A SIMPLIFIED APPROACH FOR SOLUTION OF TIME UPDATE PROBLEM DURING TOXIC WASTE PLUME SPREADING IN THE ATMOSPHERE

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Abstract: Reliable and up to date information represents principal prerequisite for effective management of intervention operations targeted on emergency situations during accidental releases of harmful substances into the atmosphere. Promising way of this trend insists in development of assimilation techniques for improvement of model prognosis reliability on basis of optimal blending of predictions with observations incoming from terrain. In this paper we are concentrating on the forecast procedure which generates the new state predictions from the initial conditions standing for previous time. Two problems are encountered here. At first, the resulting predictions from the previous time step can be assimilated with incoming data before the next time predictions are evaluated. The initial conditions for the next time are then modified in advance and trajectory information accumulated from the same beginning can become fuzzy. So, the trajectory models can have troubles how to propagate plume in the next time. At second, reliable and up to date information at medium distances from the source of pollution represents basic inevitable conditions for effective management of intervention operations targeted on consequence mitigation during emergency situations. But justifiability of Gaussian plume model application in medium range distances is questionable. A simplified solution offers segmented Gaussian plume model (SGPM) which can account stepwise for the time dynamics of the admixture release and hourly changes of meteorological conditions. The extension of modelling to medium distances is facilitated by availability of the new quality of gridded spatial short-term meteorological forecasts. The Czech meteorological service provides 3-D data in ALADIN format for medium domain 160 km × 160 km around each nuclear power plant (NPP) in the Czech Republic. In the following text we are describing the SGPM application in longer distances taking into account the new gridded meteorological predictions. The comparison with former methodology is illustrated on one real meteorological situation from June 25, 2008.

Key words: *Gaussian plume, Mesoscale domain, 3-D meteorological forecast, Time update, Data assimilation.*

1. THE MAIN OBJECTIVES OF RESEARCH ACTIVITIES

The definitive aim of our development is construction of proper software tool which could support some partial procedures of decision-making during nuclear emergencies (Hofman, 2007). From this global view the effort should accept recent trends in risk assessment methodology insisting in transition from deterministic procedures to probabilistic approach, which enables generate more informative probabilistic answers on assessment questions (our approach in (Pecha, 2005)). Corresponding analysis should involve uncertainties due to stochastic character of input data, insufficient description of real physical processes by parametrisation, incomplete knowledge of submodel parameters, uncertain release scenario, simplifications in computational procedure etc. Simulation of uncertainties propagation through the model (Irwing, 2004) brings data not only for the probabilistic assessment mentioned above but also for another main task of analysis called assimilation of model predictions with real measurements ncoming from terrain. Data assimilation represents the way from model to reality and can substantially improve precision of model predictions. Nevertheless, an inevitable prerequisite for any of the global tasks is availability of reasonable code for basic deterministic predictions of environmental pollution. The main problem of such analysis evidently inheres in necessary compromise between computer code speed and attained precision of the results.

2. MOTIVATION FOR CHOICE AND DEVELOPMENT OF ENVIRONMENTAL MODEL

Methods selected for predictions of harmful admixtures propagation and subsequent consequences on population health differ in dependency on dimension of analysed domain and the phase of accident. Considerations should distinguish various domains with different scales and typical resolutions from microscale through mesoscale up to regional or continental. Our interest is concentrated on mesoscale domain up to 100 km around each NPP. Here we are limited on early phase of accident sometimes called “plume phase” starting from the same beginning of the accidental atmospheric release up to the moment when cloud leaves observed domain. Time scale of the plume phase is several hours to a few days. The advanced technique of advection and dispersion modelling is formulated by Lagrangian or Eulerian approach. We still use the traditional Gaussian dispersion scheme and introduce a certain modifications in order to extend the bounds of its applicability. Even simple, the Gaussian model is consistent with the random nature of turbulence, it is a solution of Fickian diffusion equation for constant K and u (Hanna et al., 1982). It is tuned to experimental data and offers fast basic estimation with minimum computation effort. This plays decisive role for analysis of uncertainty propagation through the model based on Monte Carlo modelling (Pecha, 2005). Proved semi-empirical formulas are available for approximation of important effects (Hanna) like:

- interaction of the plume with near-standing buildings,
- momentum and buoyant plume rise during release,
- power-law formula for estimation of wind speed changes with height,
- depletion of the plume radioactivity due to removal processes of dry and wet deposition, dependency on physical-chemical forms of admixtures and land-use characteristics,

- description of inversion situation, plume penetration of inversion, plume lofting above inversion layer,
- approximate account for small changes in surface elevation, terrain roughness, land-use type etc.

Former development of Gaussian dispersion model was concurrently enforced by lack of proper and detailed input data. Further advance and increasing knowledge called for radical readjustment to bring the models in compliance with the latest state of art in the field. Typical example of this way is impact of progress in online meteorological forecasting on advancement in dispersion modelling. The Czech Hydro-Meteorological Institute (CHMI) provides short-term meteorological forecasts which are online available for us for purposes of modelling of pollution dispersion.

3. PREPROCESSOR OF METEOROLOGICAL FORECASTS FOR DISPERSION MODELLING

Meteorological preprocessor (MP) is an independent part of our environmental model HARP. It's main purpose is to convert spatial and temporal meteorological data provided by the Czech-Hydro-meteorological Institute into format supported by ADM submodel of the HARP system. Two kinds of short-term meteorological forecasts are generated and transmitted from CHMI to database centre of the State Office for Nuclear Safety:

- Short--term meteorological forecast for location of each NPP (Dukovany, Temelin). Hourly data for the next 48 hours are transferred to ORACLE database. Assimilation of meteorological data with measurements is performed in 12 hours lasting period. Quartet of values forecasted for each hour comprises wind direction, wind speed, category of atmospheric stability according to Pasquill, atmospheric precipitation. Wind is related to reference meteorological height 10 meters.
- Gridded 2-D and 3-D meteorological data on mesoscale region 160 × 160 km around each NPP. Resolution of the rectangular grid is 9 × 9 km. Forecast on the next 48 hours updated according to the latest measurements is provided every 12 hours and transferred to ORACLE database. The data packets are transmitted in ALADIN format, which splits the data into two groups according to their structure. The single-level fields is the data related only to a certain spatial location (precipitation intensity, fraction of land, roughness etc). Multilevel data (wind speed, wind direction etc) for 12 levels of geopotential height up to 1500 m is provided. From this data can be via interpolation evaluated the quantity of interest in an arbitrary point.

The fact that the calculation grid used in the HARP is not rectangular but polar and its finest precision in the surroundings of NPP begins at 1 km implies that the ALADIN data has to be via interpolation resampled. This can be efficiently done in MP which also allows for visualization of both the 2-D and 3-D data. MP can be run in two modes. Basic mode provides values of wind speed u_{10} and wind direction φ_{10} in the points of polar grid at reference height 10m. For estimation of wind speed changes with height is used classical power-law formula. Particularly, for wind speed $u(H_{ef})$ at effective height H_{ef} or for average wind speed $\bar{u}(10,H_{ef})$ between height 10 meters and H_{ef} are used expressions:

$$u(H_{ef}) = u_{10} \cdot (H_{ef}/10)^p \quad ; \qquad \bar{u}(10,H_{ef}) = \frac{u_{10}}{10^{\varepsilon} - drs^{\varepsilon}} \cdot \left(\frac{H_{ef}^{\varepsilon}}{\varepsilon+1} - drs^{\varepsilon}\right) \qquad (1)$$

The power p and coefficient ε are estimated for six categories of atmospheric stability according to Pasquill classification and for urban and rural type of terrain roughness *drs* [m]. In advanced mode user obtains values of wind speed and direction in a given height by interpolation of forecasted values in 3-D. It is also possible to obtain forecasted values of rain intensity [mm/hour] in polar grid points on demand. Incorporation of this information into dispersion model allows accounting for the local precipitation which has major influence on deposition processes and consequently on the radioactive plume spreading.

4. SYNCHRONIZATION OF RELEASE DYNAMICS WITH METEOROLOGICAL FORECAST

Complicated scenario of release dynamics has to be synchronized with available meteorological forecasts. The total release interval is split into a certain number of equivalent one-hour intervals. Using assumption of activity conservation, corresponding one-hour release segment with constant release source strength is assigned to each interval. Each one-hour segment is modelled in its all subsequent hourly meteo-phases when stepwise segment movement is driven by meteorological forecast for the corresponding hours. The final solution is given by superposition of results of all segments in all their consecutive phases of movement.

The movement is modelled in correspondence with quality of available meteorological forecast. Different algorithms distinguish different assumptions related to the type of hourly changes implementation:

Scheme 1: Meteorological fields are constant during the whole release until the radioactive cloud leaves observed terrain (*time constant, spatially constant*).

Scheme 2: Each hourly segment of release is driven by hourly meteorological conditions that are changing in time (each hour) but in the same way in the whole region at once (*time dependant, spatially constant*)

Scheme 3: Each hourly segment of release is driven by hourly meteorological conditions that are changing in time (each hour) and space (*time dependant, spatially dependant*)

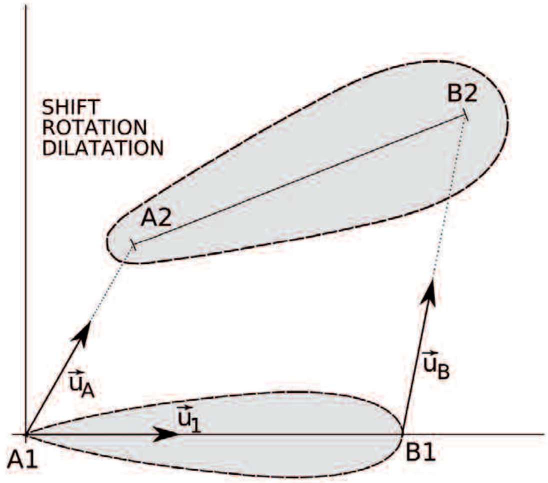

Figure 1. ***Scheme 3*** - Hourly meteorological conditions are changing in each hour and in the whole space (time dependant, spatially dependant).

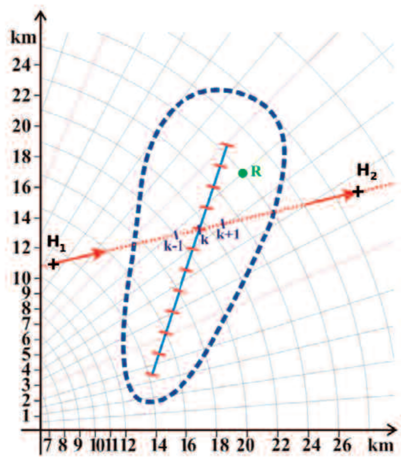

Figure 2. Stepwise simulation of the plume segment movement from hour H1 to hour H2 by elemental shifts *k*.

The simplest solution of diffusion equation implements ***Scheme 1*** and assumes mean velocity u (usually in effective height) constant in time and space, which is taken from meteorological measurements or forecast related to the point of NPP. All segments are overlapping and form the Gaussian straight-line plume. It is evident, that this straight-line solution is limited for its use to short distances from the source (up to few tens of kilometres). As was mentioned above, the further progress is governed by an effort for including meteorological conditions more realistically. It has resulted to development of Segmented Gaussian Plume Model (SGPM), which consists in a hybrid plume-puff solution. (Päsler -Sauer, 2000). Our version of SGPM model (more details in Pecha, 2007) enables to implement both ***Scheme 2*** and ***Scheme 3*** (see Figure 1)**.**

The first hourly segment of release propagates with velocity $\boldsymbol{u_1}$ and the plume just after the first hour is demonstrated in Figure 1 by Gaussian trace with axis A_1B_1. Just during the second hour the original plume segment A_1B_1 propagates to the final trace A_2B_2, within the process is submitted to dispersion and depletion. As vectors of velocities $\boldsymbol{u_A}$ and $\boldsymbol{u_B}$ are different in general, the second plume A_2B_2 is subjected to shift, rotation and dilatation with regard to the first hourly trace A_1B_1. For such calculations the gridded meteorological forecast is inevitable.

5. ACCOUNTING FOR LOCAL CHARACTERISTICS OF ACCIDENTAL RELEASE SCENARIO

Spatial discrimination of the meteorological conditions requires equivalent approach for other input fields such surface elevation and surface roughness, surface land-use characteristics, gridded demographical data and straightforward specification of local rain areas. The local idea is introduced within a basic stepwise approach of determination of radioactivity concentration in air, its time integral in the near-ground level (TIC) and activity deposition on the ground. Let us analyze segment movement from its position between hour H1 and subsequent hour H2 according to the sketch in Figure 2. Meteorological forecast for the hour H1 is known and let corresponding plume segment is drifted within the whole next hour up to H2 with wind direction φ_2, wind speed $\bar{u}_2$, class of atmospheric stability $class_2$ and precipitation intensity υ_2. Total movement from position H1 to H2 is modelled as a sequence of K partial elemental shifts starting from known initial position of the plume segment at H1. Near-ground activity concentrations in air C (Bqm^{-3}) are calculated step by step, where the corresponding time step is 3600/K seconds (values of K ≥ 30 proved to be sufficient). Having results for partial shift *k* (see dashed contour in Fig. 2), then the activity concentrations in the next elemental step *k+1* are approximated using difference scheme for basic phenomena. It concerns to increasing of dispersion coefficients σ_y, σ_z in horizontal and vertical directions which are estimated differentially according to atmospheric stability. User can select alternative expressions for a certain roughness of terrain represented by Hosker, KFK-J lich or SCK/CEN formulae. Plume activity depletion factors during plume elemental shift $k \rightarrow k+1$ account for radioactive decay:

$$\Delta f_R^{\,k\rightarrow k+1} \;=\; \exp\left(-\lambda\cdot\Delta x^{k,k+1}/\bar{u}\right) \quad ; \quad \Delta x^{k,k+1} = \left(x_{k+1}-x_k\right) \tag{2a}$$

For dry fallout:

$$\Delta f_F^{\,k\rightarrow k+1} \;=\; 1-\sqrt{2/\pi}\cdot\frac{v_g(k,k+1)\cdot\Delta x^{k,k+1}}{\bar{u}\cdot\sigma_z(\bar{x}^{k,k+1})}\cdot\exp\left(-\frac{H_{ef}^2(k,k+1)}{2\cdot\sigma_z^2(\bar{x}^{k,k+1})}\right) \tag{2b}$$

Dry deposition velocity v_g *(k,k+1)* depends on surface type within elemental shift (land use characteristics are differentiated according to the land-use categories (water, grass, agricultural fields, forest and urban areas) and physical-chemical form of bounded admixtures (noble gases, elemental form, aerosol form, organically bounded). Conservative calculations assume v_g values [m.s^{-1}] related to fully developed vegetation. $H_{ef}(k,k+1)$ stands for local effective height of the plume with corrections on local surface elevation.

For the plume activity depletion factor Δf_W due to atmospheric precipitation during the plume passes through the elemental shift $k \rightarrow k+1$ on interval $\Delta x^{k,k+1}$ is:

$$\Delta f_W^{k \rightarrow k+1} = \exp\left(-\Lambda \cdot \frac{\Delta x^{k,k+1}}{\bar{u}} \right) \tag{2c}$$

For determination of washout constant Λ [s^{-1}] is used power function $\Lambda = a \cdot I^b(k,k+1)$, where empirical constants a, b depend on physical chemical form of admixtures in the plume and local precipitation intensity I [mmh^{-1}] on interval $\Delta x^{k,k+1}$.

Determination of contribution of the segment to the *TIC* values in receptor point R (see Fig. 2) during its movement from partial position k to the next partial position $k+1$ is expressed as:

$$\Delta TIC(R;k) = \frac{C(R,k) + C(R,k+1)}{2} \cdot \Delta t(k) \tag{3}$$

TIC values at receptor point R from all consecutive partial shifts k, $k=1, ..., K$ is given by:

$$TIC(R;K) = \sum_{k=1}^{K} \Delta TIC(R;k) \tag{4}$$

Similar considerations concerning activity deposition on terrain around receptor point R can be adopted. Deposited activity at receptor point R due to dry and wet effect during elemental shift $k \rightarrow k+1$ is approximated as:

$$\Delta DEP(R;k) = \Delta DEP^{dry}(R;k) + \Delta DEP^{wet}(R;k) \tag{5}$$

Activity deposition on the ground [Bqm^{-2}] from dry fallout is given by product of near-ground air activity concentration and dry velocity v_g. During each elemental shift the radioactive decay of deposited activity has to be taken into account and then the expressions become somewhat complicated (more detailed in Pecha, 2007).

6. RESULTS

Numerical calculation using environmental model HARP (complying with all improvements described above) were carried out in order to estimate significance of introduction of more realistic meteorological forecast on spatial 3-D grid around the source of possible pollution. The tests were accomplished for real meteorological situation from June 25, 2008 which has occurred in vicinity of 160 × 160 km around nuclear power plant Dukovany. Nice sunny day has been superseded in the evening by storm with intensive local rain and blasts of wind. The situation documents Table 1, which presents some part of short-term meteorological forecast for location of NPP Dukovany from hour 17.00 CET to 03.00 CET next day. The forecast was generated in CHMU on the basis of analysis procedure related to midnight (time stamp 20080625-0000 CET).

Table 1. Short-term meteorological forecast for "point" of NPP Dukovany (49.137°N × 16.263°E).

date	June 25, 2008							June 26, 2008			
hour (CET)	17.00	18.00	19.00	20.00	21.00	22.00	23.00	00.00	01.00	02.00	03.00
wind direct.(°)	162	176	182	196	222	254	279	298	299	301	301
wind speed (m.s^{-1})	2.3	2.7	3.5	3.0	2.5	3.0	3.4	3.6	4.3	4.4	4.5
Pasquill stability cl.	C	D	D	D	E	D	D	D	D	D	D
rain (mm.hour^{-1})	0	0	0.93	0.05	0	0	0	0	0	0	0

Release scenario: Fictive imaginary release of radionuclide ^{131}I from NPP Dukovany; release start on June 25, 17.00 CET; release duration 1 hour, total activity release of 131I into atmosphere is 7.48E+13 [Bq]; release height 45 m; dispersion calculated for smooth terrain of European type (SCK/CEN formulae).

Figure 3 demonstrates differences between trajectories constructed under assumption of 1-D or 2-D forecasts. More detailed comparison oriented on general consequence assessment can be concluded from Figure 4. The results illustrate isolines of spatial distribution of time integrated near ground activity concentration in air [Bqsm^{-3}]. Parameters of scenarios enter the environmental model HARP and two alternative results are generated for meteorological conditions marked as 1-D (the results are in left part of Fig. 4) and 2-D (right part of Fig. 4). More realistically is considered effective height of the plume H_{ef}. We are generating the proper local values $\bar{u}(10, H_{ef}, x, y)$ for location with coordinates (x,y) when substituting into equation (1) the value $u_{10}(x,y)$ extracted from 2-D ALADIN data (provisionally – application of the advance function of meteo-preprocessor MP mentioned above is in progress).

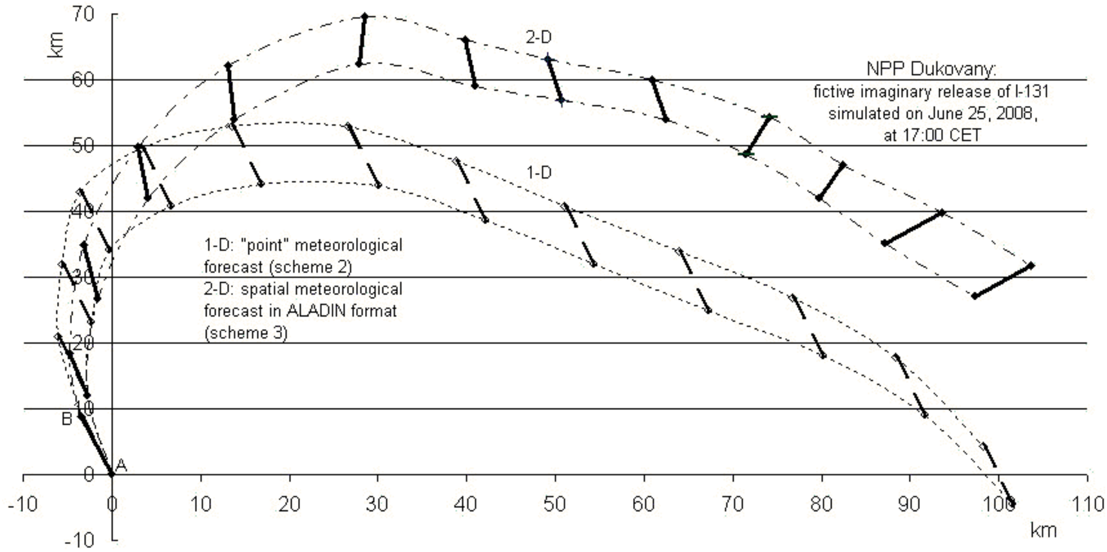

Figure 3. Abscissa AB illustrates trace of ^{131}I plume in the first hour of release. Its stepwise movement in the next hours is modelled alternatively using 1-D meteorological forecast (***Scheme 2***) or more realistic spatial forecast 2-D (***Scheme 3***) in ALADIN gridded format. Even if the advection is driven by wind speed in 10 meters, both trajectories differ noticeably.

It is clear that differences between two traces 1-D and 2D from Figure 3 demonstrate significance of the new approach based on more precise input forecasts. The fact is still more noticeable in Figure 4 when comparing isolines on the left and right side of the picture. This is mainly due to consideration of the plume travel with $\bar{u}(10,H_{ef}, x,y)$ in height greater then 10 meters. We can anticipate that significance of the new 2-D approach will increase for scenarios with large values of H_{ef} (high sources of release, large plume rise due to initial buoyancy and momentum flux of discharges).

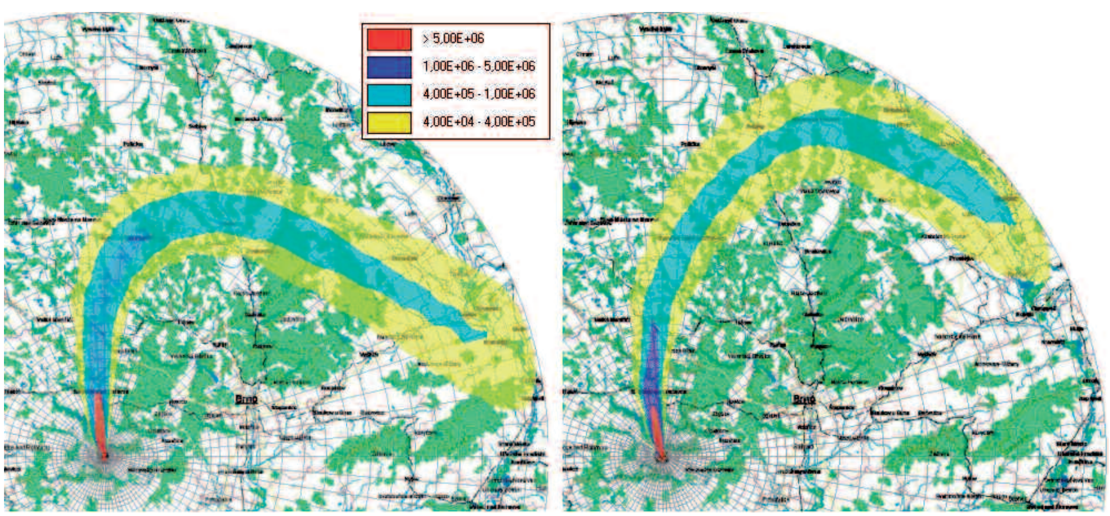

Figure 4. Time integral of activity concentration (TIC) of nuclide ^{131}I [$Bq.s.m^{-3}$] in air in near ground level. Left: Under simple meteo-forecast for point of discharges. Right: More realistic 3-D meteo-forecast on mesoscale domain 160 × 160 km around NPP Dukovany.

7. CONCLUSION

Firstly, an advancement described above will contribute to improvement of time update of background radiological fields that can enter succeeding assimilation procedure with real measurements from terrain. Secondly, there is no doubt, that more informative meteorological data contributes to more precise identification of areas, which are adversely impacted by dangerous harmful substances. It significantly supports effective and advance introduction of urgent protective actions on mitigation of radiological impact on population. Evacuation or sheltering of inhabitants and iodine prophylaxis should come on force promptly in the early plume phase. Giving example from our results, emergency management coming from former estimation according to the situation in Figure 4 (left) can mislead to application of countermeasures at erroneous positions and can lead to wasting of rescue resources. To the contrary, any neglect of urgent actions in really stricken areas could have fatal consequences and detrimental impact on population health.

Acknowledgments: *This work is part of the grant project GAČR No. 102/07/1596, which is founded by Grant Agency of the Czech Republic. Authors thank to specialists from CHMI and from National Radiation Protection Institute for possibility to connect online system HARP to meteo-data.*

REFERENCES

Carruthers, D. J, W.S. Weng, J. C. R. Hunt, C. A. McHugh and S, J. Dyster, 2003: PLUME/PUFF Spread and Mean Concentration Module Specifications. UK-ADMS – UKADMS3, P12/01S/03.

Hanna, S.R, G. A. Briggs and R. P. Hosker Jr, 1982: Handbook on Atmospheric Diffusion, DOE/TIC-11223 (DE82002045), US Dpt. of Energy.

Hofman, R. and P. Pecha, 2007: Integration of data assimilation subsystem into environmental model of harmful substances propagation. In *Proc. 11th Int. Conf. on Harmon. within Atm. Dispersion Modelling,* (Cambridge, UK, July 2-5, 2007), 111-115.

Irwing, J.S. and S. R. Hanna, 2004: Characterizing Uncertainty in Plume Dispersion Models. In *Proc. 9th Int. Conf. on Harmon. within Atm. Dispersion Modelling,* (Garmisch-Partenkirchen, Germany), **1**, 287-292.

Kalnay, E., 2003: Atmospheric modeling, data assimilation and predictability. Cambridge University Press, ISBN 0-521-79179-0.

Kuca, P., R. Hofman and P. Pecha. 2008. Assimilation techniques in consequence assessment of accidental radioactivity releases – the way for increase of reliability of predictions. In. *Proc. ECORAD 2008 Int. Conf. on Radioecology & Environmental Radioactivity* (Bergen, Norway, 15-20 June 2008).

Päsler-Sauer, J., 2000: Description of the Atmospheric Dispersion Model ATSTEP. Report of project RODOS(WG2)-TN(99)-11.

Pecha, P., R. Hofman and E. Pechova. 2007: Training simulator for analysis of environmental consequences of accidental radioactivity releases. In *Proc. 6th EUROSIM Congress on Modelling and Simulation* (Ljubljana, Slovenia, September 9-13, 2007), 18 pp. on conf. CD – ISBN 978-3-901608-32-2.

Pecha, P. and E. Pechova, 2005: Modeling of random activity concentration fields in air for purposes of probabilistic estimation of radiological burden of population. *HARMO10 – 10th Internal Conf. on Harmonisation within Atm. Dispersion Modelling for Regulatory Purposes,* Sissi (Crete)Greece, 17-20 October 2005, paper No. H11-069.

Pecha, P. and M. Janoušek, 2004: Mathematical Modelling as a Tool for Decision Support Management. Conf. CMP’04 Multiple Participant Decision Making, Prague.

Rojas Palma, C. (ed.)., 2005: Data Assimilation for Off site Nuclear Emergency Management. Research Report RODOS(RA5)-RE(04)-01.