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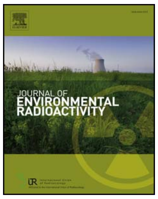

A review of numerical models to predict the atmospheric dispersion of radionuclides

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ABSTRACT

The field of atmospheric dispersion modeling has evolved together with nuclear risk assessment and emergency response systems. Atmospheric concentration and deposition of radionuclides originating from an unintended release provide the basis of dose estimations and countermeasure strategies. To predict the atmospheric dispersion and deposition of radionuclides several numerical models are available coupled with numerical weather prediction (NWP) systems. This work provides a review of the main concepts and different approaches of atmospheric dispersion modeling. Key processes of the atmospheric transport of radionuclides are emission, advection, turbulent diffusion, dry and wet deposition, radioactive decay and other physical and chemical transformations. A wide range of modeling software are available to simulate these processes with different physical assumptions, numerical approaches and implementation. The most appropriate modeling tool for a specific purpose can be selected based on the spatial scale, the complexity of meteorology, land surface and physical and chemical transformations, also considering the available data and computational resource. For most regulatory and operational applications, offline coupled NWP-dispersion systems are used, either with a local scale Gaussian, or a regional to global scale Eulerian or Lagrangian approach. The dispersion model results show large sensitivity on the accuracy of the coupled NWP model, especially through the description of planetary boundary layer turbulence, deep convection and wet deposition. Improvement of dispersion predictions can be achieved by online coupling of mesoscale meteorology and atmospheric transport models. The 2011 Fukushima event was the first large-scale nuclear accident where real-time prognostic dispersion modeling provided decision support. Dozens of dispersion models with different approaches were used for prognostic and retrospective simulations of the Fukushima release. An unknown release rate proved to be the largest factor of uncertainty, underlining the importance of inverse modeling and data assimilation in future developments.

1. Introduction

Among all environmental pathways of radionuclides originating from an unintended release, atmospheric transport is usually the fastest, reaches the widest area, and affects the largest number of people. Therefore, numerical prediction of the atmospheric dispersion of radionuclides is of primary importance. Atmospheric transport is largely determined by the wind-driven advection of the plume. Turbulent diffusion provides horizontal and vertical mixing, while deposition, radioactive decay, chemical reactions and physical transformations take place in the moving cloud. These processes are described by the atmospheric transport equation:

$$\frac{\partial c}{\partial t} = -\underline{v}\nabla c + \nabla \underline{\underline{K}}\nabla c + E + R + D, \qquad (1)$$

where c is the concentration, $\underline{v}$ is the wind vector and $\underline{\underline{K}}$ is the matrix of turbulent diffusion coefficients (Leelőssy et al., 2016). The first two terms on the right-hand side describe advection and turbulent diffusion, respectively. The terms E, R and D refer to sources and sinks due to emissions, chemical reactions and deposition, respectively. The latter two terms are either calculated with attached simulations or parameterized with simple equations. The equation can be solved in an analytic, deterministic or stochastic way (Leelőssy et al., 2014). This leads to the Gaussian (plume), Eulerian (grid) and Lagrangian (particle) dispersion models, respectively (see Section 2).

The most appropriate modeling tool for a specific application largely depends on the spatial scale of the dispersion. On the local scale (in the order of 1–10 km), the assumption of a homogenous and stationary wind field largely simplifies the numerical model. However, this

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assumption ignores the mesoscale atmospheric phenomena that might become a serious source of error. On the regional scale (in the order of 100–1000 km), the spatial and temporal changes in the meteorological situation must be considered. As the scale increases, the limited computational capacities become a serious issue. In global simulations, the amount of meteorological data and the large number of particles or grid points often require compromise between a sophisticated physical model and a feasible computational demand. On the other hand, microscale simulations (on the scale of 10–1000 m) are based on the detailed solution of the flow and concentration field among buildings and other surface obstacles. These simulations have extreme hardware requirements comparable to or even larger than global scale problems.

Spatial scale is not the only aspect that determines the complexity of the atmospheric transport process and thus the accuracy of a modeling approach. More sophisticated models with larger computational cost are required if the dispersion takes place over complex terrain (Raskob et al., 2010); if the weather is rapidly changing or is strongly affected by local effects, i.e. urban or coastal circulation, convective clouds and frontal systems (Venkatesan et al., 2002); or if the emitted material has significant feedbacks on the flow field, i.e. in case of large fires or dense gases (Venetsanos et al., 2003). To assess this wide range of complexities and possible assumptions, as well as to satisfy different user needs ranging from basic research to civil defense, a rich variety of atmospheric dispersion models have been developed and applied for radioactive releases (Becker et al., 2007; Connan et al., 2013; Draxler et al., 2015; Holmes and Morawska, 2006).

Atmospheric dispersion models are frequently applied both for research and operational decision support. Research applications typically deal with retrospective events, they can access large amounts of data, and high-performance computing. Research simulations are conducted by modeling experts, can be repeated, and tuned to provide the best possible results. The models are used as standalone software with specified input and output formats, or through a web interface.

Decision support applications are run in emergencies and practices, where a well-defined operational protocol must be performed based on the real-time accessible data, human resource and infrastructure. Therefore, reliability, robustness and fast response are key features of an operational model. The software is usually integrated into geographic information systems (GIS) or complex decision support toolboxes (Bianconi et al., 2004; Bozon and Mohammadi, 2009). An advanced nuclear emergency decision support system, such as the European RODOS/JRODOS and the American NARAC, integrates automated data acquisition and preprocessing tools, multiple atmospheric dispersion models for different scales, modules for dose and health effect estimation and GIS-based visualization (Bartzis et al., 2000; Bradley, 2007).

In case of an accidental release, an efficient multidisciplinary cooperation is necessary for high quality decision support (Managi and Guan, 2017). Different levels of model results are available in the decision process: the meteorological situation and forecast; atmospheric concentration and ground deposition maps from several dispersion models; the expected dose rates and health effects at certain receptors; the combined effect of atmospheric pollution with other environmental risks and exposures; and quantitative information on uncertainties and sensitivities. This range of model outputs is not always accessible or meaningful for all partners in the information chain, and can be confusing if they get released to the public in an unorganized way (Benamrane et al., 2013). The lack of real-time data, but also the overwhelming amount of monitoring and model results can challenge the emergency response (Sugiyama et al., 2012). Besides the state-of-the-art modeling software, only the clear definition of tasks and responsibilities of each participant, as well as the establishment of an efficient data flow can achieve the best possible support for decision making.

2. Principles of atmospheric dispersion modeling

2.1. Meteorological data

Atmospheric transport processes of radionuclides are governed by the weather, therefore meteorological data is an essential input for dispersion models. All terms in the atmospheric transport equation depend on atmospheric variables. In case of a simple local scale simulation, meteorological observations from a fixed monitoring site are used. However, the spatial representativity of a single measurement is very limited, and the three-dimensional structure of meteorological parameters can only be described by numerical weather prediction (NWP) models. Atmospheric dispersion models are coupled with NWPs; however, the extent of coupling shows large variability among different software.

The simplest way of meteorology-dispersion coupling is the offline approach. In this case, the atmospheric dispersion model uses precomputed meteorological fields as input parameters. Avoiding the calculation of the atmospheric flow field largely reduces the computational cost that has made offline coupling popular in operational practice (Bartzis et al., 2000; Bradley, 2007). As a tradeoff, up-to-date meteorological analysis or forecast data must be downloaded to run the model. This requires a secure, large bandwidth connection to an NWP operator, typically the national weather service. The offline approach enables flexible selection among different NWPs, as the change of input data only requires file format conversions. The difference between the NWP and dispersion model grid requires interpolation that can cover a significant portion of the computational cost.

Online coupled models perform the simulation of meteorology and dispersion simultaneously (Baklanov et al., 2014; Grell et al., 2005; Ngan et al., 2015). In this approach, the NWP simulation is performed by the dispersion model operator that requires higher computational capacities. However, initial and boundary conditions still have to be provided from an external resource. The dispersion model is developed to be used with the coupled NWP: it enables a more efficient usage of model-specific variables and parameterizations than the general formulation of an offline model. Online coupling can largely improve model accuracy in complex weather conditions (Leelőssy et al., 2017), and also allows the optimization of the NWP model to the release area with the possibility of a nested fine-grid simulation around the release site (Tewari et al., 2010).

There are two ways of online coupling: the online integrated and the online access models (Baklanov et al., 2014). In an online integrated system, the meteorological and the dispersion components use the same grid and numerical schemes; and they also share the same model timestep, therefore interpolation is not required. In online access models, the independent meteorology and chemistry modules may not operate on the same grids, but do share data in certain intervals. Online coupling has been an important development in air pollution meteorology because in the real atmosphere, physical and chemical processes are in a complex interaction. Most importantly, aerosol particles have an impact on weather and climate by altering the radiation budget and acting as cloud condensation nuclei (CCN) (Zhang et al., 2015). Clouds are strongly affected by indirect effects of aerosols, e.g. the cloud drop size decreases if the number of CCNs increases that can modify the intensity of precipitation (Zhang et al., 2010). On the other hand, precipitation plays a key role in the removal processes of atmospheric aerosols (Leadbetter et al., 2015). With online coupled models, not only the effects of meteorology on the air pollution, but also the feedbacks of atmospheric chemistry on the weather can be studied (Grell et al., 2005).

The accuracy of a dispersion simulation is largely determined by the accuracy of the coupled NWP model that can be either global or regional (Arnold et al., 2015; Leadbetter et al., 2015; Van dop et al., 1998). Regional models usually have better spatial resolution and are typically non-hydrostatic, while most global models are hydrostatic.