IMPROVED SCHEME FOR PARAMETRIZATION OF CONVECTIVE TRANSPORT IN NAME III

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Abstract: This paper describes an updated scheme for parametrization of atmospheric convection to be used in the Met Office Atmospheric Dispersion Model (NAME III). In this scheme, the vertical transport of particles due to convection is represented in a 1-dimensional model based on a 'mass-flux' approach. Empirical formulas are used to obtain the mass fluxes and the convective precipitation is used for closure. Results of preliminary simulations are encouraging and worth pursuing further.

Key words: *parametrization, convection, dispersion, particles, mass fluxes.*

INTRODUCTION

Atmospheric convection is responsible for transport and mixing of air resulting into a large exchange of heat and energy above the boundary layer. Although convection can transport material through the whole troposphere, convective clouds have a small horizontal length scale (of the order of a few kilometres). Therefore, for large-scale models of the atmosphere the horizontal scale on which the convection exists is below the resolution used and convection must be parametrized (Emanuel, K.A., 1994).

The Numerical Atmospheric-dispersion Modelling Environment (NAME III) is the Met Office's short-to-long range atmospheric dispersion model based on Lagrangian particle trajectories. Initially developed as a nuclear accident model following the Chernobyl incident in 1986, it has then evolved to predict the transport, transformation and deposition of a wide class of airborne materials (e.g. volcanic ash, radionuclides, viruses etc.) The model is used operationally as an emergency-response model for government emergency control and regulatory bodies, and as such is subjected to continuous development to improve the numerical representation of the physical phenomena involved (Jones, A. et al, 2004).

Meteorological data are provided to NAME III by the Met Office's operational Numerical Weather Prediction model, the Unified Model (UM). The UM is currently run mainly on two grid resolutions: UKV and Global. The first has grid size 1.5km and therefore convection is explicit (i.e. does not require parametrization). However, the horizontal size of the Global resolution is 25km: convection is here subscale and must be parametrized. To do so, the UM uses a 'mass-flux' scheme originated by Gregory D. and P.R. Rowntree (1990) which quantifies, for each grid box, the amount of mass transported in updraughts, in downdraughts, in entrainment of environmental air and in detrainment of cloudy air. Such mass fluxes are not available yet for operational use in NAME III, and their representation is therefore challenging.

In this paper, a revised scheme for parametrization of convective transport based on the mass flux approach and suitable for integration into NAME III is presented. After a short reference to the convection scheme currently employed in NAME III, the next section describes the modelling of the vertical convective displacements using mass fluxes obtained from the UM Single Column Model (SCM). A test case is run with 2,000 particles to show that the model correctly reproduces the 'well mixed condition' (Thomson, D.J., 1987). The next-to-last section focuses on the derivation of the mass flux profiles which are benchmarked with those obtained with the SCM, showing good agreement. A brief summary and suggestions for future improvements are the subject of the last section.

DESCRIPTION OF THE MODELS FOR VERTICAL DISPLACEMENT

Current convection scheme

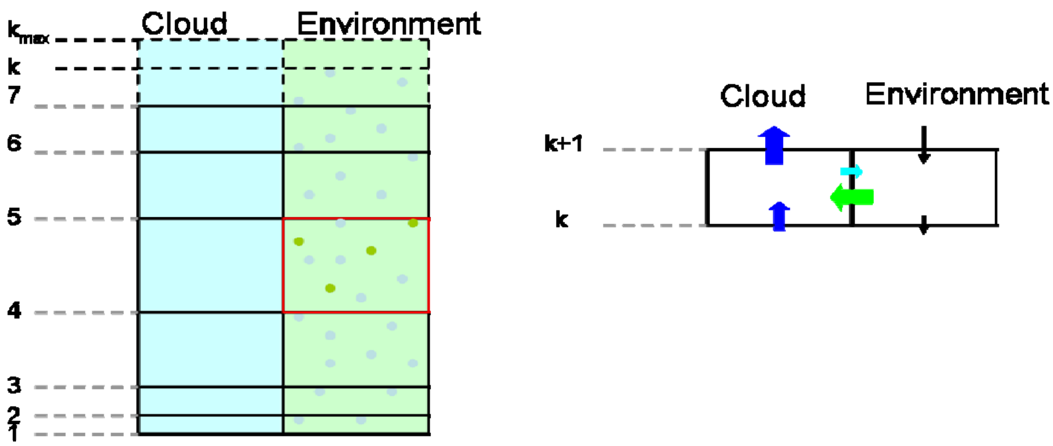
The convection scheme currently in place in NAME III is a crude approximation of the physical transport due to atmospheric convection. It uses the following UM diagnostics: height of cloud top, height of cloud base and cloud fraction, the latter representing the section of the grid box covered by the cloud. If the cloud depth exceeds 500m (i.e. the cloud has ‘enough’ vertical extension), a number of particles corresponding to the cloud fraction are randomly redistributed along the vertical direction of the cloud (Maryon R.H. et al, 1999). It is clear that such scheme could be improved by estimating the amount of material transported for each vertical level. This would capture more realistically what happens inside the cloud (e.g. updraughts, downdraughts etc).

Revised convection scheme
Similarly to what done by Collins W.J. et al, 2002 for convective transport of chemical species, a 1-dimensional model for vertical transport based on mass fluxes is here proposed. In this model, the vertical extension of the atmosphere is represented by a number of non-equally spaced vertical pressure levels (i.e. up to 30km). The transport of particles inside the convective cloud is represented as follows. At the beginning of each time step, particles are distributed in the environmental column as shown in Figure 1(a). For each column box, a number of particles entrain into the cloud column according to a given probability. This is again illustrated in Figure 1(a): in the example shown, the probability of entrainment between level 4 and 5 is 0.44% (the particles that entrain are highlighted in green).

Once the particles are in the cloud, they can either move upward or detrain into the environment, the type of motion being decided in a probabilistic way. Eventually, at the end of each time step, all particles are brought back to the environmental column. As illustrated in Figure 1(b), for each grid box, identified at the bottom by the subscript *k* and on top by the subscript *k*+1, the following must hold:

$$M_{k+1} + D_k = M_k + E_k \tag{1}$$

where *M*, *D* and *E* are respectively updraught, entrainment and detrainment mass fluxes in Pa/s.



(a) (b)

Figure 1. (a) represents the environment and the cloud columns used in the model for vertical transport. The particles that entrain between level 4 and 5 are shown in green. (b) shows a sketch of updraught mass fluxes (blue arrows) and the entrainment and detrainment fluxes (respectively green and sky-blue arrows) between two pressure levels.

The above fluxes are used to estimate how many particles entrain, move upward and detrain via a set of probabilities:

$$P_{ent,k} = dtE_k / \Delta p_k\,,\quad P_{up,k} = M_{k+1} / (M_k + E_k)\,,\quad P_{\det,k} = 1 - P_{up,k} \tag{2}$$

For a given pressure layer *k*, the probability of entrainment is calculated by taking into account the mass that entrains in a given time step over the depth of the layer. The probability of moving in an updraught is evaluated by estimating the fraction of mass that moves upward with respect to the mass that enters into the cloud column. The probability of detrainment is calculated in a similar way. Lastly, a subsidence flux equal to the updraught flux is applied to all the particles to compensate for upward motion.

Test Case

Such a scheme is tested by using mass fluxes provided by the SCM run with data from the TWP-ICE field campaign around Darwin, Australia, from 20 January 2006 to 13 February 2006. Figure 2 illustrates four time snapshots of 2,000 particles initially released between 56233 Pa and 63752 Pa. Each time step is associated with a given mass flux profile (not shown) so that the cloud properties can vary with time. It is clear that particles in the environment column are moved upward under the action of the updraughts.

No downdraughts are currently included in the transport model, but it is possible to include them by adding a separate scheme in a similar fashion. The mass fluxes of downdraughts are around one tenth of the ones of the updraughts and are therefore neglected by some authors (e.g. Collins W.J. et al, 2002). The extension towards the surface level (e.g. 100000 Pa) is due to subsidence. Lastly, it can also be noticed that as time advances, particles distribute uniformly with pressure in the environment column according to the ‘well mixed condition’.

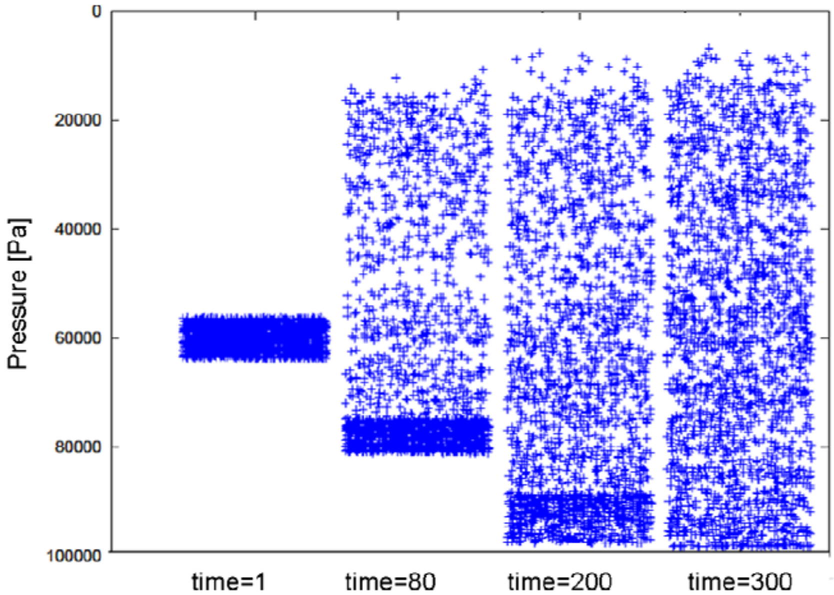


Figure 2. Time snapshots of particle distribution in the environment column. Time shown is the number of time steps.

DERIVATION OF MASS FLUXES

Shape of the mass fluxes profile

Empirical formulas (Grant, A.L.M, 2012, pers. comm.) derived from Cloud Resolving Models (CRM) are used to estimate the mass flux profiles and are based on the height of the freezing level. In fact, when cloud droplets reach the freezing level, ice-nuclei form and precipitation is more likely to occur. If the freezing level is inside the cloud, then the mass flux profile has a maximum corresponding to the height of the freezing level, i.e.:

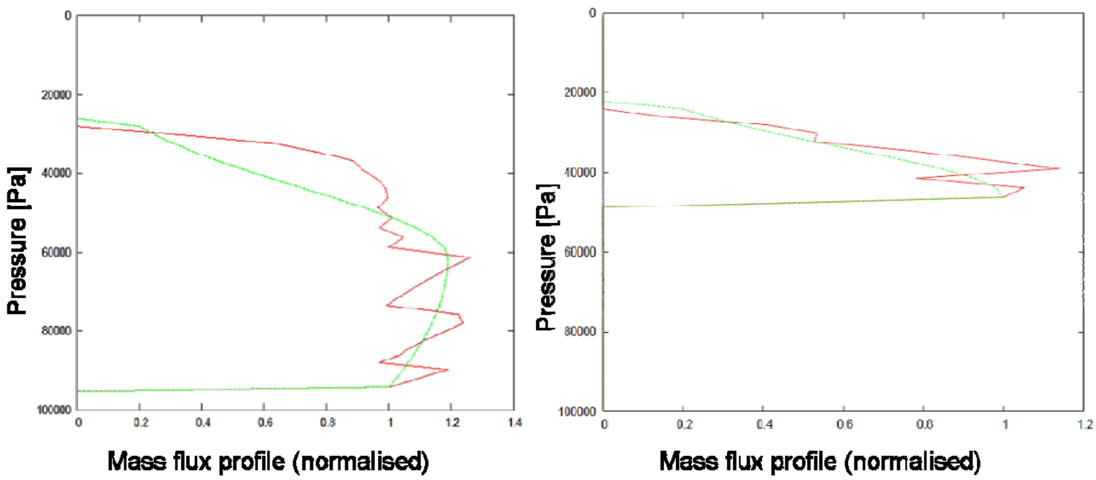
$$
\begin{aligned}
M_k &= M_{\max} M_{CB} \exp\left(-\beta_1 \left(\frac{P_k - P_{FL}}{P_{CB} - P_{FL}} \right)^2 \right) \quad if \quad P_k \geq P_{FL} \\
M_k &= M_{\max} M_{CB} \exp\left(-\beta_2 \left(\frac{P_k - P_{FL}}{P_{CT} - P_{FL}} \right)^2 \right) \quad if \quad P_k < P_{FL}
\end{aligned}
\qquad (4)
$$

In equation 4, $M_{\max}$ is the normalised maximum value of the profile (its parametrization is here omitted for the sake of simplicity), M_{CB} is the mass flux at the cloud base, $\beta_1 = \ln(M_{\max})$, $\beta_2 = \ln(M_{\max} / a_{\max})$ with $a_{\max} = 0.2$ and $P_k, P_{FL}, P_{CT}, P_{CB}$ are respectively the pressure at the *k*-th level, at the freezing level, at cloud top and at cloud base.

On the other hand, if the freezing level is outside the cloud then the normalised mass flux profile decreases with height according to equation 5:

$$M_k = M_{CB} \exp\left(-\beta_2 \left(\frac{P_k - P_{CB}}{P_{CT} - P_{CB}} \right)^2 \right) \tag{5}$$

On Figure 3(a) and (b), the mass fluxes profiles obtained using these formulas are compared with those provided by the SCM runs for two separate times. Similar tests are repeated for a number of timesteps and all cases show good agreement between the two methods.



(a) (b)

Figure 3. The figure shows the mass flux profiles obtained with (a) equation (4) and with (b) equation (5) (green dashed line) compared with those provided by the SCM (red solid line), for two given times.

The cloud base mass flux

Equations 4 and 5 contain an unknown: the cloud base mass flux. Other convective schemes (e.g. Derbyshire, S.H. et al, 2011) use the Convective Available Potential Energy (CAPE) as a closure method to estimate the cloud base mass flux. The amount of convective precipitation at the ground should be a valid alternative as it ‘mirrors’ the convective activity inside the cloud within a reasonable approximation. In addition, it is readily available for use in the Met Office’s atmospheric dispersion model unlike CAPE which requires expensive calculations.

In Figure 4, the integral of the mass fluxes over the depth of the cloud is plotted against the Convective Rain at the ground using data available from the SCM for the TWP-ICE field campaign. In discretized form, the integral is calculated as:

$$I = \int_{P_{CT}}^{P_{CB}} M(p)dp \approx \sum_{k=1}^{k=k_{\max}} M_k \Delta p_k \tag{6}$$

The figure shows a good correlation. The cloud base mass flux can then be estimated from the corresponding amount of Convective Rain by using the regression relation together with equations (4-6) (which depend on the cloud base mass flux).

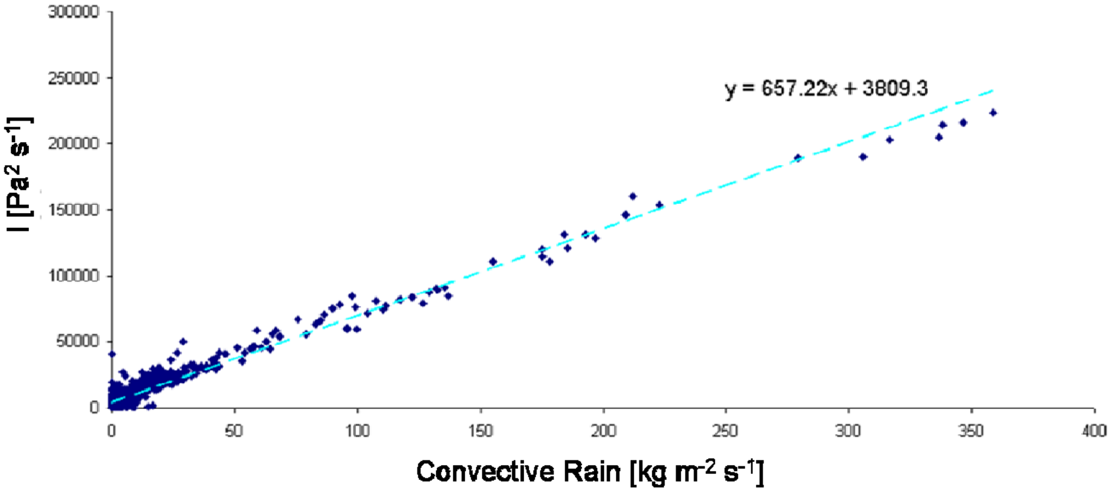


Figure 4. The integral in equation 6 is plotted against the Convective Rain diagnostics (blue dots). The corresponding regression line is also shown (blue-sky dashed line).

SUMMARY AND SUGGESTIONS FOR FUTURE IMPROVEMENT

In this work, a 1-dimensional model for vertical convective transport is proposed for integration into NAME III. The scheme models the physical transport of material in the atmosphere in a satisfactory way and fulfils the 'well mixed condition'. The parametrization of mass fluxes with empirical formulas from CRM studies is consistent with the mass fluxes produced with SCM runs. It is currently under investigation whether derivation of such mass fluxes by other means is possible and offers significant advantages.

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