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APPLICATION OF DECISION SUPPORT SYSTEM JRODOS FOR ASSESSMENTS OF ATMOSPHERIC DISPERSION AND DEPOSITION FROM FUKUSHIMA DAIICHI NUCLEAR POWER PLANT ACCIDENT

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After the Chernobyl accident, the European Commission – under the auspices of its Research and Technological Development Framework Programme – has supported the development of the RODOS (Real-time On-line DecisiOn Support) system for off-site emergency management. The multiplatform version of RODOS was recently redesigned as a user friendly system applicable for various computational platforms and easy customizable for different sites of nuclear power production. This new version was named JRODOS as its software implementation base is Java language. In March 2011 JRODOS was customized for the site of Fukushima Daiichi Nuclear Power Plant (NPP). JRODOS was applied to perform atmospheric dispersion and deposition calculations and to assess the doses to the public in the vicinity of the NPP. From the second half of March 2011 onwards, results of the assessments were presented to the public and mass media on the web site of the Karlsruhe Institute of Technology. The Numerical Weather Forecast model WRF has been implemented for the region around the NPP to produce 3D fields of the meteorological parameters that were further used by the JRODOS system. Prognostic and diagnostic assessments of the radiological situation in the vicinity of the site have been performed at least once per day with various source terms. Taking into account the high uncertainties in the source term estimation, the simulated results show a reasonable fit to the monitoring data obtained later. The study demonstrated the flexibility of JRODOS for the assessment of the consequences of nuclear accidents at different nuclear energy production sites.

KEY WORDS: *nuclear power plant, accident, radionuclide, model, decision support system, atmospheric dispersion, Fukushima*

1. INTRODUCTION

Under the auspices of its 3rd - 7th RTD (Research and Technological Development) Framework Programmes, the European Commission has supported the development of the RODOS (Real-time On-line DecisiOn Support) system for off-site emergency management (Raskob and Ehrhardt, 2000; Raskob, 2010). The main objectives of these RODOS related projects were on the one hand side to develop a comprehensive and integrated decision support system that is generally applicable across Europe and also to provide a common framework for incorporating the best features of existing decision support systems and future developments. The mathematical models of the RODOS were developed in more than 20 European institutions. These simulation models, managed by comprehensive user interfaces and operated with real-time data base and GIS functionalities, use radiological monitoring information, operational weather forecast data and hydro-meteorological scenarios to perform the modeling of the transport of radionuclides in the atmosphere, their deposition to land and water, the transport of the nuclides in water, their distribution in the ecosystems and the estimation of potential doses to the public.

Finally it also provides a tool for the evaluation of optimal post accidental countermeasures and strategies.

At the beginning of 2011 the RODOS system was installed operationally in Germany and used in many European countries. Since 2006 a new version of RODOS system named JRODOS was under development (Ievdin et al., 2010). The main objective of the JRODOS re-engineering was to obtain a multiplatform system that should be much more user friendly than previous UNIX based RODOS version. In addition the customization of the system for any potential site around a globe should be carried out easily. The analyses of the consequences of the Fukushima Daiichi Nuclear Power Plant (NPP) accident in March 2011 was one of the first serious tests for JRODOS as it was applied to a real on-going incident with the dispersion and transport of radionuclides released into the environment.

The customization of JRODOS for the site of Fukushima Daiichi NPP has been started by the RODOS team of the Karlsruhe Institute of Technology (KIT), Germany, the first Monday after the release. The work has been performed in close collaboration with the Ukrainian participants of the project. The board of KIT intended to provide unbiased information about the incident to the public, mass media and politicians. Therefore, KIT has set up a public web site publishing at least one prognostic dose assessment per day. The current paper presents the results achieved in spring 2011 concerning the predictions of atmospheric dispersion and depositions of radionuclides from Fukushima Daiichi NPP and their associated potential doses.

2. JRODOS – MULTIPLATFORM VERSION OF RODOS SYSTEM

Initially, RODOS has been developed and implemented as a software system under the UNIX operating system for HP RISC servers and workstations. The extended usage of other operating systems (Windows, Linux) also in the European emergency centers required modifications of RODOS.

Within the 6th EC Framework Programme, the re-engineering of RODOS into a new distributed multiplatform version based on the Java environment and named JRODOS has started (Ievdin et al., 2010, Zheleznyak et al., 2010,). Following very positive feedback from the end users organized in the RODOS Users Group (RUG), activities continued within the 7th Framework project NERIS-TP.

The following requirements to the new JRODOS system have been formulated by the RUG participants:

- a possibility of using the system within modern server and workstation environments running MS Windows or Linux operating systems;
- user interface with easy to use forms and comfortable result representations;
- simple procedures to customize the system to new regions;
- re-utilization of existing simulation models;
- simple integration of new models;
- GIS functionality in the system and user interfaces.

Based on the requirements listed above, the Java language has been selected for the system development, while the simulation model codes written in Fortran, C and C++ remained unchanged and were then integrated into the re-engineered DSS (Ievdin et al., 2010, Zheleznyak et al., 2010). This decision was supported by the fact that Java contains powerful instruments for the development of user interfaces and overall data management. Many open source libraries with non-binding license (LGPL, MIT, Apache etc.) increased the development speed.

JRODOS is a distributed system containing (Ievdin et al., 2010):

- Computational Server, triggering mathematical calculations and collecting model results;
- Client for processing model input data and results visualization;
- Management Server responsible for communications between the system parts and the database.

The system allows installing its components to several physical PCs for the load balance in a multi-user solution as well as deploying all the parts into a single desktop or laptop PC for the autonomous usage.

The new RODOS version – JRODOS – is used in several European emergency centers both as online prognostic system and as a nuclear preparedness tool for emergency planning. The DSS is deployed in Germany, Spain, Austria, the Netherlands, Switzerland, Belgium, Finland and several other countries. The system is being continuously improved by adding new mathematical models and specific functionalities requested by JRODOS users.

3. ADAPTATION OF JRODOS TO THE SITE OF FUKUSHIMA DAIICHI NPP

JRODOS allows performing calculations for accidental releases of radionuclides into the atmosphere almost anywhere in the world. Modeling of atmospheric transport and dispersion processes followed by an analysis of early countermeasures are the most important tasks required to assess the consequences at the early stage of an incident. The simulation of the atmospheric transport and dispersion as well as the assessment of potential doses and the effectiveness of countermeasures (evacuation, sheltering, administration of stable iodine) are performed by two modules integrated into JRODOS (chain of the local-scale atmospheric transport models LSMC, consisting of the meteorological preprocessor (Andronopoulos et al., 2010), the dispersion models RIMPUFF (Thykier-Nielsen et al., 1999) and DIPCOT (Andronopoulos et al., 2010), and the early countermeasures model EMERSIM (Päsler-Sauer, 1998)). These models require a set of geographic data and relevant, regularly updated numerical weather prediction (NWP) data.

Geographical data have been prepared from open sources and include an elevation map, a map of land use categories, soil maps and the population density based on a census from the year 2000. All maps with the resolution of 1km * 1km were created as uncompressed GeoTIFF files and placed into the JRODOS system.

Regularly updated weather forecast was provided by:

- A joint team of the Institute of Mathematical Machines and System Problems (IMMSP) of the NAS of Ukraine together with the Ukrainian Center of Environmental and Water Projects;
- The Institute of Meteorology and Climate Research (IMK-IFU), Karlsruhe Institute of Technology (KIT), Germany.

Both teams used the mesoscale numerical weather prediction system WRF (Skamarock et al., 2008). The boundary and initial conditions are taken from the results of the U.S. Global Forecasting System (GFS), operated by the National Center for Environmental Prediction (NCEP, http://www.ncep.noaa.gov/), USA. Data were downloaded from the NOMADS servers (Rutledge et al., 2006).

The IMMSP/UCEWP team has applied WRF with the default model parameters. The calculation domain of 1500 km * 1500 km was selected to cover Japan and the neighboring territory. The grid was created in latitude-longitude projection and the cell size of 0.1 degree was selected. The WRF model domain used for the calculation by IMK was set to 1500 km x 1000 km with 10km cell size.

Both teams provided regularly updated numerical weather forecast data for 72 hours (WRF provided calculations for up to 168 hours, but mainly only the first 72 hours were used in the assessments) with 3 hours time step. The forecasts were updated every 6 hours (analysis time at 00, 06, 12 and 18 hours UTC each day).

Originally IMMSP/UCEWP used data from the global model GFS with a resolution of 1.0 degree for boundary and initial conditions while IMK used the same model but with a resolution of 0.5 degree. Later IMMSP/UCEWP also switched to 0.5 degree grid input.

The standard output for WRF results is a binary NetCDF file. Before the Fukushima nuclear incident JRODOS could handle weather prediction data only in a special ASCII format or in GRIB1 binary format. In the frame of the preparation of a special version for Japan, an importer for NetCDF files produced by WRF was developed and implemented. This functionality has been built using a Java open source NetCDF library (http://www.unidata.ucar.edu/software/netcdf/). Consequently, meteorological fields in three formats can be handled now by the system and stored in the NWP database. Later the meteo data can be extracted and used for visualizations or calculations. Additionally, special tools were developed to automatically download new WRF results directly into the JRODOS NWP database, thus enabling usage of the latest synoptic data in calculations.

Figure 1 shows the visualization of WRF calculation results (the wind field at a height of 10 meters for the area near Fukushima for two time steps) in the JRODOS user interface.

In order to ensure a fast and easy way to present time-dependent results for reports, meetings, presentations and publications on web pages, the functionality of creating animated GIF-files was implemented on the client side of JRODOS. A user can specify background map layers, zoom level and time-dependent field on the map in the user interface (e.g. the concentration of the radionuclide in air or wind field forecast). By selecting the command to create GIF-file the JRODOS system automatically moves the time slider, performs map snapshots for each step and stores the pictures as an animated GIF-file.

The 3D numerical fields of the meteorological parameters produced by WRF have been used by the RIMPUFF model to simulate the atmospheric transport, dispersion and deposition of radionuclides followed by the EMERSIM model with European intervention levels to analyze the appropriate countermeasures.

KIT used the system to create daily updated forecasts of the radioactive cloud movement. These maps, together with results of further models (both integrated into JRODOS and stand-alone) as well as information about the current state of the reactor and a potential sourceterm (if available) have been published daily on the KIT web server as well as on a server for extreme events (http://www.wettergefahren-fruehwarnung.de/Artikel/20110314_fuk.html).

4. PREDICTIONS AND ASSESSMENTS

Studies conducted with the support of the U.S. Nuclear Regulatory Commission show that in real NPP accidents the estimated source strength may differ by several orders of magnitude from the true values. Thus errors in the source term estimation are the dominant ones in the predictions of atmospheric transport and dispersion. Even with detailed information about the reasons of accident and by using databases of pre-calculated source terms, the error in the estimated release rate may be higher than one order of magnitude (Acharya et al., 1991).

During the accidental releases in March-April 2011 the German Society for Reactor Safety (GRS) has provided the following source estimations (Table 1). It should be noted that the conservative estimations of GRS are consistent with data from other nuclear agencies, such as the Austrian Institute for Meteorology and Geodynamics, according to which the conservative release from Fukushima nuclear power plant is estimated as about 20% of Chernobyl for ^{131}I, and ranging from 20 to 60% for ^{137}Cs (Farivar, 2011). According to the estimations of the Japanese Agency of Nuclear and Industrial Safety (NISA) conducted after the accident, the amount of the emission during the incident was close to the conservative estimates of GRS (Table 1). Some of the later estimates based on the data collected on the territory of Japan (e.g., Chino et al., 2011) fully agree with the estimates provided by NISA. A recent publication (Sugiyama et al., 2012) that describes the experience of the DOE – NARAC system application for analyses of the atmospheric transport and dispersion from FD NPP based on a similar approach of WRF implementation for NPP site, presents a detailed analyses of the different source term estimates provided at different times after the accident which are now slightly lower than the estimates of NISA (Table 1). In their assessment of the potential source term, (Sugiyama et al., 2012) also used measurement data collected on the territory of Japan. Other assessments based on the monitoring data collected far from the source – in the USA, etc., (e.g. Stohl et al., 2011) show significantly higher values for the total amount of the released radioactivity (Table 1). All in all, the resulting range of the available source estimates for ^{137}Cs is within one order of magnitude.

Such discrepancy in the estimation might result from the fact that in the first days most of the time the wind was blowing towards the Pacific Ocean and therefore significant parts of the plume might have been detected only far from the source. Therefore, source estimations based on different data (collected in the territory of Japan and/or in the US territory) may give quite different results. Since we are interested in our assessments only in the near range up to 300 kilometers around the site, we use the values of NISA.

Apparently, the above mentioned assessments of the source term are related mainly to the period from March 14 to 16, when, according to some reports, a nuclear meltdown occurred. During this period there was a change in the wind direction (Figure 1). The wind was blowing first to the East (March 15) and then turned to the West (March 16). In this respect, the results of calculations were sensitive to the errors in predictions produced by the numerical weather forecast model WRF, as well as the errors in the source term temporal distribution.

Some verification of WRF for the conditions of Japan have been performed by comparing the WRF results with measurements of the weather stations located at the airports Fukushima and Tokyo, for the period from 17 to 22 March (Figure 2). In this verification procedure WRF was using the final analysis of NCEP for setting the initial and boundary conditions. As can be seen from the data presented in Figure 2, the WRF model closely reproduces the time dependency of the wind velocity and direction. That result justifies the usage of WRF for diagnostic and prognostic calculations of radionuclides in the vicinity of the Fukushima nuclear power plant.

The total amount of radionuclides following the NISA data (Table 1) has been manually distributed in time so the release had three peaks between March 13 and 16 (GRS, internal communication). The simulation scenario started on March, 14, 14:00 UTC. The first peak release occurred during the first hour and the released activity of ^{137}Cs was set to $2.5 \cdot 10^{15}$ Bq. The second peak occurred between the 19th and the 20th hour of calculation, the released activity of

^{137}Cs was set to $5.0 \cdot 10^{15}$ Bq. The third peak occurred between the 30th and the 31st hour, the released activity of ^{137}Cs was set to $2.5 \cdot 10^{15}$ Bq.

The fallout of ^{137}Cs calculated with JRODOS using the WRF data is shown in Figure 3. It has to be noted that the comparison is not entirely complete, since the measurements were obtained over a longer period. However, during most of the time the wind was directed towards the sea and the period covered by the calculations seemed to be the one with the most intense release of radioactivity. Thus, the results of JRODOS calculations can be well compared with measurements carried out by joint US-Japan Aerial Measurement System (Lyons and Colton, 2012). As it can be seen from Figure 3 the calculations and the measurements are in good agreement.

The results presented in Figure 3 have been obtained on the basis of source term assessments by the Karlsruhe Institute of Technology. At the time of the accident, prognostic calculations of the atmospheric transport and dispersion of radionuclides have been performed with JRODOS using the operational numerical weather forecast data produced by WRF and some more conservative source term estimations. In this way, the worst case estimations of potential consequences of releases from the Fukushima NPP were performed for the next few days. As a conservative estimate, a source term was taken equal to $3 \cdot 10^{16}$ Bq for ^{137}Cs and $3 \cdot 10^{16}$ Bq for ^{131}I. Emission rate was assumed to be uniformly distributed over the relevant period of the forecast (three days).

Figure 4 and 5 show the results of such a conservative forecast performed for the period of April 1-3, 2011. At this time the wind turned again to the coast and the cloud moved towards Tokyo (Figure 4). However, the predicted countermeasures such as the maximum distribution of iodine tablets did not reach Tokyo. The area for the distribution of iodine tablets for children was significantly larger than the corresponding area for adults, which would have been distributed only within a 50 km radius from the reactor.

5. CONCLUSIONS

The JRODOS application to the Fukushima Daiichi incident demonstrated the flexibility of the JRODOS architecture by fast customization to a new geographical location. Additional system components to support a new type of binary input data (NetCDF) have been developed.

The JRODOS system has been used for diagnostic and prognostic estimations of the transport of radionuclides following the incident at the Fukushima Daiichi NPP. The source term estimates by GRS and the numerical weather data provided by the meteorological model WRF have been used in JRODOS for all assessments. The diagnostic results of JRODOS reproduce the pattern of the surface contamination with ^{137}Cs near the power plant quite well.

As part of the JRODOS application to the Fukushima incident, a conservative prognostic simulation of the atmospheric transport and dispersion have been performed based on the operational numerical weather prediction data calculated by WRF. Even with such a conservative source term, the countermeasure area of the distribution of iodine tablets for children did not reach Tokyo. This was demonstrated for the meteorological scenario of April 1-3, 2011 when the wind was blowing to the South which usually does not occur often and thus can be defined as one of the worst case scenarios for Tokyo.

The experience gained in setting up the JRODOS system for operational application to the Japanese NPP will be further used by the developers to improve the system continuously and their adaptation work to other countries inside and outside the European Union.

6. ACKNOWLEDGEMENTS

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REFERENCES

Acharya, S., Agrawal, B., Cunningham, M., Denning, R., Glynn, J., Johnson, J., Niyogi, P. and Van der Molen, H., (1991) Severe accident risks: an assessment for five U.S. nuclear power plants. *Report NUREG-1150,* USA, Washington DC.: US Nuclear Regulatory Commission, 252 p.

Andronopoulos, S., Davakis, E., Bartzis, J.G. and Kovalets, I.V., (2010) RODOS meteorological pre-processor and atmospheric dispersion model DIPCOT: a model suite for radionuclides dispersion in complex terrain, *Radioprotection*, vol. 45, n 5, pp. 77–84.

Chino, M., Nakayama, H., Nagai, H., Terada, H., Katata, G. and Yamazawa, H., (2011) Preliminary Estimation of Release Amounts of 131I and 137Cs Accidentally Discharged from the Fukushima Daiichi Nuclear Power Plant into the Atmosphere, *Journal of Nuclear Science and Technology*, vol. 48:7, pp. 1129-1134.

Farivar, C., (2011) *Austrian authorities release detailed data on Japan radiation. Deutsche Welle*. Retrieved March 23, 2011, from http://www.dw-world.de/dw/article/0,,14938445,00.html.

Ievdin, I., Trybushnyi, D., Zheleznyak, M. and Raskob, W., (2010) RODOS re-engineering: aims and implementation details, *Radioprotection*, vol. 45, n 5, pp. 181–189.

Lyons, C. and Colton, D., (2012) Aerial Measuring System in Japan, *Health Physics,* vol. 102(5), pp. 509–515.

Päsler-Sauer, J., (1998) Model Description of the Early Countermeasures Module ECM-EMERSIM, *Report RODOS WG2_TN98_02*, Denmark, Roskilde: RISO National Laboratory, 48 p. Available at: http://www.rodos.fzk.de.

Raskob, W., (2010) Overview on the model development carried out in the EURANOS project. *Radioprotection,* vol. 45, n 5, pp. 45-54.

Raskob, W. and Ehrhardt, J., (2000) The RODOS System: Decision Support for Nuclear Off-site Emergency Management in Europe, *10th International Congress of the International Radiation Protection Association*, CD published May 14–19, 2000. Hiroshima, Japan. Available at: http://www.iscram.org/dmdocuments/P269_278.pdf .

Rutledge, G., Apert, J. and Ebusizaki, W., (2006) NOMADS – a climate and weather model archive at the National Oceanic and Atmospheric Administration, *Bulletin of the American Meteorological Society*, vol. 87, pp. 327–341.

Skamarock, W.C., Klemp, J.B., Dudhia, J. , Gill, D. O., Barker, D. M., Wang, W. and Powers, J. G., (2008) A description of the advanced research WRF version 3, *NCAR Technical Note NCAR/TN-475+STR,* USA, Boulder: National Center for Atmospheric Research, 125 p. Available at: http://wrf-model.org.

Stohl, A., Seibert, P., Wotawa, G., Arnold, D., Burkhart, J. F., Eckhardt, S., Tapia, C., Vargas, A. and Yasunari, T. J., (2011) Xenon-133 and Caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition. *Atmos. Chem. Phys.*, vol. 12, pp. 2313–2343.

Sugiyama, G., Nasstrom, J., Pobanz, B., Foster, K., Simpson, M. P., Vogt, P., Aluzzi, F. and Homann, S., (2012) Atmospheric dispersion modeling: challenges of the Fukushima Dai-ichi response, *Health Physics,* 102 (5), pp. 493-508.

Thykier-Nielsen, S., Deme, S. and Mikkelsen, T., (1999) Description of the atmospheric dispersion module RIMPUFF, *Report RODOS WG3_TN98_13*, Germany, Karlsruhe: Foschungszentrum karlsruhe, 17 p. Available at: http://www.rodos.fzk.de.

Zheleznyak, M., Potempski, S., Bezhenar, R., Boyko, A., Ievdin, I., Kadlubovski, A. and Trybushnyi, D., (2010) Hydrological dispersion module of JRODOS: development and pilot implementation – the Vistula river basin, *Radioprotection,* vol. 45, n 5, pp. 113–122.

TABLE 1. Estimated source terms (in Bq), provided by GRS in the beginning of the accident, by NISA after the initial phase of the accident and by other authors.

	Gap release (GRS)	Core melt, (GRS)	Conservative estimates, (GRS)	Estimates from NISA (by 06 June 2011)	Estimates from Sugiyama, et al., (2012)	Estimates from Stohl, et al., (2011)
^{133}Xe	$4 \cdot 10^{14}$	$3 \cdot 10^{18}$	$3 \cdot 10^{18}$	-	$3.7 \cdot 10^{17}$	$1.5 \cdot 10^{19}$
^{131}I	$4 \cdot 10^{13}$	$4 \cdot 10^{16}$	$4 \cdot 10^{17}$	$2.6 \cdot 10^{17}$	$7.4 \cdot 10^{16}$	-
^{137}Cs	$2 \cdot 10^{13}$	$3 \cdot 10^{15}$	$3 \cdot 10^{16}$	$1.2 \cdot 10^{16}$	$3.7 \cdot 10^{15}$	$3.66 \cdot 10^{16}$
^{241}Pu	0	$9 \cdot 10^{11}$	$9 \cdot 10^{12}$	-	-	-

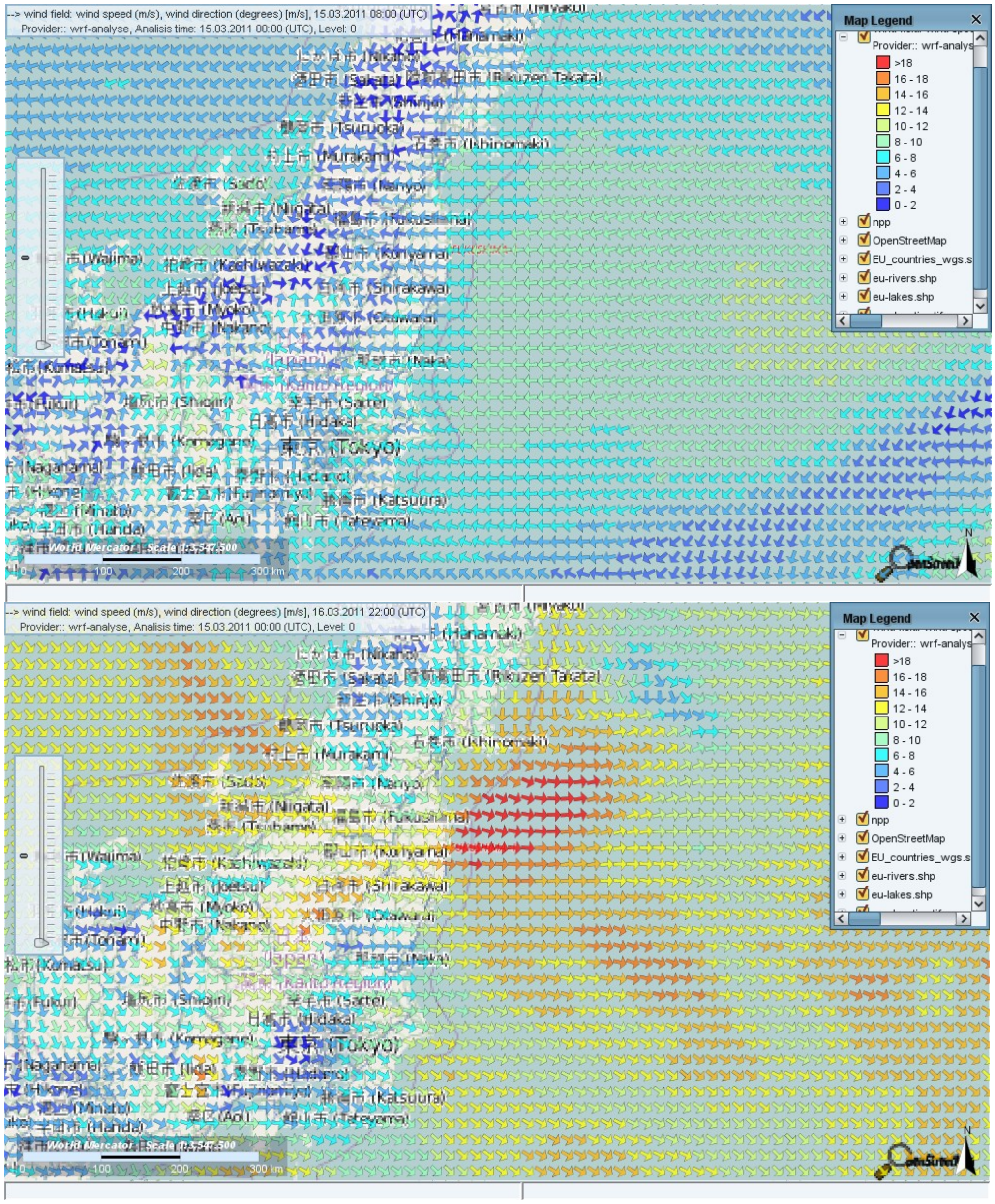

FIG. 1: Visualization of WRF results in JRODOS. The wind field at a height of 10 meters for the area near Fukushima. Data for March 15, 2011 08:00 UTC (upper picture) and for March 16, 2011 (UTC).

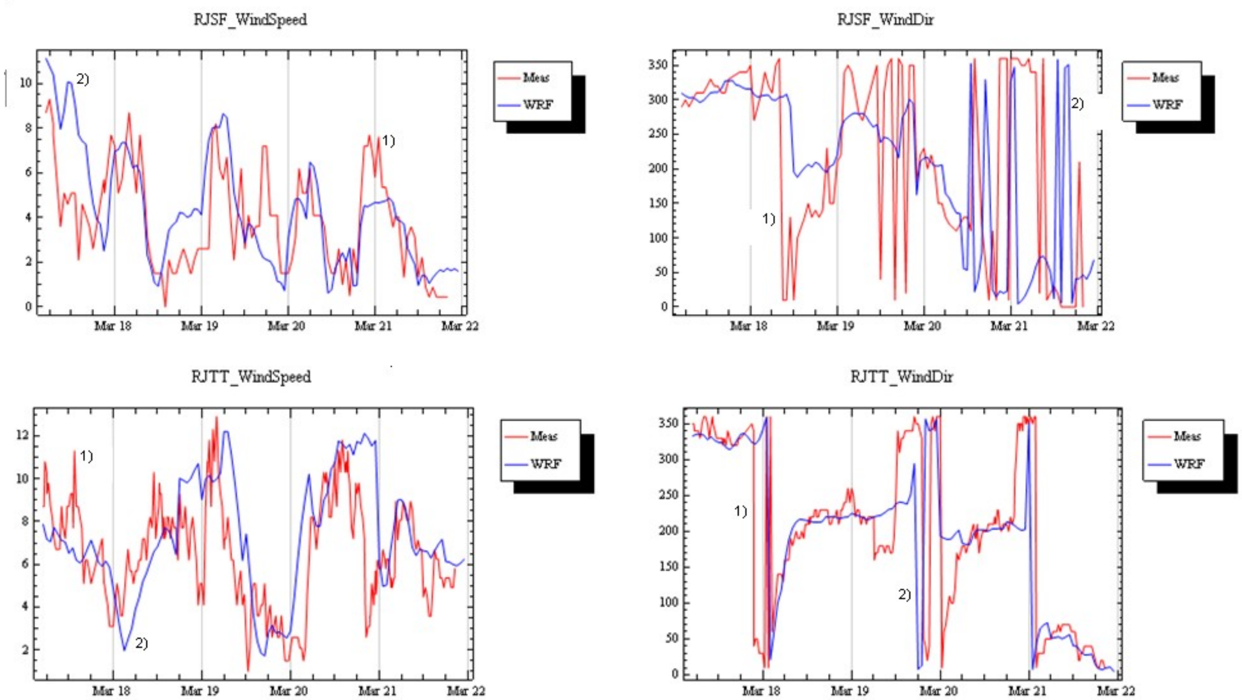

FIG. 2: Comparison of measured (curve 1) and by WRF calculated (curve 2) wind speed (left) and wind direction (right) for the weather stations at Fukushima Airport (top, RJSF) and at Tokyo Airport (bottom, RJTT). Measurements data is taken from Wolfram Mathematica database (http://www.wolfram.com).

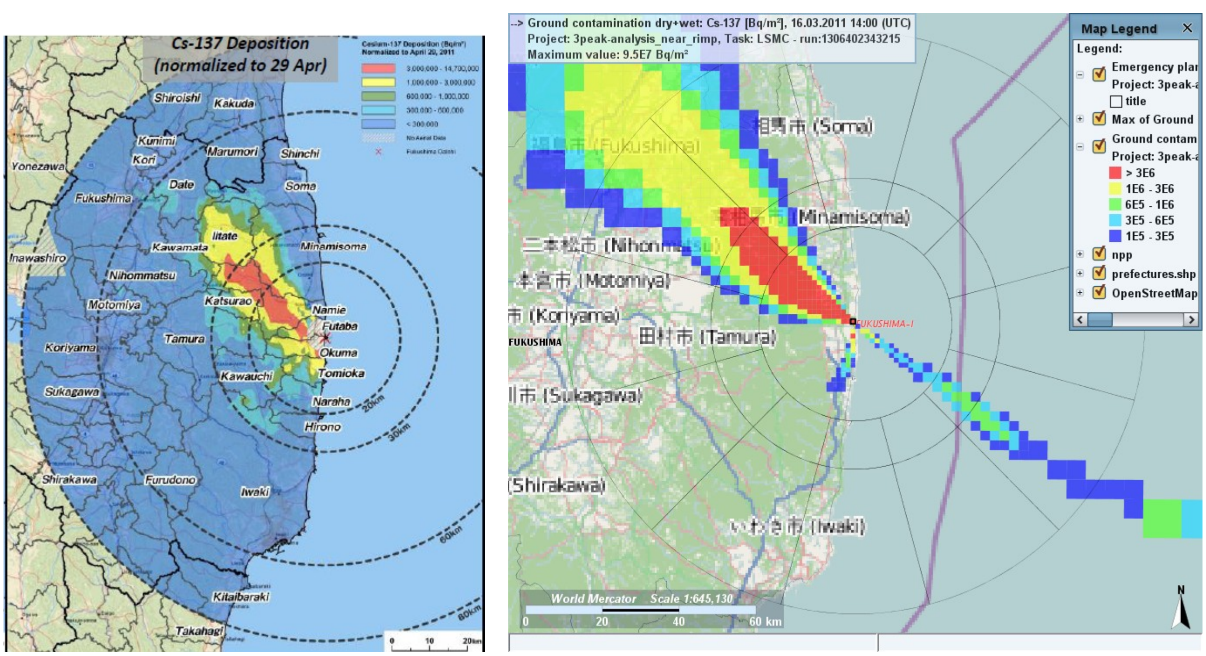

FIG. 3: Deposition of ^{137}Cs. Left: measured (image courtesy of the US Department of Energy and of the Japan Nuclear and Industrial Safety Agency, www.energy.gov/japan2011). Right: results of JRODOS calculations. Both figures have the same color code.

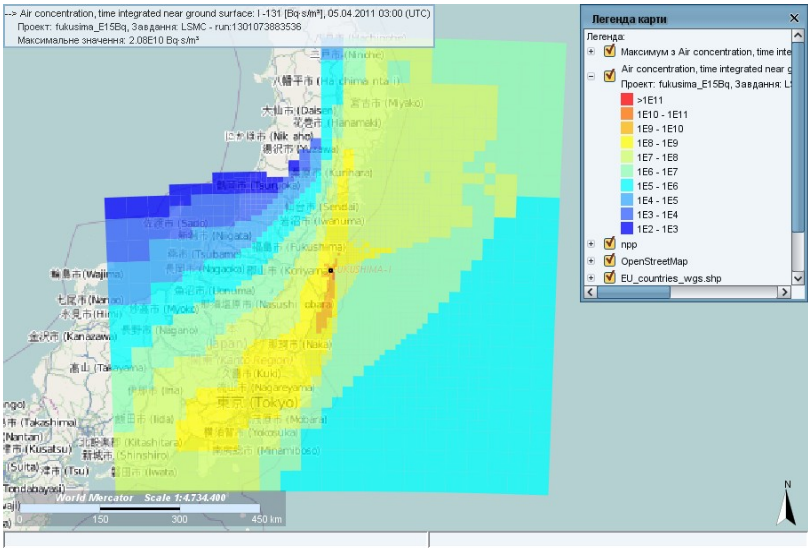

FIG. 4: Integrated concentration of ^{131}I near the surface, calculated by JRODOS according to a conservative emission scenario and meteorological conditions for the period from 1 to 3 of April, 2011.

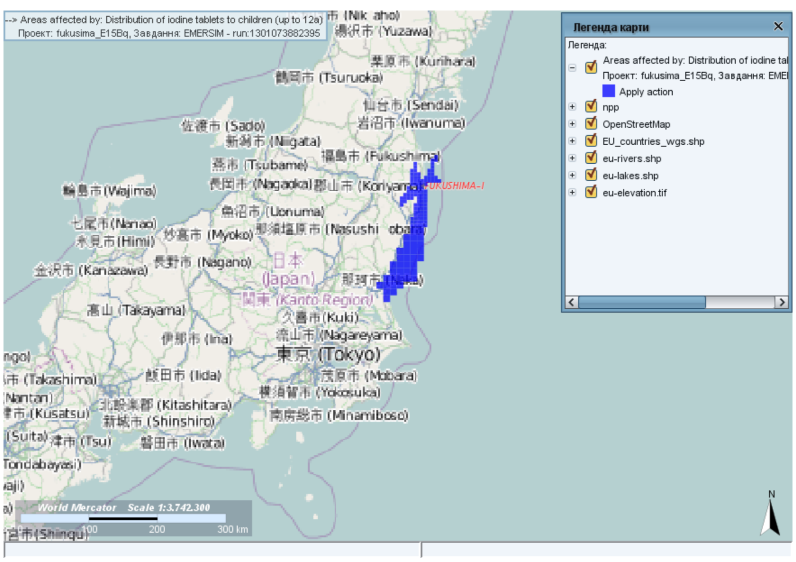

FIG. 5: The area of iodine tablets distribution for children, calculated by JRODOS according to a conservative emission scenario and meteorological conditions for the period from 1 to 3 of April, 2011.