ANS PSA 2011 International Topical Meeting on Probabilistic Safety Assessment and Analysis
Wilmington, NC, March 13-17, 2011, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2011)

APPLICATION OF REGIONAL ENVIRONMENTAL CODE HARP IN THE FIELD OF OFF-SITE CONSEQUENCE ASSESSMENT

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ABSTRACT

The environmental code HARP (HAzardous Radioactivity Propagation) estimates consequences of accidental radioactivity releases from a nuclear facility and on basis of simulation of dispersion in atmosphere, deposition of radionuclides on the ground and further propagation through the food chains towards human body. Classical Gaussian approach in the form of hybrid puff-plume segmented model SGPM is introduced for simulation of pollution dissemination in the atmosphere. The ingestion pathway is modeled dynamically. The system architecture consists of the inner kernel designated for deterministic calculations and outer probabilistic shell, which ensures application of probabilistic approach in the consequence assessment. Propagation of uncertainties through the model towards the output values of interest is realized through the multiple recalling procedure of the inner kernel, which is optimized for such intensive Monte Carlo (MC) computations. The HARP code is primarily designed for application of advanced statistical data assimilation techniques based on sequential MC methods (SMCM) allowing an improvement of model predictions using real measurements incoming from terrain. In this paper we shall demonstrate two additional specific applications of the HARP code based on the repeated sampling. Firstly, a partial PSA-Level3 study of ecological risk assessment is accomplished taking into account variability of meteorological inputs represented by historical long sequences of archived values (for each hour in the years 2008 and 2009). Output radiological quantities are then processed statistically. Secondly, a long term release of radioactive material is simulated through the superposition of a large number of one-hour fractional release rates. The procedure is applied on annual radioactivity releases from a nuclear power plant (NPP) during its routine normal operation when each partial hourly release is driven by the real meteorology archived at that time.

Key Words: pollution dispersion, MC sampling, PSA Level3, data assimilation

1 INTRODUCTION

The activities related to the modeling of radioactive pollution propagation have a long tradition in the Institute of Information Theory and Automation (UTIA). In the late nineties the UTIA had become a member of the International MACCS User Group and active participated on the Group meetings. Since 1997 there were in progress the customization activities of the RODOS system (Real-time Online DecisiOn Support system) for its use in the Czech Republic. The experience has been utilized during development of the new PC user friendly program product HARP. The main objective of the progression is application of knowledge accumulated in Dept. of Adaptive systems of UTIA in the field of advanced statistical Bayesian techniques. The improvement of model predictions is accomplished on basis of optimal blending of all information sources including a prior physical knowledge given by a model, observations incoming from terrain, past experience, expert judgment and intuition. The structure of the HARP system is in Fig. 1.

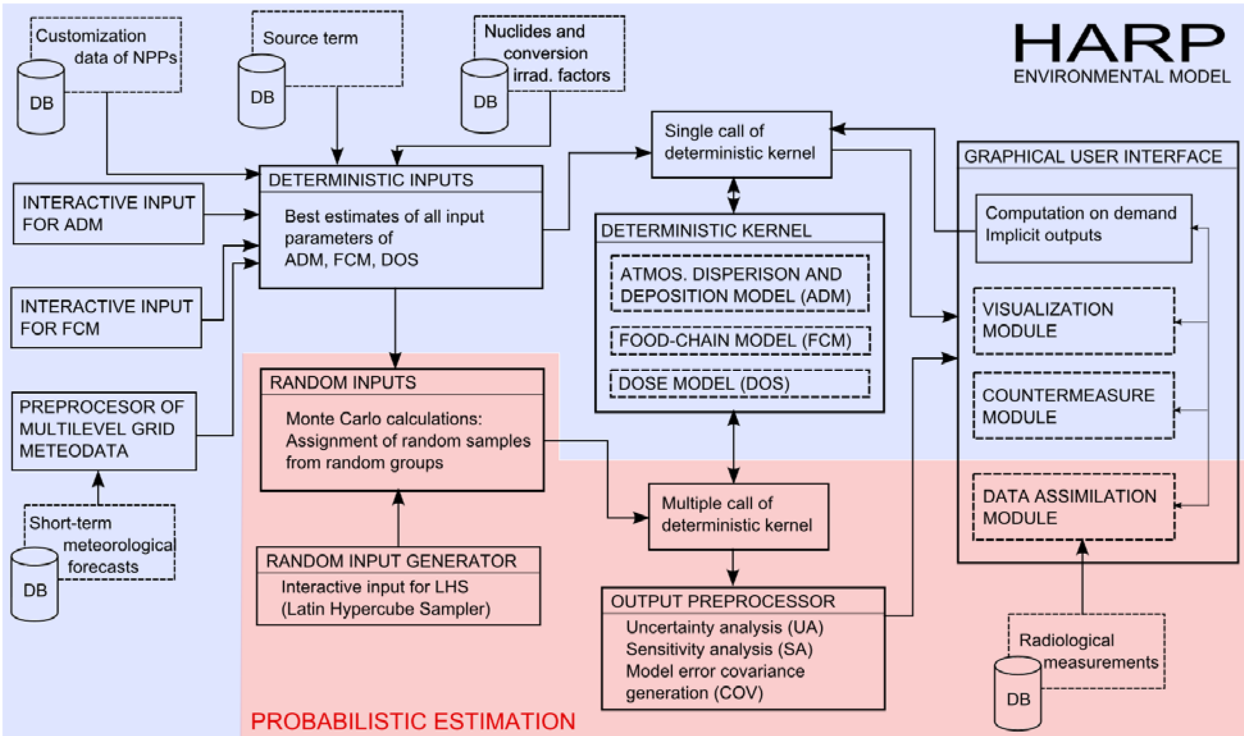


Figure 1: Block diagram of environmental system HARP

Deterministic kernel of the code provides various kinds of outputs, specifically:

- Standalone deterministic analysis of certain important accident scenarios (worst-case analysis, design bases accident (DBA) examination, analysis of various postulated accidents necessitated for Safety reports, calculations for comparative procedures with other codes etc.).
- Within the uncertainty analysis the kernel is recalled many times with concrete sets of realizations of random model parameters. The final statistical processing of output realizations provides a rational basis for probabilistic consequence assessment.
- Provides estimation of the prior system state and evaluation of model error covariance structure or purposes of data assimilation.

More detailed description of stand-alone utilization of the deterministic kernel of the code mentioned above and utilization of the probabilistic shell for the probabilistic approach in the consequence assessment and for assimilation procedures are given in [6]. In this paper we shall concentrate on description of capability of deterministic kernel to produce reasonable results for so called WVA (Weather Variability Assessment) belonging to a special application from the domain of PSA-Level 3 analysis. At the same time, such computationally extensive MC calculations based on many times repeated sampling and recalling of the kernel have brought interesting results for analysis of long term releases of radioactive pollution. In this sense we shall illustrate the simulation of assessment of annual radiological consequences during normal routine operation of a NPP.

2 SEGMENTED GAUSSIAN PLUME MODEL (SGPM) OF AERIAL TRANSPORT

Development of an adequate code for simulation of contamination propagation in all compartments of the living environment is crucial for successive evaluation of accident consequences. Moreover, the algorithm is designated for the MC procedure of multiple recalling. The solution should be as fast as possible on one hand, and sufficiently accurate on the other hand. For this purposes has been developed segmented Gaussian plume model SGPM which seems to be a reasonable compromise between computational speed (it should manage real-time predictions of pollution propagation in the early stage of accident) and sufficient accuracy of the output simulated values of interest.

Atmospheric transport of pollutant is simulated on basis of Gaussian dispersion modeling using further modifications of a numerical scheme which ensures an accounting for the real situation. A basic idea insists in synchronization of available short-term meteorological forecast (hourly forecast for the next 48 hours) provided by the Czech meteorological service with release dynamic of harmful substances discharged into the atmosphere. The real dynamics of the accidental release is transformed into an equivalent number G of consecutive homogeneous segments with duration 1 hour. Movement of each segment is driven by short-term meteorological forecast for the corresponding hours of propagation (phases). The shape of the segment spreading is simulated by “Gaussian droplet” coming out from the simplified solution of the diffusion equation. Implemented idea of hybrid puff-plume model assumes the droplet to be composed of superposition of a certain number of instantaneous puffs. In principle, the total movement of each partial Gaussian one-hour segment within the next one hour interval is driven according to the meteorological forecast for the corresponding hour and is modeled as a sequence of partial elemental shifts k (k=1, ... , K ; K = 30 ÷ 50). Specific volume activity in air at effective height of the plume and at near ground level are modeled in each step k together with their time integrals. The SGPM model uses “source depletion” approach based on separation of the pure dispersion solution C^{disper} and “removal” component given by the plume depletion factors $f^n{}_R$, $f^n{}_F$, $f^n{}_W$ due to the radioactive decay ($_R$) and dry ($_F$) and wet ($_W$) deposition in dependence on the physical-chemical form of the nuclide n.

3 GENERAL SCHEME FOR COMPOSITION OF OUTPUT RADIOLOGICAL QUANTITIES

In summary to the numerical scheme, a hypothetical radioactivity release is equivalently split into hourly segments g, $g \in \{1,2,\ldots,G\}$. Each segment g is modeled in its subsequent meteorological phases f, $f \in \{1,2,\ldots,NFAZ(g)\}$ taking into account hourly meteorological forecast. $NFAZ(g)$ is the total number of consecutive hours of the segment g tracking. The final total values of a certain significant output χ at the receptor point R belonging to the effect of nuclide n is given by superposition of the results for all plume segments in their all meteorological phases according to the scheme

$$ {}^{n}\chi_{TOTAL}(R) = \sum_{g=1}^{G} \left\{ \sum_{f=g}^{f=NFAZ(g)} {}^{n}\chi^{\{g;f\}}(R) \right\} \qquad (1) $$

Here the hourly plume segment g in its hourly meteorological phase f is labeled as puff $\{g;f\}$. We should have on mind, that the scheme (1) is somewhat simplified. For example, numerical calculations of radionuclide deposition on the ground must respect also radioactive decay due to time-delays between both time steps *k* and between phases *f* of the segments *g*. Another special modification was introduced for a simple parent-daughter decay during the radioactive cloud drifting over the terrain and in deposited components on the ground.

Fundamental role among simulated output categories plays the following four main nuclide dependent variables χ related to the early phase of an accident. Specifically, the values of χ can represent respectively:

- Near-ground activity concentration in air - spatial distribution around the source in polar nodes (Bq.m^{-3})
- Time integral of near-ground activity concentration in air – spatial distr. (Bq.s. m^{-3})
- Activity deposited on terrain - spatial distribution (Bq.m^{-2})
- Time integral of activity deposited on terrain - spatial distribution (Bq.s.m^{-2})

All other possible consequences χ like spatial distributions of irradiation doses both in early and late stage of accident, countermeasure estimation, long-term evolution of specific activities in agricultural products and food bans effectiveness examination, long-term doses from resuspension etc. can be calculated directly from these four early phase driving quantities applying just additional time integration. For example, estimated doses Ψ (related to the age category *a*) at the receptor point R can be schematically described as:

$$\Psi_{TOTAL}\left(R;a;T\right) \;\approx\; \sum_{n=1}^{NU} \left[{}^{n}\gamma_{TOTAL}\left(R\right)\cdot I(T)\cdot {}^{n}\Omega^{conv}(a) \right] \tag{2}$$

Ω covers up eventual dose conversion factors. Time integration of long-lasting effects (e.g. decay, activity migration in soil) up to time *T* is formally marked as *I(T)*. It can be usually expressed analytically. Somewhat complicated is computation of the time-integrated activity intakes according to the dynamical model of ingestion developed specially for the HARP system.

4 DEMONSTRATION OF SOME COMPUTATIONALLY INTENSIVE APPLICATIONS

The design of the HARP system comprises an efficient tool for automatic repetitive evaluation of a release scenario which allows study of propagation of uncertainties or variability through the atmospheric, deposition, ingestion and dosimetric model chain. Generally, the versatility of the framework allows for insertion of an arbitrary dispersion model. We use atmospheric dispersion model SGPM. Here we present two rather distinct scenarios having a special uncommon character but significant relevance. Before anything else we should mention different understanding of **variability** and **uncertainty** of a certain model variable. Variability reflects changes of a certain quantity over time, over space or across individuals in a population. Variability represents diversity or heterogeneity in a well characterized population. Unlike this, the term uncertainty covers stochastic uncertainties, structural uncertainties representing partial ignorance or incomplete knowledge associated with poorly-characterized phenomena or submodels and input model uncertainties. The HARP system respects the variability concept wherever possible. The quantity with variability character is not treated as a single variable, but is split into a set of particular variables entering the calculations solo. As an example we can mention calculation of doses, when instead of one single quantity related to all age categories of population (comprising a certain effect of inter-categorical variability) we are generating a set of values, each specific for a separate age category.

Perception of distinction between variability and uncertainty of meteorological inputs is crucial. Seasonal and diurnal changes result in variability in meteorological data and their statistical processing provides certain information related to the averaged (weighted) values. Unlike this, uncertainty analysis and assimilation procedures are always related to the **concrete moment of an accident initiation**. Meteorological situation related to the specific time of release is given by superposition of their nominal values (measurements or forecasted for that moment) and random fluctuations due to stochastic nature of the turbulent processes in atmosphere.

4.1 One Special Application Related to the Probability Safety Assessment (PSA)

Probability safety assessment (PSA) in its complete probabilistic view should take into account the frequencies of all parameters involved. The final goal of the PSA in its Level 3 is assessment of off-site consequences to estimate public risks. The analysis uses results of the previous steps of PSA:

- Level1 - On basis of probabilistic assessment of plant failures provides to estimate reactor core damage frequency
- Level2 - Examines containment response on various plant fault tree occurrences, generates containment release frequencies and estimates the quantities of radionuclides released to the living environment.

The resulting radionuclide source terms enter the estimation of public risk assessment.

Following [1], the number of accidents which lead to radioactive emission is generally too large to be evaluated separately. A common practice is to group those accident sequences which could lead to similar consequences and assign to them representative source term parameters and frequencies of occurrence. Various source terms parameters enter successive consequence assessment such amounts and percentual composition of radionuclides, physical-chemical forms, source height, heat content, release timing (release duration) etc. All the parameters should be assumed as random and together with other random model parameters should be treated their uncertainty propagation through the environmental model. In the next text we shall confine to the atmospheric dispersion model SGPM described above. The model is strongly nonlinear. Let $\mathfrak{R}^{\boldsymbol{SGPM}}$ symbol stand for operator of the implemented numerical algorithm. A certain output quantity χ from (1) represents a certain realization of random variable X according to the scheme:

$$X = \mathfrak{R}^{\boldsymbol{SGPM}} (\Theta_1, \Theta_2, \ldots, \Theta_M) \quad (3)$$

The capital symbols are related to the random variable, lower case symbols stand for concrete values selected from the corresponding random distribution. Let $\boldsymbol{\Theta} \equiv [\Theta_1, \Theta_2, \ldots, \Theta_M]^T$ be a vector of M random model parameters Θ_m with corresponding sequence of random distributions $D_1, D_2, \ldots, D_M$ which are usually selected on the basis of commonly accepted agreement of experts (range, type of distribution, potential mutual dependencies). The model parameters have usually a physical meaning like initial magnitude of discharged radioactivity, parameters of atmospheric dispersion, uncertainties related to dry and wet fallout of radioactivity, components of wind field and many others. The expression (1) should be valid for all nodes $R_{i\ /\ i \in \{1,\ldots,N\}}$ of the polar computational grid ($N=3360$ for 80 angular sectors and 42 radial distances up to 100 km from the source).

Overall PSA should be theoretically based on sampling according to the scheme (3). Because of practicability the value of dimension M of input random vector $\boldsymbol{\Theta}$ is in general rather high. Further reduction of number M should be done on basis of sensitivity studies. Only those parameters (denoted as J) having significant influence on the output fluctuations are assumed to have random character. The others are substituted by their deterministic "best estimated" values θ^{best} and expression (3) can be rewritten as:

$$X = \Re^{SGPM}(\Theta_1, \Theta_2, \ldots, \Theta_J, \theta_{J+1}^{best}, \theta_{J+1}^{best}, \theta_{J+2}^{best}, \ldots, \theta_M^{best}) \qquad (4)$$

Uncertainty analysis for J=12 parameters of dispersion and deposition SGPM model was performed in [3] for purposes of recursive Bayesian filtering in the early phase of an accident.

In this paper we are presenting simple PSA analysis having an alternative meaning of WVA - Weather Variability Assessment. We come out from presumption that only the four main meteorological model parameters can fluctuate:

θ_{dir} - wind direction (deg); θ_{vel} - wind speed ($m.s^{-1}$);
θ_{kat} - atmospheric stability class (according to Pasquill, kat= A, B, C, D, E, F)
θ_{rai} - rain -precipitation intensity ($mm.h^{-1}$)

Their variability enters to the sampling scheme (4) which is now formally reduced to:

$$X = \Re^{SGPM}(\theta_{dir}, \theta_{vel}, \theta_{kat}, \theta_{rai}, \theta_5^{best}, \theta_6^{best}, \ldots, \theta_M^{best}) \qquad (5)$$

Hereunto nothing new, such approach is commonly utilized in some other similar codes where the meteorological variability is treated with a stratified random sampling algorithm. In our approach we have used for further successive processing the real sequence of meteorological data archived in the period 2008-2009 instead of any speculative construction of meteorological sampling scheme. It concerns a HIRLAM 3-D gridded data covering area 160 × 160 km around NPP (9 × 9 km grid cells, 15 vertical levels). For each hour from the continuous chain of 17520 hours one hour identical discharge is analyzed. Each such hourly release is driven the next 23 hours by real hourly meteorological phases valid for that time stamp. Finally, the results of all partial hourly scenarios (17520 samples) are statistically processed. The consequences are derived from their sampled distributions of the meteorologically based doses and interpreted by terms of sample averages, CDFs, CCDFs functions, consequence percentiles etc. This procedure is described by a modified scheme, which accounts for true spatial distribution of meteorological conditions (including local rain) and local parameters of terrain (orography and landuse in a certain approximation) in each receptor point R (in each node of polar computational grid):

$$X = \Re^{SGPM}(\theta_{dir}(R), \theta_{vel}(R), \theta_{kat}(R), \theta_{rai}(R), \theta_5^{best}(R), \theta_6^{best}, \ldots, \theta_M^{best}(R)) \qquad (6)$$

The difference between (5) and (6) seems to be formal, but it brings remarkable advance in comparison with former application of Gaussian straight-line model based on meteorology related to "point" forecast from the NPP site. Expression (6) comprises implicitly hourly changes of meteorological conditions with spatial resolution (that means variable both in time and space).

The choice of source term was based on European utility requirements [2]. Even for severe hypothetical accident with very low frequency of occurrence ($f \sim 10^{-6}$/year) the declared release targets should not be exceeded by a modern, well designed plant. Chosen total release of four main nuclides is given in Table 1.

Table I. Hourly source term for repeated calculations

Isotope	chosen release targets (TBq)	comment
Sr-90	5	aerosol form
I-131	1000	prevalent elemental form
Cs-137	30	aerosol form
Xe-133	770000	noble gas

Other isotopes with lower contribution are also included: Ru-103, Te-131M, Ba-140, La-140, Ce-141. We assume a hypothetical release from NPP Temelin, release height H=45 m; no thermal power of release; with effect of near buildings; dispersion formulas: KFK-Jülich.

In summary, in each hour *h* is released the source term from Table I and the plume is driven by corresponding spatially distributed weather conditions expressed by quartet $\{\theta_{dir}(R), \theta_{vel}(R), \theta_{kat}(R), \theta_{rai}(R)\}_h$. This single one-hour plume transport is modeled up to distance 100 km from the source (but no more than 23 successive hours) and corresponding consequences are calculated and stored. The next one-hour plume is analyzed for the next hour *h+1* with corresponding quartet $\{\theta_{dir}(R), \theta_{vel}(R), \theta_{kat}(R), \theta_{rai}(R)\}_{h+1}$ and so on. The cycle for period of years 2008-2009 is repeated 17520 times for each hour of the period. Finally, we have N= 17520 samples for each output value of interest (specific activity concentration in air and on the ground, their time integrals, various doses/committed doses from external or internal irradiation in the early and late phases of an accident differentiated according to organ/tissue and age category etc.). Each particular output value is represented by a vector of dimension N (in all nodes of the polar computational grid).

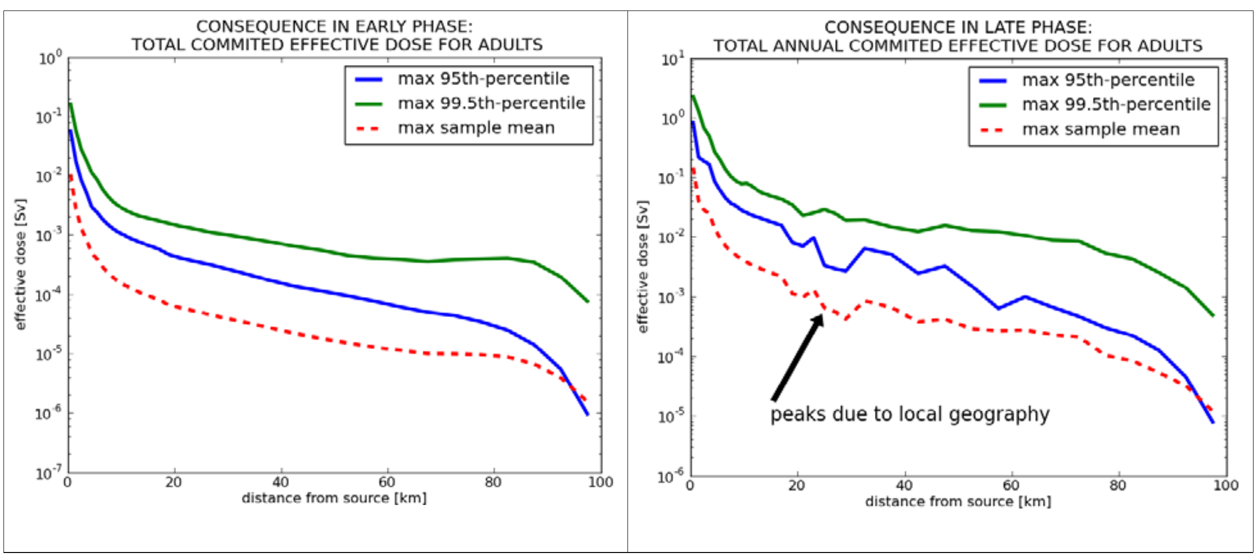
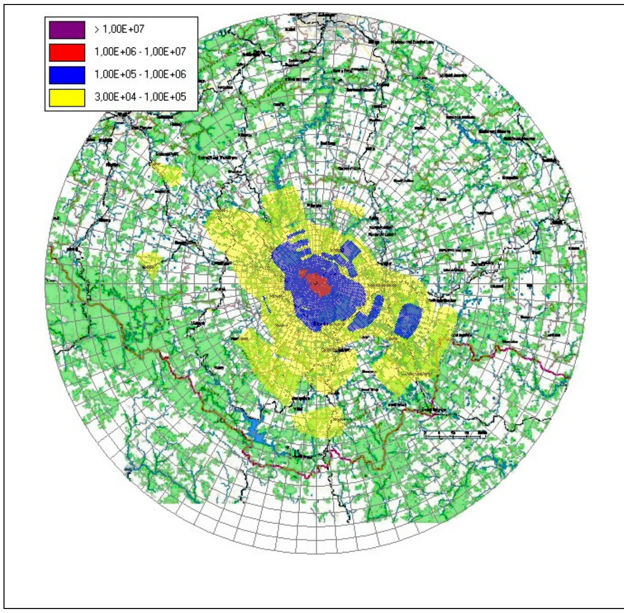


Figure 2: Sample mean and pth-percentiles consequence –probability of exceeding no more than 100-p percent; angular maximum (from 80 sectors) at each radial distance



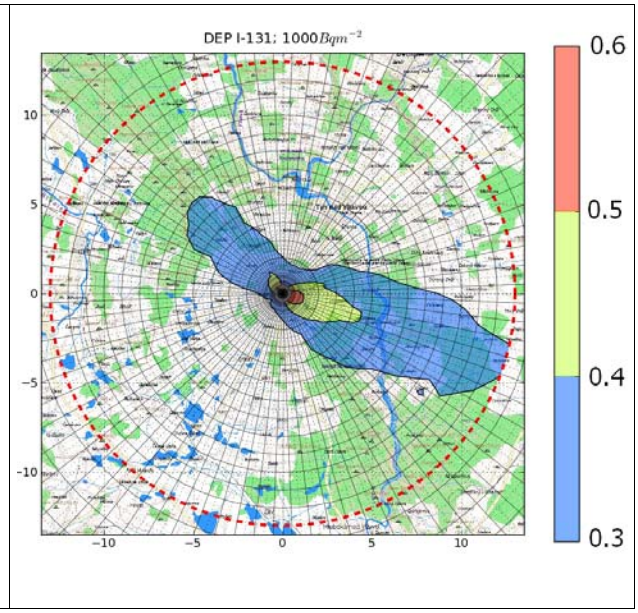


Figure 3: 2-D representation of I-131 deposition sample mean (Bq/m^2)

Figure 4: 2-D representation of Complementary CDF – probability of exceeding deposition limit 1000Bq/m^2

The term "probability" stands for a certain statistical level. Consequences determined from a distribution of the meteorologically based samples of output values are processed statistically and some results are illustrated in Fig. 2, 3, 4 and 5. 2-D results are presented on NPP Temelin map backgrounds.

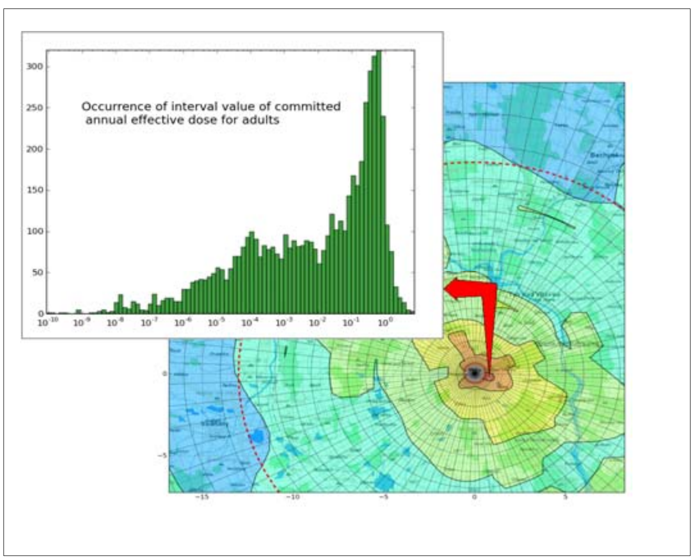


Figure 5: interactive 2-D visualization of sample mean of annual committed effective dose for adults; histogram shows distribution at cursor position

4.2 Simulation of Consequences of Long Term Discharges of Radionuclides into Atmosphere

The procedure is applied on consequences of annual radioactivity releases from NPP Temelin during its routine operation in 2008. The annual discharges are divided by number of hours in a year and each the partial hourly release is driven by the meteorology archived at that time. For demonstration purposes the pollution propagation is simulated using somewhat curious method when applying the HARP system repeatedly for all 8760 hours of a year and annual output values are summed up. In Fig. 6 we are comparing annual TIC of tritium with results of program code NORMAL [7] designed solely for estimation of routine operation and using long term weather statistics (see Fig. 8 left). The results show surprisingly good agreement for the annual TIC values, somewhat higher values gives NORMAL for real orography and landuse. 2-D illustrations in Fig. 7 show a good resemblance of respective isopleths. On the other hand we can expect higher differences for committed doses, because the ingestion models are different. Moreover, we have not good ingestion model for an accidental H-3 and C-14 transport.

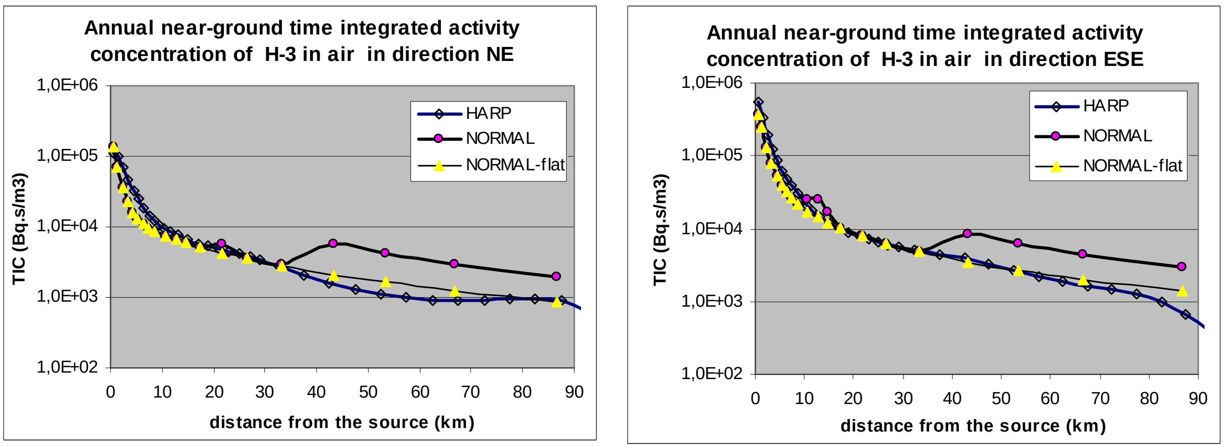


Figure 6: Comparison of annual near ground H-3 time integrated concentration values generated by HARP and NORMAL systems in two selected directions.

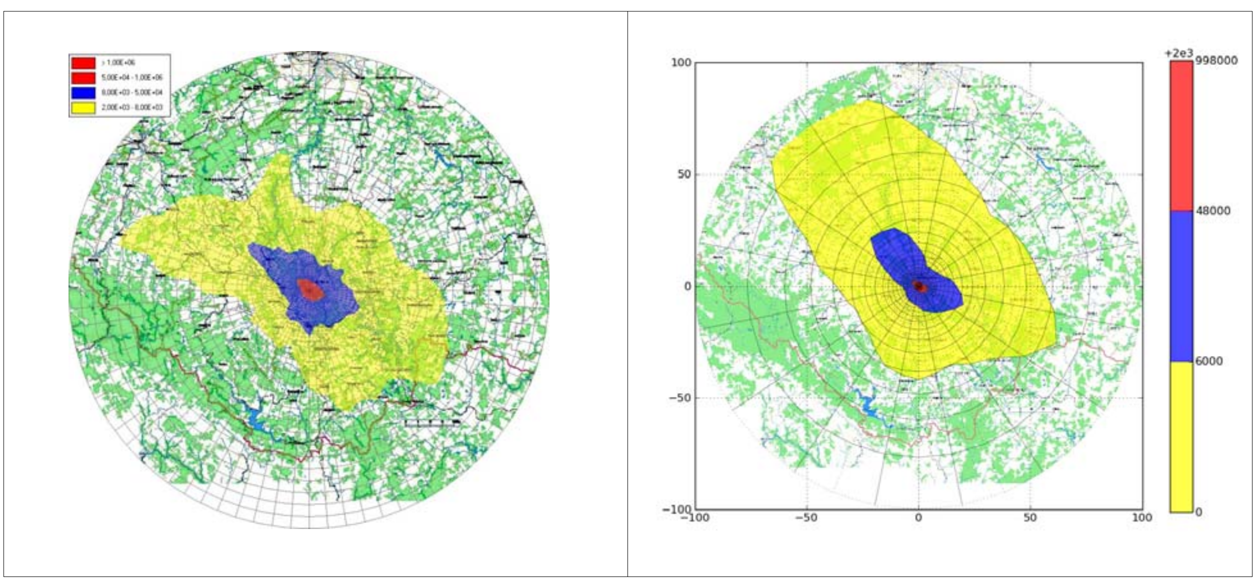


Figure 7: Comparison of 2-D distribution of annual near ground H-3 time integrated concentration values (Bq.s/m^3) generated by HARP (left) and NORMAL systems (right – with use of long term weather statistic from Fig. 8 left, flat terrain).

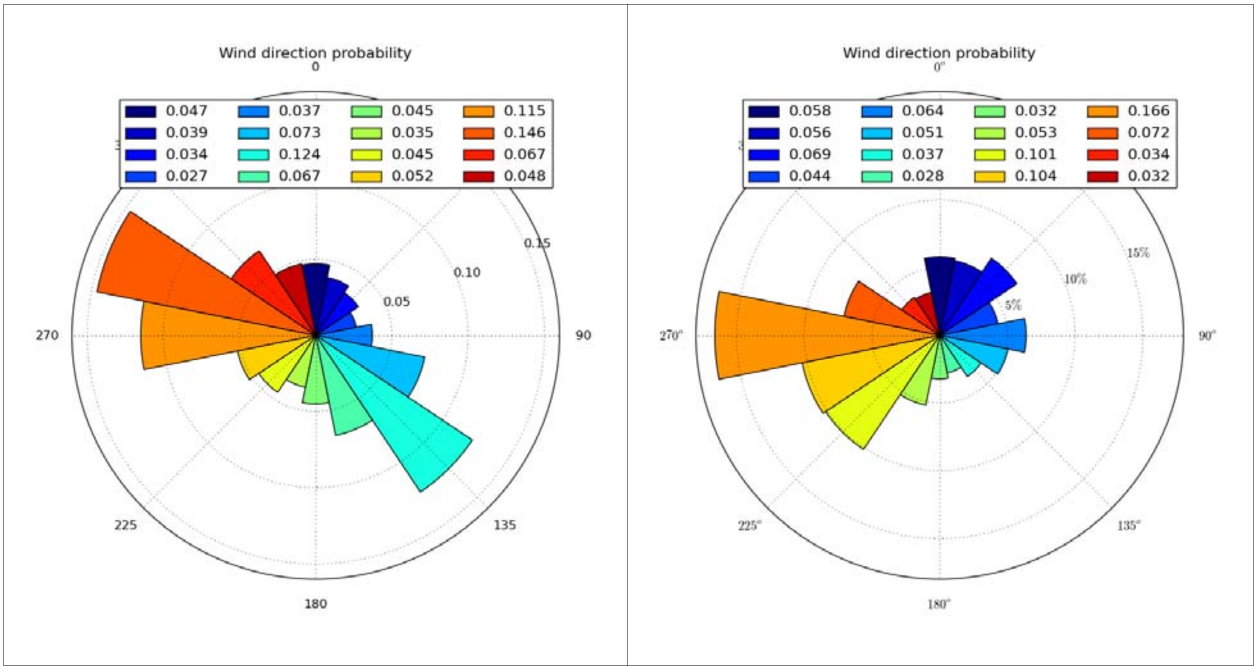


Figure 8: Annual (2008) wind direction statistics for the site of NPP Temelin. Left: generated from archived 3-D HIRLAM data; Right: generated from meteorological measurements in place of the NPP. Sense of direction: from where the wind blows.

4.3 Application in the Field of Data Assimilation During the Early Stage

In case of an accidental aerial release of radionuclides we use atmospheric dispersion models for prediction of release consequences. Reliability of meteorological inputs is crucial for accurate estimation of spatio-temporal distribution of radiation pollution. In Fig. 8 we see comparison of annual wind direction statistics for site of NPP Temelin. Statistics are obtained from hourly meteorological forecasts (left) and from meteorological measurements in NPP site (right). From a certain discrepancy between the statistics is apparent that the numerical weather predictions differ from the true meteorology represented by meteorological measurements. This is due to model imperfections, sub-grid effects because of the sparse computational grid etc.

It is obvious that relying on model predictions evaluated using biased or wrong meteorological forecast can lead to fatal errors in countermeasures planning. Data assimilation refers to a group of mathematical methods for estimation of a state of a dynamic system by the means of combining multiple sources of information, typically observational data with a numerical model of the system under investigation. It makes possible to consistently account for all uncertainties in the model, its inputs, observations and other factors and produces probabilistic answers which are more informative than those deterministic. Data assimilation is a compromise between the pure modeling approach on one hand and the data mining approach on the other hand.

We propose a data assimilation algorithm based on particle filtering [3], which results from sequential Monte Carlo methods [4]. We attempt for reduction of uncertainty regarding selected inputs to the dispersion model using measured data from a radiation monitoring network. This can be understood as an automated selection of a model from a parametrized class of dispersion models best fitting gamma dose rate measurements from a terrestrial radiation monitoring network during the plume passage. The most important parameters are meteorological conditions during the release, particularly wind speed and wind direction, and parameterization of magnitude of release.

Basic principle of the assimilation algorithm is illustrated in Fig. 9. In the figure, the release from a NPP is represented with isopleths. Radiation monitoring network is denoted with triangles and we assume that it provides gamma dose measurements in regular intervals. In real assimilation scenarios we generate hundreds or thousands of puffs. Here for sake of simplicity is the approach illustrated on four puffs P1-P4. We track them for the first three time steps. Puffs are propagated forward using different meteorology and with different source term. In the first time step, puffs P2 and P3 cover receptors influenced with the release and obtain high weights. During re-sampling step, puffs with high weights are copied and propagated in next time step. Puff P2 is re-sampled for three times and puff P3 once. In the second time step, three puff obtain high weights and are re-sampled: P2.2, P2.3 and P3.1. In the next time step, puff P2.2.1 and P3.1.1 are advected to areas unaffected with the release and obtain small weights. This means that they are discarded in time step t=3 puffs P2.3.1 and P2.3.2 are re-sampled.

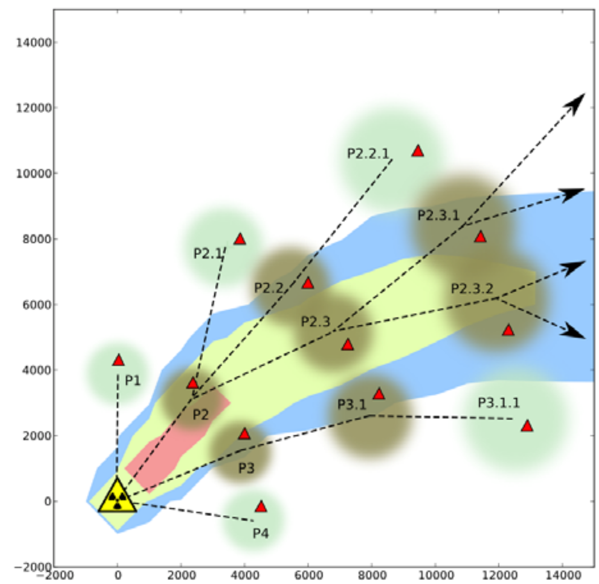


Figure 9: Illustration of data assimilation algorithm

5 CONCLUSIONS

We have demonstrated application of the environmental code HARP in some fields of computationally intensive PSA studies. Weather variability assessment (WVA) comprises diurnal and seasonal changes of meteorological conditions and distributions of the meteorological based doses are interpreted statistically and illustrated as an example of probabilistic assessment approach. We have introduced an alternative way to meteorological sampling scheme when archived sequences for every hour (17520 consecutive hours for period 2008-2009) were repeatedly entered to analysis of the one-hour reference accidental scenario from Table 1. The second area mentioned here is application of the code for consequences assessment of scenarios with long term release of radioactivity with periods many days up to scenario of annual discharges of radionuclides during normal routine operation. The curious procedure substitutes total annual release by equivalent partial hourly releases (8760 hours for 2008 year). Partial results have provided good bases for comparative benchmark of HARP and NORMAL codes. As for model improvement, more realistic modeling under low-wind conditions is in preparation.

However, the main objective of the further development of the HARP code is construction of assimilation subsystem ASIM based on advanced SMCM methods of Bayesian filtering. The technique enables optimal blending of all available information with aim to improve model predictions and better identification of affected areas determined for countermeasures introduction. The problem is currently being solved within the grant project which should support decision making taking into account usually fragmentary measurements from various sources (stabile radiation networks, mobile groups, aerial vehicles) with asynchronous timing and incomplete, uncertain or missing information.

6 ACKNOWLEDGMENTS

These activities are supported thanks to grant project No. VG20102013018, Ministry of the Interior of the Czech Republic.

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