UDC 504.75.05:504.3.054+66.011

A. Mahura[1], *Ph.D.*, **A. Baklanov**[1], *Prof.*, **S. Hoe**[2], *Ph.D.*, **J. H. Sørensen**[1], *Ph.D.*, **C. Petersen**[1], *M.Sc.*
[1]*Danish Meteorological Institute, Copenhagen, Denmark*
[2]*Danish Emergency Management Agency, Birkerød, Denmark*

CHANGES IN METEOROLOGICAL AND ATMOSPHERIC TRANSPORT AND DEPOSITION PATTERNS DUE TO INFLUENCE OF METROPOLITAN AREAS

Abstract. *The spatial and temporal variability of the meteorological (for temperature and wind), concentration and deposition fields resulted from hypothetical accidental releases occurred in the metropolitan area is evaluated on an example of the urban area of Copenhagen, Denmark. Dependence of these fields on the temporal variability of meteorological variables in the lower surface layer was estimated as a function of modified parameters.*

Keywords: *urbanization of numerical weather prediction model, anthropogenic heat flux, roughness, urban fabric, hypothetical accidental release of radioactivity.*

1 Introduction

In urban areas, in contrast with rural areas, the urban boundary layer is more complex, and hence, it requires a special treatment. The surface energy balance is the major equation used in many models to evaluate thermodynamical and dynamical patterns above the ground surface. In respect with the urban areas it includes the storage, sensible, and latent heat fluxes (plus, anthropogenic heat flux). The urban areas are characterized by the local-scale inhomogeneties, sharp changes of roughness and heat fluxes. In these areas the wind velocity and redistribution of eddies are changed due to effects of buildings. Moreover, the trapping of radiation in street canyons is observed as well as there is influence of urban soil structure, diffusivities heat and water vapor content. In addition, such areas are affected by anthropogenic heat fluxes and are seen as so-called the urban heat islands with specific structures of internal urban boundary layers and dependent urban mixing heights. The effects of pollutants emissions due to traffic, their transformations, and substantial changes in land cover are of importance for the urban meteorology and climate as well. All these urban features influence formation of airflow, its turbulence regime, microclimate, and accordingly modify transport, dispersion, and deposition of atmospheric pollutants in urban areas.
In this study, we focus on evaluation of effects of urbanization in numerical weather prediction (NWP) modelling on simulated meteorological and pollution patterns over the urbanized areas and surroundings of the Copenhagen metropolitan area (Denmark). The main objectives of the study include, at first, the modification of the existing NWP land surface scheme using different approaches: 1) anthropogenic heat flux and roughness (AHF+R), 2) building effect parameterization (BEP) and 3) soil model for submeso scales urban version (SM2-U) modules. At second, we perform simulations of meteorological fields using DMI-HIRLAM model in two modes/runs: control and modified/urban, and for two types: selected case studies and long-term simulations over selected period of time. At third, then for the case studies: we simulate on a diurnal cycle pollution patterns (concentration and deposition fields) for selected specific dates reflecting different atmospheric conditions such as low, typical, and high winds conditions. For case studies we evaluate effects of urbanization on structure of concentration and deposition fields resulted from hypothetical accidental releases in urban areas. For all types of runs we evaluate effects of urbanization on temporal-spatial structure and variability of meteorological fields by estimation on a diurnal cycle the differences between control and urban runs for meteorological variables (temperature, wind velocity,

relative humidity). In our study, the diurnal variations of meteorological fields in the low surface layer produced by the NWP model are evaluated taking into account modifications done in the Interaction Soil-Biosphere-Atmosphere (ISBA) land surface scheme. The variability in spatial distribution of concentration and deposition patterns produced by the Local Scale Chain Model of the ARGOS system is also analyzed. Combined impacts were estimated for the Copenhagen metropolitan area and surroundings.

2 Methodology

2.1 Meteorological modelling

The present DMI weather forecasting system [9] performs daily forecasts of meteorological fields employing the HIgh Resolution Limited Area Model (HIRLAM) model [10] consisted of two nested models called DMI-HIRLAM-S05 and -T15 with horizontal resolutions of 5 vs. 15 km, respectively. The boundary conditions for T15 are supplied every 6 hours from the ECMWF model. The recent operational DMI model is semi-implicit, with semi-Lagrangian advection and leapfrog time stepping (with the semi-Lagrangian advection as optional). Physics such as short and long wave radiation, turbulence (except gravity wave drag), deep and shallow convection, cloud, and precipitation generation and air-sea/air-land interactions are parameterized. There are also experimental research DMI-HILRLAM models with a higher resolution such as DMI-HIRLAM-U01/I01 models. These models run mostly with a focus on the Copenhagen metropolitan area. The main assumptions in these models are identical to the operational versions, and boundary conditions are taken from S05. Moreover, the land use classification for the current version of DMI-HIRLAM is based on several datasets including high resolution CORINE dataset. In HIRLAM some fields, such as roughness, albedo, vegetation type, orography, etc. are assumed to be constant in modelling domains during operational runs. These fields are once produced and stored in the climate generation files and are available for analyses and forecasts. Modifications for the urban effects, considered in the following section, were included into high resolution runs.

2.2 Urbanization

There are several ways of improving the NWP forecasting due to inclusion of urban effects. The urbanisation includes the following aspects and processes (*Baklanov et al., 2008*): 1) down-scaling, including increasing vertical and horizontal resolution and nesting techniques; 2) modified high-resolution urban land-use classifications, parameterizations and algorithms for roughness parameters in urban areas based on morphologic methods; 3) specific parameterization of urban fluxes; 4) modelling/ parameterization of meteorological fields in the urban sublayer; 5) estimation of the urban mixing height based on prognostic approaches. In particular, for our study, several ways of urbanization were tested for specific dates and long-term runs and these include several modules [1,4]. The first module (which considers modifications of the roughness and anthropogenic heat flux – AHF+R – is the cheapest way of "urbanizing" the model and it can be easily implemented into operational NWP models. The second – Building Effect Parameterization (BEP) [6] – module gives a possibility to consider the energy budget components and fluxes inside the urban canopy although it is a relatively more expensive (≈ 5 % computational time increase) [4]. However, this approach is sensitive to the vertical resolution of NWP models and is not very effective if the first model level is higher than 30 meters. Therefore, the increasing of the vertical resolution of current NWP models is required. The third – Soil Model for SubMeso Urbanized (SM2-U) version [2,3] – module is considerably more expensive computationally than the first two modules [4]. However, the third one provides the possibility to study accurately the urban soil and canopy energy exchange including the water budget. Therefore, the second and third modules can be used in advanced urban-scale NWP and meso-meteorological research models.

2.3 Pollution modelling

To simulate atmospheric transport, dispersion, and deposition resulted from hypothetical accidental releases of radioactive matter from a selected location the ARGOS system with the Local Scale Model Chain (LSMC) [8] was employed. It consists of the atmospheric dispersion model called RIso Mesoscale PUFF (RIMPUFF) model [7]. In consisted of plume rise, inversion, ground level reflection, and gamma dose formulations and algorithms. The model output includes the surface level air concentration, deposition, and gamma dose rates. As input, the 3D meteorological fields produced by the DMI-HIRLAM model were used. For all selected dates the release point is located in the Copenhagen metropolitan area, the duration of release is equal to 12 hours (i.e. starting at 03 UTC and ending at 15 UTC), the radionuclide considered is ^{137}Cs, and the emission rate is equal to 10^{11} Bq/s.

3 Results and discussion

3.1 Models runs and analysis

The HIRLAM research model (with a resolution of 1.4 km) was run with modified land use and climate generation files. The meteorological fields' simulations were driven using the HIRLAM-S05 model boundary conditions. Several specific dates – low wind conditions, high precipitation, high winds, and typical conditions – were studied in details. The land surface scheme was modified for urban cells represented domain. For each specific date several independent runs were performed for: no modifications in scheme. The meteorological fields serve as input in many applications, and especially in those related to atmospheric pollution tasks, and these were used to simulate atmospheric transport, dispersion, and deposition of short- and/or long-term releases of harmful matter. I.e. afterwards the Local Scale Model Chain of the ARGOS system was employed to simulate the atmospheric transport and deposition of hypothetical accidental releases. Finally, the diurnal cycle of meteorological variables was analyzed comparing (difference fields at each UTC term) outputs from control run with those where changes were made.

3.2 Comparison of AHF+R and BEP urban modules

For the first two – AHF+R and BEP – urban modules the short- and long-terms runs during summers of 2004–2005 were performed employing DMI-HIRLAM high resolution model. Several specific dates were selected using the wind velocity and direction from the surface and radiosounding observations as criteria. These dates have represented typical, low, high winds and high precipitation conditions for atmospheric transport over the Island of Zeland (Denmark) where Copenhagen is situated. In these runs in the ISBA scheme, the roughness for cells (where the urban class was represented in the modelling domain) was increased up to 2 m; the contribution of the anthropogenic heat flux ranging from 10 to 200 W/m^2 was incorporated into the scheme; as well as typical characteristics of different urban classes was included. The diurnal cycle of meteorological variables such as wind velocity (at 10 m) and temperature (at 2 m) was analyzed comparing outputs of the control run vs. runs with modified parameters in urban cells. At each UTC term, the 2D (values in latitude vs.

longitude gridded domain) difference fields for mentioned variables were produced/analyzed by subtracting outputs from the control run without any changes made vs. run with changes made using different urban modules (as shown in Figs. 1 and 2 for the AHF+R and BEP urban modules).

(a) (b)

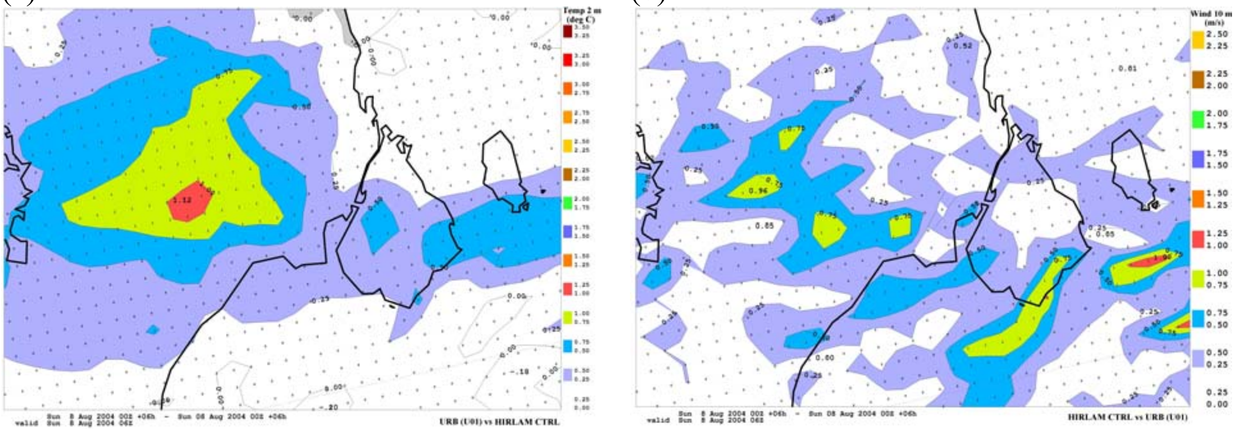

Fig. 1 – Difference fields between the control vs. urbanized (AHF+R module) runs of the DMI-HIRLAM model for the (a) air temperature at 2 m and (b) wind velocity at 10 m on 08 Aug 2004, 06 UTC.

(a) (b)

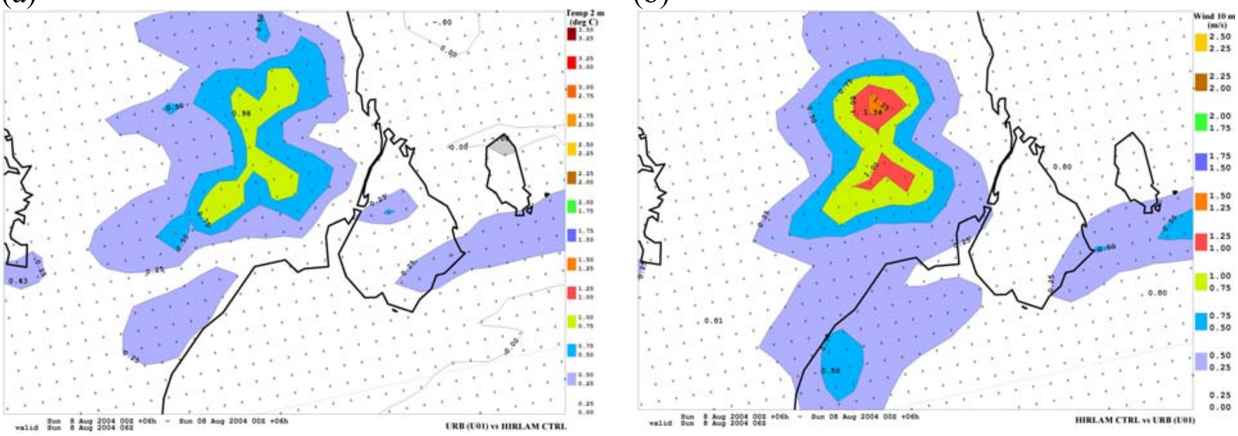

Fig. 2 – Difference fields between the control vs. urbanized (BEP module) runs of the DMI-HIRLAM model for the (a) air temperature at 2 m and (b) wind velocity at 10 m on 08 Aug 2004, 06 UTC.

It was found, that for the low wind conditions (LWC) dates, the modified run showed an increase in temperature at 2 m over the urban areas. This increase was more than 1ºC during 18-06 UTC (with a maximum of more than 1.5ºC at 04-05 UTC), and it was less than 1ºC during 07-17 (with a minimum of 0.5ºC at 16-17 UTC). On average, decrease in wind velocity at 10 m was around 2 m/s during nighttime, and it was up to 1.5 m/s during daytime, with a maximum of more than 3 m/s. For the typical wind conditions (TWC) date, the urbanized run showed also increase in temperature at 2 m, but this increase was substantially lower than for LWC. For the high wind conditions (HWC) date, during all terms the temperature increase over the urbanized areas was always less than 0.3ºC (with higher values at early morning hours). On average, the decrease in wind velocity at 10 m was less than 0.5

m/s during evening and nighttime hours, and it became slightly larger after late morning hours reaching a maximum of 1.5 m/s at 15 UTC. For the high precipitation conditions (HPC) date, the temperature differences over the urban areas showed a variability of up to 1ºC, but a clear pattern on a diurnal cycle was not identified. Similar situation was also observed for the wind velocity.

3.3 Modeled temperatures of surfaces using SM2-U module

The SM2–U module was used to estimate the month-to-moth variability of the main meteorological variables as well as the net radiation, sensible, latent, and storage heat fluxes for different parts of the city as well as different types of the underlying surfaces. Here, let's focus on the surface temperatures. For the Copenhagen metropolitan area throughout the year the mean temperature of the surface is always positive for the artificial and water surfaces compared with other types. The highest temperatures are characteristic for the artificial and building types in July reaching up to 22 and 20.3ºC, respectively (with maxima of 31.3 and 35.4ºC in some cells of domain containing these types). But in August, the soil and water has own highest (on an annual scale) mean temperatures of 15.6 and 18.7ºC, respectively. During December-February, for the vegetation on artificial and natural surfaces, bare soils and building types (November – also for the both vegetation on natural and artificial surfaces), the temperature is negative, although in other months it is always positive with maxima in July. During September-March, it is the lowest for both the vegetation on artificial and natural surfaces among other land types of surfaces. In January, in some cells it reached even -7.6ºC, although on average it was –4.7ºC during this month. Note, in some cells of domain, for these two types the negative temperatures can be observed starting already in August and extended farther into April. For urban type, such situation is observed during November-April. The averaged modeled surface temperature in January is shown in Fig. 3.

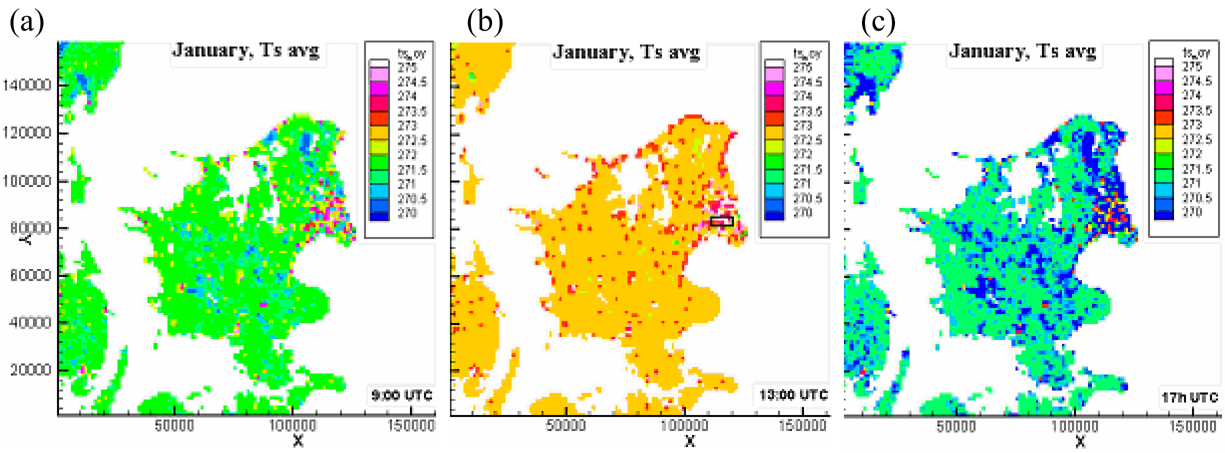

Fig. 3 – January surface temperature (deg K) simulated using SM2-U urban module for the Copenhagen metropolitan area/ averaged over 7 types of surfaces/ at (a) 09:00, (b) 13:00, and (c) 17:00 UTCs.

On a diurnal cycle, the temperature variability of the water surface is significantly smaller compared with the "land" types of surfaces. The largest difference is seen between vegetation on artificial and natural vs. completely artificial surfaces reaching of more than 5ºC during 16-04 hours (maximum of 8ºC at 18 h). Moreover, the daily maximum of the artificial surface temperature is comparable with other urban types of surfaces, although occurred 2 hours later. The minima are characteristic for the both vegetation on natural and artificial surfaces during the late evening and night hours.

The monthly and diurnal cycle variability of the mean surface temperature (calculated taking into account influence from all types of surfaces presented in each grid cell) varies for different types of urban districts such as the high buildings, industrial commercial and residential districts. For the HBD cells, on a diurnal cycle, the temperature is always positive (i.e. above 0ºC) during May-October. Beginning of January it became positive (but only less than 1ºC) between 11–12 hours. Further, the duration of positive temperatures is increased gradually until April, as well as it gradually decreased during November-December. The daily maximum of up to 30ºC can be observed in July in the middle of the day, and a minimum of -6ºC in January in the late evening hours. For the ICD cells, on a diurnal cycle, the positive temperatures are dominant during all months, except January-February. Moreover, they also positive, at least, during 08-16 h for these two months. Similarly to the HBD cells, the daily maximum (33ºC) can be observed in July in the middle of the day, and a minimum (-0.4ºC) in January in the late evening hours. Moreover, for CC/HBD, the monthly variability showed that throughout the year, except December-February, the daily mean temperature is always positive. Note, for ICD – it is always positive.

3.4 Changes in pollution patterns

The differences in concentration and deposition fields resulted from modifications of the land surface scheme were estimated. The impacts of these on the Copenhagen metropolitan area of Denmark and surroundings were evaluated for different meteorological situations. It was found that only for the low wind conditions, the differences in concentration and deposition patterns were significant. It has been characterized by a wider spreading of the contaminated cloud over the urbanized areas and surroundings (example is shown in Fig. 4 for 19 June 2005), and hence, affecting a larger group of population. For the typical and high wind conditions, there are no significant differences between the control vs. urban runs, due to smaller changes in meteorological variables' values on a scale of diurnal cycle as well as smaller sizes of urbanized areas affected by these changes. For the high precipitation conditions, the situation is more complex due to substantial removal of pollution from the contaminated cloud at the initial stages of emissions into the atmosphere.

(a) (b)

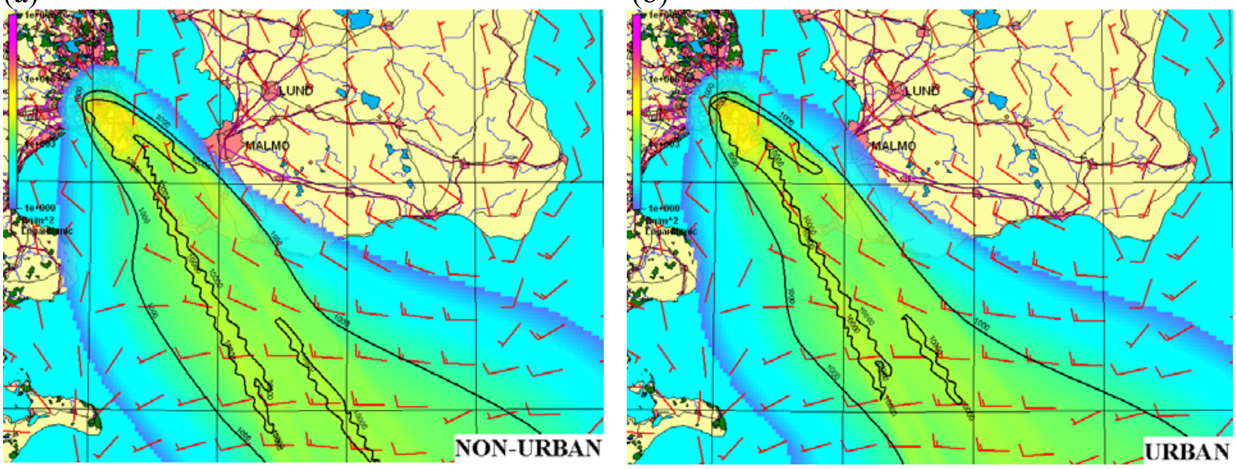

Fig. 4 – Total deposition patterns of ^{137}Cs resulted from hypothetical accidental release in the Copenhagen metropolitan area /logarithmic scale ranging from 1 to 1e+9 Bq/m2/.

4 Conclusion

In our study, the spatial and temporal variability of meteorological and contamination patterns (resulted from hypothetical accidental releases of harmful matter) is analyzed for urban areas. For that, the short- and long-term runs, employing the operational model of high resolution, were performed with different urban modules such as AHF+R, BEP, and SM2-U integrated into the land surface scheme of the meteorological model.

It was found that such modify the structure of the surface layer wind and temperature fields over urban areas. On average, the decrease in wind velocity is the highest for low wind situations, and it is the lowest for the high winds. Similarly, the average increase in temperature is the highest for the low winds, and it is the lowest for others. The urbanization of meteorological model with modified roughness, anthropogenic heat fluxes, and building effects allowed the modelling of effects over urbanized areas. On average, the differences between NWP control vs. urbanized runs over the Copenhagen metropolitan area and surroundings were the following. For the typical wind conditions, the differences for the air temperature are less than 0.3ºC (with a maximum up to 0.5 ºC, at nighttime) and the wind velocity are less than 0.5 m/s (with a maximum up to 1.5, at midday). For the low wind conditions, the differences for the air temperature at 2 m are more than 0.5ºC (with a maximum up to 1.5ºC, at nighttime) and for the wind velocity are more than 1 m/s (with a maximum up to 3 m/s, at nighttime).

The significant differences in concentration and deposition patterns were observed only for the low wind conditions. For the typical and high wind conditions, there are no large differences in spatial and temporal structure of pollution related patterns. For the high precipitation situations, this impact was not observed due to substantial removal of pollution at the initial stages.

It can be summarized that in specific meteorological situations, especially during the low wind conditions, the urban effects may be of considerable importance over the large metropolitan areas. The high-resolution simulations with urbanization showed a slight improvement in overall NWP model performance (where this improvement is more significant over the urban areas), and it provides a possibility to incorporate the urban effects into NWP modelling.

Acknowledgments. Thanks to the DMI Computer Support and HIRLAM group for the collaboration. The DMI facilities of NEC SX6 had been used for simulations. This research has been done within the frameworks of the DMI-Enviro-HIRLAM project activities.

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Изменения метеорологических полей, атмосферного переноса и выпадения за счет влияния урбанизированных территорий

Аннотация. *Пространственная и временная изменчивость метеорологических полей (температуры и ветра), концентрации и выпадения при гипотетических аварийных выбросах происходящих на урбанизированной территории оценивается на примере Копенгагена (Дания). Зависимость этих полей от временной изменчивости метеорологических величин в нижнем приземном слое оценивается как функция модифицированных параметров.*

Ключевые слова: *урбанизация численной модели прогноза погоды, антропогенный поток тепла, параметр шероховатости, городская застройка, гипотетический аварийный выброс радиоактивности.*