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LONG-TERM DISPERSION MODELLING. PART I: METHODOLOGY FOR PROBABILISTIC ATMOSPHERIC STUDIES

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Цель данной работы — разработка методологии мультидисциплинарной оценки ядерных рисков и уязвимости, а также проверка этой методологии путем оценки ядерного риска для населения стран Северной Европы в случае крупной аварии на ядерном объекте. Основной темой данной статьи является описание методологии вероятностных и долговременных оценок атмосферного переноса радиоактивных выбросов из районов ядерных рисков. Каковы вероятности и время, концентрации и выпадения при атмосферном переносе радионуклидов для разных соседних стран и территорий в случае гипотетического случайного выброса на ядерном объекте? Какие географические территории и страны подвергаются наибольшему риску в случае гипотетического случайного выброса? Для ответа на эти вопросы были использованы следующие средства вероятностных исследований:

— дисперсное моделирование (модели DERMA и DMI-HIRLAM) для расчета долговременного переноса и рассмотрение конкретного примера переноса радионуклидов при гипотетических выбросах на ядерных объектах;

— анализ вероятностных полей для построения годичных, месячных и сезонных индикаторов на основе результатов дисперсного моделирования, для идентификации наиболее пострадавших географических регионов.

Полученные результаты применимы для дальнейшего ГИС-анализа при оценке рисков и уязвимости, а также при разработке мер подготовки к аварийным ситуациям в случае выбросов на ядерных и других промышленных объектах.

Introduction

Many international research projects have realised models and methods describing separate parts of the nuclear risk assessment problem, e.g. the probabilistic safety assessment (PSA), long-range transport and contamination modelling, radioecological sensitivity, dose simulation etc. However, methodologies for multidisciplinary work of nuclear risk assessments and mapping

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are poorly developed (for an overview cf. e. g. [1]). Thus, a multidisciplinary approach towards problems connected to the regional nuclear risk and vulnerability should be further developed.

The purpose of the Arctic Risk NARP Programme [2] was to develop a methodology for airborne nuclear risk and vulnerability assessment and mapping, and to test it on estimation of a possible radiation risk to populations in the North European countries in case of a severe accident at a nuclear risk site (NRS).

The general selected approaches, tools and models, methodology results of probabilistic analysis of atmospheric transport patterns and assessment based on trajectory modelling approach were discussed by [3]. In this paper, the methodological aspects of the long-term dispersion and deposition modelling, statistical analysis of dispersion modelling results are considered.

Risk-assessment strategy for analyses of source-effect relationships, used in different studies, includes the following methods [4].

1. Inference from actual events: accident-release-consequences.
2. Physical model based on known input and prevalent levels.
3. Theoretical model: simulated response to assumed release scenarios.

The first method is basically used for most of the risk objects using known consequences from some real events (weapon tests, the Chernobyl accident, the Thule accident with warheads, accidents with nuclear submarines like one in the Chazhma bay, etc.). For example, some long-term consequences have been estimated for regional-scale by empirical models and correlations between fallout and doses for humans, obtained by Nordic researchers on a basis of the Chernobyl effects on Scandinavia [5, 6]. The second method, based also on published results of numerous projects and assessments of possible risk levels, is used for many risk sites in the Arctic and European regions or for some other countries from similar NRSs (e. g., [7]). These both methods are limited by similarities of the existing accidents and consequences to considered cases. The third method of mathematical modelling of geophysical processes of radionuclide transport is more universal and useful for different studies of hypothetical releases from nuclear power plants (NPPs), nuclear submarines, or from radioactive waste, etc.

To study possible consequences and nuclear risk from NRSs there could be *two approaches* — case studies and probabilistic risk analysis [8]. 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 source to man. This way is very useful for estimating possible consequences of hypothetical accidents for typical or worst-case scenarios and meteorological situations. However, during the previous decades such approach was expensive for long-term (e. g. multiyear) simulations and probabilistic assessments. So, for probabilistic analysis, alongside with the first method, some authors suggested more *simpler approaches*, e. g. based on very simple transport models and a combination of different factors and probabilities of separate processes with appropriate weights.

The first map of risk in Europe due to severe accidents for all European NPPs mapped the probability of excess cancer mortality after such accidents [9]. Since detailed safety analyses were not available for many of more than 200 European NPPs, a generalisation was made to estimate accident probabilities and probabilistic releases by relating each reactor type to a specific probability and release category. Dispersion of the radioactive plume was evaluated by a simple model based on only one meteorological station. Acute health effects in vicinity of NPPs and countermeasures to reduce radiation doses were excluded. The main shortcomings of this approach are a limitation of the dispersion model for short distances and non-applicability of the dose model to the Arctic peculiarities.

In IIASA studies [10] some empirical factors were used to describe the influences of geography resulting in normalised damage factors for the main cities of Europe. An alternative statistical description for estimating the risk associated with a large accidental release of hazardous materials at long-range was developed by Smith [11].

Lauritzen and Mikkelsen [12] suggested for rough assessments a very simplified probabilistic dispersion model applied to the long-range transport of radionuclides from the Chernobyl accident.

Andreev et al. [13, 14] simulated dispersion and deposition with a Lagrangian particle model and calculated the frequency of exceedance of certain thresholds for the long-lived radionuclide ^{137}Cs, regarded as risk indicator. Sensitivity analysis demonstrated that the results strongly depended on the release frequencies. Additionally, GIS-based export/import matrices of risk were calculated for the European countries. Shortcoming of this method is the use of a limited number of case studies/meteorological situations, which can not satisfactory represent the long-term statistics.

Saltbones et al. [15] also realised the long-term trajectory analysis and case studies of long-range transport modelling for the Kola NPP, however they used two-dimensional trajectories and limited the study to the trajectory analysis with several case studies and did not realise the risk mapping.

The recent networking project "Atmospheric Transport Pathways, Vulnerability and Possible Accidental Consequences from the Nuclear Risk Sites in the European Arctic (Arctic Risk)", involving 7 research groups from four Nordic countries and supported by the Nordic Arctic Research Programme (NARP), is aimed at developing and testing such a risk methodology for the Euro-Arctic region [2]. The methodology, developed in the bounds of the Arctic Risk project [16–18, 3] is a logical continuation of several previous studies.

Each of the two basic approaches — the probabilistic assessments and the "case study" — has some advantages and shortcomings, and neither of them is sufficient for the risk assessments. So, it is suggested to use a combination of both methods, which gives a quite complex and non-expensive approach.

During last decades new generation powerful computers considerably extend possibilities of long-term dispersion modelling and integrated modelling approaches. So, the next step should be a comprehensive regional scale long-term dispersion model for probabilistic studies and multidisciplinary approach towards problems connected to the regional nuclear risk and vulnerability [1].

1. Methodology for risk analysis based on atmospheric dispersion modelling of various patterns from risk sites

The suggested scheme for multidisciplinary risk assessment, which includes a combination of trajectory and dispersion modelling and statistical analysis, is shown in fig. 1. For assessment of risk and vulnerability different indicators are considered, including the social-geophysical factors, which depend on the location and population of the area of interest and probabilities, as well as approaches and modelling tools. As shown in fig. 1, there is a variety of research tools in the methodology scheme of probabilistic risk and vulnerability assessments. In this paper the suggested multidisciplinary approach and illustration of dispersion modelling tool involved are described. Note that, for example, other approaches also include modelling and clustering of trajectories [3], specific case studies [17], and evaluation of vulnerability and consequences to radioactive deposition [18, 19].

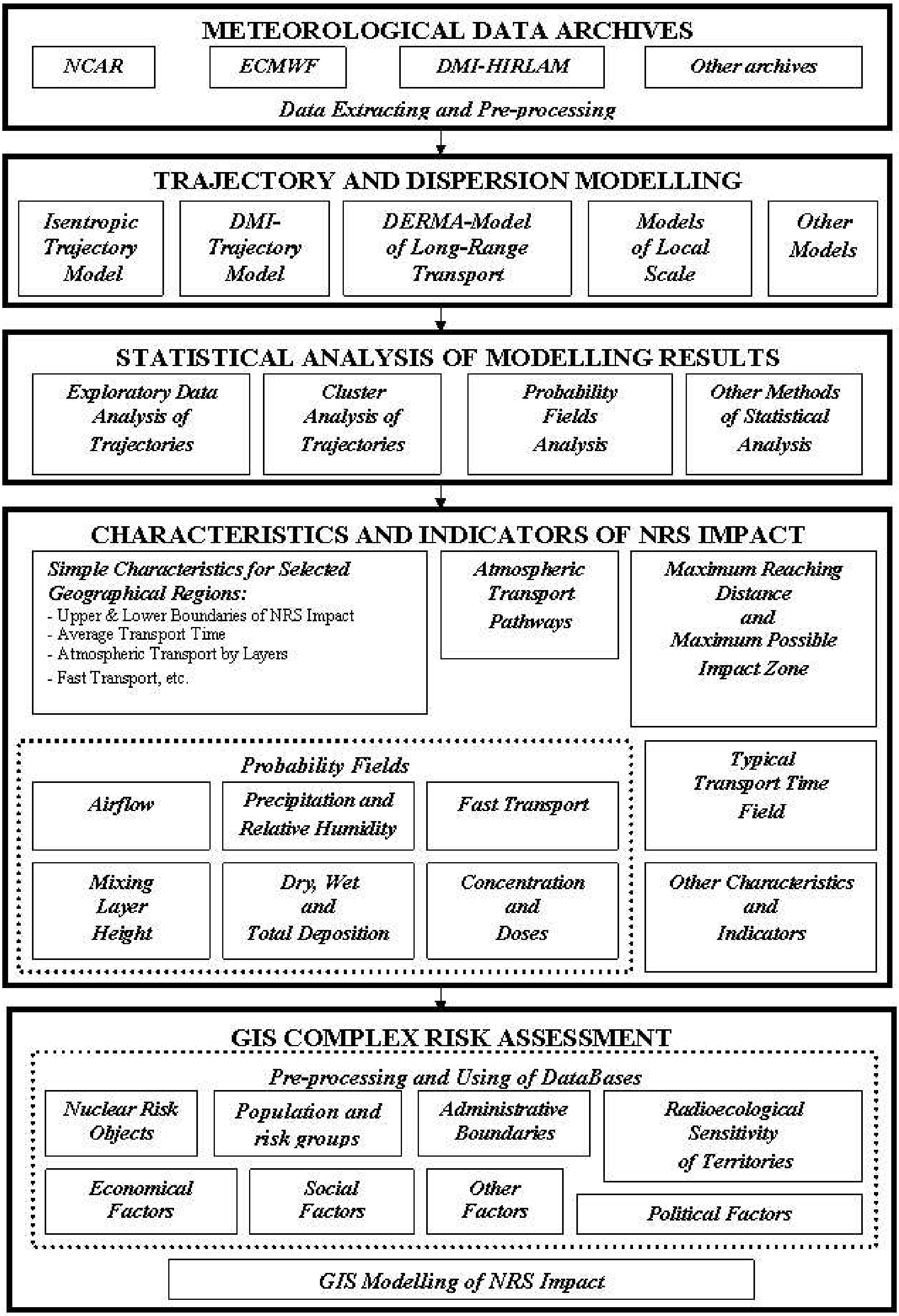

Fig. 1. Scheme of the probabilistic risk analysis based on dispersion and trajectory modelling approaches.

If assume either a unit puff release or continuous release every time interval at an NRS, and run a model of atmospheric transport, dispersion, and deposition of the radioactive material a field for the concentration/deposition accumulated during a multiyear period can be produced. From one side, we can estimate what would be accumulated deposition if a continuous release took place. From the other side, we can identify the geographical areas affected (when wet deposition is considered — presumably of a cellular nature). These areas are the territories where the greatest deposition/removal of radionuclides is possible during transport from the site. Note that such fields are also (as in the trajectory modelling approach) valid with respect to the particular NRS of interest. The statistical analysis of concentration/deposition fields allowed to produce average and summary fields for concentration and depositions of radionuclides, although it is possible in addition to construct and identify areas with maximum values of variables and its standard deviations.

Additionally, useful information can be obtained from the average climatological (annual, seasonal, and monthly) patterns for the regional or local scale. We can evaluate the seasonal and monthly average deposition fields applying averages for wind characteristics, precipitation, temperature, relative humidity, etc. For this case, the 3-D meteorological fields are simulated, and then they are used in the transport model to calculate such characteristics as the average air concentration, surface deposition, and doses. Specific cases for both unit and hypothetical, such as maximum possible accident (MPA), releases can be considered. Additional cases of unfavourable meteorological conditions can be evaluated too [20]. Moreover, monthly or seasonal fields of air concentration, deposition, and various doses could be used in the decision-making process at the first stages of the NRS accident.

The dispersion and deposition models can be successfully used for individual case studies of typical or worst-case scenarios, as well as for probabilistic risk mapping (as a more expensive but precise alternative of the trajectory analysis method shown by Baklanov et al.) [21]. Applicability and examples of different models for accidental release dispersion and deposition simulation for the local and regional scales were discussed by Klug et al. [22]; Baklanov et al. [23]; Thaning and Baklanov [24]; Sørensen et al. [25]; Baklanov and Sørensen [26]; Galmarini et al. [27]. Some methodological aspects, discussed in this paper, were preliminarily tested for hypothetical accidental radioactive releases from the nuclear submarine "Kursk" during its lifting and transportation to the harbour on the Kola Peninsula [21].

In addition, specific case study simulations, in comparison with long-term dispersion modelling, have the following peculiarities: (i) higher special and temporal resolution; (ii) many nuclides of concern; (iii) different release heights; (iv) different categories of releases; (v) more complex release composition (particle size etc.); (vi) different scenarios (time evolution of the release strength, etc.). Therefore, the specific case studies give additional, very important information about the possible consequences in case of accidents for extreme or typical situations, which are not available from the probabilistic analysis.

Note, that specific case study approach is computationally less expensive compared to dispersion modelling for a multiyear period, although it provides less reliable output and allows us to consider further risk and vulnerability analysis only on particular dates. Alternatively, this approach provides a possibility of seeing potential consequences of an accident for worst-case meteorological situations. In this study, we followed several ways suggested by [23, 20] (for local scale) and [28, 17, 29] (for regional scale) on examples of the Kola NPP as well as nuclear submarines and spent nuclear fuel facilities in the northern latitudes.

For simulation of possible consequences on a regional scale, the DERMA model [30, 25, 26] with the DMI-HIRLAM [31] high-resolution meteorological data (E-version: 0.15° or G-version:

0.45°) will be used. DMI's 3D Lagrangian transport model calculates forward and backward trajectories for any point in the area.

2. Methodology for long-term dispersion modelling

In this section the methodology, developed for the probabilistic atmospheric studies based on long-term dispersion modelling for risk assessment of nuclear risk sites, is described. Note, depending on the scale considered — local, regional or global — different atmospheric dispersion models can be used. In this study, the DERMA model was used for meso- and long-range transport simulations. Besides, for the long-term simulations we aimed to build a relatively cheap modelling system, therefore a number of assumptions and simplifications were realised for the model.

2.1. Description of the Derma model

The Danish Emergency Response Model for Atmosphere (DERMA) is a numerical three-dimensional atmospheric dispersion model of Lagrangian type [30, 25, 26]. This model describes atmospheric transport, diffusion, deposition, and radioactive decay within a range from about 20 kilometres from the local and up to the global scale. DERMA is developed at the Danish Meteorological Institute (DMI) for nuclear emergency preparedness purposes and has become integrated with the ARGOS decision support system [32]. This model uses Numerical Weather Prediction (NWP) model data from different operational versions of the HIgh Resolution Limited Area Model (HIRLAM) running at DMI or from the global model of the European Centre for Medium-Range Weather Forecast (ECMWF).

Basics

The basic equation for the concentration of radioactive species in the atmosphere, c, taking into account the removal processes in the atmosphere and the interaction of the radionuclides with the Earth's surface, can be expressed:

$$\frac{\partial c}{\partial t} = -\mathrm{div}(u\, c) + \mathrm{Turb} - D\mathrm{dep} - W\mathrm{dep} - \lambda c + \lambda' c' + \mathrm{Res} + Q \tag{1}$$

where:
$\mathrm{div}(uc)$ — advection transport by vector velocity u,
Turb — turbulent diffusion of passive tracers in the atmosphere,
Ddep — dry deposition on the surface,
Wdep — wet deposition processes,
λc — radioactive decay to daughter nuclides,
$\lambda' c'$ — decay from parent nuclides,
λ — decay constant for the corresponding nuclide,
Res — resuspension processes,
Q — release source.

The temporal resolution of the currently available operational DMI-NWP model data is 1 hour. The DERMA model interpolates these data linearly in time to the advection time steps. The advection time step of DERMA is equal to 15 minutes (which is a typical turn-over time of the large vertical eddies within the atmospheric boundary layer, ABL). Thus, it is assumed that material released into the boundary layer becomes well mixed in this layer within a few time steps. Moreover, the assumption of complete mixing within the boundary layer is used in the DERMA model. In order to simulate a cold release at ground level, and following the assumption of complete mixing, all particles are emitted at equidistant heights from the surface to the top of the boundary layer. These particles are advected by 3-D wind fields from the NWP model.

Turbulent diffusion and transport

DERMA is a dispersion model based on a multi-level puff parameterization [30]. A "puff" (i. e. a concentration field surrounding a particle) is associated with each particle adding up to the total concentration field. In the horizontal, a Gaussian distribution of the concentration is assumed for each puff. For puffs inside the boundary layer, an assumption of complete mixing is employed in the vertical, while for puffs above the boundary layer, a Gaussian distribution is employed.

For a puff p positioned at point (x_p, y_p, z_p) above the boundary layer $(z_p > h)$, the Gaussian formula given by Zanetti [33] is used. The height of the boundary layer (the mixing layer) is denoted by h. For a puff located within the boundary layer (i. e. for $z_p \leq h$), we assume complete mixing in this layer, and therefore the following expression for the contribution to the total concentration field is used:

$$C_p = \frac{Q_p}{2\pi\sigma_y^2 h} \exp\left\{-\frac{1}{2}\left(\frac{x - x_p}{\sigma_y}\right)^2 - \frac{1}{2}\left(\frac{y - y_p}{\sigma_y}\right)^2\right\} \delta(z, h) \tag{2}$$

where:
C_p — amount (mass) of tracer gas associated with the puff depending on the emission rate,
σ_y — horizontal standard deviation of the spatial concentration distribution, $\delta(x, h)$ is equal to 1 for $z \leq h$ and to 0 for $z > h$.

From Gifford's random-force theory [34] the following expression for the horizontal standard deviation and its asymptotic expressions are obtained:

$$\sigma_y^2 = 2K_y t_L \left\{\tau - \left(1 - e^{-\tau}\right) - \frac{1}{2}\left(1 - e^{-\tau}\right)^2\right\} \cong \begin{cases} \frac{2}{3} K_y t_L^{-2} t^{-3} & \text{for} \quad t \ll t_L, \\ 2K_y t & \text{for} \quad t \gg t_L. \end{cases} \tag{3}$$

The parameter τ is the travel time, t, in units of the Lagrangian time scale, $t_L, (\tau = t/t_L)$. For the simulations, we have used the value of the horizontal eddy diffusivity, K_y, of $6 \cdot 10^3$ m^2/s, and for the Lagrangian time scale, t_L, 10^4 s.

The selected value of K_y for the horizontal eddy diffusivity was obtained by fitting results of DERMA using DMI-HIRLAM data to the official set of the ETEX tracer gas measurements [30]. The horizontal and temporal resolutions of NWP data define an upper limit of the value of the horizontal eddy diffusivity mainly describing sub-grid scale diffusion.

For puff centres above the boundary layer, a Gaussian distribution is assumed for the vertical spatial distribution using the following expression for the standard deviation, σ_z:

$$\sigma_z^2 = 2K_z t_L \left\{\tau - \left(1 - e^{-\tau}\right) - \frac{1}{2}\left(1 - e^{-\tau}\right)^2\right\} = \left(\frac{K_z}{K_y}\right) \sigma_y^2. \tag{4}$$

The height of the boundary layer is estimated by a bulk Richardson number approach [35]. This approach is useful in cases where the vertical resolution of temperature and wind is limited as e.g. in output from NWP models. The bulk Richardson number, Ri_B, at height z above the ground surface is given by the following expression:

$$Ri_B = \frac{gz\left(\theta_v - \theta_s\right)}{\theta_s\left(u^2 + v^2\right)}, \tag{5}$$

where:

θ_s, θ_z — virtual potential temperature at the surface s and at the height z, respectively;

u, v — horizontal wind components at height z;

g — gravitational acceleration.

The top of the boundary layer is given by the height at which the bulk Richardson number reaches a critical value. This approach could be improved for the stably stratified boundary layer following [36].

Dry deposition and gravitational settling

Dry deposition is the removal of gaseous and particulate nuclides or other pollutants from the atmosphere to the earth surface by vegetation or other biological or mechanical means. It plays an important role for most nuclides (excluding the noble gases).

For the DERMA model, it was included via the mass loss due to dry deposition in the calculation of source term Q_p — the amount of radionuclide associated with each puff p depending on the emission rate (the so-called source depletion method). As a first simple parameterisation of dry deposition we used a classic approach, based on the concept of the deposition velocity v_d. The dry deposition takes place in the lower surface layer and is not valid in the free troposphere ($z > h$).

Therefore, using the assumption employed in the DERMA model about complete vertical mixing within the atmospheric boundary layer (ABL) for each puff p, we can obtain the following simple formula for the mass loss due to dry deposition:

$$Q_p|_{n+1} = Q_p|_n \exp\left\{-\frac{\Delta t v_d}{h}\right\}, \tag{6}$$

where Δt — time step of the model.

Prahm & Berkowicz [37] showed that the source depletion method could give considerable errors of the surface air concentration in case of stable stratification of ABL. If an air pollution model can simulate the vertical structure/profile of concentration within ABL, especially for the local scale, the surface depletion approach is more suitable for simulation of dry deposition. However, in case of using the approach of complete vertical mixing within ABL, the difference between both methods is not significant. Calculation of the radionuclide amount deposited on the surface due to dry deposition is performed at each time step.

The dry deposition velocity depends on many parameters describing particles and characteristics of the ground surface and surface layer. For the simplest case of dry deposition parameterisation, we assume that the dry deposition velocity is constant for each nuclide and surface type [38].

However, note that this parameterisation is not very suitable for simulation of accidental releases, because numerous experimental studies (cf. e. g. an overview by Baklanov & Sørensen [26]) showed that the dry deposition velocity depend on the size of the deposited particles. Therefore, for the dry deposition velocity of more than 300 radionuclides different values are used in the DERMA model.

For particles, especially for heavy particles (radius $r_p > 1\,\mu$m), the gravitational settling strongly affects the process of deposition to the surface. The effect of gravitational settling, described through the gravitation settling velocity, v_g, is included in the dry deposition velocity value. For particles with diameter of less than $4\,\mu$m, for which the airflow around the falling particle can be considered laminar, the gravitational settling velocity is given by Stokes' law with the Cunningham correction factor for very small particles ($r_p < 0.5\,\mu$m) [33].

Wet deposition

The Chernobyl accident has shown that the wet deposition or pollutant scavenging by precipitation processes is very important for the evaluation of the radionuclide atmospheric transport from nuclear accidental releases as well as estimation of the deposited radioactivity pattern. Usually the wet deposition is treated in a standard way with a washout coefficient for the below-cloud scavenging and a rainout coefficient for the in-cloud scavenging [39].

As a first approximation we can describe the local rate of material removal as the first-order process:

$$\frac{dc}{dt} = \Lambda\left(r_p, x_i, t\right) c\left(x_i, t\right) \tag{7}$$

where $\Lambda\left(r_p, x_i, t\right)$ — total scavenging (washout or rainout) coefficient (depends on the height above the surface and time).

The wet deposition flux to the surface, in contrast to the dry deposition flux, is the sum of wet removal from all volume elements aloft, assuming that the scavenged material comes down as precipitation. For the DERMA model, by using the assumption of complete vertical mixing within ABL and assuming that the rain clouds are contained in ABL, the wet deposition velocity can be expressed as:

$$v_w = \Lambda' H_r, \tag{8}$$

where:

Λ' — vertically averaged washout coefficient,

H_r — the height of the cloud base.

In case of simulation without splitting the scavenging process in washout and rainout, H_r will be the height of the cloud top. Thus, a formula similar to eq. 6 for the calculation of the mass loss by wet deposition is obtained:

$$Q_p|_{n+1} = Q_p|_n \exp\left(-\frac{\Delta t H_r \Lambda'}{h}\right). \tag{9}$$

If the height of the rain cloud base H_r is unknown, one can assume that $H_r = h$.

As it was mentioned above, the scavenging coefficient $\Lambda\left(r_p, x_i, t\right)$ includes the washout and rainout coefficients, and hence, it is possible to present it as a sum of two coefficients: $\Lambda\left(r_p, x_i, t\right) = \Lambda_w\left(r_p, x_i, t\right) + \Lambda_r\left(r_p, x_i, t\right)$. The washout and rainout mechanisms are spatially separated (the rainout is effective within the clouds, the washout — below the clouds).

Washout

The below-cloud scavenging (washout) coefficient, Λ_w, for aerosol particles of radius r_p can be expressed in a general form as:

$$\Lambda_w = -\pi N_r \int a^2 w_a(a) E(r_p, a) f_a(a) da, \tag{10}$$

where:

N_r — total number of raindrops residing in a unit volume,

a — raindrop projected radius,

$E(r_p, a)$ — aerosol capture efficiency term,

$w_a(a)$ — vertical velocity of the raindrops (negative if downward),

$f_a(a)$ — probability-density function of the raindrop size distribution.

The limits of integration are from the ground surface to the cloud base. The aerosol capture efficiency $E(r_p, a)$ is a function of the radius of particle, r_p, and of rain drops, a, and depends upon several mechanisms mentioned by Hales [40]: (i) impaction of aerosol particles on the rain drop, (ii) interception of particles by the rain drop, (iii) Brownian motion of particles to the rain drop, (iv) nucleation of a water drop by the particle, (v) electrical attraction, (vi) thermal attraction, (vii) diffusioforesis.

The washout coefficient, Λ_w, varies spatially and temporally. However, in order to simplify, one may use a vertically averaged washout coefficient, Λ'_w, below the clouds in combination with the surface precipitation data.

In most models of long-range air pollution transport the washout coefficient does not depend on particle radius. However, as it is mentioned in an overview by Baklanov & Sørensen [26], the $E(r_p, a)$ and correspondingly Λ_w strongly depend on the particle size (the so-called "Greenfield gap"). According to experimental data [41, 42], the washout coefficient for particle radii in the range of 0.01–0.5 μm is about of $0.1{\cdot}10^{-3}$–$0.5{\cdot}10^{-3}$ sec^{-1}, and it is two orders of magnitude smaller than that for particles larger than 4 μm.

Therefore, as a first approximation, Baklanov & Sørensen [26] suggested a revised formulation of the vertically averaged washout coefficient for particles of different size:

$$\Lambda'(r_p, q) = \begin{cases} a_0 q^{0.79} & \text{if} \quad r_p \leq 1.4\,\mu\text{m} \\ \left(b_0 + b_1 r_p + b_2 r_p^2 + b_3 r_p^3\right) f(q) & \text{if} \quad 1.4\,\mu\text{m} < r_p < 10\,\mu\text{m}, \\ f(q) & \text{if} \quad r_p \geq 10\,\mu\text{m}, \end{cases}$$
$$f(q) = a_1 q + a_2 q^2 \tag{11}$$

where:

q — precipitation rate (mm/h), $a_0 = 8.4 \cdot 10^{-5}$, $a_1 = 2.7 \cdot 10^{-4}$, $a_2 = -3.618 \cdot 10^{-6}$, $b_0 = -0.1483$, $b_1 = 0.3220133$, $b_2 = -3.0062 \cdot 10^{-2}$, and $b_3 = 9.34458 \cdot 10^{-4}$.

The effects of particle size and rain intensity on the washout coefficient, as calculated by the revised formulation (11) were analysed by Baklanov & Sørensen [26] and it was shown that this formulation had a higher correlation with the measurement data compared with the formulation of Näslund & Holmström [43] and other formulations, which did not consider effects of the particle size.

Rainout

Beside washout below a cloud base, there are the following additional effects of wet deposition when air pollutants are transported inside clouds: 1) rainout between the cloud base and top (scavenging within the cloud), and 2) wet deposition caused by deposition by fog. The first process of rainout between the cloud base and top depends on the types of precipitation (i. e. convective or dynamic types).

The rainout coefficient for the convective precipitation is more effective/intensive than the washout coefficient, and it can be estimated (according to [44]) by the following formula:

$$\Lambda'_r(r_p, q) = a_0 q^{0.79}, \tag{12}$$

where: $a_0 = 3.36 \cdot 10^{-4}$. Crandall et al. [45] showed simulations of different mechanisms for rainout in which the rainout coefficient was not a strong function of the particle size.

The rainout coefficient for the dynamic precipitation is approximately equal to the washout coefficient, and hence, the rainout effect in this case can be also estimated by Eq. 11.

Snow scavenging

According to recent publications (e. g. [46, 44]) in most models the processes of scavenging by snow are described by the same formulae as for rain (e. g. eqs. 9, 11, and 12), but with other values of the scavenging coefficient, Λ. The values of Λ for snow are 2–10 times lower than the washout coefficient for rain with equivalent precipitation rates.

For scavenging by snow (according to [44]), the following simple formulation without any dependence of the coefficient Λ' on the particle radius could be used:

$$\Lambda'_s(q) = a_0 q^b, \tag{13}$$

where: $a_0 = 8.0 \cdot 10^{-5}$ and $b = 0.305$ for scavenging by snow below the cloud base and between the cloud base and top for dynamic precipitation; and $a_0 = 3.36 \cdot 10^{-4}$ and $b = 0.79$ for scavenging by snow between the cloud base and top for convective precipitation.

Radioactive decay

Radioactive decay transforms many basic dose contributing nuclides and should be taken into consideration for simulation of the possible radioactive contamination. The decay takes place in the following ways:

- — simple decay to non-radioactive elements;
- — radioactive daughter nuclides (B, or B1, B2);
- — secondary decay of daughter nuclides (C, D, etc.).

It is possible to split the DERMA modelling of the radioactive decay into two basic phases. The first phase is employed during the airborne transport of the short-living nuclides (like as ^{131}I). The second phase is employed after the airborne transport has been completed and the long-living nuclides (like as ^{137}Cs) have been deposited to the ground surface. This phase could be done in a separate subprogram/submodel.

For ^{131}I, the simulation of physical and chemical form of nuclides includes three forms of iodine: gaseous forms — elemental iodine and organic iodine (e. g., CH_3I), aerosol form — iodine attached to aerosol particles. During the first week, the gaseous forms of ^{131}I dominate. The dry deposition velocity, v_d, is corrected/ recalculated for 70 % of gaseous ^{131}I, and for the rest of the particles it is almost equal to v_d of SO_4 particles.

DERMA Model verification

Earlier comparisons of simulations by the DERMA model vs. ETEX experiment involving passive tracers showed good results. Institutions (in total 28) from the European countries, USA, Canada, and Japan contributed to the real-time model evaluation. Based on analyses from this experiment, the DERMA model was emphasised as being very successful [47]. In order to verify the deposition parameterisations and study effects of deposition, DERMA simulations for several cases (the INEX and RTMOD exercises, and Algeciras accidental ^{137}Cs release in Spain) were conducted taking into account different approaches for the deposition processes. In particular, the comparison of simulation results for the Algeciras accidental release with measurement data from the European monitoring network were analysed by Baklanov & Sørensen [26].

2.2. Input meteorological data for dispersion modelling

The DMI provides meteorological and related services within the large geographical area of the Kingdom of Denmark (including Denmark, the Faeroe Islands, and Greenland), and surrounding waters and airspace.

In our study, two types of the gridded datasets — DMI-HIRLAM and ECMWF — were used as input data. The DMI-HIRLAM dataset was used for the long-term (Fal 2001 — Fal 2003) modelling of atmospheric transport, dispersion, and deposition from risk sites of ^{137}Cs. The ECMWF dataset was used for the long-term (Jan 2000 — Dec 2000) modelling of atmospheric transport, dispersion, and deposition of three radionuclides — ^{137}Cs, ^{131}I, and ^{90}Sr — but only from one risk site (Leningrad nuclear power plant). The model runs based on different types of datasets were performed for comparison purposes, and first of all, to compare the accuracy of the wet deposition patterns. For the specific case studies, both datasets were used. The NEC SX6 supercomputer system of DMI was employed for the DMI-HIRLAM runs.

DMI-HIRLAM dataset

The DMI-HIRLAM high-resolution meteorological data (D-version: 0.05°, N- and E-versions: 0.15° or G-version: 0.45°, with output of 1 hour time resolution) are used as input data for the trajectory or dispersion simulations. The vertical model levels (31 levels in total — before December 2002, and 40 levels presently) are presently located at 33, 106, 188, 308, etc. meters for a standard atmosphere. The HIRLAM NWP model has been run operationally by DMI for the European territory and Arctic region since the late 1980s, but it can be run also for other geographical regions. The DMI 3D Lagrangian trajectory model [48] calculates forward and backward trajectories for any point in the area of interest. It can utilize meteorological data from different versions of DMI-HIRLAM as well as the ECMWF global model. The DMI weather forecasting system is based on HIRLAM 6.3 [31]. The forecast model is a grid point model. The data assimilation is intermittent and based on the 3-D variation data assimilation (3DVAR) scheme. The DMI-HIRLAM data can be used in the operational mode or from the archives.

ECMWF dataset

The meteorological data from the ECMWF (Reading, UK) are based on the ECMWF's global model forecasts and analyses having a resolution up to 0.5° × 0.5° latitude vs. longitude and 3 hour output time interval for both the Northern and Southern hemispheres. It consists of the geopotential, temperature, vertical velocity, horizontal components of wind, relative 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.

In this study, we used ECMWF data, available at DMI for the forecast mode or analysed and archived mode. Note, the horizontal resolutions of the meteorological data are different from year to year. For the year of 2000 the data had a resolution of 1° latitude × 1° longitude and 6 hour output time resolution. It consisted of temperature, horizontal components of wind, and specific humidity at each level, plus surface fields. Analyses have been carried out at 00 and 12 UTC.

2.3. Long-term dispersion modelling approach

The long-term dispersion modelling approach is another useful tool in the risk assessment methodology. In our study, the DERMA model (see § 2.1) was employed in a long-term simulation mode. It means that the simulation for a time period not shorter than one year (it could be months or seasons for some purposes as well) with a continuous or discrete release from a risk site. As input data, the model used meteorological operational forecast and archived analysed data (see § 2.2). The DERMA model can simulate radionuclide atmospheric transport, dispersion, and deposition for atmospheric releases of radioactivity at selected geographical locations.

The approach suggested for the long-term dispersion modelling has several important points and peculiarities depending on the particular problem studied as well as type of models used:

(i) type and parameters of release (continuous, discrete, periodical; height, etc);

(ii) time range for simulations: time limit for plume transport (e. g., number of days) and total study period (e. g., month, season, year, multiperiod);

(iii) radionuclides of main interest and their particle size distributions;

(iv) calculation of radioactive decay of deposited nuclides taking place after the end of the simulation period (i. e. for long-term consequence studies).

The main peculiarities of the Eulerian and Lagrangian types of models are important for the choice of the release type and time range for simulations. In general, the Lagrangian models involve a shorter computational time, because the Eulerian models perform calculations in every grid cell of the model atmosphere, whereas the Lagrangian models confine calculations to the limited volume of the plume. Regarding the advection properties, the Eulerian models need to use advanced and computationally expensive methods, whereas the Lagrangian models are inherently accurate. Besides, the Eulerian models respond to singularities such as a point source by creating numerical noise, which is not the case for the Lagrangian models. In case of Lagrangian model the time limit for plume (or particle) transport (e. g., number of days) is an important parameter due to related computational expenses. However, it can be controlled in the model by excluding further consideration of puffs leaving the study area or puffs reaching a lowest limit of concentration.

In our studies (using the Lagrangian model of DERMA), we found that the chosen limitation of puff modelling by 5–6 days after the release ended is suitable. The contaminated cloud, in general, has left the area of interest (30°N–90°N and 60°W–135°E) within this time period. For the Eulerian models there is no need to care about the lifetime of airborne release and to limit the simulation time for each released portion. Besides, the choice of the release type (continuous or discrete) does not affect the computation time in the Eulerian models.

The release height is also an important parameter. However, previous sensitivity studies [28, 17] showed that variations of the initial plume rise below the mixing height only slightly affected the results outside the local scale, while plume rise above that level led to significantly changed patterns with relatively little depositions on the local- and meso-scales. Thus, a release into ABL compared with a release to the free troposphere leads to large differences in the deposition patterns and lifetimes (a week or more) of radionuclides within the atmosphere. However, most accidental releases from risk sites initially rise to less than 700 meters [22].

The suggested approach can be realised practically by the following ways of using NWP data: (i) simulations from meteorological data archives, (ii) every day real-time runs using analysed NWP model data available in the NWP database followed by archiving of the dispersion simulation data. Certain national meteorological services perform daily forecasting of atmospheric dispersion from hypothetical accidental releases from a number of NPPs. Such data could be archived for long-term statistical risk analyses. However, the quality will be lower than for results based on analysed NWP data.

The simulated fields of air concentrations and depositions on the surface can be interpreted as:

(i) the long-term effects (accumulated or average contamination) of existing continuous release sources (ventilation emission from NRSs [e.g., ^{129}I from Sellafield, noble gases from NPPs], natural radioactivity emission [e. g., Rn products], industrial pollution, etc.);

(ii) the probabilistic characteristics of possible radioactive contamination of different territories in case of an accident at an NRS.

In the “Arctic Risk” NARP Project, several basic assumptions were followed in the long-term simulations.

First, for simplicity, for all risk sites the continuous hypothetical release of radioactivity (at a fixed rate of 10^{11} Bq/s) into the boundary layer with a discrete emitting of puffs (every 15 minutes) during 24 hours was selected. This release was called the “**u**nit **d**iscrete **h**ypothetical **r**elease” (UDHR). The total amount of radioactivity released during one day is equal to $8.64{\cdot}10^{15}$ Bq.

Second, only one radionuclide ^{137}Cs, as a radionuclide of key importance, was selected. However, calculation can be done for any of more than 300 radionuclides incorporated into database of the DERMA model. In particular, for the specific case studies — ^{131}I and ^{90}Sr were selected additionally. For one NRS (Leningrad nuclear plant) these two radionuclides were also used for long-term simulation. Note, the simulations for many nuclides request a longer computing times. However, this time is not proportional to the number of nuclides considered. Run times for DERMA simulations as a function of the number of simultaneously handled nuclides are presented in fig. 2.

Third, the simulations for all risk sites were performed for a multiyear period (Fal 2001 — Fal 2003, and continue during years of 2004–2005) on a daily basis considering the length of the 5-day trajectories (i. e. after release of radioactivity occurred from the site, the tracking of the contaminated cloud was limited to 5 days of atmospheric transport from the site). The DERMA model was run daily (between 2–6 a.m.) on the SGI Origin scalar server of the DMI computer system. The dispersion modelling results were compressed and archived on the DMI UniTree mass storage system (as the first backup of data) as well as recorded on CDs (as the second backup of data). The directory size of each daily run varied between 35–50 Mb (or up to 1.5 Gb per month).

Fourth, to minimize the computing resources, in our study we selected only one year, although note that for the statistical analysis the multiyear period is more preferred.

Fifth, as input data for the DERMA model runs, the meteorological fields simulated by the DMI-HIRLAM model were used when modelling for ^{137}Cs. As input data in a separate run of the DERMA model the ECMWF meteorological fields were used when modelling for all three radionuclides — ^{137}Cs, ^{131}I, and ^{90}Sr — for the Leningrad plant.

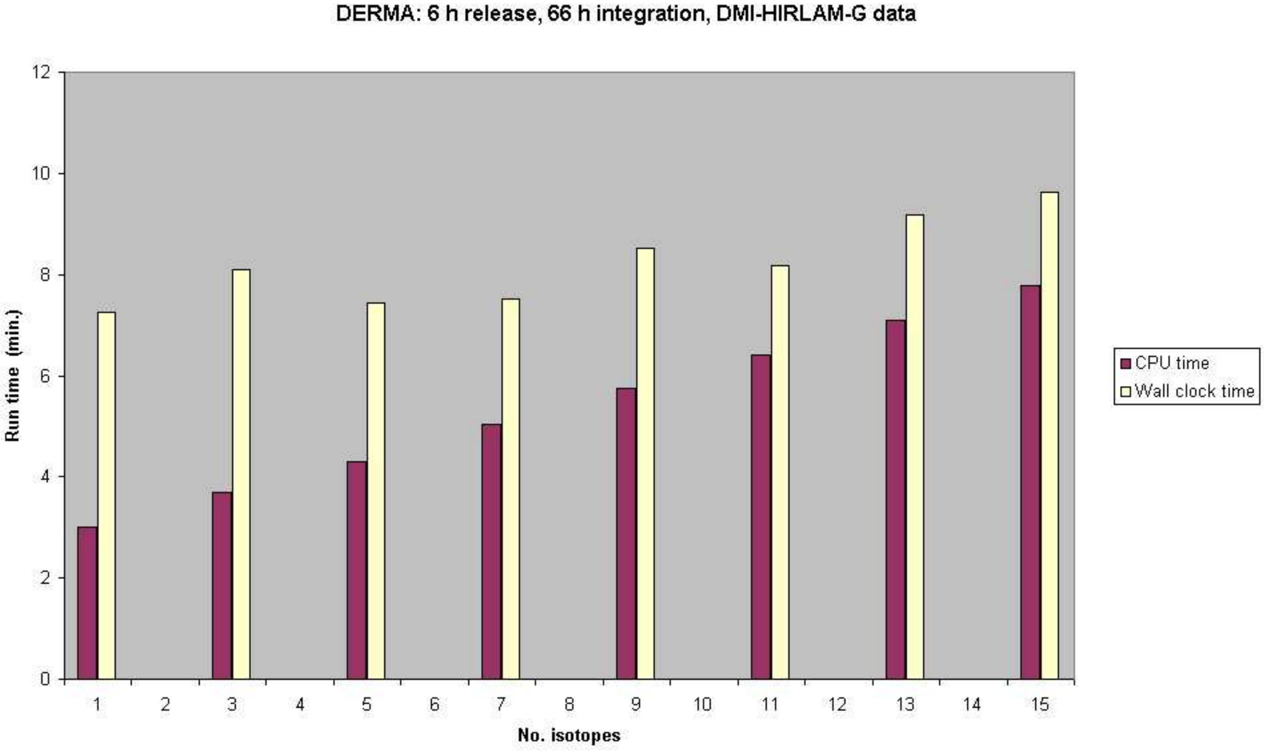

Fig. 2. Run times for the DERMA simulations as a function of the number of simultaneously handled isotopes (the simulations involved 66 hours integration corresponding to 6-hours release and used the DMI-HIRLAM-G model data).

Sixth, several important variables were calculated: 1. air concentration (Bq/m^3) of the radionuclide in the surface layer; time-integrated air concentration (Bq·h/m^3) of the radionuclide in the surface layer; and dry and wet depositions (Bq/m^2) of the radionuclide on the underlying surface. Note, the total deposition for a radionuclide can be calculated as a sum of the dry and wet depositions. All calculated variables can be represented by 2D fields where the value of the calculated variable is given in the latitude-longitude grids of the model grid domain. The output fields were recorded in separate output files every 3 hours starting from the moment of release.

Seventh, the calculated variables were extracted and incorporated into a new grid domain in the region of interest. The new domain covers territories of the North Atlantic and Arctic Oceans, and Eurasian continent between 30–89°N and 60°W–135°E. It has a resolution of 0.5° latitude vs. 0.5° longitude. It consisted of 391 vs. 119 grid points along longitude vs. latitude. To save storage space, the recalculated fields were re-recorded every 6 hours instead of original 3-hour intervals. Moreover, because of missing data in the archives and processing problems, we did not calculate fields for a few percent for some days during studied period.

An example of the DERMA model simulations (using the DMI-HIRLAM dataset) is shown in fig. 3. As shown on the top plate of the figure, the contaminated cloud originated over the Novaya Zemlya Archipelago travelled initially over the Barents and Kara Seas, and then passed over the large areas of the Russian Arctic territories in the southern direction arriving to Siberia with westerlies. It even reached the northern borders of Kazakhstan. The "sharp cut" of the cloud over this region is due to the limitation of the G-version of the DMI-HIRLAM model. The

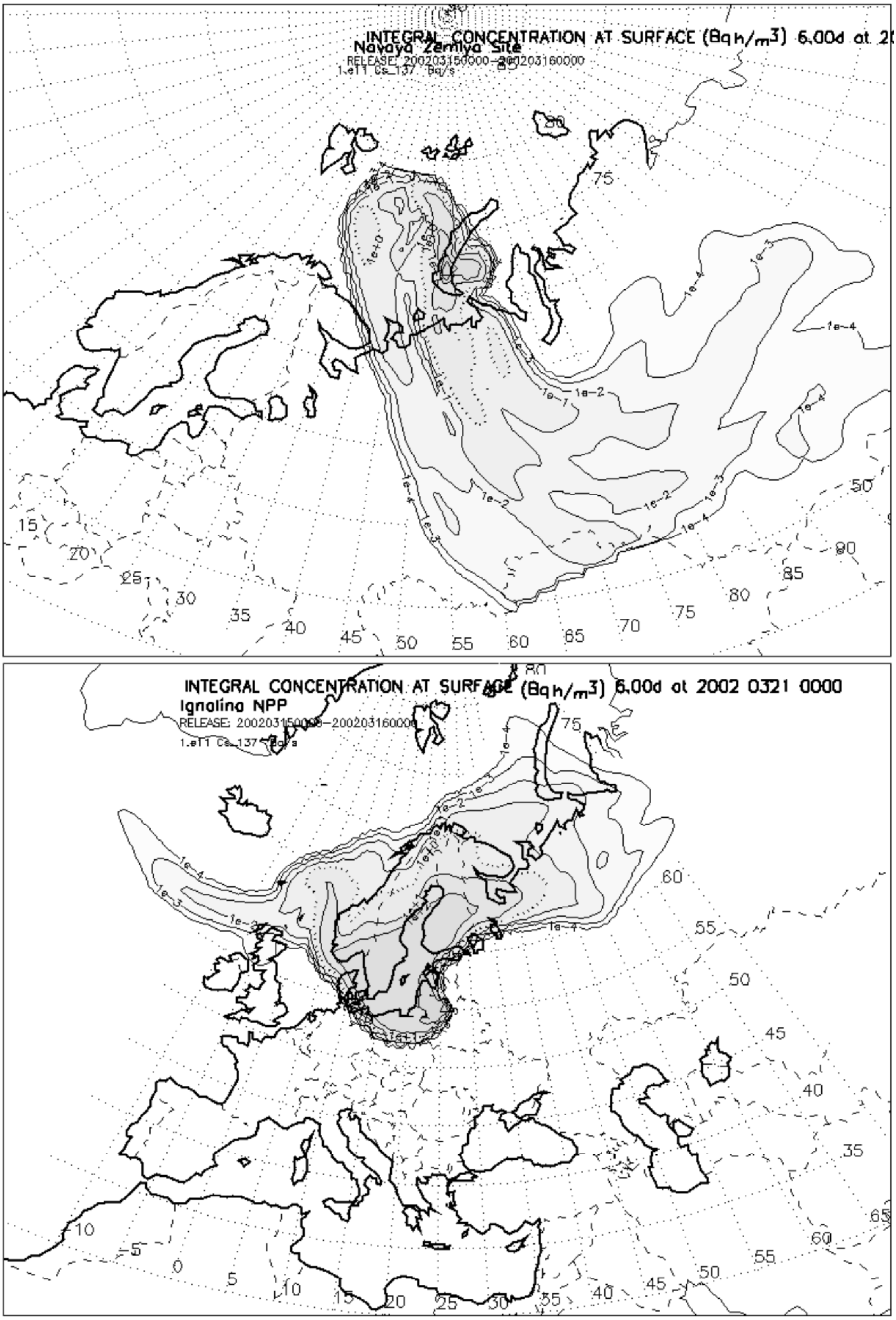

Fig. 3. ^{137}Cs time integrated air concentration at surface after 6 days of the "unit discrete hypothetical release" occurred during 15–16 March 2002, 00 UTC at the Novaya Zemlya test site (top) and Ignalina nuclear power plant (bottom).

bottom plate shows that the contaminated cloud was transported in both the north-eastern and north-western directions from the site passing over the Baltic States, Nordic countries, Poland, Belarus, Northwest Russia and aquatoria of the North Atlantic and Arctic seas.

Detailed analysis of the long-term dispersion modelling results for selected nuclear risk sites of the Euro-Arctic region is given by [49].

3. Conclusion

In this study, we have outlined developed a methodology for risk and vulnerability assessment and mapping. The main question to answer was: Which regions are at the highest risk from a hypothetical accidental release at an NRS?

To answer this question we suggest applying a variety of research tools considering them as a sequence of interrelated approaches. Among these tools are the following: atmospheric trajectory and dispersion modelling, methods of statistical analysis, specific case studies, evaluation of vulnerability to radioactive contamination, and risk evaluation and mapping.

In comparison with the previous studies the methodology considered in this paper focuses on the long-term dispersion and deposition modelling, statistical analysis of dispersion modelling results.

We assume that the suggested approach for risk assessment provides useful information for further studies and it is applicable for the:

(i) initial estimates of the probability of atmospheric transport and deposition in case of an accidental release at an NRS;

(ii) improvement of emergency preparedness to possible accidents at an NRS;

(iii) social and economical consequence studies of the impact for the populations and environment of the neighbouring countries;

(iv) multidisciplinary risk and vulnerability analysis, probabilistic assessment of radionuclide meso-, regional-, and long-range transport.

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