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**Assessment of
possible airborne
impact from nuclear
risk sites – Part II**

A. G. Mahura and
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Assessment of possible airborne impact from nuclear risk sites – Part II: probabilistic analysis of atmospheric transport patterns in Euro-Arctic region

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Abstract

The probabilistic analysis of atmospheric transport patterns from most important nuclear risk sites in the Euro-Arctic region is performed employing the methodology developed within the “Arctic Risk” Project of the NARP Programme (Baklanov and Mahura, 2003). The risk sites are the nuclear power plants in the Northwest Russia, Finland, Sweden, Lithuania, United Kingdom, and Germany as well as the Novaya Zemlya test site of Russia. The geographical regions of interest are the Northern and Central European countries and Northwest Russia.

In this study, the employed research tools are the trajectory model to calculate a multiyear dataset of forward trajectories that originated over the risk site locations, and a set of statistical methods (including exploratory, cluster, and probability fields analyses) for analysis of trajectory modelling results. The probabilistic analyses of trajectory modelling results for eleven sites are presented as a set of various indicators of the risk sites possible impact on geographical regions and countries of interest.

The nuclear risk site possible impact (on a particular geographical region, territory, country, site, etc.) due to atmospheric transport from the site after hypothetical accidental release of radioactivity can be properly estimated based on a combined interpretation of the indicators (simple characteristics, atmospheric transport pathways, airflow and fast transport probability fields, maximum reaching distance and maximum possible impact zone, typical transport time and precipitation factor fields) for different time periods (annual, seasonal, and monthly) for any selected site (both separately for each site or grouped for several sites) in the Euro-Arctic region. Such estimation could be the useful input information for the decision-making process, risk assessment, and planning of emergency response systems for sites of nuclear, chemical, and biological danger.

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1. Introduction

A number of nuclear risk sites (NRSs) having nuclear reactors, weapons, and radioactive wastes and posing concern for the population are situated in the Northern Europe territories. Among these is the Northwest Russia, where there are about 180 nuclear reactors in operation, 140 reactors are waiting to be decommissioned, more than 10 storage sites for radioactive waste containing large amounts of spent nuclear fuel (Bergman and Baklanov, 1998). “The State of the Arctic Environment” report of the Arctic Monitoring and Assessment Programme (AMAP, 1998) had emphasized: “there are considerable shortcomings in the analysis... that allow conclusions to be drawn about the probability and consequences of potential accidents in the nuclear power plants in the Arctic”. This report gave 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”.

The main aim of our study is the following. First, it is testing of the methodology for evaluation of the atmospheric transport of radioactive pollutants from the nuclear risk sites (NRSs) on different geographical regions, territories, countries, etc. Second, it is combining of the atmospheric transport modelling and statistical analyses to evaluate possible impact due to atmospheric transport from accidental releases at NRSs located in the Euro-Arctic region. The main purpose of our study is a probabilistic analysis of atmospheric transport patterns from selected sites for further GIS-based studies of vulnerability to radioactive deposition and risk assessment of the NRS impact on the environment and population.

The risk sites of concern (in total 11) located in the European countries and Russia (Fig. 1) are the nuclear power plants (NPPs) and former nuclear weapons test site. The geographical regions and countries of interest are the Northern and Central European

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countries and Northwest Russia. In this study several research tools developed within the “Arctic Risk” Project (AR-NARP, 2001–2003; Baklanov and Mahura, 2001; Mahura, 2001; Mahura and Baklanov, 2002; Baklanov et al., 2002b) were applied. Baklanov and Mahura (2003) noted that for assessment of risk and vulnerability it is important to consider a set of various social-geophysical factors and probability indicators. These depend on the geographical location of the area of interest and structure of its population. Thus, for estimation of the potential nuclear risk and vulnerability levels for the nuclear risk sites it will be important to know:

- Which geographical regions are the most likely to be impacted?
- What are the fast, average, typical times and their probabilities for atmospheric transport from NRSs to neighbouring countries?
- What are precipitation probability and contribution during atmospheric transport for various atmospheric layers and over different geographical territories?
- What are temporal (annual, seasonal, and monthly) and spatial variability for the above mentioned characteristics?

2. Selected approaches

The suggested methodology by Baklanov and Mahura (2003) mentioned several research tools and approaches, which could be applied for the probabilistic atmospheric studies. The main focus of this paper will be only on a consideration of the trajectory modelling approach and statistical analyses of trajectory modelling results in order to evaluate the possible impact due to atmospheric transport from the selected NRSs on the geographical territories within the Euro-Arctic region. The further papers will describe analysis of the NRS impact indicators based on dispersion modelling approach as well as the GIS-based risk and vulnerability analysis for the risk sites in the Euro-Arctic region.

2.1. Nuclear risk sites of concern

The selected sites of concern include the nuclear power plants in Russia, Lithuania, Germany, United Kingdom, Finland, and Sweden (Table 1, Fig. 1). All these sites are located within the area of the study's interest. Moreover, the Kola NPP (Murmansk Region, Russia) has the old type of reactors (VVER-230); Leningrad (Leningrad Region, Russia) and Ignalina (Lithuania) NPPs have the RBMK type of reactor (having the most concern of experts); and the Novaya Zemlya Archipelago of Russia was considered as a former nuclear weapons test site and potential site for nuclear waste deposit. The Block of the British NPPs (BBP) is represented by a group of the risk sites: Chapelcross (Annan, Dumfriesshire), Calder Hall (Seascale, Cumbria), Heysham (Heysham, Lancashire), and Hunterston (Ayrshire, Strathclyde) NPPs and the Sellafield reprocessing plant. The Block of the German NPPs (BGP) is represented by a group of NPPs: Stade (Stade, Niedersachsen), Kruemmel (Geesthacht, Schleswig-Holstein), Brunsbuettel (Brunsbuettel, Schleswig-Holstein), Brokdorf (Brokdorf, Schleswig-Holstein), and Unterweser (Rodenkirchen, Niedersachsen). Although these NPPs use different reactor types and, hence, they could have different risks of accidental releases, the grouping is useful for airborne transport studies because all NPPs are located geographically close to each other and, hence, atmospheric transport patterns will be relatively similar. It is important to note that the probability of accidents at NRSs is not considered in our study, and the focus is only on the geophysical airborne transport aspects.

2.2. Research tools

The first research tool is the trajectory modelling. In our study, an isentropic trajectory model based on a technique described by Merrill et al. (1985) was applied. A multiyear dataset (1991–1996) of 5-day forward trajectories originated over the NRS locations (shown in Table 1, Fig. 1) at various altitudes above sea level (asl) was calculated. For the trajectory calculation, the National Center for Environmental Prediction (NCEP) Global Tropospheric Analyses was used. For each site, trajectories were calculated

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twice per day at 00:00 and 12:00 UTC at 16 isentropic surfaces (i.e. more than 280 thousand trajectories). Then, from calculated trajectories only about of 17.5 thousand of whose originated near the surface were selected for further statistical analysis.

The second research tool is the cluster analysis. This approach should be considered as the simple approach. The cluster analysis was applied in several studies related to NRSs located in the Chukotka Region (Mahura et al., 1999), Kola Peninsula (Baklanov et al., 2002a), and Russian Far East (Mahura et al., 2002). The potential risk sources considered there were the nuclear power plants, spent nuclear fuel storage facilities, and nuclear submarine bases. In general, this technique allows identifying atmospheric transport pathways from the sites.

The third research tool is the probability fields analysis. The attempt to use this analysis to interpret atmospheric transport patterns from the nuclear risk sites was performed by Mahura et al. (2001) and Baklanov et al. (2002a), on example of the Kola NPP (Murmansk region, Russia). The major focus was the annual airflow probability fields which allowed testing the quality of the cluster analysis of trajectories used for identification of atmospheric transport pathways from the sites. Such probability fields analysis provides additional information and detailed structure of the airflow patterns from the site on a geographical map. In our study, the annual, seasonal, and monthly probability fields for the airflow, fast transport, and other indicators were constructed and evaluated for the selected NRSs.

2.3. Indicators of risk site possible impact due to atmospheric transport

The results of probabilistic analysis for the nuclear risk sites are presented in a form of various indicators (Fig. 2) of the NRS possible impact on geographical regions, territories, and countries of concern. These indicators are based on evaluation of the trajectory modelling results. Among these indicators, the following should be mentioned: 1) simple characteristics of the NRS possible impact, 2) atmospheric transport pathways (ATP), 3) airflow (AF) probability fields, 4) fast transport (FT) probability fields, 5) maximum possible impact zone (MPIZ), 6) maximum reaching distance (MRD), 7)

precipitation factor (PF), and 8) typical transport time (TTT) fields.

3. Results and discussion

In this section of the paper the combined analyses and interpretation of various indicators of the NRS possible impact will be given on examples of eleven NRSs located in the Euro-Arctic region. More details (including annual, seasonal, and monthly variability of indicators) can be found in Mahura and Baklanov (2002).

3.1. Simple characteristics of the nuclear risk site impact and atmospheric transport pathways

In this study, all calculated forward trajectories that originated over the NRS locations were analyzed in order to investigate the likelihood that the risk sites might have impact on the neighbouring countries or distant geographical regions. As a first approximation, trajectories can be separated into groups by altitudes of initial trajectory points. The boundaries of geographical regions can be selected depending on political borders, climatic regimes, areas of research interest, etc. For simplicity, it can be assumed that any trajectory, which crosses the boundaries of the chosen geographical region, might bring air parcels containing radionuclides. Therefore, only trajectories crossing boundaries of these regions should be selected in further evaluation of the NRS impact.

Among the simple characteristics the following could be suggested. First, it is the number and percentage of trajectories reaching the boundaries of the chosen geographical regions (upper boundary of the NRS impact). Second, it is the number and percentage of days when, at least, one trajectory had reached the region (lower boundary of the NRS impact). Third, it is the average transport time of air parcels to reach the chosen regions. Fourth, it is the probability of atmospheric transport within different atmospheric layers (boundary layer and free troposphere). Fifth, it is the likelihood of very rapid (or fast) atmospheric transport of air parcels, i.e. transport in one day or

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less. All these characteristics can be evaluated over a multiyear dataset of calculated trajectories, by individual year, season, and month. Such analyses allow investigating possible spatial and temporal variation in the airflow patterns from the NRS region to the chosen geographical regions of concern. Another approach in the simple analysis is to apply, as a research tool, a cluster analysis technique for trajectories originated at each site. As a result, the mean trajectories for each cluster will be produced. These mean trajectories are atmospheric transport pathways from the sites, and they can be explained based on existing synoptic features and peculiarities in the studied regions. These pathways show the general direction and probability of atmospheric transport from the site region.

Although results of the cluster analysis are useful, they are not completely representative, because information between clusters represented by mean trajectories (or transport pathways), reflecting only the general direction of airflow from the site, is “missing”. Therefore, another research tool – probability fields analysis – is required to extract this additional information.

It should be noted that evaluation of simple characteristics and atmospheric transport pathways for several NRSs in the Russian Far East and Northwest Russia are discussed by Mahura et al. (1999); Mahura (2001); Baklanov et al. (2002a); Mahura (2002).

3.2. Airflow and fast transport probability fields

3.2.1. Airflow probability fields

The first type of probabilistic fields – airflow probability fields (constructed based on 5-day isentropic trajectories) – shows the common features in the atmospheric transport patterns from NRSs. First, it could provide a general insight on the possible main direction of atmospheric transport for radioactive plume. Second, it shows a probability that radioactive plume will reach or pass over a given area on a geographical map. In comparison with the atmospheric transport pathways, the AF probability fields

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show more detailed information about distribution of direction and probabilities of atmospheric transport from the sites toward a particular geographical territory, region, country, etc. in the studied area. These fields characterize not only the highly possible direction of the contaminated cloud atmospheric transport from the risk sites, but also

5 define boundaries of territories on a geographical map where the order of magnitude of the NRS possible impact could be evaluated. In this case, it is possible to depict the region (i.e. Area of the Highest Probability of the Possible Impact – AHPPI; see Baklanov and Mahura, 2003) on a map where the risk site impact might be the highest, and for other regions to re-calculate the NRS possible impact as a part of NRS AHPPI.

10 Moreover, the airflow probability field is a reliable test to reject or support results of the cluster analysis (which can be applied to identify the general atmospheric transport pathways from NRSs), because the calculated clusters (or mean trajectories) will be located in the troughs and crests of probabilistic fields.

The regions, where the highest crossing by trajectories is occurred, have the highest

15 probability of the NRS possible impact. In this study, all airflow probability fields were constructed by averaging airflow patterns over a selected time period: year, season, and month (based on a multiyear dataset). The seasonal division was considered as standard (i.e. each season included three months; for example, spring includes March, April, and May). Although it should be noted that for a particular application the

20 different scale might be considered: by the vegetation period, by snow cover presence, by prevailing wind direction, etc.

3.2.2. Temporal variability of the airflow probability fields

On an annual scale, the westerly transport dominates for all NRSs considered in this study (Fig. 3). Some additional transport patterns are seen. For the block of the British

25 NPP (BBP) Oskarshamn NPP (ONP) and Olkiluoto NPP (TRS), the airflow pattern is shifted toward the northeast of the sites. For the Ignalina NPP (INP), the AF probability field is shifted toward the southeast of the site. For NRSs located closer to the North Atlantic region (i.e. blocks of the British (BBP) and German (BGP) NPPs, and

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Barsebaeck NPP (BBP)), the boundaries of probabilistic fields are extended farther (approximately on 1/3 in comparison with other NRSs) in the western direction from the sites. Therefore, the probability to reach more remote (in the western direction) territories from the sites is increased.

5 As any meteorological variable, the calculated AF probability fields based on the wind characteristics have a temporal variability. Let us consider, as examples, the variability of the airflow patterns for the Kola NPP by seasons (Fig. 4) and Leningrad NPP by months (Fig. 5).

10 For the Kola NPP (Fig. 4), during all seasons, the predominant transport is in the eastern direction from the site. Although, during spring, there is increase of transport in the south-western direction (it is reflected by shifting of the AHHPPI boundaries to the central territories of Finland). During summer, these boundaries are extended to the south of the site (reaching 65° N), but in other seasons they are located northerly of this latitude. During winter, the probability to reach Sweden is minimal; but the north-western and central regions of Russia are at the higher risk of being impacted during atmospheric transport from the site. Moreover, it should be noted, that isolines of the airflow probability fields could be represented as the varying boundaries showing an order of the NRS possible impact on a particular geographical territory. For example, for the Yamal Peninsula (Russia), likelihood of the KNP possible impact is the lowest during summer compared with other seasons, whereas for the Baltic States this likelihood is the lowest during spring.

20 For the Leningrad NPP (LNP), more detailed consideration of temporal variability by months (Fig. 5) showed some peculiarities in the airflow patterns, which are not seen on both annual and seasonal scales. In July, atmospheric transport in the southern direction dominates for trajectories originated within the boundary layer over the LNP region. The LNP AHHPPI boundaries reach territories southerly of 55° N. During February–March, the boundaries are extended significantly to the west of the site. During October–November, the probability for air parcels to pass over the Barents Sea is decreased. In September, there is a probability to reach the western seashore of the

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Southern Norway, although during other months, only a small part of the northern territories of this country could be affected due to atmospheric transport from the LNP region. Throughout the year, the boundaries of LNP AHPPI are located within the Russian territories, except in March, September, and November when these are extended also to the northern territories of Estonia.

3.2.3. Fast transport probability fields

The second type of probabilistic fields – fast transport probability fields (constructed based on 0.5 and 1-day isentropic trajectories) – indicates the probability of the air parcels movement during the first day of transport. It is important information, especially, for the impact estimating of the short-lived radionuclides such as $^{133,131}\text{I}$, ^{132}Te and Noble gases such as ^{85}Kr , $^{131,133,135}\text{Xe}$. These fast transport fields show those territories that can be reached during the first day of atmospheric transport from the site, and those areas that are at the most danger due to atmospheric transport. In this study, the fast transport probability fields were calculated after 12 and 24 h of atmospheric transport from the risk sites. Similarly to the AF probability fields, the FT probability fields could be used for evaluation of the risk site impact during the first day after accidental release at site.

Let us consider several examples of result interpretation. First, it is an individual interpretation of the fast transport probability fields for one or more NRSs with respect to geographical regions, territories, and countries of concern. Second, it is a combined interpretation of the airflow and fast transport probability fields for two or more NRSs with respect to each other and geographical regions, territories, or countries of concern.

3.2.4. Individual interpretation of the fast transport probability fields for one or more sites

Let us consider some NRSs for such an analysis. For the Kola NPP (KNP), the annual FT probability field after the first 12 h of atmospheric transport (Fig. 6a) showed that the

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entire Kola Peninsula is located within the boundaries of KNP AHPPI. During the first 12 h, the atmospheric transport from KNP is dominated by westerlies, although after 24 h the transport to southwest can be also identified (Fig. 6b). Two maxima of AHPPI could be seen. The first maximum is located in the eastern part of the Kola Peninsula, the second – in the central regions of Karelia and Finland. Both maxima show that after a day of transport, there is the highest possibility that the contaminated cloud could arrive to the mentioned territories, and hence, the NRS possible impact might be higher compared with other territories. On a seasonal scale, for the Kola NPP, during fall the FT probability field after 24 h showed a shift of AHPPI in the eastern direction from the site toward less populated territories of the Northwest Russia. During summer, the total area of the FT probability fields is smaller (due to significant decrease of wind speeds) compared with other seasons. This tendency is observed for all NRSs. In the same time, more southern regions with respect to the KNP location are included in the boundaries of AHPPI. There are also several maxima of AHPPI throughout the year, except summer.

On an annual scale, for the Novaya Zemlya test site (NZS) there is a pattern showing transport in the western direction from the site after the first 12 h of atmospheric transport (Fig. 6c), and a pattern showing transport in the southern direction from the site after the first 24 h of atmospheric transport. It should be noted that for the FT probability field after 12 h, the AHPPI, although it is located near the site, is separated into two maxima located over the Arctic seas: one to the east and one to the west of the site. After the first day, the NZS possible impact could be the highest on the territories of the Russian Arctic seashore (Fig. 6d), and there are also two maxima of NZS AHPPI located to the south of the site.

Let us compare the NRS possible impact from two or more NRSs on a particular country and region of concern – e.g. 1) Denmark and 2) Kaliningrad Region (Russia). For this purpose, for simplicity, the annual (although seasonal or monthly variability could be used) fast transport probability fields after 12 and 24 h of atmospheric transport were evaluate for 1) the blocks of the British (BBP) and German (BGP) NPPs (as

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example 1; see Fig. 7); 2) the Ignalina (INP) and Barsebaeck (BNP) NPPs (as example 2; see Fig. 8). Such an analysis could allow determining: which of NRSs will represent the highest danger due to atmospheric transport, from the probabilistic point of view, to a considered geographical region, territory, country, etc.

5 In the first example, for both blocks of NPPs – German and British, during the first 12 h, the tendency dominating of westerly flows is observed (Figs. 7a, c). The area of BGP AHPPI is larger compared with the area of BBP AHPPI. The boundaries of the BGP AHPPI's middle and high values (>50%) reach the central and southern territories of Denmark. For BBP, the maximal values of AHPPI are located in vicinity of the
10 British Islands, and probability to reach the Danish territories is minimal. The FT probability fields after 24 h (Figs. 7b, d) showed that although the dominating atmospheric transport for both sites is still toward the east, for BBP the transport in the southern and northern directions is observed. The BBP AHPPI area is significantly increased, and its boundaries are extended farther in the meridional direction compared with latitudinal
15 direction. Hence, the probability to reach the western territories of Denmark has risen.

In the second example, for two NRSs – Ignalina and Barsebaeck NPPs – the westerly flows dominate during the first 12 h of atmospheric transport (Figs. 8a, c). For INP, the end of the first day shows a tendency of the airflow shifting in the south-eastern direction from the site. For BNP, the western territories of the Kaliningrad Region will be located within the AHPPI boundaries of this site. Moreover, the entire Kaliningrad
20 Region, Lithuania, and Latvia lie inside the BNP AHPPI after 24 h of atmospheric transport (Figs. 8b, d). Although, for INP, the medium values of INP AHPPI are observed only on the eastern territories of the Kaliningrad Region.

3.2.5. Combined interpretation of airflow and fast transport probability fields for several sites
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In this section, the combined analysis of the AF and both FT (12 and 24 h) probability fields for several NRSs is considered. The seasonal variability of the airflow and fast transport patterns is compared (Fig. 9) for the blocks of the British (BBP) and German

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(BGP) NPPs, Loviisa (LRS) and Barsebaeck (BNP) NPPs with respect to the Nordic countries: Denmark, Finland, Norway, Sweden, Iceland, and Faeroe Islands. It is a convenient step for such analysis to plot a selected field on one figure for several NRSs simultaneously, and to choose several critical isolines (for example, 10, 25, 50, 75, >90% of NRS AHPPI) for better and easier interpretation of results.

The seasonal variability of the airflow patterns for two NRSs – BBP and BGP – is shown in Fig. 9a, and it reflects the dominance of the westerly flows in the atmospheric transport from these sites. The AHPPI boundaries (>90) for both sites intersect each other over the North Sea throughout the year, except summer. The total area of the BBP airflow pattern is larger compared with BGP, and moreover, in spring it almost covers the BGP airflow pattern area. During spring and fall, the BGP AF probability field is more extended in the western direction from the site toward the North Atlantic Ocean. Throughout the year, except winter, the Faeroe Islands will be located within 25–50% of BBP AHPPI. Considering a minimal isoline of 25% of AHPPI, it should be noted that the central parts of the Scandinavian Peninsula are less reachable throughout the year, except spring, and hence, the NRS possible impact is lower compared with Denmark. For the Faeroe Islands, the BBP possible impact will vary between 25–55% of AHPPI, although for Iceland it is lower than 25% of AHPPI.

The seasonal variability of the fast transport patterns (for 24 h of atmospheric transport) for two NRSs BBP and LRS is shown in Fig. 9b. For BBP, during spring and fall the AHPPI boundaries extended significantly to the south of the site, and moreover, in spring three maxima of BBP AHPPI could be identified over the United Kingdom, Denmark, and Ireland. During winter and spring, the boundaries of this FT probability field (enclosed by 25% of AHPPI isoline), are extended farther to north and south compared with other seasons. Among the Scandinavian countries only Denmark and the southern territories of Norway and Sweden might be affected by the end of the first day if an accidental release of radioactivity occurred at the site.

For LRS, in summer, the AHPPI boundaries are more extended to the southeast of the site, in winter – to the northeast of the site. Throughout the year, the total area

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of the LRS FT probability field is smaller compared with BBP, which could be also affected by the difference in the continental vs. maritime climatic regimes of the sites, respectively. The probability of reaching the eastern seashore of Sweden is low, and the NRS possible impact there will be only 25% of AHPPI. The southern territories of Finland are always inside the LRS AHPPI boundaries throughout the year, except summer.

The seasonal variability of the FT patterns (for 12 h of atmospheric transport) for three NRSs – BBP, LRS, and BNP – is shown in Fig. 9c. For these sites, the dominating transport pattern is transport in the eastern direction from the sites. The AHPPI boundaries are extended to the east of the sites, although for BBP it is extended more to the north of BBP in summer and to the west of BBP in spring, as well as for BNP it is extended to the west of BNP during fall. The seasonal variability for LRS is less pronounced, and throughout the year, the LRS AHPPI boundaries are located within the same geographical regions. Only neighbouring to NRSs countries and regions will be located within the AHPPI boundaries. For LRS, it is the border regions of the North-west Russia, Finland, and Estonia. For BNP, it is the Baltic seashore of Germany and Poland, Denmark, and the south of Sweden. For BBP, it is only the United Kingdom with the western parts of the North Sea.

If consider Denmark as a country of concern than, throughout the year, after the first 12 h of atmospheric transport: 1) Loviisa NPP does not affect the Danish territory 2) Barsebaeck NPP will always represent the highest probability of atmospheric transport to Denmark, and this probability is higher during spring and fall (when the BNP AHPPI boundaries pass over the Danish borders) compared with other seasons, and 3) block of the British NPPs shows the relatively fast transport toward Denmark, and the NRS possible impact over Denmark will be 10-25% of BBP AHPPI.

Finally, the NRS possible impact (on a particular geographical region, territory, country, etc.) due to atmospheric transport based on selected probabilistic fields (airflow and fast transport) for different time periods (annual, seasonal, and monthly) for any of 11 selected NRSs in the Euro-Arctic region both separately for each site or combined

for several sites can be evaluated.

Moreover, it should be noted that both types of probability fields could be used for emergency planning and preparedness, in advance, for estimates of possible atmospheric transport (including probabilities, direction, speed, etc.) of the radionuclide plume after hypothetical accidental releases at NRSs.

3.3. Maximum possible impact zone and maximum reaching distance indicators

In this section, two additional indicators – maximum reaching distance (MRD) and maximum possible impact zone (MPIZ), which could play a role of indicators of the NRS possible impact, are introduced and analyzed. In addition to the airflow and fast transport probability fields, these are the third type of probabilistic fields. It should be noted that this type of the field, first, indicates boundaries of regions with the highest probability of being reached by trajectories during the first day of atmospheric transport from the risk sites (i.e. MPIZ indicator). Second, this type of the field shows the farthest boundaries on the geographical map that might be reached during the first day by, at least, one trajectory originating over the NRS location (i.e. MRD indicator).

3.3.1. Maximum possible impact zone

Maximum possible impact zone (MPIZ) indicator, similarly to the FT probability fields, is important characteristic during the first day of atmospheric transport after an accidental release at the site. The boundaries of the MPIZ indicators calculated for selected NRSs in the Euro-Arctic region are shown in Fig. 10. It should be noted, that although MPIZs are concentrated in vicinity of the sites, the configuration of the MPIZ isolines will depend on the dominating transport patterns during the first day of atmospheric transport, and isolines are extended along the direction of the main flow. For most of the considered NRSs, the dominating airflows from the sites are westerlies. Additionally, for the BBP site the MPIZ boundaries are extended to the north of the site. For the NZS, KNP, LNP, and INP sites these boundaries are extended to the south of the sites.

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For studies of the long-term consequences of routine discharges or accidental releases at NRSs it is important to evaluate not only boundaries of MPIZ, but also areas of regions enclosed by the MPIZ isolines. To estimate areas, at first, the figure inside the MPIZ boundary (or isoline) was approximated by a set of triangles, where each triangle has a top at the NRS coordinates and a side on the MPIZ isoline. Then, the areas of all triangles were calculated, and the total area under the MPIZ isoline was calculated as a sum of areas of all triangles. The estimation of seasonal maximum and minimum, and annual average areas for MPIZ is given in Table 2. It should be noted that this variability depends on the wind velocities on the synoptic- and mesoscales throughout the year. And although, during winter the wind speeds are higher compared with summer, there is a variability defined by the local peculiarities near the sites.

On a seasonal scale (Table 2), among 11 NRSs the MPIZ area reaches a minimum in summer, except for the Leningrad (LNP), Ignalina (INP), and Barsebaeck (BNP) NPPs, where a minimum is in fall; and Olkiluoto NPP (TRS), where a minimum is in spring. For the NZS site, throughout the year, the MPIZ area is maximal among 11 considered NRSs.

3.3.2. Maximum reaching distance

Maximum reaching distance (MRD) indicator, similarly to the maximum possible impact zone indicator, is important characteristic during the first day of atmospheric transport after an accidental release at the site. The boundaries of the MRD indicators for the selected NRSs in the Euro-Arctic region are shown in Fig. 11. If to consider a large dataset of trajectories, there is a situation after accidental release when the contaminated air parcels might reach the most remote geographical regions. The distance to these remote boundaries might vary between hundreds and thousands kilometers. Boundaries, depicted on Fig. 11 reflect such possibility. They could be interpreted as probable boundaries of the NRS possible impact during the first day after the hypothetical accidental release when atmospheric transport from the site was the fastest. This indicator helps for decision-makers to evaluate what time (in a worst-case scenario)

will be available before taking possible countermeasures.

For example, as shown in Fig. 11a, for the Kola NPP (KNP), the zone of such impact is extended to the northern territories of Sweden and Norway, most of the territory of Finland, and north-western territories of Russia (including the Barents, White, and Kara Seas). For the Leningrad NPP (LNP), the boundaries include a significant part of Finland, Baltic States Byelorussia, north-western and central regions of Russia. For the Novaya Zemlya test site (NZS), the atmospheric transport is extended in the latitudinal direction by 20–30° from the site, and in the meridional direction – 8–10° from the site. For the Olkiluoto NPP (TRS), as shown in Fig. 11b, the MRD boundaries are extended over the large part of the Scandinavian Peninsula, Northwest Russia, Baltic States, and, partially over Belarus and Poland.

Similarly to MPIZ, it is possible to estimate areas enclosed by the MRD isolines for each NRS (see Table 3). The MRD areas, of course, are significantly larger than the MPIZ areas, and the latter is also included in the MRD area. The dominating direction of atmospheric transport is less underlined by MRD compared with MPIZ. Because the construction of the MRD indicator boundaries includes cells of gridded domain with the lowest probabilities of transport through the cells (i.e. at least one trajectory reached a cell), it is not possible to explain such variability only by the general synoptic and mesoscale features (i.e. there is a contribution of anomalies in the general transport patterns from the sites throughout the year). Among 11 NRSs, for NZS, the annual MRD area is the highest and it is equal to $903.5 \cdot 10^4 \text{ km}^2$ with a maximum in winter and a minimum in summer. For the Oskarshamn NPP (ONP), this area is the lowest and it is equal to $595.1 \cdot 10^4 \text{ km}^2$ with a maximum in winter and a minimum in spring. For all NRSs, the maximum of MRD area is observed in winter, except for KNP and BGP (when it is observed in spring).

3.4. Typical transport time fields

In the emergency response systems for nuclear accidents, the estimation of the radionuclide transport time to a particular territory, region, country, etc. is one of im-

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portant input parameters in the decision-making process. This information could be extracted from calculated trajectories by constructing the fourth type of probabilistic fields called the typical transport time (TTT) fields. These fields show: first, how long it will take for an air parcel to reach a particular geographical region from the NRS location, and second, what territories would be at the highest risk during the first few days of the contaminated cloud transport after an accident at NRS.

Several examples of the annual typical transport time fields for evaluation of the NRS possible impact are shown in Fig. 12. For BBP, during the first day the typical situation would be atmospheric transport over the United Kingdom territories and adjacent seas without reaching the populated territories of the continental European countries (Fig. 12a). After 2 days, the air mass might reach the southern territories of Norway and Sweden, as well as countries on the seashore of the North and Baltic Seas. The atmospheric transport in the southern and south-eastern directions is minimal. For KNP, during the first day the territories of the Murmansk and Archangelsk Regions, north of Karelia, and Finland could be reached, and on the second day, the large territory of the Northwest Russia, northern and central regions of the Scandinavian Peninsula are included (Fig. 12b). Moreover, a significant shift of the TTT isoline at 2 days is seen in the eastern direction (dominating airflow pattern for the KNP site).

If to assume, that the nuclear weapons testing (considering possible vent emissions during underground testing as a possible source of radioactivity) would be resumed on the Novaya Zemlya Archipelago than the typical transport time field shows that, on average, during the first day the contaminated air parcels could reach only the Russian Arctic seashore (Fig. 12c). During two days of transport the boundaries are extended significantly in both eastern and southern directions reaching 60° N, although countries of the Northern Europe will remain unaffected.

Detailed analysis of the TTT fields for individual and several combined NRSs allows identifying geographical regions and territories of the neighbouring countries which could be reached during atmospheric transport and might be impacted by radioactive pollution during a selected period of time, if an accidental release (or releases)

occurred at NRSs. This information could be used to forecast the arrival of the contaminated cloud to a particular territory, and hence, it will allow planning countermeasures, including informing and evacuating of population. The overlapping of isolines (shown in Fig. 12) occurred because daily the airflow propagates in the direction of prevailing atmospheric transport, and hence, the TTT isolines will be shifted in the same direction.

4. Conclusions

In this study the methodology (Baklanov and Mahura, 2003) for evaluation of the atmospheric transport of radioactive pollutants from the nuclear risk sites (NRSs) to different geographical regions and countries of concern was tested. The combination of atmospheric transport modelling and statistical analyses was used to evaluate possible impact due to atmospheric transport from the hypothetical accidental release at NRSs located in the Euro-Arctic region.

The nuclear risk sites of concern (in total 11), selected in this study, are nuclear power plants (NPPs) located in Russia (Kola and Leningrad NPPs), Finland (Lovisa and Olkiluoto NPPs), Sweden (Barsebaeck, Oskarshamn, and Ringhals NPPs), Lithuania (Ignalina NPP), groups of the British and German NPPs as well as the Novaya Zemlya test site of Russia. The geographical regions and countries of interest are the Northern and Central European countries and Northwest Russia.

Once the nuclear risk sites of concern and geographical region of interest were defined, it was of particular interest to answer the following questions: Which geographical territories are at highest risk from the hypothetical accidental releases at selected NRSs? What are probabilities and times for radionuclide atmospheric transport to different neighbouring countries in case of accidents at these NRSs?

To answer these questions, several research tools developed within the Arctic Risk Project (AR-NARP, 2001–2003) were applied. First, an isentropic trajectory model was used to calculate a multiyear (1991–1996) dataset of 5-day forward trajectories that originated over the NRS locations at various altitudes. As input data for modelling

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purposes we used NCAR meteorological gridded fields. Second, a set of statistical methods (including exploratory, cluster, and probability fields analyses) was used for evaluation of trajectory modelling results.

The results of probabilistic analysis of trajectory modelling results for 11 NRSs are presented as a set of various indicators of the NRS possible impact on geographical regions and countries of interest. In this study, we calculated, constructed, and evaluated several important indicators based on trajectory modelling results: 1) atmospheric transport pathways (ATP), 2) airflow (AF) probability fields, 3) fast transport (FT) probability fields, 4) maximum reaching distance (MRD), 5) maximum possible impact zone (MPIZ), and 6) typical transport time (TTT) fields. To evaluate the temporal variability of all these indicators, analyses were performed annually, seasonally, and monthly.

In this study, for all selected NRSs, throughout the year, the westerly atmospheric transport dominates within the boundary layer. For the block of the British, Oskarshamn, and Olkiluoto NPPs, the airflow pattern is shifted toward the northeast of the sites. For the Ignalina NPP, the AF probability field is shifted toward the southeast of the site. For NRSs located closer to the North Atlantic region (i.e. blocks of the British and German NPPs, and Barsebaeck NPP), the boundaries of probabilistic fields are extended farther (approximately on 1/3 in comparison with other NRSs) in the western direction from the sites.

Considering Denmark as a country of concern it should be noted that throughout the year after the first 12 h of atmospheric transport: 1) Barsebaeck NPP will always represent the highest probability of atmospheric transport toward Denmark, especially in spring and fall, 2) block of the German NPPs shows the possible impact of 60–80% of AHPPI as well as the block of the British NPPs shows the possible impact of 10–25% of AHPPI over the Danish territory.

The NRS possible impact (on a particular geographical region, territory, country, site, etc.) due to atmospheric transport from NRS after hypothetical accidental releases of radioactivity can be properly estimated based on a combined interpretation of the indicators (simple characteristics, atmospheric transport pathways, airflow and

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fast transport probability fields, maximum reaching distance and maximum possible impact zone, typical transport time, and precipitation factor fields) for different time periods (annual, seasonal, and monthly) for any selected NRSs (both separately for each site or grouped for several sites) in the Euro-Arctic region. Such estimation could be the useful input information for the decision-making process, risk assessment, and planning of emergency response systems at risk sites of nuclear, chemical, biological, etc. danger.

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Table 1. Nuclear risk sites selected for the study

#	Site	Lat, ° N	Lon, ° E	Site names	Country
1	KNP	67.75	32.75	Kola NPP	Russia
2	LNP	59.90	29.00	Leningrad NPP	Russia
3	NZS	72.50	54.50	Novaya Zemlya Test Site	Russia
4	INP	55.50	26.00	Ignalina NPP	Lithuania
5	BBP	54.50	−3.50° W	Block of the British NPPs	UK
6	BGP	53.50	9.00	Block of the German NPPs	Germany
7	LRS	60.50	26.50	Loviisa NPP	Finland
8	TRS	61.50	21.50	Olkiluoto (TVO) NPP	Finland
9	ONP	57.25	16.50	Oskarshamn NPP	Sweden
10	RNP	57.75	12.00	Ringhals NPP	Sweden
11	BNP	55.75	13.00	Barsebaeck NPP	Sweden

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Table 2. Seasonal variability of the maximum possible impact zone indicator

Nuclear risk sites	NRS	Area of MPIZ $\cdot 10^4 \text{ km}^2$		
		Maximum	Minimum	Annual average
Novaya Zemlya Test Site	NZS	79.7 (Win)	47.1 (Sum)	57.4
Kola NPP	KNP	41.9 (Spr)	33.6 (Sum)	42.8
Leningrad NPP	LNP	57.4 (Win)	34.4 (Fal)	40.2
Ignalina NPP	INP	56.9 (Win)	32.1 (Fal)	42.0
Oskarshamn NPP	ONP	62.3 (Win)	37.7 (Sum)	41.8
Ringhals NPP	RNP	46.0 (Spr)	27.9 (Sum)	38.3
Barsebaeck NPP	BNP	44.9 (Win)	35.8 (Fal)	40.2
Loviisa NPP	LRS	43.8 (Fal)	31.4 (Sum)	40.9
Olkiluoto (TVO) NPP	TRS	48.1 (Fal)	33.9 (Spr)	44.6
Block of the British NPPs	BBP	66.8 (Spr)	32.1 (Sum)	43.7
Block of the German NPPs	BGP	45.6 (Win)	30.3 (Sum)	42.1

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Table 3. Seasonal variability of the maximum reaching distance indicator

Nuclear risk sites	NRS	Area of MRD · 10 ⁴ km ²		
		Maximum	Minimum	Annual average
Novaya Zemlya Test Site	NZS	1200.0 (Win)	361.4 (Sum)	903.5
Kola NPP	KNP	975.2 (Spr)	427.1 (Win)	596.0
Leningrad NPP	LNP	785.5 (Win)	330.9 (Fal)	691.6
Ignalina NPP	INP	842.7 (Win)	540.0 (Sum)	703.0
Oskarshamn NPP	ONP	1007.4 (Win)	457.1 (Spr)	595.1
Ringhals NPP	RNP	1307.2 (Win)	618.1 (Fal)	854.5
Barsebaeck NPP	BNP	1296.3 (Win)	547.9 (Fal)	815.6
Loviisa NPP	LRS	1039.3 (Win)	475.9 (Sum)	810.3
Olkiluoto (TVO) NPP	TRS	1160.4 (Win)	647.9 (Sum)	780.9
Block of the British NPPs	BBP	1100.0 (Win)	385.9 (Spr)	817.0
Block of the German NPPs	BGP	962.4 (Spr)	568.6 (Sum)	735.6

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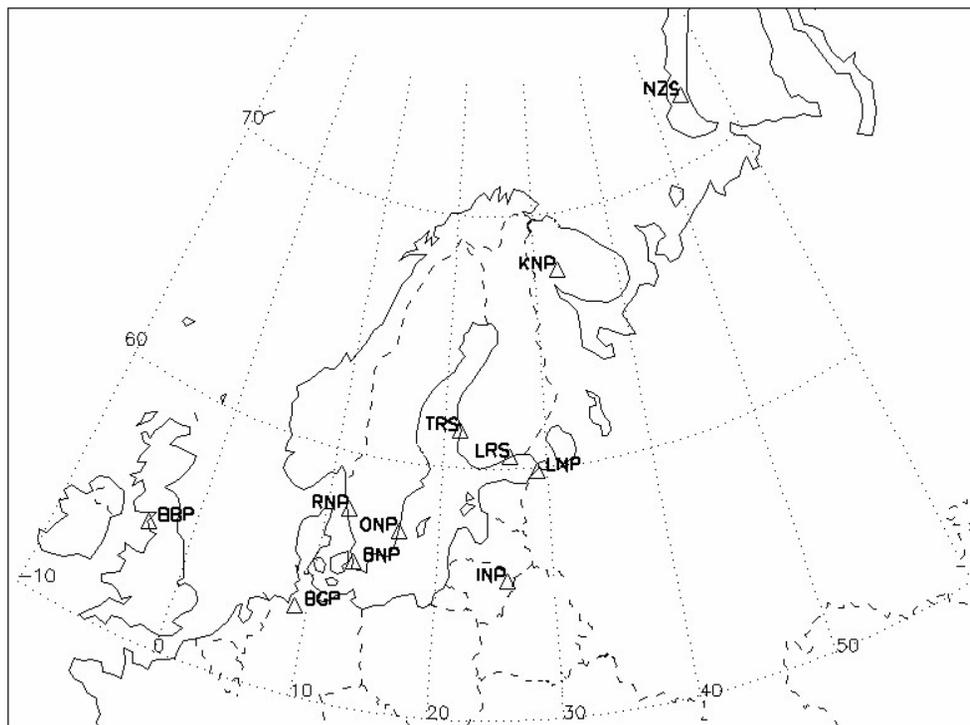
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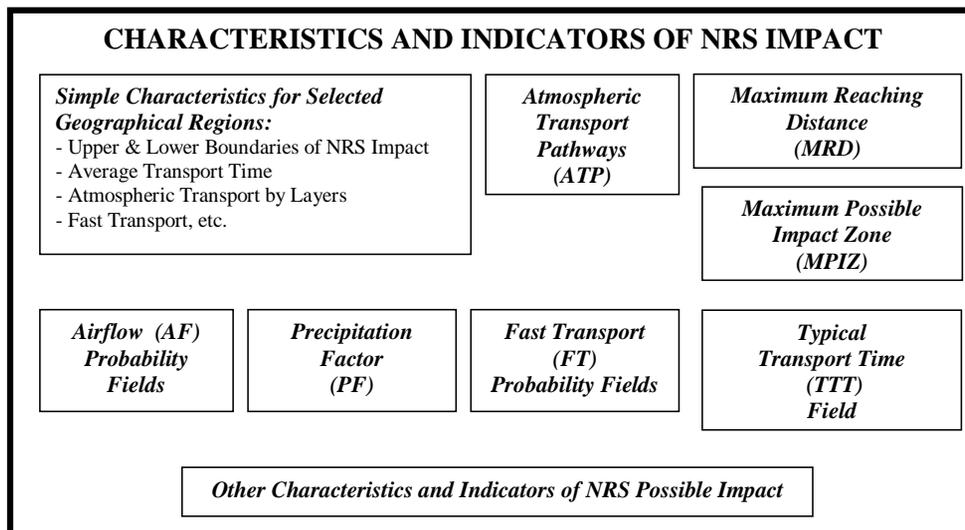


Fig. 2. Characteristics and indicators of the risk site possible impact due to atmospheric transport.

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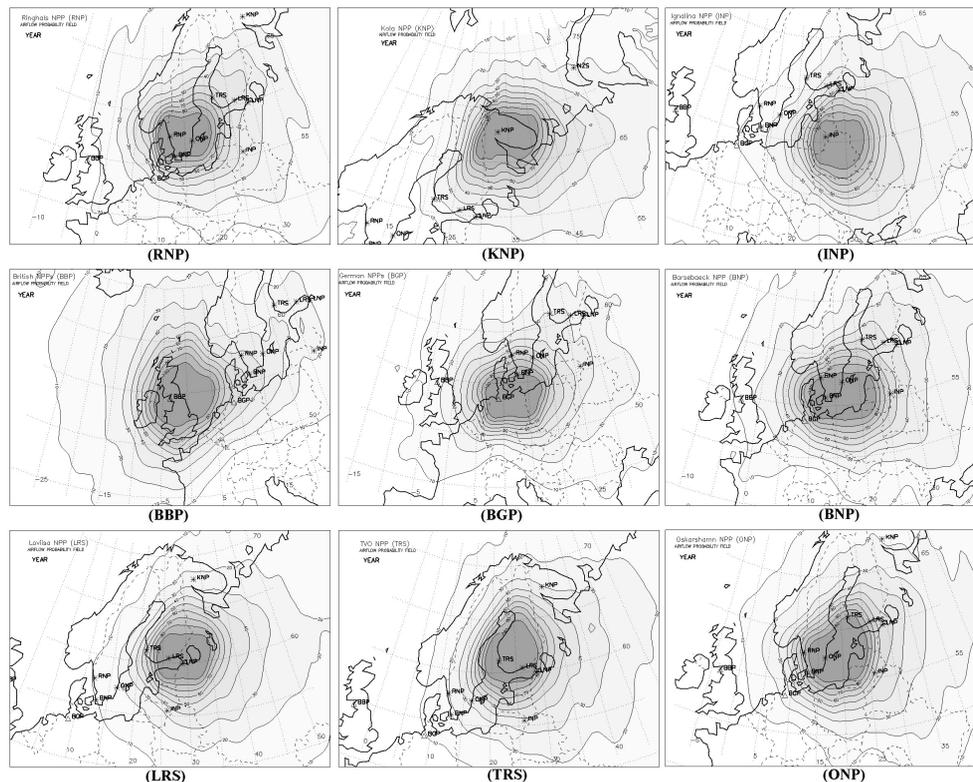


Fig. 3. Annual airflow probability fields for selected NRSs in the Euro-Arctic region.

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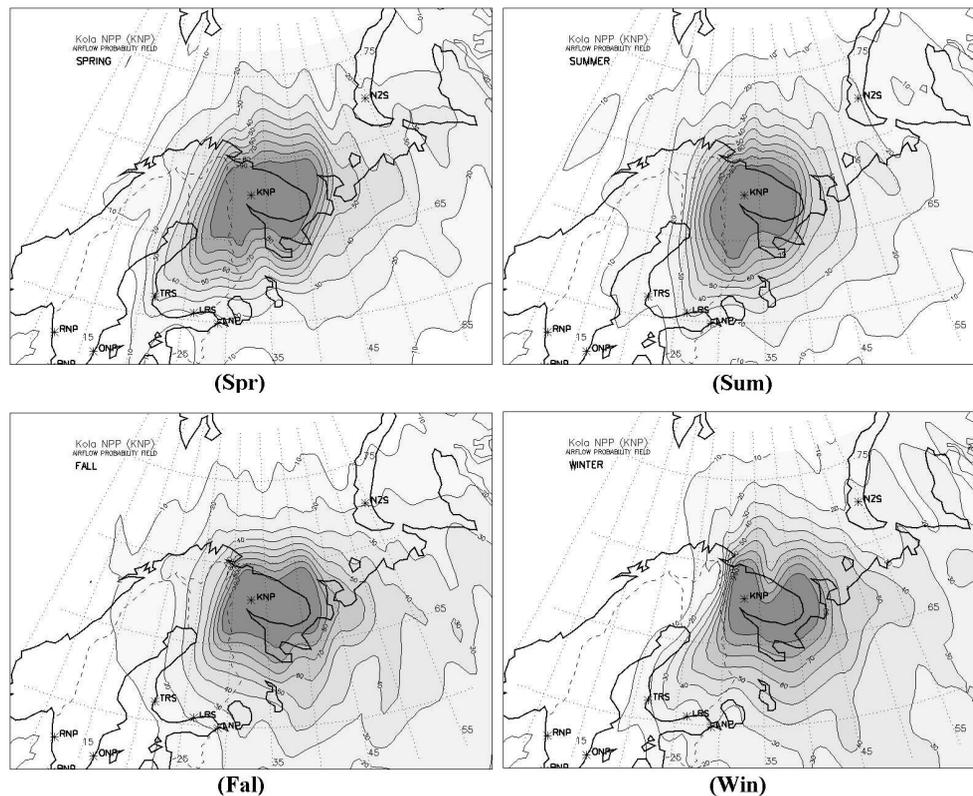
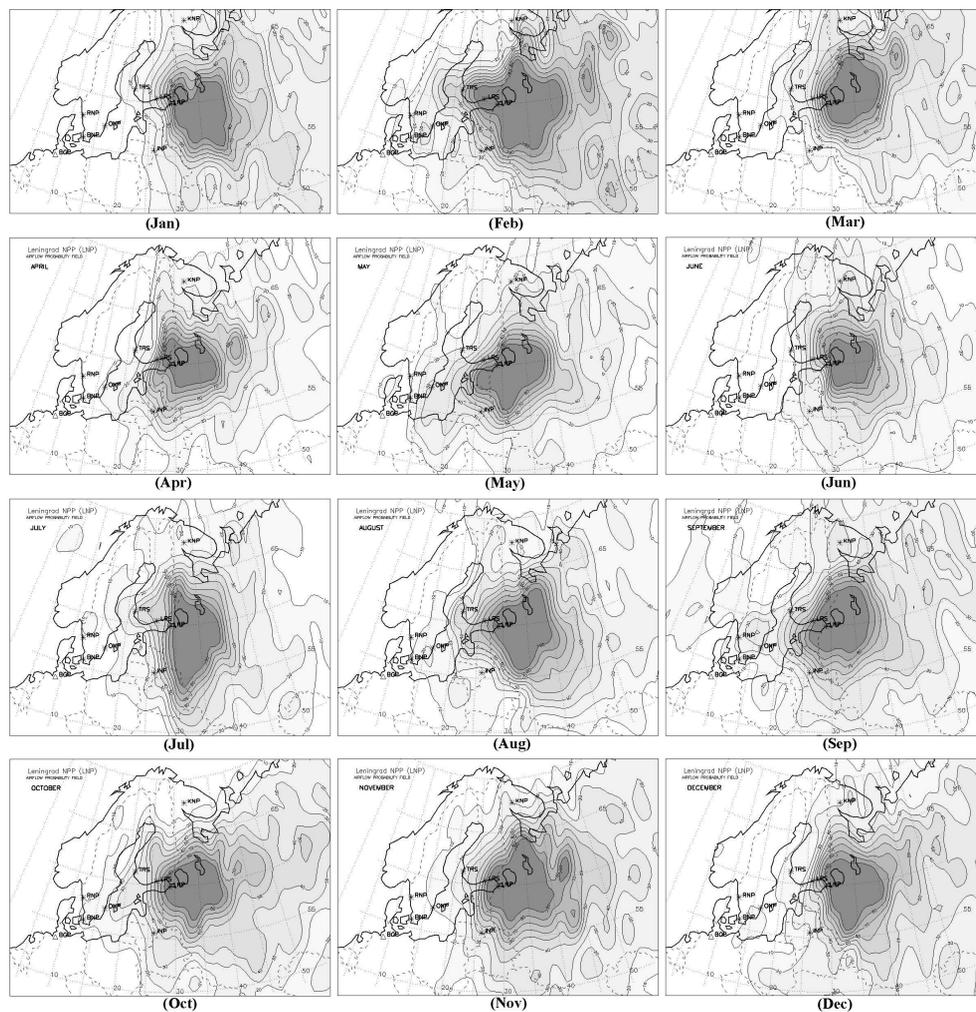


Fig. 4. Seasonal airflow probability fields for the Kola NPP (KNP).

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**Fig. 5.** Monthly airflow probability fields for the Leningrad NPP (LNP).[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

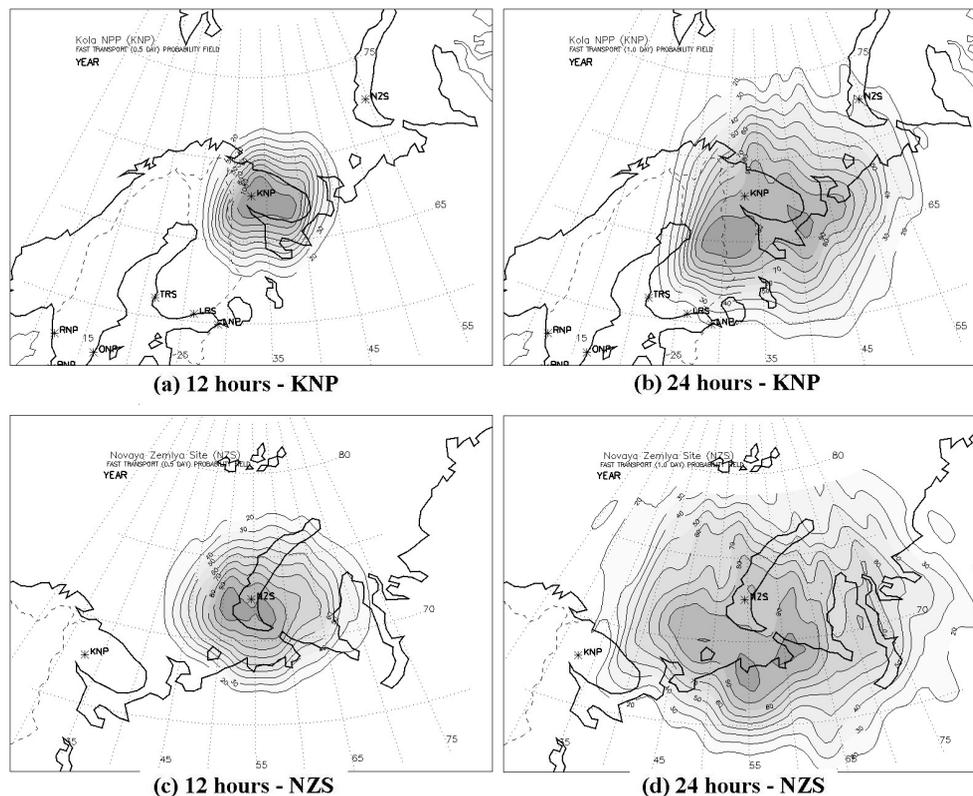
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Fig. 6. Annual fast transport probability fields after 12 and 24 h of atmospheric transport from the Kola NPP (KNP) and Novaya Zemlya test site (NZS).

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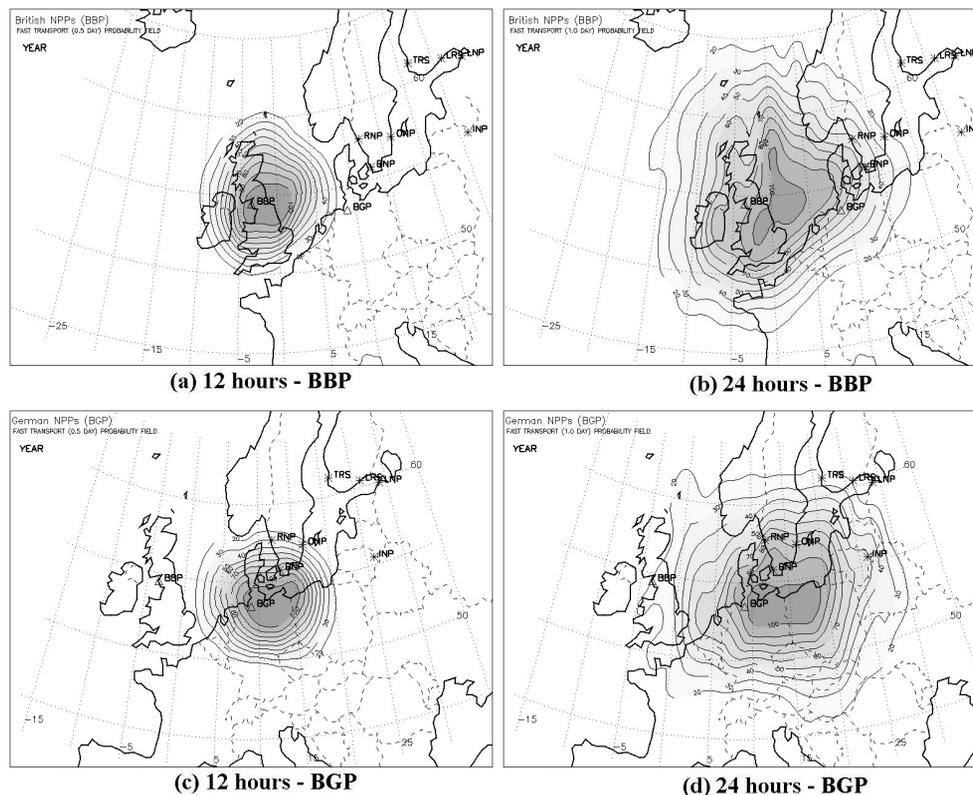


Fig. 7. Annual fast transport probability fields after 12 and 24 h of atmospheric transport from the blocks of the British NPPs (BBP) and German NPPs (BGP).

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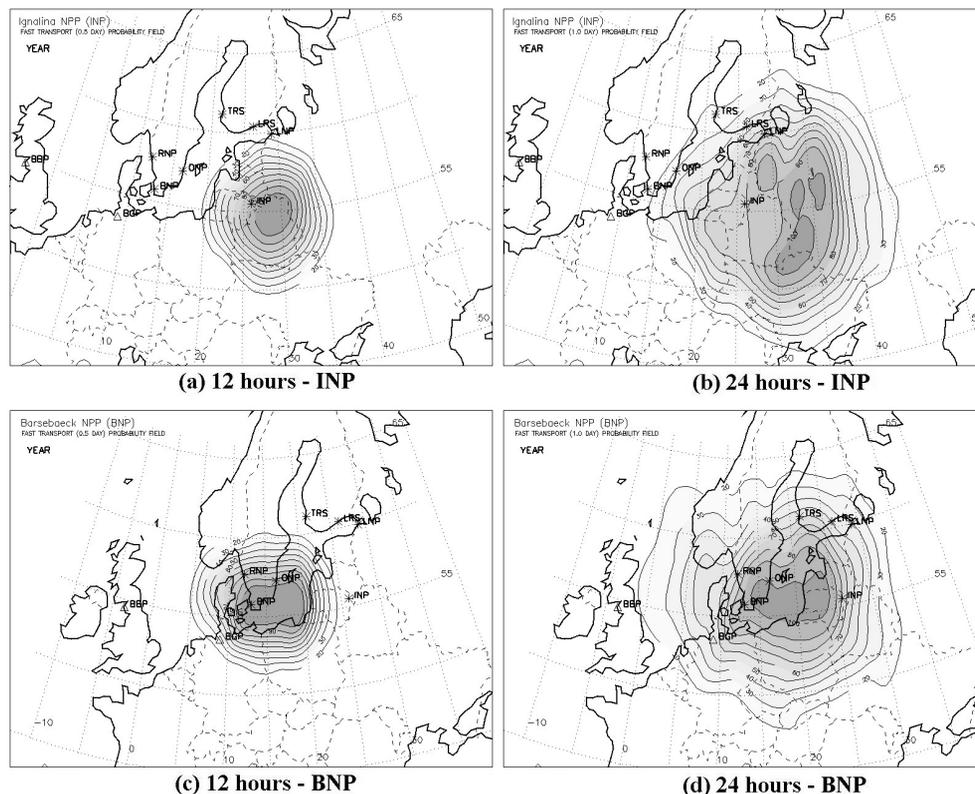


Fig. 8. Annual fast transport probability fields after 12 and 24 h of atmospheric transport from the Ilnalina NPP (INP) and Barsebaeck NPP (BNP).

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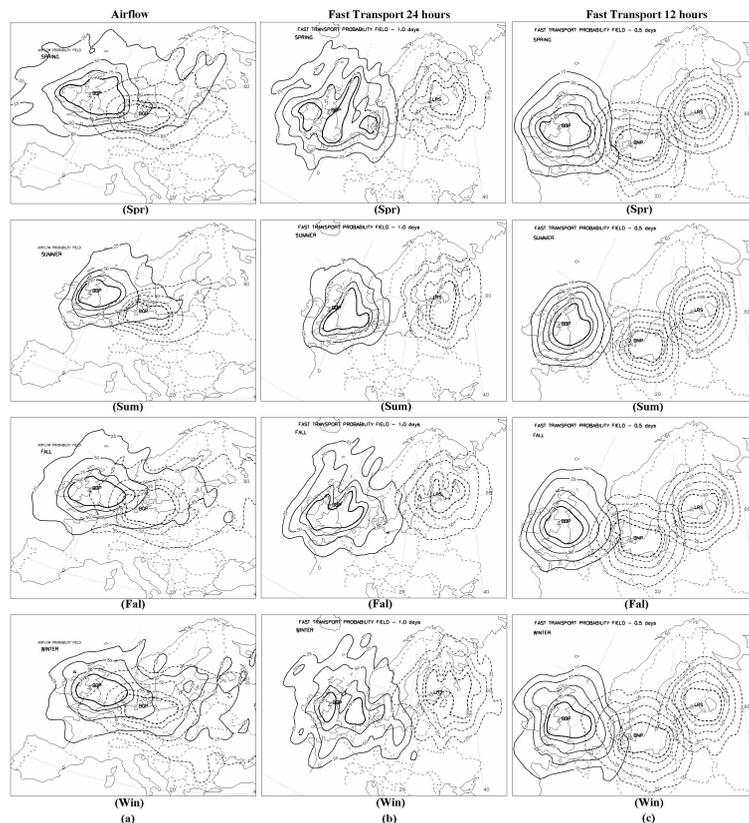


Fig. 9. Seasonal variability of the: **(a)** airflow probability fields for the blocks of the British (BBP) and German (BGP) NPPs; **(b)** fast transport probability fields after 24 h of atmospheric transport from the block of the British (BBP) and Loviisa (LRS) NPPs, and **(c)** fast transport probability fields after 12 h of atmospheric transport from the block of the British (BBP), Loviisa (LRS), and Barsebaeck (BNP) NPPs.

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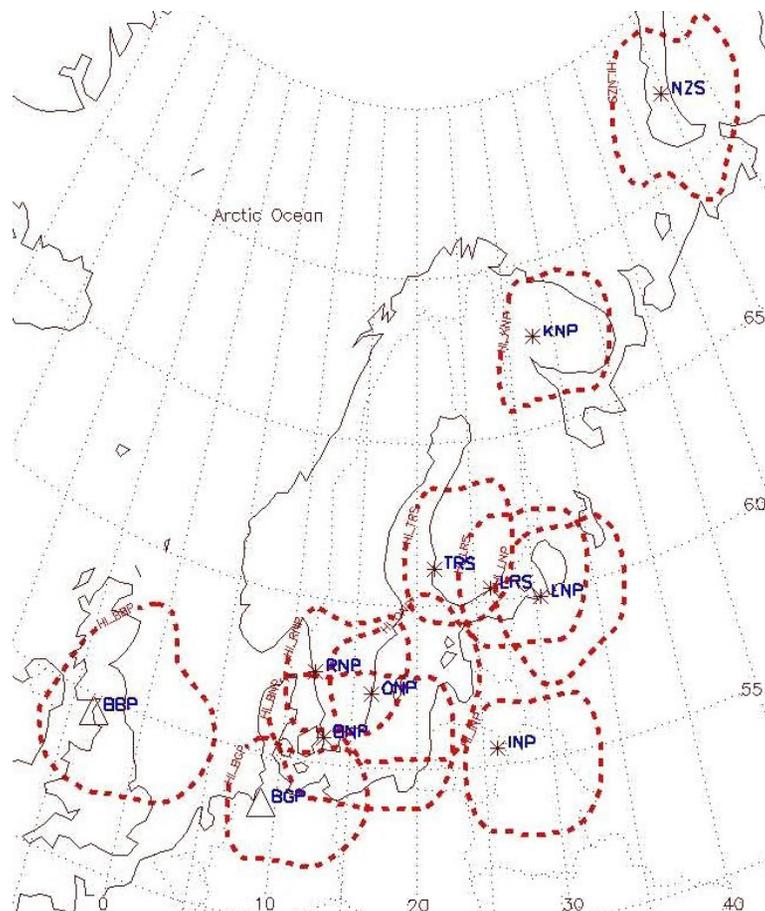
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Fig. 10. Annual boundaries of the maximum possible impact zone indicators (–HI_SiteName–) after 24 h of atmospheric transport for selected NRSs in the Euro-Arctic region.

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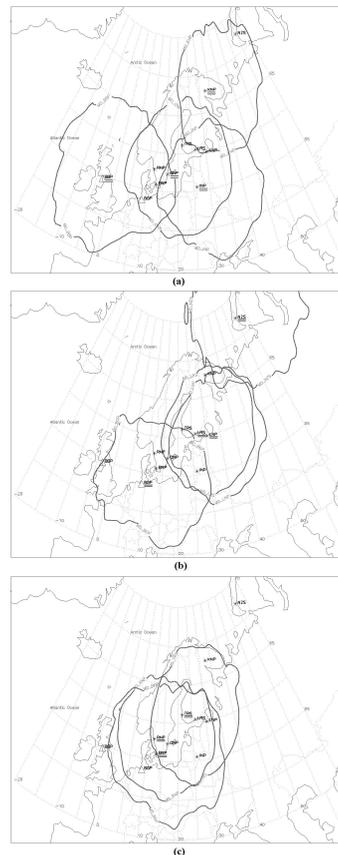
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Fig. 11. Annual boundaries of the maximum reaching distance indicators after 24 h of) atmospheric transport for the **(a)** Block of the British NPPs (MD_BBP), Oskarshamn NPP (MD_ONP), Ignalina NPP (MD_INP), and Kola NPP (MD_KNP), **(b)** Block of the German NPPs (MD_BGP), Loviisa NPP (MD_LRS), Novaya Zemlya Test Site (MD_NZS), and Leningrad NPP (MD_LNP); and **(c)** Barsebaeck NPP (MD_BNP), Ringhals NPP (MD_RNP), and Olkiluoto NPP (MD_TRS).

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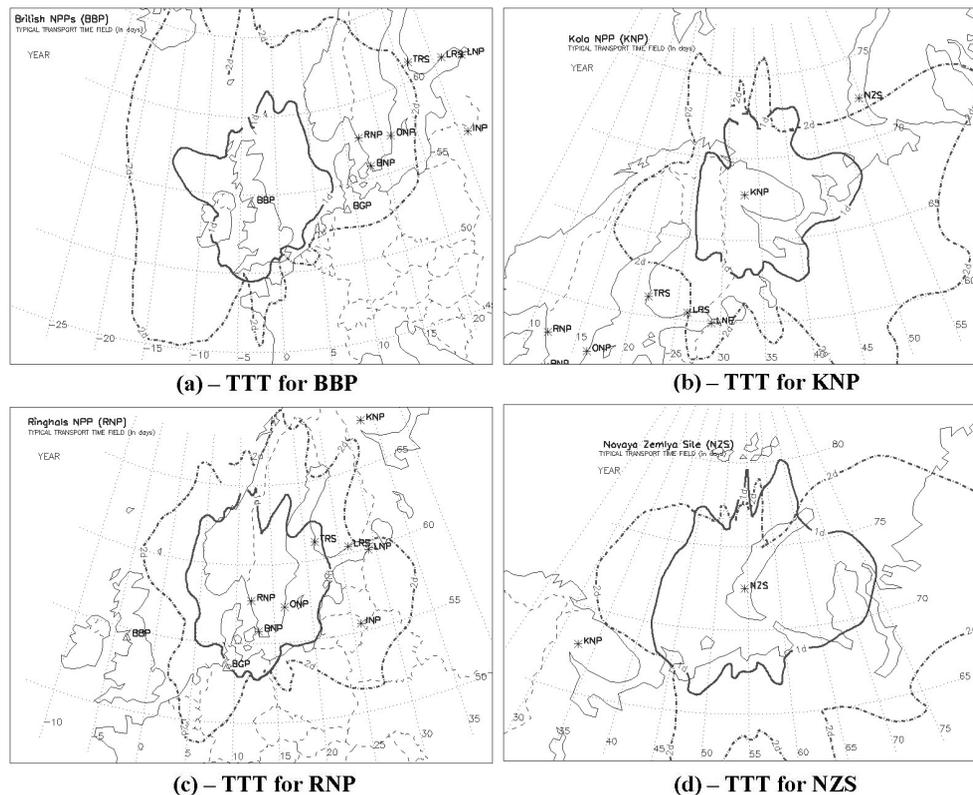


Fig. 12. Annual typical transport time (TTT) fields at 1 (1d) and 2 (–2d) days of atmospheric transport for the (a) block of the British NPPs (BBP), (b) Kola NPP (KNP), (c) Ringhals NPP (RNP), and (d) Novaya Zemlya test site (NZS).

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