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OPERATIONAL MODEL FOR ATMOSPHERIC TRANSPORT AND DEPOSITION OF AIR POLLUTION

OPERACYJNY MODEL ATMOSFERYCZNEGO TRANSPORTU I DEPOZYCJI ZANIECZYSZCZEŃ

Abstract: An assessment of the current state of natural environment affected by air pollution, as well as, forecasts of pro-ecologic, economic and social activities are very often performed using models for atmospheric transport and deposition of air pollutants. In the present paper, we present an operational dispersion model developed at the Institute of Meteorology and Water Management in Warsaw. The basic assumptions and principles of the model are described together with the operational domain and examples of model applications. Two examples of model application are described and discussed here. The first, application is a simulation of the atmospheric transport and deposition of the radioactive isotopes released into the atmosphere during the Chernobyl Accident in 1998. The second example is related to simulation of atmospheric transport of the tracer released into the air during the ETEX experiment. These two examples and previous applications of the model showed that presented dispersion model is fully operational, not only for long term applications, but especially for emergency situations, like nuclear accidents or volcanic eruptions affecting Polish territory

Keywords: emergency, atmospheric pollutants, dispersion model, radioactive contamination, volcanic ash

Introduction

Over the past several decades, air pollution has become a serious problem all over the world including Europe. It has been a significant factor in deterioration of human health and in environmental degradation. In order to understand the link between air pollution sources and adverse affects on health and environment, it was necessary to develop different analytical tools including mathematical models. Among these tools, air pollution models play a very important role, because they provide a direct link between air pollution sources on one side and concentrations, as well as depositions, of selected pollutants on the other side.

Air pollution models have been developed for different spatial scales from local (several kilometers) to global covering the entire Earth. The air pollution issue in Europe

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has very international character, because pollutants emitted in one European country can be deposited in another. Therefore, from the perspective of Europe in general, and Poland more specifically, the most important among air pollution models are those for the long range transport, operating in the scale of one to several thousand kilometers.

One of many environmental problems in Europe and probably the most important in the early seventies was the so-called "acid rain". It was caused by extremely high atmospheric emission level of sulfur and nitrogen all over Europe. The harmful effects of acid rain could be especially seen in the area of Black Triangle and in southern part of Poland [1]. A number of models of air transport of pollutants over Europe were used for the analysis of this phenomenon. The most commonly used model for this purpose was developed in the framework of EMEP (European Monitoring and Evaluation Programme) activities. Initially, in the 1980s, it started as a relatively simple Lagrangian trajectory model [2]. After many years of development it was transformed to a complex Eulerian model with more than 300 chemical reactions and species [3].

The latest version is called EMEP MSC-W model and is used for the acidifying substances, ozone and particulate matter. There is also another EMEP model, called EMEP MSC-E and this one is used for heavy metals [4] and persistent organic pollutants [5]. The EMEP MSC-W model is presently used for both, analysis of air quality during one to several years [6] as well as for air quality forecasts for five days ahead [7]. The EMEP MSC-W model has been also used to evaluate nitrogen deposition to the European seas and among them, to the Baltic Sea [8], which is particularly vulnerable to eutrophication.

In recent years high concentrations of particulate matter (PM₁₀, PM_{2.5}) and ozone have become a problem throughout Europe and especially in Poland [9]. In this context, an interesting example of the application of air pollution models for different spatial scales is the analysis of the impact of air pollution on health in the region of Krakow [10]. This analysis uses both, the global model GEM-AQ [11, 13-16] and the local model MC2-AQ [12]. In both cases the dispersion models are linked on-line to the meteorological models. GEM-AQ model was also used to analyze the effects of urbanization on meteorological conditions and the level of contamination in southern Poland [16].

Another interesting example of the application of air pollution transport models was the analysis of climate change effects on ozone and particulate matter [10] as well as on SO₂ [11], in Central and Eastern Europe. For this purpose models CAMx (www.camx.com) and CAMQ (www.camq-model.org) were used.

Severe nuclear accident at nuclear power plant in Chernobyl in 1986 contributed to the development of a whole range of models for emergency situations that are currently used for assessment of nuclear incidents (*eg* [17-22]), nuclear explosions (*eg* [23]), transport of dangerous bacteria in the atmosphere [24, 25]), transport of harmful organic pollen [21], large fires affecting air quality on the scale of several hundred kilometers [25, 26], as well as volcanic eruptions [20, 22, 25]. More than 20 models of this type from European institutions and from the United States, Canada and Japan took part in the project ENSEMBLE [27] which was intended to replace the deterministic forecasts from the individual model with the probabilistic, ensemble-based forecast. In this way, the decision makers in national radiation protection agencies could better assess the uncertainty of emergency forecast in case of nuclear accident [28].

The model developed at the Institute of Meteorology and Water Management (IMWM) [29] belongs to the emergency group, but it can also be used for diagnostic analysis of

atmospheric transport and deposition of various pollutants (*eg* acidifying compounds, heavy metals and persistent organic compounds) over Europe, during many years.

For operational applications the IMWM dispersion model is coupled with operational meteorological models. This paper describes the basic concept and principles of operational air pollution model at IMWM, as well as selected examples of its application. Concerning earlier prognostic tasks, the IMWM model was used to simulate the dispersion of tropospheric ozone. It was also successfully applied for diagnostic tasks such as simulation of atmospheric transport and deposition of heavy metals [30] and acidifying compounds. The model was also successfully used for real emergency situations, like release of toxic phosphorus in Ukraine in 2007 or eruption of Eyjafjallajökull in 2010 [31].

Operational air pollution transport model at IMWM

Operational model for simulating atmospheric transport and deposition of selected pollutants has been developed, implemented and tested at IMWM [29]. This model is, fully operational at present, first of all, for prognostic applications. Operational means in this case that the model can be run at any time of day and night in case of emergency, such as nuclear accident or volcano eruption. Operational in case of diagnostic application, means that there exists, and is continuously updated, a long-term meteorological database which allows multi-year model simulations for pollutants, like for example reactive nitrogen.

Several assumptions were made in development of the operational IMWM air pollution model. All of them can be found in [29], but two of them are also presented here. The first one states that pollutants taken into account in the model calculations (*eg.* aerosol) do not affect the state of meteorological elements (for example, do not change the balance of radiation). So, the dispersion equations can be solved independent of the meteorological equations and in practical applications the dispersion model can be used off-line as well. The second assumption states that computational domain of the IMWM model is flexible in principle both, in terms of size and resolution, depending on the user needs. However, for operational applications in case of emergency, the dispersion model domain is exactly the same as the domain of the Numerical Weather Prediction (NWP) model COSMO (Consortium for Small-Scale Modeling, [29]), which is also operational at IMWM. This domain covers the entire territory of Poland and most of Europe with the resolution of not less than 14km×14km. This direct link between the models avoids the time-consuming and accuracy-reducing interpolation of input data. It should also be mentioned that vertical boundary of the dispersion model domain can be on a very high level (*eg* 20 km) for some specific applications like, for example, simulation of dispersion from nuclear detonation. This was a basis for mathematical formulation of the model as a set of prognostic equations.

Model equations

Atmospheric dispersion of pollutants in the Eulerian approach adopted by the IMWM model is described by a system of partial differential equations of the following form [29]:

$$\frac{\partial \chi_m}{\partial t} = -u_j \frac{\partial \chi_m}{\partial x_j} + S_{\chi_m}, \quad m = 1, 2, \dots, M \quad (1)$$

In the set of equations (1) spatial coordinates $x_1 = x$, $x_2 = y$, $x_3 = z$ and time t are independent variables, while dependent variables are components of the wind velocity field

$u1 = u, u2 = v, u3 = w$, pollutant(s) mixing ratio $\chi_m, m = 1, 2, \dots, M$, and positive or negative sources of pollution $S_{\chi m}$ taking into account emissions and removal of pollutants, as well as, chemical reactions between them.

The dispersion model is based on a set (1) of partial nonlinear differential equations, containing M independent variables - mixing ratios of selected pollutants which are functions of space and time. However, both in the measurements, as well as in the wide range of practical applications, the main variable of concern is the concentration of air pollutant - expressed as mass of pollutant per unit volume of air. The equations describing concentrations of pollutants in the air are equivalent to the equations defining the mixing ratio (1) and have the following form [32]:

$$\frac{\partial c_m}{\partial t} = - \frac{\partial (u_j \cdot c_m)}{\partial x_j} + Q_{c_m}, \quad m = 1, 2, \dots, M \quad (2)$$

where $c_m = c_m(x, y, z, t)$ is the concentration of pollutant m and $Q = Q(x, y, z, t)$ is a general source term (positive or negative).

Application of Reynolds' decomposition separates the average (over time) and fluctuating (perturbations) parts of each variable in Eq. (2). The perturbations are defined such that their time average equals zero. In this formulation, the diffusion part of Eq. (2) is associated with the tensor of turbulent diffusion K_{jl} :

$$\overline{c_i' u_j'} = -K_{jl} \frac{\partial c_i}{\partial x_j} \quad (3)$$

Additional simplification used was the assumption that the tensor of turbulent diffusion K_{jl} is diagonal ($K_{11} = K_{22} = K_H, K_{33} = K_v$ with $K_{jl} = 0$ for $j \neq l$) with K_H being horizontal- and K_v - vertical turbulent diffusion coefficient. Finally Eq. (2) becomes:

$$\frac{\partial c_m}{\partial t} + \frac{\partial u c_m}{\partial x} + \frac{\partial v c_m}{\partial y} + \frac{\partial w c_m}{\partial z} = \frac{\partial}{\partial x} \left(K_H \frac{\partial c_m}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_H \frac{\partial c_m}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_v \frac{\partial c_m}{\partial z} \right) + G + Q \quad (4)$$

where operator $G = G(x, y, z, t)$ describes chemical transformations and operator $Q = Q(x, y, z, t)$ describes emissions and removal of air pollutants.

In the operational version of the model and in almost all diagnostic applications with the grid resolution of 10-20 km, the parts of Eq. (4) associated with horizontal diffusion are neglected due to strong effects of the so-called numerical diffusion. These effects are of the same order of magnitude as the actual horizontal diffusion [33].

The system of equations (4) together with parameterizations described in [29] is the formulation of the IMWM air pollution transport model from mathematical point of view.

Numerical algorithms

For the numerical solution of Eq. (4) a directional splitting method was used [34], which allows the solution of three-dimensional dispersion equation as a system of one-dimensional processes. Each of these processes can be treated with a different numerical method, appropriate for a given problem. In Eq. (4) processes of emission, advection, diffusion, deposition and chemical transformations are separated. The sequence of processes solved numerically in this method is the following: (1) emissions, (2) advection, (3) diffusion, (4) depositions (wet, dry, total) and (5) chemical and/or

radioactive transformations. For this purpose, the Eq. (2) can be reformulated in the following way:

$$\frac{\partial c_m}{\partial t} = \frac{\partial c_m}{\partial t_{\text{emission}}} + \frac{\partial c_m}{\partial t_{\text{advection}}} + \frac{\partial c_m}{\partial t_{\text{diffusion}}} + \frac{\partial c_m}{\partial t_{\text{deposition}}} + \frac{\partial c_m}{\partial t_{\text{chemistry}}} \quad (5)$$

where the sub-script „chemistry” means both, chemical reactions and radioactive decay, depending on application.

Emission in Eq. (5) can be long-term, short-term and in extreme cases instantaneous depending on model application. In all these cases it is assumed that the mass of pollutant injected at one time step into the air is instantaneously well mixed in the box defined by the grid size in horizontal direction and the thickness of the layer where release occurs.

Advection part of Eq. (5) is solved using a numerical AFP (Area Preserving Flux) algorithm developed by Bott [35, 36]. This algorithm is applied separately to each co-ordinate of the advection equation at each model time step. The AFP algorithm is time-implicit, positive defined and mass-conservative. This method belongs to the class of conservative methods of type FC (*Flux Correction*). Changes of concentration due to horizontal advection are calculated separately for each vertical level and for orthogonal directions, x and y . The vertical advection term is solved using the version of AFP algorithm developed for irregular grid. The open boundary conditions in the horizontal plane are applied, *ie* substances can go free outside the domain model. The closed boundary conditions are applied to vertical advection. On the lower boundary pollutants are removed from the atmosphere via dry deposition process.

Diffusion term in Eq. (5) is solved with a slightly modified Crank-Nicholson method [29, 37], which is semi-implicit in time. Knowing the turbulent diffusion coefficient $K(z)$ (or K_V in Eq. (4)) one can specify the vertical derivatives of concentrations in Cartesian co-ordinates using the following boundary conditions:

$$z = z_0, K \frac{\partial c}{\partial z} = v_d \cdot c, \quad z = H, \frac{\partial c}{\partial z} = 0 \quad (6)$$

Vertical diffusion term in Eq. (5) can be solved numerically using the following semi-implicit approximation [29]:

$$\frac{\partial}{\partial z} K(z) \frac{\partial c}{\partial z} \approx \frac{K_{j+\frac{1}{2}} \cdot \frac{c_{j+1} - c_j}{\Delta z_{j+\frac{1}{2}}} - K_{j-\frac{1}{2}} \cdot \frac{c_j - c_{j-1}}{\Delta z_{j-\frac{1}{2}}}}{\Delta z_j} \quad (7)$$

where c_j , K_j are the concentration and coefficient of vertical diffusion, respectively, at j level (vertical grid node), $\Delta z_{j+1/2}$ is the thickness of the layer between levels k and $k+1$. For practical reasons, the above algorithm, explained in Cartesian coordinates, is implemented in the IMWM model in so-called terrain-following vertical co-ordinate defined as:

$$\xi = H \cdot \left(1 - \frac{H - z}{H - z_g}\right) = H \cdot \frac{z - z_g}{H - z_g} \quad (8)$$

with H being top (constant upper boundary) of the model, z - height above the sea level, and z_g - terrain elevation above the sea level.

Chemistry in Eq. (5) includes both, chemical reactions between pollutants and alternatively their radioactive decay during the transport. Chemical reactions are dependant, in particular, on the model applications and pollutants taken into account in the model simulations. The same applies to radioactive decay. Details of the parameterizations of these processes in the model are presented in [29].

Model domain and vertical structure

As mentioned before, the computational domain of the IMWM model is quite flexible and can be changed for different applications. However, for operational applications and especially for emergency applications, the dispersion model domain is compatible with the domain of NWP model COSMO [38] which supplies all necessary meteorological data for the dispersion IMWM model. The COSMO domain covers a significant part of the European continent with territory of Poland located close to the center (Fig. 1). For local applications, the domain of the dispersion model should be within the COSMO domain with some security margin necessary for proper treatment of the lateral boundary conditions. As an example, the domain of the dispersion model used to simulate the transport and deposition of pollutants on Polish territory is also shown in Figure 1. The vertical structure of the operational IMWM air pollution model is shown in the same Figure 1. For typical operational applications it consists of ten layers, as in the COSMO model. In diagnostic version user can define it accordingly to task's specifications.

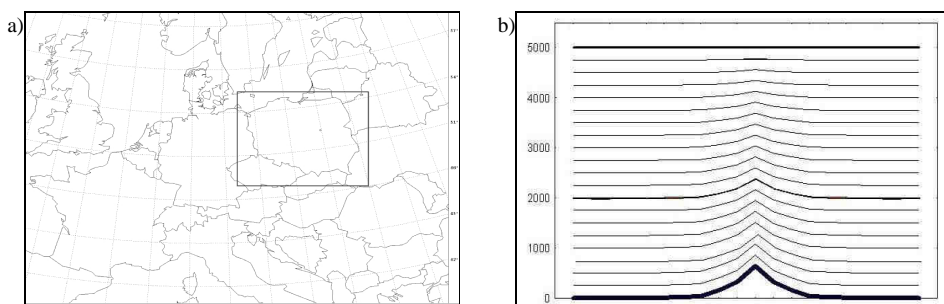


Fig. 1. Left - computational domain of the operational meteorological COSMO model at IMWM and example of domain of the dispersion model (inner rectangle) used to simulate the transport and deposition of pollutants on Polish territory. Right - an example of vertical structure of the IMWM air pollution model (the number of vertical layers is 21 for diagnostic version)

Examples of model applications

From many applications of the IMWM air pollution model, those related to emergency situations are of special interest, not only from the scientific point of view, but also from the decision making perspective in connection with the emergency preparedness organization in Poland. Therefore here, we have selected two cases of the emergency applications for which the IMWM model was applied in the past. One of these situations - Chernobyl accident was a historical case, but the other, the ETEX experiment required the simulation in real time. However, since Poland was not taking part in the ETEX experiment in real time, the IMWM model was applied a posteriori for this case.

The Chernobyl disaster

Approximately at 2:00 at night on 26 April 1986, there was an explosion at reactor unit No. 4 of nuclear power plant at Chernobyl in the Ukraine. This explosion destroyed the safety shields and the reactor building. At the same time, the first release of radioactive substances into the atmosphere occurred. Parts of the core (graphite and nuclear fuel) were scattered outside the reactor building. Next, there was a second explosion of an accumulated mixture of hydrogen and air formed when hot steam reacted with zirconium and graphite of the core. The consequence of the second explosion was a fire in the reactor building and in the machine room. The fire outside was extinguished in the morning the same day, however, the remains of the core continue to burn inside the reactor building, causing strong release of fission products to the atmosphere [39]. It has been assessed that about 4% of nuclear fuel from the core entered the atmosphere, with about 20% of iodine radioactive isotope I - 121, 13% of the cesium-123 (Cs-137) and about 4% of strontium-90 (Sr-90). In absolute numbers, this corresponds to about 28 kg of cesium and 0.37 kg of iodine. Activity of the total emission of radioactive substances was at least $2 \cdot 10^9$ GBq (more than 50 MCi). About 30% of the total activity was released into the atmosphere during the first day [40].

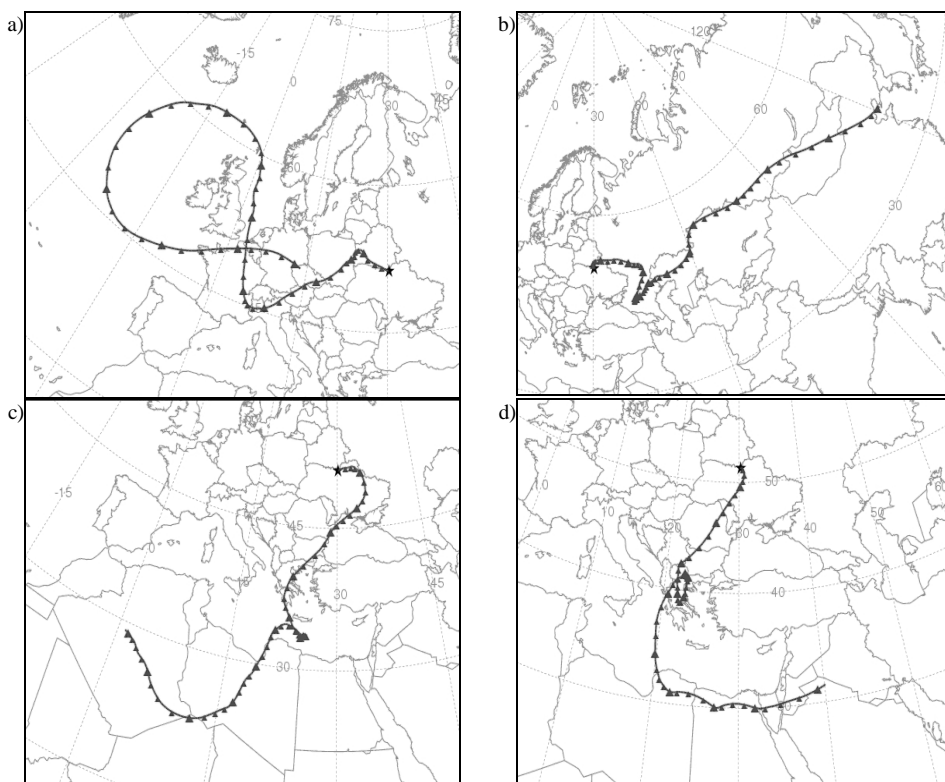


Fig. 2. Trajectories departing from the site of Chernobyl disaster (starting point marked with an asterisk, 500 meters above ground level) calculated for the following periods: a) 27.04.1986, 0:00 UTC, b) 28.04.1986, 0:00 UTC, c) 29.04.1986, 0:00 UTC and d) 30.04.1986, 0:00 UTC

To illustrate the meteorological situation and initial transport directions, trajectories released from the Chernobyl reactor (coordinates: 50.23°N, 31.27°E) on the level 500 m above the surface are shown in Figure 3. Trajectories were calculated for the period of first three days after the accident start. They were calculated using the NOAA HYSPLIT model [41] on the basis of archive data (CDC Climate Data Center). Figure 3 indicates that the territory of Poland was mainly contaminated by radioactive material released into the atmosphere during the most active emission period, that is, during the first day of accident.

The IMWM model was used for a-posteriori modeling of atmospheric transport and nuclear contamination. Dispersion simulations were carried out from April 27th, 1986, 00:00 UTC for twenty four days, when the radioactive cloud entirely left the model domain. Total activity was accepted as a variable determining the level of contamination and estimated for the entire period of release to be about 50 MCi. This assumption has been caused by the fact that uncertainty of emission levels of individual isotopes was far greater than the total activity - as an equivalent of overall contamination.

Figure 4 shows the development and location of the radioactive cloud in time.

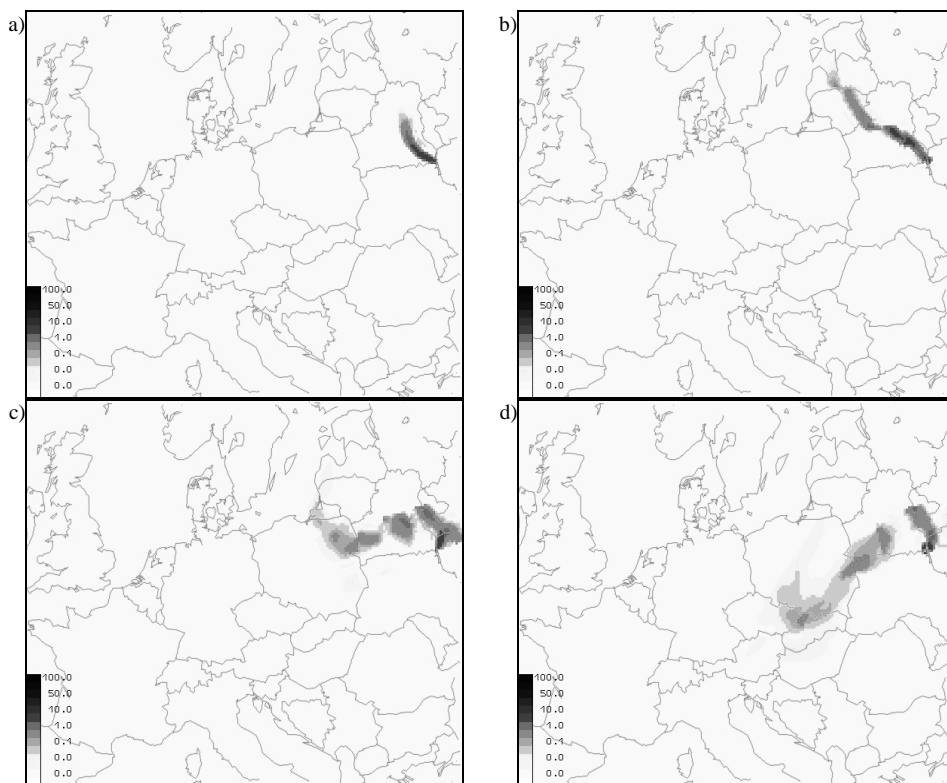


Fig. 4. Simulation of dispersion of the radioactive cloud of pollution released from the Chernobyl accident. The results are presented for the following dates: (a) 27.04.1986, 12:00 UTC, (b) 28.04.1986, 0:00 UTC, (c) 28.04.1986, 12:00 UTC, (d) 29.04.1986, 0:00 UTC. Units - percent of maximum activity concentration (2.5 MBq/m^3) in the surface layer at the disaster location

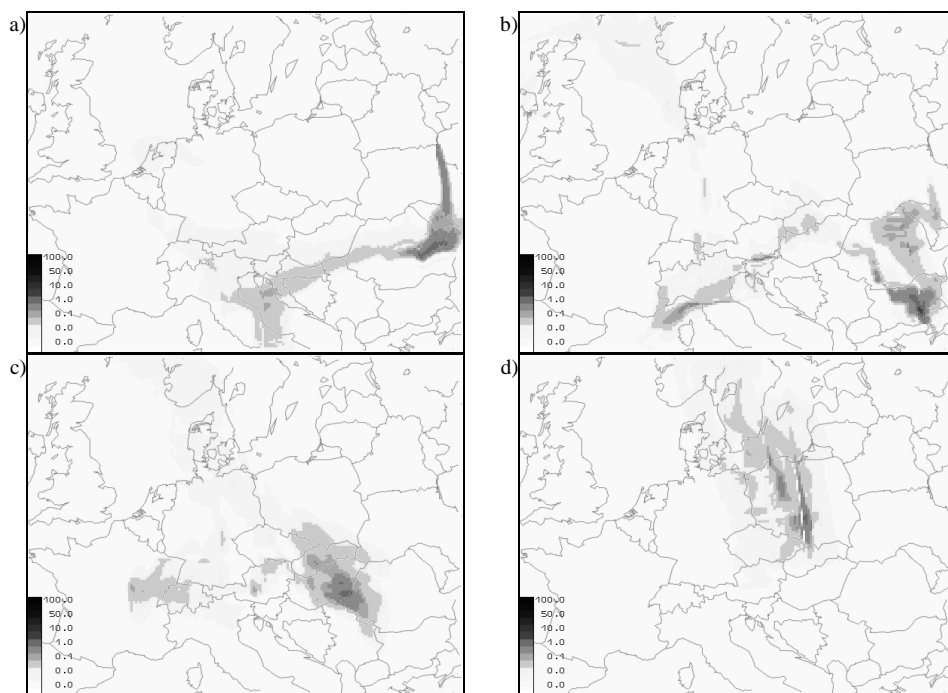


Fig. 5. Simulation of dispersion of the radioactive cloud of pollution released from the Chernobyl accident. The results are presented for the following dates: a) 30.04.1986, 0:00 UTC, b) 01.05.1986, 0:00 UTC, c) 02.05.1986, 0:00 UTC and d) 03.05.1986, 0:00 UTC. Units - percent of maximum activity concentration (2.5 MBq/m^3) in the surface layer near the disaster location

Because of meteorological situation over central Europe in late April and early May 1986, a cloud of radioactive contamination passed several times over Poland. A centre of high pressure stayed over Poland and Belarus until May 3rd, causing pollutions to drift over the center of the continent (see *eg* Figs. 4 and 5, map 4). This effect was picked up by stations detecting radioactive contamination and model simulations. It should be noted, that in case of the forecasts prepared in real time (operational mode), it is more important to determine the direction of transport of the radioactive cloud (which was the result of this simulation) than the accurate level of the concentration or precise deposition value. This is due to the fact that in an emergency situation and in particular accidents causing emissions of harmful substances and/or hazardous waste to the air, value and nature of these emissions can only be roughly estimated, and they are only known with considerable uncertainty. In such cases, routine measurements are carried out in the vicinity of the selected receptor. Comparison of these measurements with the results of the model calculations can later be used for scaling the source term and following significant improvement of the model results.

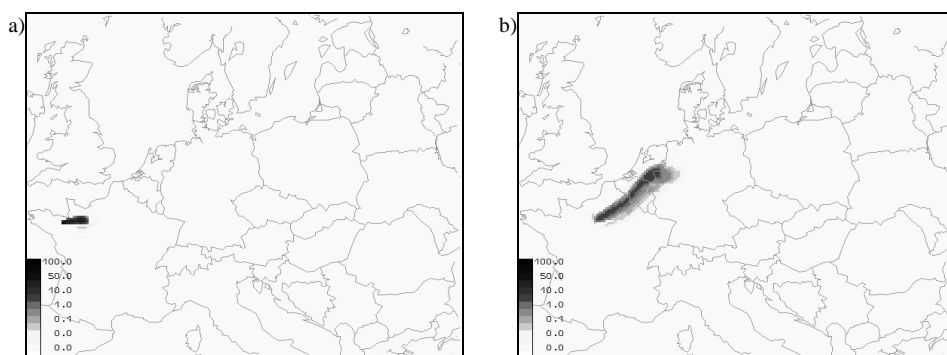
The ETEX experiment

The program *Atmospheric Transport Model Evaluation Study* (ATMES) was launched in 1986, after the accident at the Chernobyl nuclear power plant, under the auspices of the

European Commission (CEC), the World Meteorological Organization (WMO) and the International Atomic Energy Agency (IAEA). It resulted, *inter alia*, in identification of main problems associated with modeling severe emission events (industrial accidents) in real time. Due to the considerable interest of the international scientific community and success of ATMES, similar experiments were conducted in the United States (*Across North America Tracer Experiment* - ANATEX and *Cross-Appalachian Tracer Experiment* - CAPTEX). Based on the success and important results of previous experiments, a new project was launched in Europe in 1995. It was called the *European Tracer Experiment* (ETEX). The main task of Phase I of ETEX was a comparison of computed tracer concentration at a specific time and place with the carried out relevant measurements. The released tracer was a chemically passive, not degradable substance, dispersed only as a result of atmospheric transport. The tracer was released at a specific time and place with known to modelers, who were asked to perform the model simulations in real time. However, only *a posteriori* simulations performed with the IMWM model are presented here. Later on, the Phase II of ETEX was organized. The main goal of this phase was *a posteriori* modeling of tracer concentration and comparison of results with measurements at ETEX stations [42]. Two experimental releases, ETEX 1 and ETEX 2, were carried out at the end of 1995. Tracer was released into the atmosphere when weather conditions indicated that the cloud will pass over most of all measuring stations. This procedure was successful during the first experiment, but failed (due to an incorrect meteorological forecast) for the second release, when a large part of the tracer passed outside the area covered by the measurement network. The simulations with the IMWM model were carried out using as input relevant meteorological data and meteorological fields³.

ETEX 1

Figures 6 and 7 show simulated positions of the tracer cloud released in the ETEX 1 experiment, which was in the form of per-fluoro-methyl-cyclohexane (PMCH). These positions were calculated first after 6 hours and then in 12-hour intervals from the beginning of release in October 23rd, 1995, 16:00 UTC, to October 24th, 1995, 3:50 UTC. Calculated maximum concentration, for the entire period of the simulation was approximately 10 ng/m^3 .



³ Data for calculations were provided by Data Support Section, DSS, of National Center for Atmospheric Research, NCAR and Computational and Information Systems Laboratory, CISL, USA

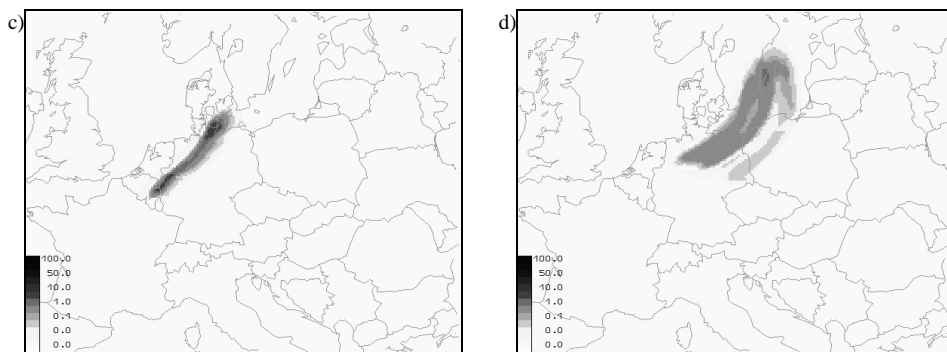


Fig. 6. Simulation of the movement of PMCH cloud in the ETEX 1 experiment: a) - after 6 hours, b) - 18 hours, c) - 30 hours, d) - 42 hours from the start of release. Units - percent of the maximum concentration of tracer (10 ng/m^3)

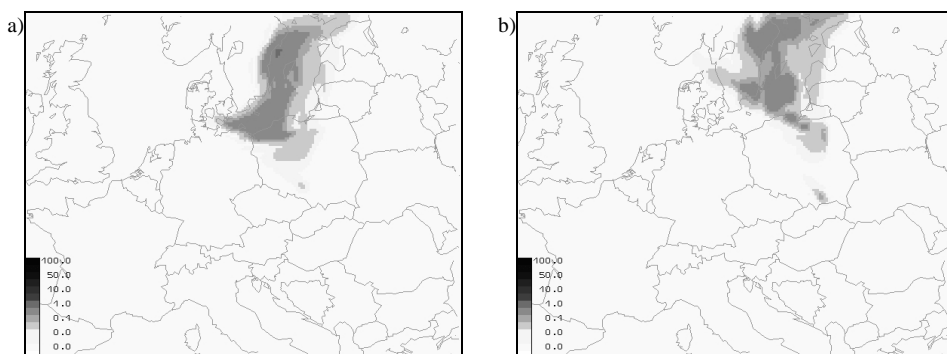


Fig. 7. Simulation of the movement of PMCH cloud in the ETEX 1 experiment: a) - after 54 hours, b) - 66 hours from the start of release. Units - percent of the maximum concentration of tracer (10 g/m^3)

ETEX 2

The simulation results of the second ETEX experiment are shown in Figures 8 and 9. The positions of the tracer cloud (PMCP - per-fluoro-methyl-cyclopentane) as simulated by the IMWM model are shown first after 6 hours and then in 12-hour intervals from the beginning of the release in November 14th, 1995, 15:00 UTC, until November 15th, 1995, 2:45 UTC. Calculated maximum concentration for the entire period of the simulation was approximately 8 ng/m^3 .

The results of two ETEX experiments showed that the IMWM model was able to properly simulate the movement of the tracer cloud in the atmosphere. The problems appeared when the calculated tracer concentrations at the stations were compared with the measured values. In some stations the differences between the calculated and measured values were significant. However, it was not only a problem of the IMWM model, but it was a common problem for all models which took part in the experiments.

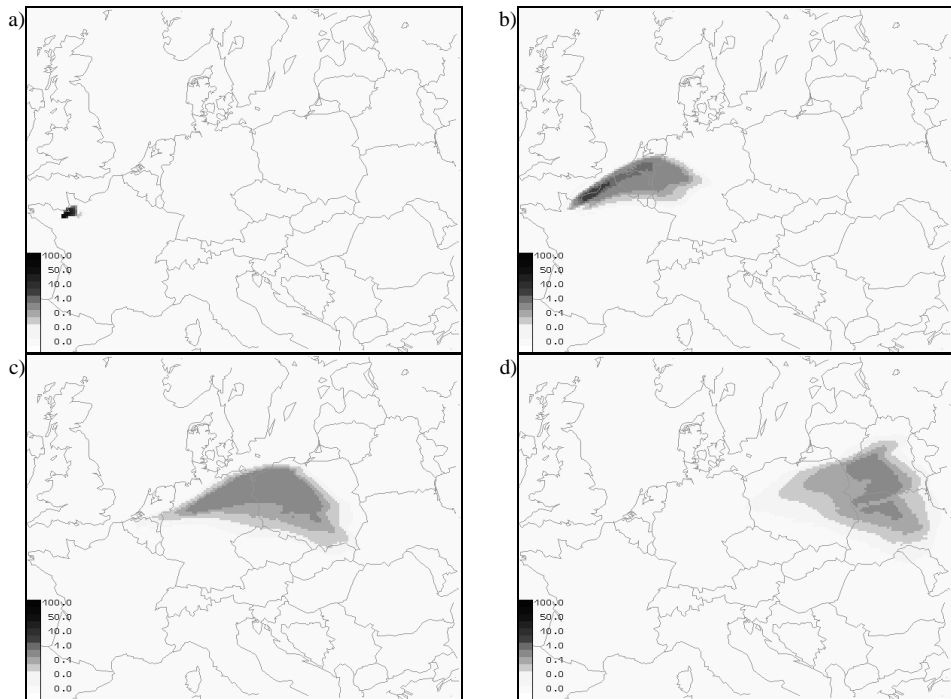


Fig. 8. Simulation of the movement of PMCP cloud in the ETEX 2 experiment: a) - after 6 hours, b) - 18 hours, c) - 30 hours, d) - 42 hours from the start of release. Units - percent of the maximum concentration of tracer (8 ng/m^3)

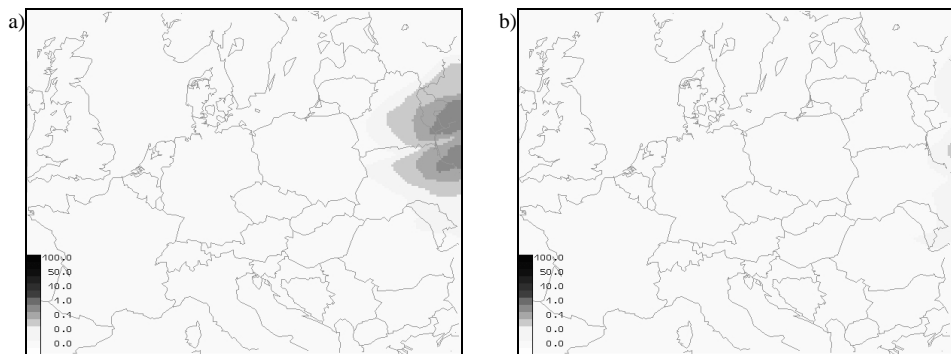


Fig. 9. Simulation of the movement of PMCP cloud in the ETEX 2 experiment: a) - after 54 hours, b) - 66 hours from the start of release of the tracer. Units - percent of the maximum concentration of tracer (8 ng/m^3)

This problem was mainly caused by the technical difficulties associated with the analysis of the samples. The concentrations of the tracer in the samples were exceptionally small, close to the detection limit. Therefore, the accuracy of obtained values was relatively low. Furthermore, poor representativeness of the selected measurement locations for

corresponding grid squares of the model domains created additional problem. This was particularly evident in case of ETEX 2 experiment, when inaccurate weather forecast made difficult the detection of the passing tracer cloud at the stations [43].

Discussion and conclusions

The operational IMWM model for atmospheric transport of pollutants linked to operational NWP models at was presented. The IMWM model takes into account the most important processes related to emission, atmospheric transport, chemical and radioactive transformations and dry and wet deposition of pollutants. It can be used both for prognostic and diagnostic purposes. In the past, the IMWM model was verified on a large group of measurement data [29], showing good agreement with the measurements for all analysed contaminants. This agreement is quite acceptable both for the simulation of atmospheric transport of acidifying compounds and heavy metals over the Polish territory in the time scale of one or more years [29]. It is also acceptable for the simulation of emission events in Europe, in the scale of few days, which included atmospheric transport of volcanic ash, radioactive isotopes and other trace elements.

Two additional applications, described here included diagnostic simulation of dispersion of radioactive isotopes emitted during the Chernobyl accident and simulation of tracer movement in the ETEX experiments.

Based on the previous operational applications of the IMWM model, as well as applications described here, we can conclude that the model is able to correctly determine the dispersion of pollutants in the time horizon of several days. It performs especially well concerning the direction of the transport and time of arrival, whereas the calculated concentration can differ from the measured values, sometimes significantly. However, the information about the concentrations and depositions is much less important then the information about the direction of the transport in the initial phase of the emergency situation.

Forecast of dispersion, based on the results of numerical meteorological model is highly dependent not only on the quality of numerical weather prediction but also on the spatial- and temporal resolution as well as on the in the in period for which it is available. Thus, working in IMWM, mesoscale meteorological model COSMO, with maximum time range of forecast of 78 hours, provides data for predictive version of the multi-pollutant dispersion model for this period of time. For most applications, this type of forecasting is sufficient insofar as it allows to take early measures in case of emergency, such as, for example, evacuation of the areas in imminent danger of contamination. In addition, dispersion forecasts can be updated with the update of weather forecasts even several times a day. This coupling of the dispersion model with meteorological models is a big advantage especially during emergency situations. It should be stressed that the model presented here is fully operational in IMWM in the event of a serious threat such as nuclear power plant accident or a volcanic eruption. This is a very important feature from the perspective of practical application for emergency situation.

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OPERACYJNY MODEL ATMOSFERYCZNEGO TRANSPORTU I DEPOZYCJI ZANIECZYSZCZEŃ

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Abstrakt: Do oceny aktualnego stanu środowiska naturalnego w związku z rozprzestrzenianiem się zanieczyszczeń atmosferycznych i do związanego z tym prognozowania proekologicznych działań gospodarczych i społecznych powszechnie stosowane są modele transportu zanieczyszczeń w atmosferze. W niniejszej pracy opisano operacyjny model dyspersji opracowany w Instytucie Meteorologii i Gospodarki Wodnej w Warszawie. Omówiono obszar jego obliczeń, a także przykłady jego zastosowania: symulacja transportu atmosferycznego i depozycji substancji promieniotwórczych uwolnionych podczas awarii w Czarnobylu w 1986 roku. Drugi przykład dotyczył symulacji transportu atmosferycznego substancji pasywnej (tracera) podczas eksperymentu ETEX. Te dwa przykłady i poprzednie zastosowania modelu wykazały, że zaprezentowany model dyspersji jest w pełni funkcjonalny nie tylko do zastosowań długoterminowych, ale przede wszystkim w sytuacjach kryzysowych, takich jak wypadki jądrowe lub erupcje wulkaniczne, które mogą wpływać na stan środowiska na terytorium Polski.

Słowa kluczowe: sytuacje awaryjne, zanieczyszczenia atmosfery, model dyspersji, skażenia promieniotwórcze, pyły wulkaniczne