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An unconventional adaptation of a classical Gaussian plume dispersion scheme for the fast assessment of external irradiation from a radioactive cloud

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HIGHLIGHTS

- A new effective procedure for finite cloud dose estimation at near distances.
- Capability of real-time simulation of responses at a large sensor networks.
- Substitution of multi-nuclide scheme to effective photon multi-group design.
- Incorporation into environmental model HARP and comparison benchmarks.
- Supports assimilation of model predictions with observations from terrain.

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ABSTRACT

This article focuses on derivation of an effective algorithm for the fast estimation of cloudshine doses/dose rates induced by a large mixture of radionuclides discharged into the atmosphere. A certain special modification of the classical Gaussian plume approach is proposed for approximation of the near-field dispersion problem. Specifically, the accidental radioactivity release is subdivided into consecutive one-hour Gaussian segments, each driven by a short-term meteorological forecast for the respective hours. Determination of the physical quantity of photon fluence rate from an ambient cloud irradiation is coupled to a special decomposition of the Gaussian plume shape into the equivalent virtual elliptic disks. It facilitates solution of the formerly used time-consuming 3-D integration and provides advantages with regard to acceleration of the computational process on a local scale. An optimal choice of integration limit is adopted on the basis of the mean free path of γ-photons in the air. An efficient approach is introduced for treatment of a wide range of energetic spectrum of the emitted photons when the usual multi-nuclide approach is replaced by a new multi-group scheme. The algorithm is capable of generating the radiological responses in a large net of spatial nodes. It predetermines the proposed procedure such as a proper tool for online data assimilation analysis in the near-field areas. A specific technique for numerical integration is verified on the basis of comparison with a partial analytical solution. Convergence of the finite cloud approximation to the tabulated semi-infinite cloud values for dose conversion factors was validated.

1. Introduction

The main goal of this article is to formulate a fast and sufficiently accurate approach for estimation of the cloudshine irradiation doses which replaces the former rough estimations. The shape of a radioactive plume in the atmosphere near the source of pollution is narrow (especially for a stable atmospheric stratification like category *F*) and does not noticeably diffuse to the surface until it has travelled a distance of several kilometres from the point of discharge (even more than 10 km for a buoyant plume). Due to the buoyant and vertical momentum plume rise the effective height can markedly increase. The vertical concentration profile is gradually getting homogenous only from greater distances. Common practice introduces the calculation of the ground-level cloudshine dose rates at larger distances as a product of this homogenised near-ground activity concentration and the tabulated conversion

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coefficient R_{cloud} (Sv m^3 Bq^{-1} s^{-1}) defined in (ICRP 74, 1996). The technique of the irradiation calculations is designated as a semi-infinite cloud approach. Its application at near distances can, however, cause huge errors and the real finite plume shape should be respected. Further development led to the time-consuming calculations based on a three-dimensional integration over the finite cloud volume (e.g. ADMS4, 2009; Overcamp, 2007) or on a specially partitioned integration space (Wang et al., 2004; Raza et al., 2001). The 3-D integration of the Gaussian plume is fairly complex and computationally expensive, and in many cases sufficiently accurate approximations could be constructed. The volume integral for gamma doses was formerly approximated by using the semi-infinite cloud model combined with correction factors. The first attempt to solve the problem was the former approach based on introduction of a certain tabulated finite cloud correction factors F^{cor} (Slade, 1968). The similar approach based on a pre-calculated matrix of the cloud gamma correction factors was used in (Päsler-Sauer, 2000) – parameterisation in the photon energy, horizontal dispersion coefficient, roughness length, plume height, and stability class. An analogical procedure is used in (Thykier-Nielsen et al., 1995) in the Lagrangian puff model RIMPUFF for the calculation of gamma doses from asymmetrical puffs. The multi-parameter gamma dose values are pre-calculated as a function of the photon energy, horizontal dispersion and asymmetry factor, height of puff centre and the distance from the puff base point. We have two main objections to the pre-calculated procedures. Firstly, due to the steep gradients of activity concentration a suitable interpolation on the fixed spatial grid could be problematic. Secondly, we have to include possible elevated locations of the receptors (e.g. real orography of the terrain, monitoring towers). Our proposed method inherently solves the 3-D configuration of the receptors, which can be crucial for the determination of a dangerous flight levels for an aircrew during the aerial monitoring.

An ultimate aim of our research is improvement of the model predictions of this radiological situation based on assimilation with real observations incoming from the terrain. The assimilation procedures perform statistical merging of the model predictions and the measured values in the observation space. Its dimension equals the number of monitoring sensors on the terrain and, therefore, a parallel simulation of the dose rate responses on a large net of receptors in the terrain from a wide group of leaking radionuclides is essential. At the same time some special online examinations like predicting the time to the first alarm or investigating the weakest plume detectability can be accomplished. From a general point of view the fast and effective method for estimation of the finite cloud problem at near distances facilitates the realisation of the assimilation techniques. Advanced assimilation techniques coming from sequential Monte-Carlo methods are computationally expensive (e.g. Doucet et al., 2001) and an effective procedure for fast simulation of external irradiation has a crucial significance (ASIM, 2012). Our first attempts at Bayesian tracking began in (Pecha et al., 2009). The recent application of inverse modelling techniques for extracting of the model parameter information from the incoming terrain observations is described in (Šmídl et al., 2013).

2. Predictions of harmful admixture propagation nearby a source

This article deals with adaptation of the classical solution of a diffusion equation in the initial phase of radioactive plume drifting. The analysis should satisfactorily cover the area of a teledosimetric ring of sensors (TDS) located within a few hundred metres around a source. The 3-D distribution of the specific radioactivity concentration C^n of nuclide n in the air (Bq m^{-3}) is expressed by the straight-line Gaussian solution. This near-field model has a long tradition of use for dispersion predictions. Even though it is simple, the Gaussian model is consistent with the random nature of turbulence (Hanna et al., 1982). It is a solution of the Fickian diffusion equation for constant diffusivity coefficient K and average plume velocity $\overline{u}$. The model is tuned to experimental data and offers quicker estimation with a reasonable computational effort. Proved semi-empirical formulae are available for approximation of important effects such as interaction of the plume with *near-standing buildings* or momentum and buoyant *plume rise* during release. Semi-empirical formulae are introduced for estimation of the wind speed *changes with height* and for *depletion* of the plume radioactivity due to the *removal processes* of dry and wet deposition and radioactive decay. Separate transport mechanisms of radioactivity according to the *physical–chemical forms* of admixtures and *landuse characteristics* are considered. The effects of small changes of *surface elevation* and *terrain roughness* on atmospheric dispersion can be approximately included.

Let assume the continuous radioactivity release to be decomposed into consecutive time segments s. The straight-line Gaussian solution is taken for description of each segment s in its first time step ΔT^{segm} of propagation within the time interval $<0; \Delta T^{segm}>$. In the subsequent time phases f of the segment s the meteorological conditions have to be considered more realistically. For this purposes a segmented Gaussian plume model (SGPM) is introduced (Hofman and Pecha, 2011). The model together with the algorithm proposed here is fully integrated into the environmental code HARP (HAzardous Radioactivity Propagation). The model SGPM is initiated from the first phase $f = 1$ of the straight-line propagation supposing the longitudinal dispersion is neglected. The analytical shape of the partial plume confined on interval $x \in <0; \Delta T^{segm} \cdot \overline{u}>$ is described by expression (1). In the consecutive phases $f > 1$ the segment s is drifted according to the current changes of meteorological conditions. The further dispersion and deposition (e.g. $(s = 1; f = 1) \rightarrow (s = 1; f = 2)$ in Fig. 1) is simulated using the SGPM algorithm by means of a large number of elemental shifts driven by the new weather conditions (HARP, 2011). During each shift the activity depletion in the cloud due to dry and wet deposition and

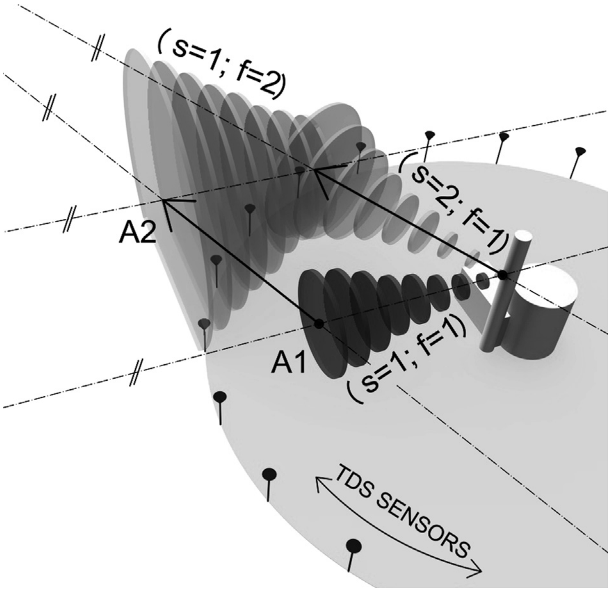

Fig. 1. The finite cloud propagation during stepwise changes of meteorological conditions. Weather changes observed/forecast for the point of release for a particular time step ΔT^{segm} are assumed to immediately impact the propagation of all previous segments in their corresponding phases.