of the ways to estimate the likelihood of occurrence of one or more phenomena or events. As we mentioned, in this study we calculated a large number of trajectories per each NRS that passed over various geographical regions. Each calculated trajectory contains information about longitude, latitude, altitude, pressure, temperature, relative humidity and other variables at each 12 hours interval. The probability fields for these characteristics, either individual or combined, can be represented by a superposition of probabilities for air parcels reaching each grid area in the chosen domain or on a geographical map. The most interest for the further analysis would be the following probabilistic fields: airflow and fast transport patterns.

The **first type** of probabilistic fields shows the common features in the atmospheric transport patterns from NRS. It could provide a general insight on a possible main direction of the radioactive cloud transport as well as probability that it will reach or pass any geographical area. The result of this analysis is an appropriate test to support or disprove results of the cluster analysis, which could be applied to identify the general atmospheric transport pathways from the site. This is because the atmospheric transport pathways, (or mean trajectory clusters), show only a common direction of airflow from NRS. However, information between these pathways (or clusters) is missing.

The **second type** of probabilistic fields indicates the probability of the fast movement of air parcels during the first day of transport. This indicator shows where contaminated air parcels might be located geographically after the first 12 and 24 hours of atmospheric transport from the NRS location. In this approach, we analysed separately only trajectories terminated exactly after 12 and 24 hours of transport. The areas with the highest occurrence of trajectory intersections with the grid domain cells will reflect territories under the higher possible impact from the nuclear risk site.

In our study, probabilistic fields were constructed for two types – airflow and fast transport fields. To construct these fields we used latitude, longitude, altitude, and time step values for each trajectory. At the first step, for each NRS, a new rectangular grid domain was created with a resolution of 2.5° x 2.5° latitude vs. longitude grid cells. The NRS is located at the centre of domain on the intersection between grid lines. At the second step, all intersections of trajectories with each grid cell were counted. Among all grid cells, the cell where the absolute maximum of intersections took place was identified as an "absolute maximum cell" (AMC). Because all trajectories start near the NRS region, to account for contribution into flow at the larger distances from the site, we extended the area of maximum to adjacent cells to the AMC. We compared the number of intersections in cells adjacent to AMC and assigned additional cells, which had less than 10% of difference between cells. Therefore, this new "area of maximums", if isolines are drawn, will represent area of the highest probability of the possible impact (AHPPI) from NRS. Assuming the value of 100% for this area, the rest could be re-calculated as percentage of the area at the highest probability of the possible impact.

There is a difference between airflow and fast transport probability fields. To construct the airflow field we used all 5 day trajectories at each time step of 12 hours, i.e. combined summation of trajectory intersections for all 11 terms - 0.0, 0.5, 1.0, 1.5, 2.0,…, and 5.0 days. Two examples of such probabilistic airflow fields for 1990-1996 are shown in Figure 8: a) for block of British NPPs and b) for the Oskarshamn NPP (Sweden).

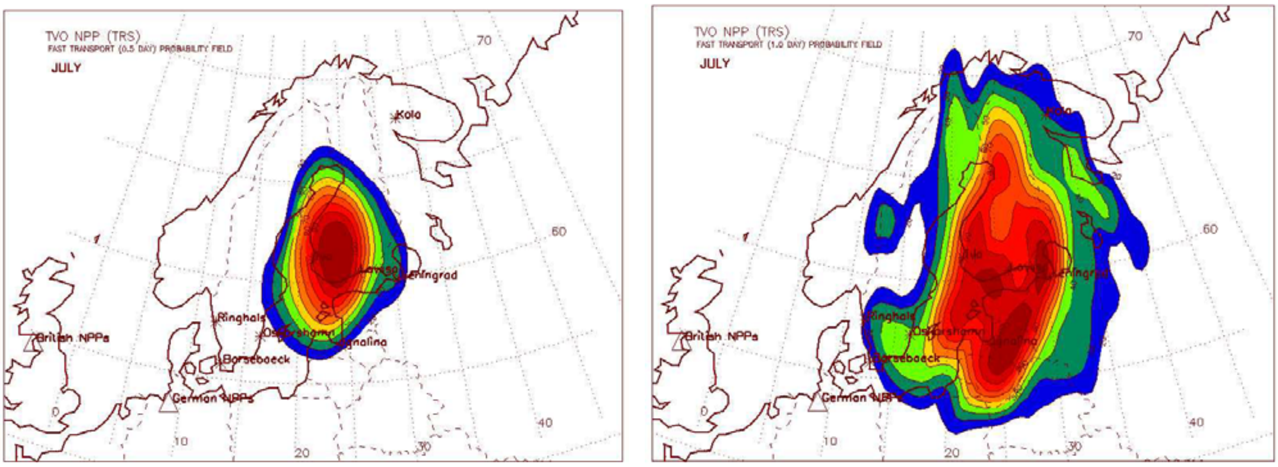


(a) (b)

**Figure 8**. The airflow probability fields during 1990-1996 for a) block of British NPPs and b) the Oskarshamn NPP.

To construct the fast transport fields we used only trajectory endpoints terminated at 0.5 and 1.0 days of transport, i.e. we counted separately intersections of trajectories with grids only after 12 and 24 hours. An illustration of the probability field for the Olkiluoto NPP (Finland) fast transport patterns is shown in Figure 9. The Figure 9a shows that in July, if an accidental release will take place at the Olkiluoto NPP, after the first 12 hours the southern territories of Finland would be at the higher risk of possible NRS impact in comparison with central and northern territories. This impact is gradually decreases from the AHPPI centre, and this decrease is faster along the latitude comparing with longitude. The westerly flow is predominant. The Figure 9b shows that in the same month, after 24 hours of transport the AHPPI extended significantly in the latitudinal direction and moved farther from the NRS location along the major direction of transport. In this case, the Baltic States as well as Russian border's areas are at the higher risk of possible NRS impact.

In our study, constructed probability fields reflect existing variations in the airflow and fast transport patterns for trajectories originating within the boundary layer. The analysis will be done for the multiyear period of 1990-1996, by season and month. Results of the probability fields analysis for the selected in this study NRSs will be presented in the next report of the ‘Arctic Risk’ Project.



(a) (b)

**Figure 9.** Oliluoto NPP fast transport probability fields during July after a) 12 hours and b) 24 hours of transport.

## 4.5. *TYPICAL TRANSPORT TIME ANALYSIS*

In the emergency response systems for the nuclear accidents, the estimation of the radionuclide transport time to a particular territory, region, county, city, and etc is one of the important input parameters in the decision-making process. We extracted this information from the calculated isentropic trajectories and constructed "Typical Transport Time" (TTT) fields. The TTT fields could show: first, how long it will take for an air parcel to reach a particular geographical area from the NRS location, and second, what areas would be at the highest risk during the first few days of transport after an accidental release at NRS.

At the first step, we constructed a new polar grid domain with NRS in the centre. For that, we divided the entire region into 36 sectors, where each sector represents 10 degrees. Along each middle line of sector, we divided distance by 2 degrees starting at the NRS location. For our study, we selected 70 degrees along each sector line. Therefore, new grid domain consists of 1260 grid cells.

At the second step, in a same way as in the probability field analysis, we counted number of trajectory intersections in each grid cell of new domain. To perform this operation we initially transformed all trajectory end points for one time interval expressed by the latitude vs. longitude into the angle and distance (or radius) from the NRS location. Then, for this time interval, we compared number of trajectory intersections in cells along each sector line to find an absolute maximum cell (AMC). It should be noted that sometimes more than one maximum could be identified along the sector line. Because our concern is a possibility of the fastest transport to the remote territory, we selected the first AMC, which is the closest to NRS.

For example, as shown in Table 1, there are three AMCs along the sector line of "0.-10." degrees and each has 11 intersections. Only one AMC, which is the closest to the NRS location, was chosen and it is the third grid cell located between 4 and 6 degrees along the sector line. For the "10.-20." degrees sector there is only one AMC and trajectories intersected this cell 24 times.

| | ***Distance from the NRS location (in deg)*** | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Sector (in deg)*** | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 | 42 | 44 | 46 | 48 | 50 |
| **0.- 10.** | 2 | 7 | 10 | **11** | **11** | 9 | **11** | 2 | 5 | 7 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10.- 20.** | 2 | 6 | 8 | 12 | **24** | 19 | 11 | 4 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **20.- 30.** | 1 | 9 | 8 | 9 | **18** | 14 | 9 | 13 | 5 | 10 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **30.- 40.** | 5 | 14 | 8 | 11 | 17 | 13 | 20 | **21** | 6 | 8 | 9 | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **40.- 50.** | 6 | 12 | 7 | 17 | 9 | **18** | 11 | 16 | 13 | 8 | 14 | 10 | 1 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **50.- 60.** | 2 | 12 | 12 | 9 | 19 | 23 | 23 | **29** | 21 | 16 | 19 | 11 | 20 | 11 | 4 | 9 | 5 | 3 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **60.- 70.** | 6 | 9 | 10 | 25 | 30 | 28 | 34 | 34 | **57** | 42 | 41 | 40 | 28 | 25 | 23 | 21 | 19 | 24 | 21 | 26 | 7 | 17 | 6 | 5 | 5 | 4 |
| **70.- 80.** | 3 | 6 | 11 | 25 | 32 | 42 | 34 | 48 | 41 | 54 | 46 | 60 | 62 | **68** | 62 | 59 | 46 | 42 | 39 | 36 | 39 | 41 | 30 | 33 | 29 | 35 |
| **80.- 90.** | 4 | 13 | 13 | 24 | 19 | 35 | 39 | 47 | 41 | 57 | 67 | 55 | 59 | **82** | 52 | 70 | 51 | 55 | 69 | 67 | 62 | 65 | 47 | 43 | 39 | 36 |
| **90.-100.** | 6 | 9 | 14 | 32 | 30 | 31 | 23 | 38 | 37 | 49 | **71** | 61 | 60 | 66 | 51 | 58 | 57 | 50 | 61 | 61 | 63 | 52 | 36 | 25 | 26 | 14 |
| **100.-110.** | 2 | 13 | 10 | 18 | 25 | 35 | 31 | 50 | **74** | 49 | 45 | 39 | 39 | 34 | 45 | 43 | 39 | 22 | 26 | 28 | 33 | 10 | 5 | 5 | 1 | 2 |
| **110.-120.** | 5 | 10 | 14 | 18 | 31 | 40 | 36 | 34 | 38 | 30 | **45** | 32 | 31 | 23 | 28 | 7 | 13 | 11 | 2 | 4 | 2 | 0 | 0 | 0 | 0 | 0 |
| **120.-130.** | 2 | 8 | 13 | 17 | 26 | 21 | 23 | 32 | 26 | **37** | 33 | 17 | 13 | 3 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **130.-140.** | 1 | 8 | 10 | 17 | 15 | 26 | **29** | 23 | 24 | 12 | 9 | 5 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **140.-150.** | 2 | 8 | 9 | 10 | 13 | **33** | 31 | 18 | 17 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **150.-160.** | 0 | 8 | 11 | 13 | 16 | 19 | **26** | 19 | 7 | 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **160.-170.** | 0 | 9 | 15 | 12 | **24** | 13 | 10 | 15 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **170.-180.** | 2 | 5 | 5 | 11 | 13 | **14** | 10 | 13 | **14** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **180.-190.** | 3 | 6 | 17 | 11 | 12 | **18** | 13 | 5 | 10 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **190.-200.** | 2 | 4 | 15 | 12 | **16** | 14 | 8 | 12 | 9 | 0 | 3 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **200.-210.** | 2 | 5 | 4 | **15** | 8 | 8 | 10 | 5 | 6 | 4 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **210.-220.** | 1 | 6 | 9 | 11 | 6 | **20** | 14 | 6 | 5 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **220.-230.** | 2 | 4 | 10 | **19** | 7 | 18 | 15 | 13 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **230.-240.** | 3 | 10 | 9 | 9 | 10 | **15** | 11 | 13 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **240.-250.** | 2 | 3 | 10 | 12 | 11 | **20** | 17 | **20** | 18 | 17 | 5 | 4 | 3 | 1 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **250.-260.** | 4 | 6 | 6 | 9 | 16 | 14 | 5 | 11 | **25** | 10 | 7 | 3 | 4 | 2 | 0 | 2 | 3 | 0 | 1 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| **260.-270.** | 0 | 6 | 8 | 15 | 13 | 14 | **18** | 15 | 16 | 15 | 17 | 8 | 7 | 10 | 3 | 6 | 11 | 4 | 7 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| **270.-280.** | 3 | 8 | 14 | **20** | **20** | 18 | 12 | 10 | 18 | 8 | 10 | 5 | 9 | 9 | 8 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **280.-290.** | 4 | 9 | 7 | 13 | 12 | 11 | 7 | 7 | 5 | 4 | 2 | **14** | 5 | 7 | 7 | 4 | 1 | 2 | 0 | 4 | 1 | 2 | 2 | 1 | 0 | 0 |
| **290.-300.** | 4 | 10 | 11 | 11 | **19** | 18 | 6 | 8 | 7 | 4 | 3 | 6 | 9 | 8 | 5 | 3 | 2 | 5 | 2 | 0 | 1 | 1 | 3 | 2 | 0 | 0 |
| **300.-310.** | 2 | 9 | 6 | 12 | 16 | **20** | 9 | 6 | 3 | 8 | 4 | 5 | 3 | 7 | 8 | 3 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **310.-320.** | 2 | 6 | 11 | 11 | 13 | 10 | 12 | **17** | 6 | 1 | 5 | 11 | 5 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **320.-330.** | 3 | 12 | **17** | 11 | 4 | 13 | 8 | 0 | 12 | 3 | 7 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **330.-340.** | 2 | 6 | 11 | 11 | **16** | 7 | 8 | 9 | 11 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **340.-350.** | 4 | 10 | 10 | 13 | **23** | 12 | 10 | 6 | 4 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **350.-360.** | 4 | 8 | 6 | **12** | **12** | 9 | 10 | 5 | 2 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 1.** Distribution of trajectory intersections along the sector lines (Case: Leningrad NPP, 2.5 days of transport).

After AMCs had been identified for all 36 sectors, the locations of sectors' centres from the polar grid domain were converted back into geographical co-ordinates of latitude vs. longitude. Finally, the isolines for the typical transport time in days had been drawn through these new geographical co-ordinates as shown in Figure 10. Applying a similar procedure, it is possible to construct isolines for other temporal terms in days of transport.

In the interpretation of these TTT fields there is a pitfall - in general, the airflow pattern is not symmetrical around NRS. And it could propagate toward the main direction of the large-scale flow pattern. After a few days of transport air parcels definitely will leave the area surrounding NRS. Therefore, the constructed TTT fields in the direction of the lower probability of atmospheric transport will not reflect a realistic figure.

It could be illustrated by analysis of results in Table 2. This table shows for each term (in days) in each sector, ranging from 0 to 360 degrees, the following characteristics. They are: 1) total number of trajectory intersections along the sector line (#SL), 2) number of trajectory intersections in AMC (#AMC), 3) percentage of trajectories contribution into the 360 degrees belt (%), and 4) test of

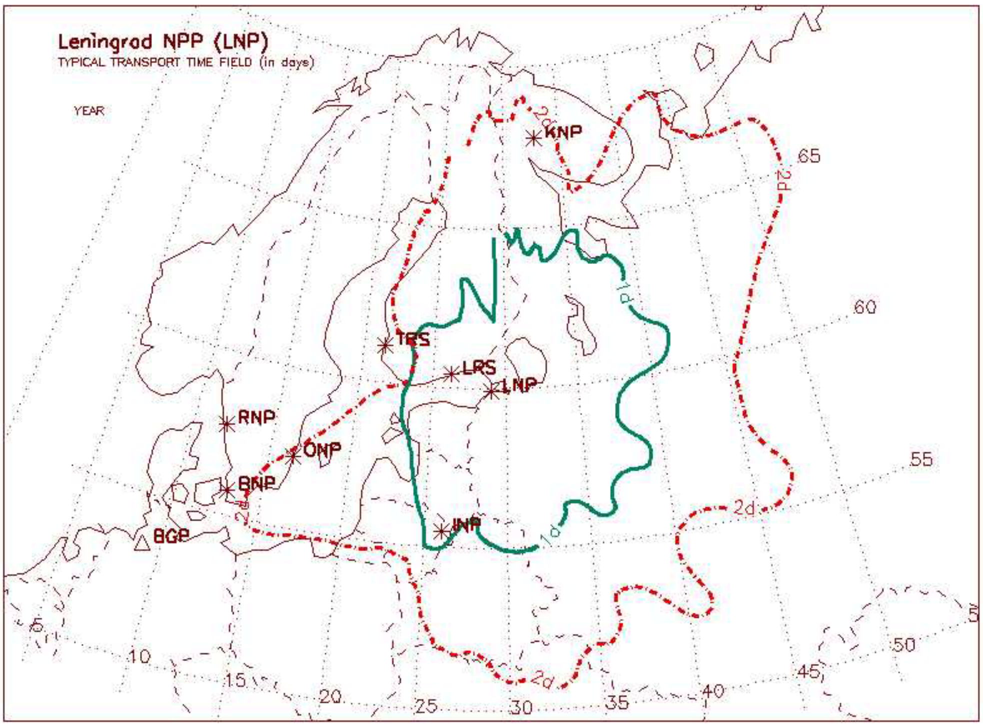


**Figure 10.** Typical transport time field at 1 and 2 days for the Leningrad NPP.

obtained data significance (SS) to plot final isoline. If the distribution is symmetrical, we will have approximately 2.78% (100% / 36 sectors = 2.78% in each sector) of each sector's contribution in the entire belt. Assuming now 2.78% as 100% of plausible contribution, we can recalculate the threshold (or separation) values for 75, 50, and 25%, which are 2.08, 1.39, and 0.69%, respectively. For example, as shown in Table 2, for term of 2.5 days in the sector between 50-60 degrees the number of trajectory intersections accounted in the AMC is equal to 29 among 252 of total along this sector line. These trajectories contribute into the 360 degrees belt 2.72% of the total, and this contribution is almost similar as for the symmetrical distribution case (2.78%). To resolve differences in contribution issue the AMC data represented in table with higher (threshold is higher than 1.39%) and lower (threshold is lower than 1.39%) percentage of occurrence were marked differently. We used the following symbols: "OK" - 100% and more of the AMC contribution into the 360 degrees belt; ">75" – 75-100%; ">50" - 50-75%, "*" - 25-50%, "-" - <25%.

It should be noted, that for further analysis (or construction of the typical transport time isolines), it seems more appropriate to use those AMCs, which are above 1.39% in the total contribution from individual sectors. In this case, we will have the braked isolines, which used only the limited number of AMCs. And therefore, some information would be missing. Accounting of all 36 AMCs per each term might still reflect more useful information for a case where an accident did happen and atmospheric transport did take place in a low probability sector.

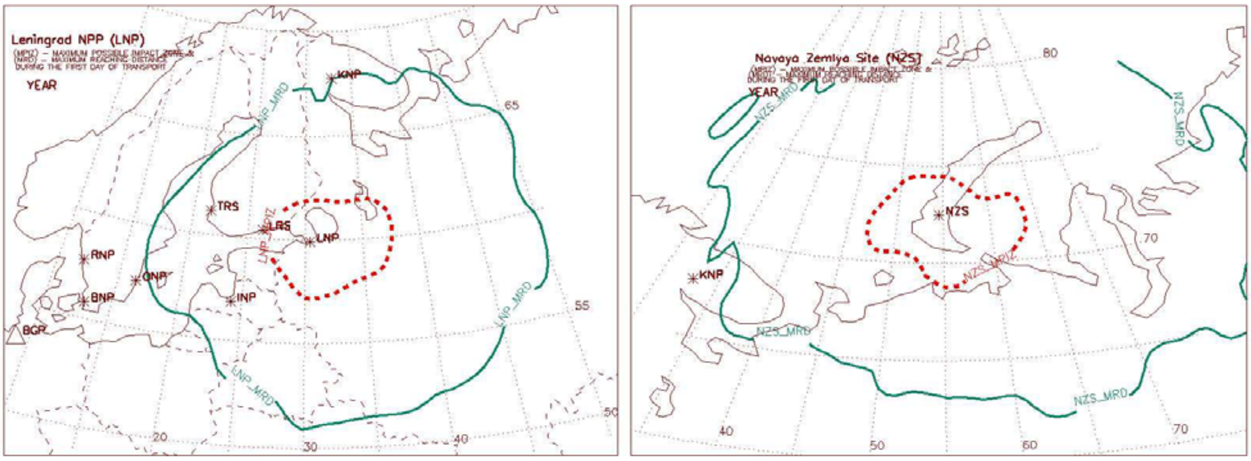
| | ***Transport time***<br>***0.5 days*** | | | | ***1.0 days*** | | | | ***1.5 days*** | | | | ***2.0 days*** | | | | ***2.5 days*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Sector*** | ***#SL*** | ***#AMC*** | ***%*** | ***SS*** | ***#SL*** | ***#AMC*** | ***%*** | ***SS*** | ***#SL*** | ***#AMC*** | ***%*** | ***SS*** | ***#SL*** | ***#AMC*** | ***%*** | ***SS*** | ***#SL*** | ***#AMC*** | ***%*** | ***SS*** |
| ***0.- 10.*** | 133 | 74 | 1.01 | -- | 145 | 51 | 1.14 | -- | 112 | 30 | 0.99 | -- | 103 | 22 | 1.01 | -- | 77 | 11 | 0.83 | -- |
| ***10.- 20.*** | 176 | 76 | 1.34 | -- | 134 | 41 | 1.06 | -- | 115 | 27 | 1.01 | -- | 121 | 23 | 1.19 | -- | 91 | 24 | 0.98 | -- |
| ***20.- 30.*** | 201 | 94 | 1.53 | >50 | 165 | 41 | 1.30 | -- | 154 | 29 | 1.36 | -- | 137 | 28 | 1.34 | -- | 100 | 18 | 1.08 | -- |
| ***30.- 40.*** | 260 | 119 | 1.98 | >50 | 242 | 64 | 1.91 | >50 | 186 | 33 | 1.64 | >50 | 167 | 27 | 1.64 | >50 | 139 | 21 | 1.50 | >50 |
| ***40.- 50.*** | 320 | 130 | 2.44 | >75 | 313 | 72 | 2.46 | >75 | 270 | 51 | 2.38 | >75 | 238 | 35 | 2.33 | >75 | 146 | 18 | 1.58 | >50 |
| ***50.- 60.*** | 412 | 163 | 3.14 | **=OK** | 445 | 73 | 3.50 | **=OK** | 421 | 61 | 3.71 | **=OK** | 308 | 35 | 3.02 | **=OK** | 252 | 29 | 2.72 | >75 |
| ***60.- 70.*** | 605 | 202 | 4.61 | **=OK** | 721 | 123 | 5.68 | **=OK** | 736 | 79 | 6.49 | **=OK** | 650 | 58 | 6.37 | **=OK** | 589 | 57 | 6.36 | **=OK** |
| ***70.- 80.*** | 884 | 255 | 6.73 | **=OK** | 1154 | 161 | 9.09 | **=OK** | 1135 | 110 | 10.02 | **=OK** | 1168 | 72 | 11.44 | **=OK** | 1151 | 68 | 12.43 | **=OK** |
| ***80.- 90.*** | 875 | 271 | 6.66 | **=OK** | 1095 | 148 | 8.62 | **=OK** | 1213 | 124 | 10.70 | **=OK** | 1327 | 94 | 13.00 | **=OK** | 1436 | 82 | 15.50 | **=OK** |
| ***90.-100.*** | 967 | 268 | 7.37 | **=OK** | 1111 | 152 | 8.75 | **=OK** | 1079 | 116 | 9.52 | **=OK** | 1104 | 89 | 10.82 | **=OK** | 1140 | 71 | 12.31 | **=OK** |
| ***100.-110.*** | 757 | 206 | 5.77 | **=OK** | 822 | 137 | 6.47 | **=OK** | 759 | 94 | 6.70 | **=OK** | 737 | 76 | 7.22 | **=OK** | 723 | 74 | 7.81 | **=OK** |
| ***110.-120.*** | 568 | 208 | 4.33 | **=OK** | 625 | 132 | 4.92 | **=OK** | 561 | 79 | 4.95 | **=OK** | 489 | 67 | 4.79 | **=OK** | 454 | 45 | 4.90 | **=OK** |
| ***120.-130.*** | 425 | 146 | 3.24 | **=OK** | 438 | 91 | 3.45 | **=OK** | 420 | 70 | 3.71 | **=OK** | 363 | 54 | 3.56 | **=OK** | 276 | 37 | 2.98 | **=OK** |
| ***130.-140.*** | 395 | 172 | 3.01 | **=OK** | 341 | 71 | 2.68 | >75 | 283 | 53 | 2.50 | >75 | 236 | 40 | 2.31 | >75 | 182 | 29 | 1.96 | >50 |
| ***140.-150.*** | 291 | 132 | 2.22 | >75 | 272 | 71 | 2.14 | >75 | 245 | 50 | 2.16 | >75 | 180 | 38 | 1.76 | >50 | 145 | 33 | 1.57 | >50 |
| ***150.-160.*** | 278 | 129 | 2.12 | >75 | 260 | 73 | 2.05 | >50 | 192 | 43 | 1.69 | >50 | 133 | 25 | 1.30 | -- | 127 | 26 | 1.37 | -- |
| ***160.-170.*** | 242 | 119 | 1.84 | >50 | 214 | 61 | 1.68 | >50 | 170 | 42 | 1.50 | >50 | 149 | 28 | 1.46 | >50 | 104 | 24 | 1.12 | -- |
| ***170.-180.*** | 181 | 100 | 1.38 | -- | 203 | 68 | 1.60 | >50 | 149 | 41 | 1.31 | -- | 122 | 25 | 1.20 | -- | 87 | 14 | 0.94 | -- |
| ***180.-190.*** | 277 | 142 | 2.11 | >75 | 227 | 63 | 1.79 | >50 | 164 | 32 | 1.45 | >50 | 127 | 22 | 1.24 | -- | 97 | 18 | 1.05 | -- |
| ***190.-200.*** | 257 | 119 | 1.96 | >50 | 209 | 58 | 1.65 | >50 | 138 | 32 | 1.22 | -- | 99 | 19 | 0.97 | -- | 98 | 16 | 1.06 | -- |
| ***200.-210.*** | 249 | 131 | 1.90 | >50 | 174 | 51 | 1.37 | -- | 122 | 35 | 1.08 | -- | 97 | 19 | 0.95 | -- | 70 | 15 | 0.76 | -- |
| ***210.-220.*** | 277 | 129 | 2.11 | >75 | 191 | 59 | 1.50 | >50 | 142 | 42 | 1.25 | -- | 95 | 25 | 0.93 | -- | 83 | 20 | 0.90 | -- |
| ***220.-230.*** | 281 | 118 | 2.14 | >75 | 185 | 51 | 1.46 | >50 | 130 | 26 | 1.15 | -- | 107 | 19 | 1.05 | -- | 92 | 19 | 0.99 | -- |
| ***230.-240.*** | 311 | 130 | 2.37 | >75 | 181 | 51 | 1.43 | >50 | 135 | 26 | 1.19 | -- | 111 | 24 | 1.09 | -- | 84 | 15 | 0.91 | -- |
| ***240.-250.*** | 351 | 117 | 2.67 | >75 | 222 | 57 | 1.75 | >50 | 179 | 34 | 1.58 | >50 | 162 | 26 | 1.59 | >50 | 149 | 20 | 1.61 | >50 |
| ***250.-260.*** | 442 | 142 | 3.37 | **=OK** | 349 | 72 | 2.75 | >75 | 275 | 44 | 2.43 | >75 | 218 | 28 | 2.14 | >75 | 131 | 25 | 1.41 | >50 |
| ***260.-270.*** | 570 | 175 | 4.34 | **=OK** | 465 | 83 | 3.66 | **=OK** | 351 | 52 | 3.10 | **=OK** | 249 | 31 | 2.44 | >75 | 195 | 18 | 2.11 | >75 |
| ***270.-280.*** | 439 | 143 | 3.34 | **=OK** | 336 | 71 | 2.65 | >75 | 293 | 53 | 2.59 | >75 | 227 | 30 | 2.22 | >75 | 176 | 20 | 1.90 | >50 |
| ***280.-290.*** | 388 | 132 | 2.96 | **=OK** | 298 | 71 | 2.35 | >75 | 209 | 27 | 1.84 | >50 | 148 | 19 | 1.45 | >50 | 133 | 14 | 1.44 | >50 |
| ***290.-300.*** | 267 | 128 | 2.03 | >50 | 225 | 55 | 1.77 | >50 | 147 | 27 | 1.30 | -- | 132 | 21 | 1.29 | -- | 148 | 19 | 1.60 | >50 |
| ***300.-310.*** | 217 | 109 | 1.65 | >50 | 176 | 50 | 1.39 | -- | 143 | 30 | 1.26 | -- | 128 | 22 | 1.25 | -- | 126 | 20 | 1.36 | -- |
| ***310.-320.*** | 186 | 81 | 1.42 | >50 | 145 | 45 | 1.14 | -- | 175 | 43 | 1.54 | >50 | 137 | 24 | 1.34 | -- | 114 | 17 | 1.23 | -- |
| ***320.-330.*** | 174 | 80 | 1.33 | -- | 152 | 38 | 1.20 | -- | 143 | 31 | 1.26 | -- | 127 | 23 | 1.24 | -- | 93 | 17 | 1.00 | -- |
| ***330.-340.*** | 135 | 63 | 1.03 | -- | 147 | 45 | 1.16 | -- | 144 | 29 | 1.27 | -- | 109 | 19 | 1.07 | -- | 85 | 16 | 0.92 | -- |
| ***340.-350.*** | 164 | 68 | 1.25 | -- | 140 | 45 | 1.10 | -- | 120 | 31 | 1.06 | -- | 119 | 23 | 1.17 | -- | 96 | 23 | 1.04 | -- |
| ***350.-360.*** | 174 | 77 | 1.33 | -- | 179 | 57 | 1.41 | >50 | 123 | 27 | 1.09 | -- | 82 | 15 | 0.80 | -- | 74 | 12 | 0.80 | -- |

**Table 2.** Contribution of the absolute maximum cells in the construction of the typical transport time fields (Case: Leningrad NPP).

### 4.6. *ADDITIONAL INDICATORS OF NRS IMPACT*

The first day after an accidental release that occurred at NRS is the most concern in the decision making process. In general, it is related to danger of the short-lived radionuclides' influence, and, in particular, iodine isotopes. Therefore, we suggest use several additional indicators for NRSs to characterise the NRS's possible impact for the surrounding and remote populated geographical territories.

The first indicator is the „Maximum Reaching Distance“ (MRD) during the first day of transport (Figure 11). This indicator shows the farthest boundaries on the geographical map, which might be reached during the first day, at least, by one trajectory originated over the NRS location. To visualise MRD indicator we used all endpoints of calculated trajectories during the first day of transport. An isoline of MRD had been drawn through the grid boxes where at least one trajectory intersected with the grid's boundaries. We should note also, that although the likelihood that an air parcel will reach these boundaries is the lowest, it is still a possible case of transport.



(a) (b)

**Figure 11.** Indicators of the Maximum Reaching Distance and Maximum Possible Impact Zone for: a) the Leningrad NPP, b) the Novaya Zemlya Test Site.

The second indicator is the „Maximum Possible Impact Zone“ (MPIZ) during the first day of transport (Figure 11). This indicator, as an integral characteristic, shows areas as well as boundaries with the highest probability of reaching by trajectories during the first day of transport. To visualise MPIZ indicator we accounted also all endpoints of calculated trajectories during the first day of transport. Then, similar approach for construction of the probability fields (as for the fast transport and airflow fields) was used to construct the MPIZ field. An isoline of MPIZ had been drawn through the areas with the highest occurrence of trajectory intersections.

The shape of both indicators depends on the prevailing flow patterns, and for example, as in the case of the Leningrad NPP - westerly flow. Additionally, we estimated also areas (in km$^2$) which are covered by these isolines. It is important to note, that the area of the MPIZ is also a part of MRD. To evaluate temporal variability we study seasonal and monthly variation for the boundaries and areas of the MPIZ and MRD indicators. Detailed analysis of indicators for all NRSs will be shown in the next report of the "Arctic Risk" Project.

Further, in the GIS approach, we will use calculated airflow patterns, wet deposition, as well as indicators of the fast transport, maximum reaching distance, and maximum possible impact zones for integration method for risk and vulnerability mapping by counties (*Rigina & Baklanov, 2001*)

### 4.7. *REMOVAL OR PRECIPITATION FACTOR*

During the transport of any kind of pollutants, including radionuclides, within the atmosphere many different processes may influence the distribution of substances. In general, the temporal change of the radionuclide concentration during atmospheric transport will depend on the following factors: 1) dispersion due to horizontal advection by a wind velocity vector and turbulent diffusion processes; 2) dry deposition of gaseous and particulate nuclides from the atmosphere by vegetation, biological, or mechanical processes; and 3) wet removal by precipitation, rainout, and snow. Other factors are 4) radioactive decay and 5) resuspension (i.e. lifting of already deposited material again back into the atmosphere), which is a secondary source of contamination and mostly appropriate on a local scale. Although contribution of all factors are important, there is always a possibility to ignore some of them depending on the scale of analysis and each term's contribution to a particular problem.

Wet deposition is the term of most concern. It is highly temporally and spatially dependent. It plays important role in the estimation of the radionuclide surface deposition. Deposition of radionuclides at the surface due to washout might produce a cellular figure as was recorded after the Chernobyl accident. Among several tens of radionuclides there are only a few of main interest, - in particular, iodine and caesium are isotopes of the major concern after the nuclear accidents, and especially during the first days.

To analyse the possible contribution of the removal processes during atmospheric transport from the NRSs locations we might apply at least three different approaches.

The **first approach** is based on the evaluation of the precipitation climatology for the particular geographical area. Such climatological maps (on a multiyear and seasonal basis for the large scale domains) might be obtained from the meteorological weather services. These maps would reflect the accumulated precipitation measured near the surface for each interval of time. It may be used for identification of the large size areas having common precipitation patterns. In particular, on such maps these areas are connected with the major centres of synoptic activity, for example, Aleutian Low. However, air parcels might travel within different atmospheric layers during their transport from the NRS region. For example, if an air parcel travels in the free troposphere and there is no precipitation in this layer, but the area is marked as precipitable at the climatological map that will raise a misleading concern.

Therefore, the **second approach** is based on the evaluation of the probabilistic fields for the "precipitation factor" (*Mahura et al., 1999b; INTAS, 2000; Mahura et al., 2001*). Relative humidity "plays a role" of the precipitation factor. As we mentioned, at each time interval of 12 hours for each forward trajectory we can calculate additional parameters including relative humidity. It is one of the factors, which will determine the possibility of radionuclide removal during transport. Increasing relative humidity in the atmosphere is one of the signals of the water vapour's increasing presence, and it may, in the presence of the cloud condensation nuclear (CCN), lead to formation of cloud cover. After clouds develop and form, under certain conditions there is a possibility of precipitation, and hence, radionuclide removal. Construction of the relative humidity fields is similar to the first steps in the probability field analysis. In this case we calculate an average value of the relative humidity in each grid cell. Both the precipitation and relative humidity fields have a cellular figure in comparison with the airflow pattern. A pitfall in this analysis is the fact that all relative humidity values are directly related to the existing flow pattern. So, each field is valid only with respect to a particular NRS. Nevertheless, it is a more realistic pattern of the possible removal during transport than calculating rainfall climatological maps used in the first approach, because it includes processes above the surface.

In *Mahura et al. (2001)* and *INTAS (2000)* to account for the contribution of radionuclide wet removal during atmospheric transport following the second approach the temporal and spatial distribution of the relative humidity were calculated by constructing the relative humidity (called "precipitation factor") probability fields over the studied geographical areas. Several atmospheric layers - surface - 1.5 (Figure 12), 1.5-3, 3-5, and above 5 km asl - were examined to determine altitudinal differences in the possibility of removal processes. It was assumed that areas with relative humidity above 65% were areas, where water vapour could be condensed and later removed in the form of precipitation. For example, for the Kola NPP the analysis showed that the precipitation factor's contribution dominates in the low troposphere layers, and areas associated with the Icelandic Low activity as well as along the main tracks of the cyclone systems.

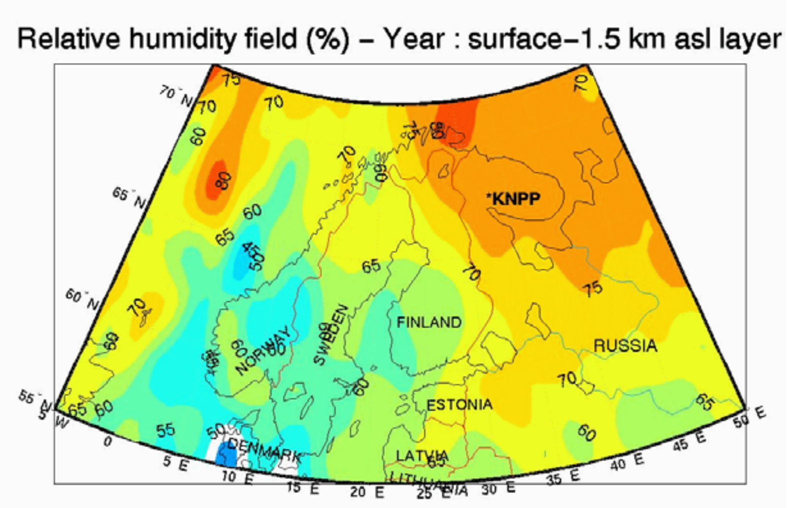


**Figure 12.** Precipitation factor probability field in the boundary layer for the Kola NPP.

The limitation always is how we might resolve precipitation processes during air parcels transport. To resolve them we would need a finer meteorological data resolution.

The **third approach** is based on the direct evaluation of the wet deposition factor fields at the surface (*AR-NARP, 2001*). It is also required to have multiyear output fields for comparison. For these purposes, we might run a transport model for a multiyear period and include one of the parameters of interest. Both the National Center for Environmental Prediction (NCEP, USA, North America) and European Centre Medium Weather Forecast (ECMWF, Reading, Great Britain, Europe) analyses, have resolution of more than 1 degree. Although HIRLAM model (at Danish Meteorological Institute, DMI) data might provide 3-D meteorological fields with a resolution of 0.15º x 0.15º latitude vs. longitude grids, there is still an issue of the computational resources usage.

### 4.8. *DISPERSION AND DEPOSITION MODELING*

If we assume either a unit puff release or continuous release every 12 hours at NRS, and run a model of atmospheric transport, dispersion, and removal of the radioactive material, we might produce a field for the wet deposition accumulated during a multiyear period. From one side, we might estimate what would be accumulated deposition field if a continuous release took place. From another side, we might identify the geographical areas, presumably of the cellular nature. These areas are territories where greatest removal of radionuclides is possible during transport from the site. It should be noted that such fields are also (as in the second approach) valid with respect to the particular NRS of interest.

Additionally, useful information might be obtained if we have the averaged climatological airflow patterns for the regional or local scale. We can evaluate seasonal and monthly average wet deposition factor fields applying averages for wind characteristics, precipitation, temperature, relative humidity, etc. For this case, the averaged 3-D meteorological fields are simulated, and then they are used in the transport model to calculate such characteristics as the air concentration, surface deposition, and doses. Specific cases for both unit and hypothetical, such as maximum projected accident (MPA), releases might be considered. Additional cases of the unfavourable meteorological conditions might be evaluated too (*INTAS, 2000; OCB, 2000*). Produced characteristic monthly or seasonal fields of the air concentration, deposition, and various doses could be used in the decision-making process at the first stages of the NRS accidents.

As we discussed above (see Chapter 3) dispersion and deposition models can be successfully used as for separate case studies for typical or worst case scenarios, and as for probabilistic risk mapping (as a more expensive alternative of the trajectory analysis method). Applicability and examples of different models for dispersion and deposition simulation for the local and regional scales were discussed in our previous study publications (*Baklanov et al., 1994; Thaning and Baklanov, 1997; Baklanov, 1999; Baklanov et al., 2001*).

At DMI we have already developed a useful methodology within the ‘Arctic Risk’ NARP project and we have tested some methodological aspects for a hypothetical accidental radioactive release from the nuclear submarine Kursk during its lifting and transportation operations to the harbour on the Kola Peninsula. The Kursk Nuclear Submarine Pilot Study results were presented in *Mahura et al. (2001)* and available on a CD-room presentation and data base (*AR-NARP, 2001*) on a request to DMI.

The methodology of dispersion modelling for the probabilistic analysis with applications to different nuclear risk sites in the European North will be a topic of the next report of the ‘Arctic Risk’ Project.

### 4.9. *CHOICE OF EPISODES FOR CASE STUDIES*

As we discussed in the methodological part (Chapter 3.1) for the complex risk assessments a combination of the both methods: a) the probabilistic risk assessment and b) the case study (Figure 2) - gives the most suitable approach. Therefore, it is important to choose correctly the most representative episodes for typical and worst case scenarios from the results of the probabilistic analysis of atmospheric transport. E.g., as the first assumption, the cluster analysis of trajectories can be very useful for such selection of typical episodes or specific case studies..

We should note, that this report doesn’t focus on simulations for the case studies; however, our previous studies (*Baklanov, 1999; Baklanov et al., 2001a; Baklanov et al., 2001b*) included some methods and results of modelling of atmospheric transport and deposition from potential accidents at the nuclear risk sites at the Kola Peninsula for meso- and regional scales for different worst-case scenarios/episodes for a certain, in common, unfavourable meteorological situations. For selection of the case scenarios/weather situations we used different criteria from the earlier analysed atmospheric transport patterns from the selected nuclear sites in the studied areas for a multiyear period. For example, in the ÖCB Project (*Mahura et al., 1999; Baklanov, 1999*) it was done from the Kola nuclear reactors for the Northern Europe using 1991-1995 data.

In general, the following criteria are used for selection of the case scenarios:

1. Direction of transport of an accidental release to the study region: the Barents Euro-Arctic region, the Nordic countries, the Baltic Sea region, central European part of the Russian Federation or some other;

2. Possibility of the precipitation over the study region during transport of a release;
3. Stable-stratified atmospheric boundary layer (ABL) and the ABL height (transport into ABL or in the free troposphere);
4. Short travel time of a release from the NRS location to the study region;
5. Large coverage of the Scandinavian and European territories by the radioactive plume;
6. Winter and summer / cold and warm seasons.

Using meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK with 0.75° and 6 hours resolution for the selected real weather situations, the analysis was based on simulating the transport in air of assumed radioactive releases and estimating the deposition pattern on local-, meso- and regional scales. By allowing unit releases to occur simultaneously from a site at a fjord and at the nuclear power plant (and with the same release profile in time) comparisons are made of differences in depositions patterns in and outside the Kola Peninsula region. In these case studies, a set of assumed release heights, duration of release, and particle size distributions were applied to indicate the dependence for the resulting deposition pattern on these parameters. These sets of values of the parameters are illustrated in *Bergman et al. (1998), Baklanov (1999), Baklanov et al. (2001).*

# CONCLUSIONS AND RECOMMENDATIONS

Methodology for assessment of complex nuclear risk and vulnerability from different nuclear risk sites for population in different regions and countries in case of a severe accident at the nuclear risk sites (NRSs) is suggested and discussed in this report. In this study, for assessment of risk/vulnerability, we considered the social-geophysical factors and indicators of possible NRSs impact on geographical areas and neighbouring countries, which depend on the location of the area of interest and its population.

The main purpose of this study was to develop a methodology for evaluation of the atmospheric transport of radioactive pollutants from NRSs, and in particular, from the nuclear power plants (NPPs) to different geographical regions. The evaluation is given from the probabilistic point of view. The main question we are trying to answer is: What is the probability for radionuclide atmospheric transport to different neighbouring countries in the case of an accident at NPPs?

To answer this question we applied for probabilistic atmospheric studies two research tools: (i) isentropic trajectory model to calculate 5-days forward trajectories originated at NRSs for a multiyear period, and (ii) statistical analysis techniques (exploratory, cluster, and probability field analyses) to explore the structure of calculated trajectory data sets seasonally and monthly in order to evaluate atmospheric transport pathways and patterns, fast transport, typical transport time, and other indicators of possible NRS impact .

The following useful indicators of possible NRS impact are suggested:

- Atmospheric Transport Pathways,
- Airflow Probability Fields,
- Removal or Precipitation Factor,
- Fast Transport Probability Fields,
- Typical Transport Time Fields,
- Maximum Reaching Distance,
- Maximum Possible Impact Zone.

We assume, that results of this study are applicable for the further GIS analysis to estimate risk and vulnerability as well as for the emergency response and preparedness measures in the cases of the accidental releases at NPPs. The applicability of the method includes:

- Initial estimates of probability of the atmospheric transport in the event of an accidental release;
- Improvement of emergency response to radionuclide releases from the NRSs locations;
- Input for the social and economical consequences studies of the NRSs impact for population & environment of the neighbouring countries;
- Input for the multidisciplinary risk and vulnerability analysis, probabilistic assessment of radionuclide meso-, regional-, and long-range transport;
- Modelling and testing of the higher resolution models.

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