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CLOUD GAMMA MODELLING IN THE UK MET OFFICE'S NAME III MODEL

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Abstract: In the United Kingdom radionuclides are discharged to the environment from a range of controlled sources, under a system of authorisation and regulation. Radiological assessments are performed for a wide range of controlled release applications, including assisting in the provision of advice and guidance to regulatory bodies responsible for setting discharge limits. Such limits are granted to nuclear licensed sites and non-nuclear operators such as universities and hospitals, many of which discharge to the atmosphere, resulting in a range of potential routes of exposure of an individual or a population. One such route, external exposure to gamma rays irradiating directly from a dispersing plume and referred to as 'cloud gamma', may contribute significantly to dose if the radionuclides discharged are strong gamma emitters or are noble gases (which do not deposit, thus limiting the number of potential exposure pathways).

The nature of cloud gamma modelling necessitates full integration within a dispersion model, unlike other exposure pathways which may be considered subsequent to the dispersion modelling. The inclusion of the ability to estimate cloud gamma dose in the Met Office's Lagrangian Particle Dispersion model, NAME III, is necessary for use in comprehensive assessments of the consequences and risks of a radiological release to atmosphere.

This paper describes the cloud gamma modelling approaches implemented within NAME III, details the testing and validation performed, and considers potential applications and future work.

Key words: *cloud gamma, modelling, NAME, radionuclide, Lagrangian.*

INTRODUCTION

In the UK, radioactivity is discharged to the environment under a system of authorisation and regulation. Controlled sources which discharge to the atmosphere include facilities in the nuclear industry, hospitals and waste incinerators. The Health Protection Agency (HPA) undertake both prospective and retrospective assessments of the impact of controlled releases to atmosphere, and require an atmospheric dispersion modelling capability as part of these assessments. The Gaussian plume model (Clarke, R. H., 1979) has provided a transparent and robust approach to atmospheric dispersion modelling in HPA assessments, to a degree of accuracy adequate for purpose to date. However, future requirements will extend the range of modelling scenarios beyond the intended capabilities of Gaussian plume modelling. The use of numerical weather prediction meteorological data, as opposed to the single site data used hitherto, is also desirable and advances in computer technology make such applications achievable. For these reasons, the HPA anticipates using the UK Met Office's NAME III model (referred to below as the NAME model for simplicity) for radiological routine release assessments in future. For NAME to be used in a comprehensive radiological assessment it is necessary to include cloud gamma modelling as a fully integrated component of the dispersion model.

MODEL DESCRIPTION

NAME (the **N**umerical **A**tmospheric-dispersion **M**odelling **E**nvironment) is a Lagrangian particle-puff trajectory model designed to predict the atmospheric dispersion and deposition of gases and particulates (Jones, A. *et al*, 2007). This paper focuses on the particle element of the NAME model, which calculates the dispersion of a pollutant by tracking model particles through the modelled atmosphere. Individual particles are dispersed according to the advection-diffusion equation; at each time step, the position of a particle is incremented by the mean flow and a degree of diffusion at that location. The mean flow is determined by the 3-d wind flow from either numerical weather prediction meteorological data or from empirical schemes, if single site observed meteorology is used. Diffusion is described by the turbulent velocity, determined by random walk (Monte Carlo) processes. Each particle represents a fraction of the released material (in this case, radioactivity) of one or more pollutant species (in this case, radionuclides) and evolves by various physical and chemical processes during its lifespan, notably wet and dry deposition processes and radioactive decay (including decay chain modelling). Particles are discrete and it is therefore necessary to use a box-averaging scheme to derive activity concentrations in air.

METHOD

Two approaches have been implemented within NAME for evaluating cloud gamma dose: the Lagrangian particle approach and the semi-infinite cloud approach.

The Lagrangian particle approach to cloud gamma modelling

The Lagrangian particle approach sums the contribution to dose at each receptor point, for each modelled time step, from each individual model particle. Raza, S. and R. Avila (2001) have described such an approach for calculating direct plume gamma dose rates assuming a point isotropic source formula as represented by equation (1).

$$\dot{D}_\gamma(x_0, y_0, z_0) = \frac{kK\mu_a E_\gamma}{\rho} \sum_{p=1}^{N} \frac{B(E_\gamma, \mu r)\exp(-\mu r) q(x', y', z')}{4\pi r^2} \quad (1)$$

where $\dot{D}_\gamma$ is the dose rate (rad s^{-1}), x_0, y_0, z_0 are the co-ordinates of the receptor point, k is the ratio of absorbed dose in tissue to that in air (dimensionless), K is the dose conversion factor (rad kg MeV^{-1}), μ_a is the energy absorption coefficient (m^{-1}), E_γ is the photon energy released per disintegration (MeV Bq^{-1}), ρ is the local air density (kg m^{-3}), p is the particle number (ranging from 1 to N), B is the build-up factor, μ is the linear attenuation coefficient in air (m^{-1}), r is the distance between the particle and the receptor (m), q is the radioactivity of the p^{th} particle (Bq) and (x', y', z') are the co-ordinates of the p^{th} particle. The exponential term in equation (1) describes the fraction of the direct gamma ray 'beam' from a particle reaching the receptor and the build-up factor accounts for the scattered radiation which reaches the receptor. The surface area of a sphere of radius r is required because a photon can be emitted in any direction. An upper bound is placed on r such that insignificant doses are not calculated unnecessarily.

This approach is akin to the finite cloud model (Simmonds, J. R. *et al*, 1995) but rather than integrating over the volume of the plume, the summation is over all particles describing the plume. To account for photon intensity and parameter values more commonly applied for conversion from photon flux to whole body or organ dose rate, equation (1) has been revised as detailed in equation (2) below:

$$\dot{D}_\gamma(x_0, y_0, z_0) = Ak \sum_{p=1}^{N} \frac{fB(E_\gamma, \mu r) exp(-\mu r) q(x', y', z')}{4\pi r^2} \tag{2}$$

where $\dot{D}_\gamma$ is the dose rate (Sv s^{-1} or Gy s^{-1}), A is the effective or organ dose per unit air kerma (Sv Gy^{-1} or Gy Gy^{-1}, respectively), k is the air kerma per unit fluence (Gy m^2), f is the photon intensity and all other parameters are as in equation (1). The term following the summation symbol in equation (2) describes the photon flux (also termed fluence), defined as the number of photons passing through a unit area per second (m^{-2} s^{-1}). The air kerma per unit flux converts the number of photons passing through a unit area per second into a dose rate (J kg^{-1} s^{-1} or Gy s^{-1}) in air (at the receptor point). The effective or organ dose per unit air kerma converts the dose in air into a dose in tissue (Sv s^{-1} or Gy s^{-1}, respectively). This is the final form of the cloud gamma dose rate equation implemented in NAME for the Lagrangian particle method.

As defaults, the calculation of cloud gamma dose in NAME assumes the linear attenuation coefficient values as recommended by Hubbell, J. H. (1982), Berger build-up factors as derived by Jaeger, R. G. *et al* (1968) and values of air kerma per unit fluence and effective or organ dose per unit air kerma as given in ICRP Publication 74 (ICRP, 1996). By default, air is both the attenuation medium and the response medium (for photon flux calculations), the irradiation at the point of the receptor is isotropic and all doses are calculated to adults only. The model input parameter values are not, however, hard-wired into the NAME code and alternative values could be substituted if deemed appropriate.

The semi-infinite cloud approach to cloud gamma modelling

The semi-infinite cloud approach (Simmonds, J. R. *et al*, 1995) assumes that the activity concentration in air is uniform over the volume of the plume from which photons can reach the point at which the dose is delivered. It also assumes that the cloud is in radiative equilibrium i.e. that the amount of energy absorbed by a given element of cloud is equal to that released by the same element. For photons with energies less than 20 keV the semi-infinite cloud model will always be adequate. The semi-infinite cloud approach as detailed in equation (3) is included in the NAME model.

$$\dot{D}_\gamma = kC \sum_{j=1}^{n} I_j E_j A_j \tag{3}$$

where $\dot{D}_\gamma$ is the dose rate (Sv s^{-1} or Gy s^{-1}), k is a conversion factor (2.0 10^{-6} Gy y^{-1} per MeV m^{-3} s^{-1}), C is the activity concentration in air (Bq m^{-3}), n is the total number of photon energies for a single radionuclide, I is the photon intensity, E is the photon energy (MeV), A is the dose per unit air kerma (Sv Gy^{-1} or Gy Gy^{-1} depending on whether the dose is effective dose or organ dose per unit air kerma, respectively). This method uses box-averaged activity concentrations in air derived from NAME's Lagrangian particle trajectory modelling.

Cloud gamma dose output from NAME

Both the Lagrangian particle approach and the semi-infinite cloud approach to cloud gamma modelling in NAME estimate instantaneous and average (over time but not space) effective and organ (e.g. thyroid and lung) dose rates in units of Sv s^{-1} and Gy s^{-1}, respectively, and integrated effective and organ dose in units of Sv and Gy, respectively. For sources considering multiple radionuclides, dose is presented as a function of radionuclide but not summed over all radionuclides; the summation of dose over radionuclide would be achieved outside the NAME model as part of a fuller radiological dose assessment capability. The effects of the possible shielding properties of, for example, buildings would also be incorporated outside the NAME model.

The two cloud gamma dose schemes are implemented separately within NAME. The schemes clearly have different areas of applicability. For example, at relatively large distances downwind from the release it is likely that the plume will be uniformly mixed within the boundary layer and the semi-infinite approach would be most appropriate, whereas at all distances downwind where the plume is not well mixed in the boundary layer the Lagrangian particle approach should be

applied. Also, the estimation of cloud gamma dose via the Lagrangian particle approach may in some circumstances suffer from statistical noise, for example at relatively large distances from the source of a release where there exists a relatively low density of particles, and under these circumstances the semi-infinite cloud approach will be preferable. NAME does not include an automated capability for switching between approaches. The user must decide on which scheme is preferred or may consider both in parallel. However, the use of two alternative approaches raises the potential difficulty of there being a significant 'step' in dose at any given point where the approaches are switched. An automated approach for switching between methods within NAME would be complex. Furthermore, in most applications the need for an automated switch will be avoided by the use of nested spatial grids with different resolutions; the inherent step change between grids of varying spatial resolution will be prominent and any minor step change as a result of switching methods will be no longer evident. Where nested spatial grids are not applied, a method for integrating approaches is required and this is an area for future work; a switch between approaches could be dynamic and dependent on the convergence of model output of each run or it could be based on the greatest distance at which all release scenarios become uniformly mixed within the boundary layer.

RESULTS

The cloud gamma predictions of NAME using the Lagrangian particle approach have been compared with PC-CREAM (Smith, J. G. and J. R. Simmonds, 2009) and ADMS (CERC, 2008) for a release of 1 10^{10} Bq s^{-1} of ^{85}Kr over a 24 hour period at a height of 10 m above ground level. A wind speed of 5 m s^{-1}, a constant wind direction, boundary layer depth of 800 m and heat flux of 0 W m^{-2} were assumed, representative of Pasquill Stability Category D. Dry conditions and a surface roughness of 0.3 m were also assumed. Three receptor points were considered, at 1, 2 and 5 km along the plume centre line. Average activity concentrations in air and adult effective cloud gamma dose rates were estimated, averaged over 24 hours after the start of the release.

Table 1. Model intercomparison of adult effective cloud gamma dose rate (mSv s^{-1}) at 3 receptors along the plume centre line

	NAME	**ADMS**	**PC CREAM**
1 km downwind	**2.3 10^{-09}**	**2.1 10^{-09}**	**3.2 10^{-09}**
2 km downwind	**1.1 10^{-09}**	**8.2 10^{-10}**	**1.3 10^{-09}**
5 km downwind	**5.1 10^{-10}**	**2.2 10^{-10}**	**3.5 10^{-10}**

As demonstrated in Table 1, adult effective cloud gamma dose rates estimated by NAME are in good agreement with PC-CREAM and ADMS estimates (within a factor of 2 and a factor of 3, respectively, at all downwind distances considered here). In the main, the differences observed reflect differences in activity concentrations in air (and therefore in the dispersion modelling) rather than in the cloud gamma dose calculations. To eliminate differences in estimates of cloud gamma dose as a result of differences in the modelling of dispersion, simple hand calculations for uniform activity concentrations in air and a single point source were undertaken and showed very strong agreement with Lagrangian particle model predictions of cloud gamma dose for equivalent scenarios. The semi-infinite cloud approach has also been tested, in particular through comparison with the HPA's PC-CREAM model and performed well. Comparison against the results of an observational dataset obtained from a tracer field study is envisaged as part of future work.

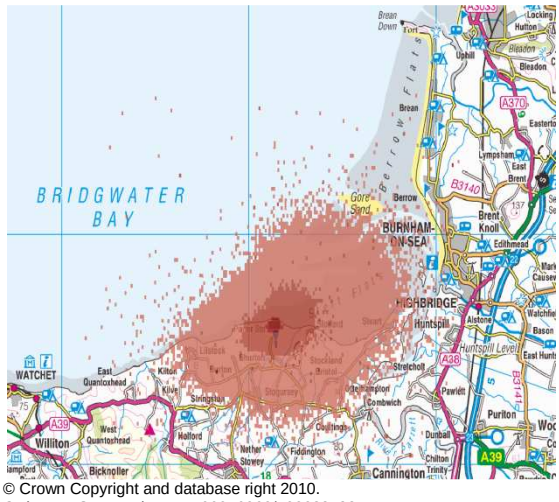

Figure 1. Adult effective cloud gamma dose rate (Sv s^{-1}), averaged over 1 year, resulting from a 1.0 10^{3} Bq s^{-1} continuous release of ^{135}I using NWP met data, on a 100 x 100 m grid (using the Lagrangian particle approach).

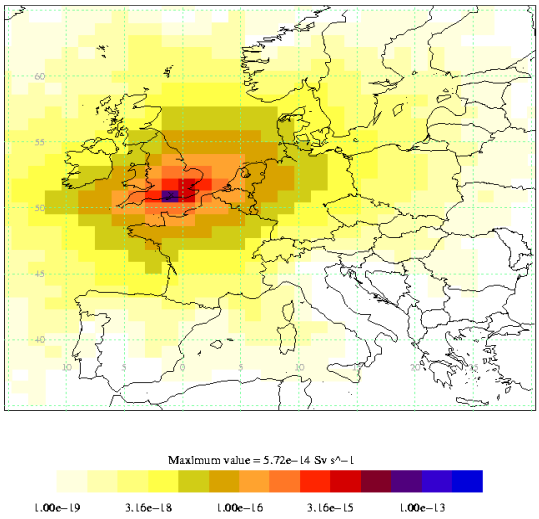

Figure 2. Adult effective cloud gamma dose rate (Sv s^{-1}), averaged over 1 year, resulting from a 1.0 10^{3} Bq s^{-1} continuous release of ^{135}I using NWP met data, on a 100 x 100 km grid (using the semi-infinite cloud approach).

The practical applicability of the two methods for calculating cloud gamma dose in NAME has also been assessed in terms of computational demands, statistical noise and clarity of model output. For routine release assessments, critical group doses are often required at short distances (e.g. tens of kilometres) from the release point but collective doses may be required to very large distances (e.g. a few thousand kilometres). Adult effective cloud gamma dose rates are presented in Figures 1 and 2, as

an example of a continuous release of 1.0 10^3 Bq s^{-1} of ^{135}I modelled using NWP meteorological data. Figure 1 shows the application of NAME over a small localised domain, which necessitates the use of the Lagrangian particle approach where the plume is not well mixed in the boundary layer. Because a relatively small domain is considered, for a moderate number of model particles, the model run used to derive Figure 1 was relatively computationally inexpensive and suffered little from statistical noise. Figure 2 shows a much larger domain, more suited to the use of the semi-infinite cloud approach. Adult effective cloud gamma dose rates presented in Figure 2 demonstrate much less statistical noise and at a much reduced computational cost than would be observed if the Lagrangian particle approach were applied.

CONCLUSIONS

Two methods of calculating cloud gamma dose have been implemented in the UK Met Office's NAME model: an approach which calculates dose from each Lagrangian particle and an approach which utilises box averaged activity concentrations in air derived from the Lagrangian particles distribution, denoted here as the semi-infinite cloud approach. The former is more suited to inhomogeneous activity concentrations in air at relatively short distances downwind and the latter is more suited to a large plume (relative to the distance over which gamma dose is significant), well mixed within the boundary layer, typically at relatively large distances downwind. Significant work has been carried out to verify and validate this additional capability of the NAME model, and further work comparing model results with an observational dataset obtained from a tracer field study is planned.

Applications of cloud gamma modelling in NAME in routine release assessments will be undertaken through an envisaged extension to the PC-CREAM system. For assessing the risk posed by potential accidents at nuclear facilities, the new probabilistic risk assessment tool, PACE, under development at HPA, will also incorporate NAME model output, including estimates of cloud gamma dose.

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