NAME III Document
MD1/3(version 1)
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Parametrization of deep convection in NAME III

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1 Introduction

Atmospheric convection is responsible for transport and mixing of air resulting in 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 typically below the resolution used and convection must be parametrized (Emanuel, 1994).

This document describes the new scheme for parametrization of convection which has been integrated into NAME version 6.4. In the scheme, the vertical transport of particles due to convection is represented via a 'mass-flux' approach. Empirical formulas are used to obtain the mass fluxes and the NWP diagnostic convective precipitation is used for closure. Please note that the scheme described in this document deals with tropospheric convection (also called deep in the remainder of this document), whilst convection in the atmospheric boundary layer is represented in NAME separately and included in the turbulence scheme.

This report is structered as follows: the next section briefly describes the convection scheme that has been in place in NAME up to the introduction of the new one and explains the reasons for upgrading. Section 3 deals with the description of the mathematical and physical approach of the new scheme, in particularly explaining the implementation of a simplified mass-flux approach (paragraph 3.1), how mass fluxes are parametrized (paragraph 3.2) and how the enhanced vertical mixing caused by convection acts on particles (paragraph 3.3). Section 4 contains useful information for users and in particular instructions on how to activate the new scheme in NAME as well as illustration of some current limitations of the scheme. The last section (5) is devoted to illustrating a test case conducted to assess the qualitative performance of the new scheme.

2 Motivation for a new scheme

The convection scheme described in Maryon et al. (1999) 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. The basic principle is the following: 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.

Users have reported that the implementation of this scheme produces results that are very similar to those obtained running NAME when the scheme is turned off, suggesting its performance is poor. It is also clear that the represention of deep convection in NAME could be improved by adopting a more realistic approach, e.g. estimating the amount of material transported inside the convective cloud.

In revising the scheme, the intention was to make best use of the diagnostic fields currently available from the UM. The potential for future tighter coupling between NAME/UM has also been a guiding criterion in the design of the scheme and the choices made from multiple options available.

3 Mathematical and physical approach

3.1 A simplified mass-flux approach

Deep convective clouds are represented in NAME as three-dimensional boxes (Figure 1; note that this is two-dimensional for the sake of simplicity), with base and top respectively coinciding with the (UM) diagnosed Convective Cloud Base and Convective Cloud Top. If there is more than one convective cloud, only the lowest one is considered.

To conveniently represent the transport of air inside the cloud, from the cloud to the environment (detrainment) and from the environment to the cloud (entrainment), pressure is chosen as a suitable coordinate to represent height and we build an *ad hoc* one-dimensional vertical grid of equally spaced pressure levels.

The total number of levels is first assumed to be $k_{max} = (p_{cb} - p_{ct})/2000$, where p_{cb} is the cloud base and p_{ct} the cloud top, both in unit of pressure.

Once k_{max} has been established, equally spaced pressure layers of depth Δp are evaluated as:

$$\Delta p = \min\left(\frac{p_{cb} - p_{ct}}{(k_{max} - 1)}, \frac{p_0 - p_{ct}}{(k_{max} - 0.5)}\right) \tag{1}$$

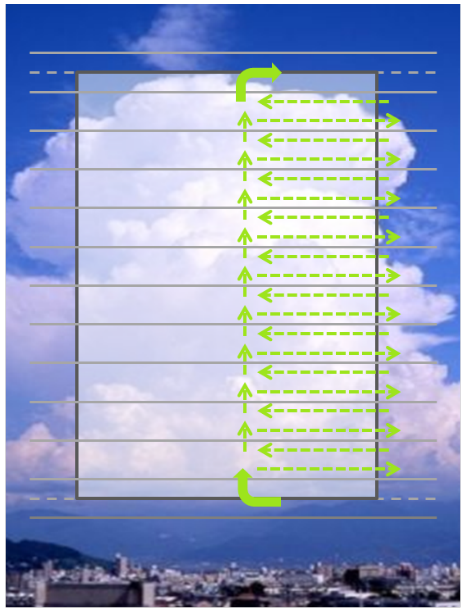


Figure 1: Simplified representation of a convective cloud and exchange of air from/to the environment according to the mass-flux approach. Grey lines correspond to pressure levels, solid green arrows to the entrainment and detrainment flux respectively in the first and last pressure layer. Green dashed arrows correspond to updraught (vertical) and entrainment/detrainment (horizontal) fluxes for any other pressure layer.

where p_0 is the surface pressure. Depending on the result of equation (1), the first pressure level is $p_1 = p_{cb} + \Delta p/2$ or $p_1 = p_0$. This method always ensures that $p_1 \leq p_0$.

It is then possible to calculate each pressure level as:

$$p_k = p_1 - (k-1)\Delta p \quad k \in [1, k_{max} + 1] \tag{2}$$

It is worth noticing that the total number of pressure levels, $k_{max} + 1$, varies depending on the vertical extent of the cloud, but a minimum of 3 and a maximum of 51 is imposed, the first to guarantee that there is at least one pressure level below the cloud base, one inside the cloud and one above the cloud.

To estimate convection, the UM uses a mass-flux approach (Gregory and Rowntree, 1990) which quantifies, for each grid box, the amount of mass transported inside the cloud as a result of exchange of air between the cloud and the environment. In NAME, a simplified mass-flux approach has been adopted based on the equation of conservation of mass which, in discretized form, can be written as:

$$M_{k+1} + D_k = M_k + E_k \tag{3}$$

where M, D and E are respectively the updraught, detrainment and entrainment mass fluxes in units of Pa/s (this choice of unit being consistent with that adopted in the UM) for each pressure level k ($k_{max} \in$ [3,51]).

This can be understood by thinking that all fluxes applied to the bottom of each vertical k-th level indeed refer to the whole layer above. In Figure 1, solid grey lines represent model vertical levels and cloud base and cloud top are represented on dashed lines.

All fluxes in equation (3) are not available yet for operational use in NAME III and their representation is therefore challenging. The next subsection illustrates their parametrization in the new convective scheme.

3.2 Parametrization of mass fluxes

3.2.1 Updraught mass flux profiles

Updraught mass flux profiles are obtained using empirical formulas (Grant, A.L.M, December 2012, pers. comm.) derived from Cloud Resolving Models (CRM). These formulae are based on the height of the freezing level according to the following criteria:

1. If the freezing level (0°C) is between the cloud base and the cloud top but at a distance of at least 10000 Pa from each of them, then the mass flux profile has a maximum at the freezing level. This is intended to represent the updraught mass flux profile at the tropics.
2. If the above condition is not satisfied then the mass flux profile decreases with height.

According to this classification, both warm rain clouds (i.e. with tops below the freezing level) and cold air clouds (i.e. with base above the freezing level) fall in the same category (Case 1.). While this might not be so intuitive, it is supported by experimental and numerical evidence (e.g. vanZanten et al., 2011 and Shipway, B.J., May 2014, pers. comm.). In all cases, at the top of the cloud the mass flux is a fixed fraction of the cloud base mass flux. Before illustrating the formulas for the mass flux profiles, the following variables and parameters must be introduced:

- p_{fl} : pressure of the freezing level
- p_{ref} : a reference pressure taken equal to 60000.0 Pa
- $a_1 = 0.5$
- $a_2 = 0.2$
- M_{max} : maximum value of the updraught mass flux profile

$$= \begin{cases} 1. + a_1\left(\frac{p_{fl}-(p_{cb}-p_{min})}{p_{ref}-(p_{cb}-p_{min})}\right) \text{ if } (p_{fl}-p_{ct}) \geq p_{min},\ (p_{cb}-p_{fl}) \geq p_{min} \text{ and } p_{fl} \geq p_{ref} \\ 3a_1 \text{ if } (p_{fl}-p_{ct}) \geq p_{min},\ (p_{cb}-p_{fl}) \geq p_{min} \text{ but } p_{fl} < p_{ref} \\ 2a_1 \text{ otherwise} \end{cases}$$

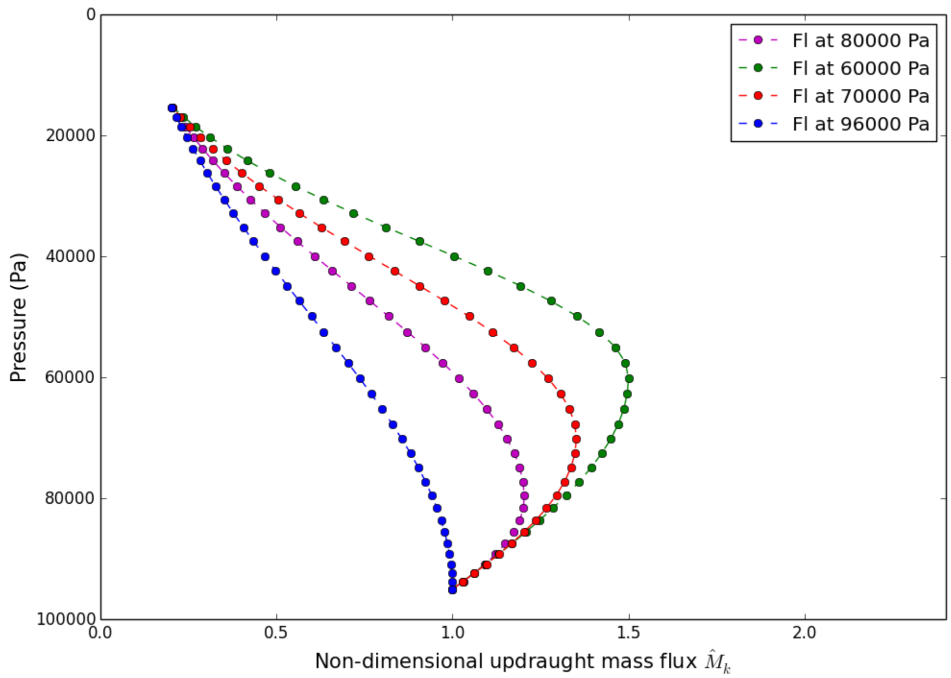


Figure 2: Examples of the variation in the non-dimensional mass flux profiles with changes in pressure of the freezing level.

- $\beta_1 = \ln(M_{max})$
- $\beta_2 = \ln(M_{max}/a_2)$

If $(p_{fl} - p_{ct}) \geq p_{min}$, $(p_{cb} - p_{fl}) \geq p_{min}$ (case 1.), then the updraught mass flux at a given pressure level k is given by:

$$M_k = M_{max} M_{cb} \exp\left(-\beta_1 \left(\frac{p(k) - p_{fl}}{p_{cb} - p_{fl}} \right)^2 \right) \;\; if \;\; p_k \geq p_{fl} \tag{4}$$

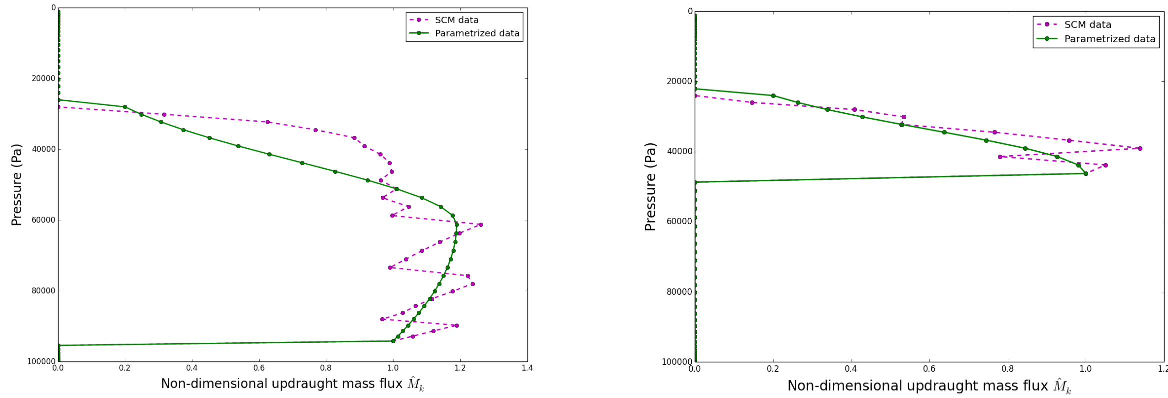
$$M_k = M_{max} M_{cb} \exp\left(-\beta_2 \left(\frac{p(k) - p_{fl}}{p_{ct} - p_{fl}} \right)^2 \right) \;\; if \;\; p_k < p_{fl} \tag{5}$$

For all other situations (case 2.):

$$M_k = M_{max} M_{cb} \exp\left(-\beta_2 \left(\frac{p(k) - p_{fl}}{p_{ct} - p_{cb}} \right)^2 \right) \tag{6}$$

It is clear that equations (4-6) contain an unknown: the cloud base mass flux M_{cb}. Examples of the variation in the non dimensional mass flux profiles (i.e. divided by M_{cb}) with changes in pressure of the freezing level are shown in Figure 2.

In order to test the validity of equations (4-6), the mass flux profiles so obtained are benchmarked against profiles obtained from running the Single Column Model (SCM) forced using data from the TWP-ICE campaign (Shipway, B. J, December 2012, pers. comm.). The campaign took place around Darwin, Australia, for nearly a month (20 Jan 2010 - 13 Feb 2010), generating nearly 1188 profile cases to look at. Figures 3(a) and 3(b)



(a) (b)

Figure 3: Comparison between updraught mass flux profiles obtained with SCM data (purple) and parametrized fluxes as described in this section (green) for two reference clouds.

illustrate two examples for comparison. In Figure 3(a) the parametrized profile has been obtained implementing equations (4) and (5) and in Figure 3(b) implementing equation (6). Both profiles are shown in green and exhibit a good qualitative agreement with the SCM data shown in purple.

3.2.2 Evaluation of the cloud base mass flux

As mentioned before, equations (4-6) contain an unknown: the cloud base mass flux. Other convective schemes (e.g., Derbyshire et al., 2011) use the Convective Available Potential Energy (CAPE) as a closure method to estimate the cloud base mass flux. As CAPE is not available as an input field into NAME, in this instance the amount of convective precipitation at the ground is taken as a valid alternative as it mirrors the convective activity inside the cloud within a reasonable approximation.

The integral of the mass fluxes over the depth of the cloud, I (Pa^2/s), is calculated as:

$$I = \int_{p_{ct}}^{p_{cb}} M(p)dp \approx \frac{M_{cb}}{2} \sum_{k=1}^{k_{max}-1} (\hat{M}_k + \hat{M}_{k+1})\Delta p_k \tag{7}$$

and applying statistical regression using mass fluxes obtained with SCM from the TWP-ICE field campaign, it is found that there exists a linear relation between the integral and the convective precipitation amount at the ground (available from the SCM forced with TWP-ICE campaign data):

$$I \approx f\Phi \tag{8}$$

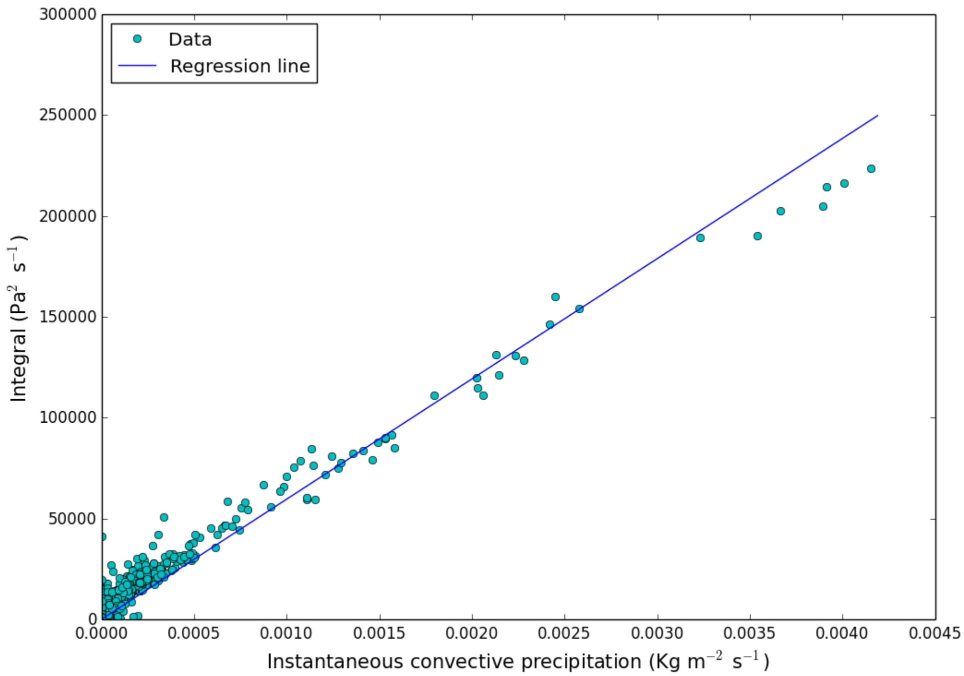


Figure 4: The integral in equation (7) is plotted against the convective precipitation amount; the corresponding regression line is also shown.

where Φ is the amount of convective precipitation at the ground in unit of $kg\ m^{-2}s^{-1}$ and $f = 59601808.43\ kg\ s^{-4}$ is a conversion factor. Figure 4 illustrates the regression relation described in equation (8). Finally, the cloud base mass flux can be calculated rearranging equation (7) and equation (8).

3.2.3 Entrainment and detrainment fluxes

To complete the scheme, entrainment and detrainment fluxes must be estimated. The entrainment flux depends on the rate at which air from the environment is drawn into the cloud through its sides as a fraction of the updraught mass flux per unit change in pressure in order to balance the increase of vertical mass flux in the cloud with height. As NAME is often run with meteorological data provided by the UM, the entrainment rate, in units of Pa^{-1}, is taken to be the same as that in use in the UM, i.e.:

$$\epsilon = f_{dp} 3 A_E \left(\frac{p_k}{p_0^2} \right) \tag{9}$$

where p_0 is the surface pressure, f_{dp}=0.9 and A_E=1.5. It is worth noting that several studies have been undertaken to determine the entrainment rate associated with convective plumes and there is still uncertainty as to what is the best choice of parameters in equation (9), which may in turn depend on the UM configuration (Stratton, R.A, October 2013, pers. comm.).

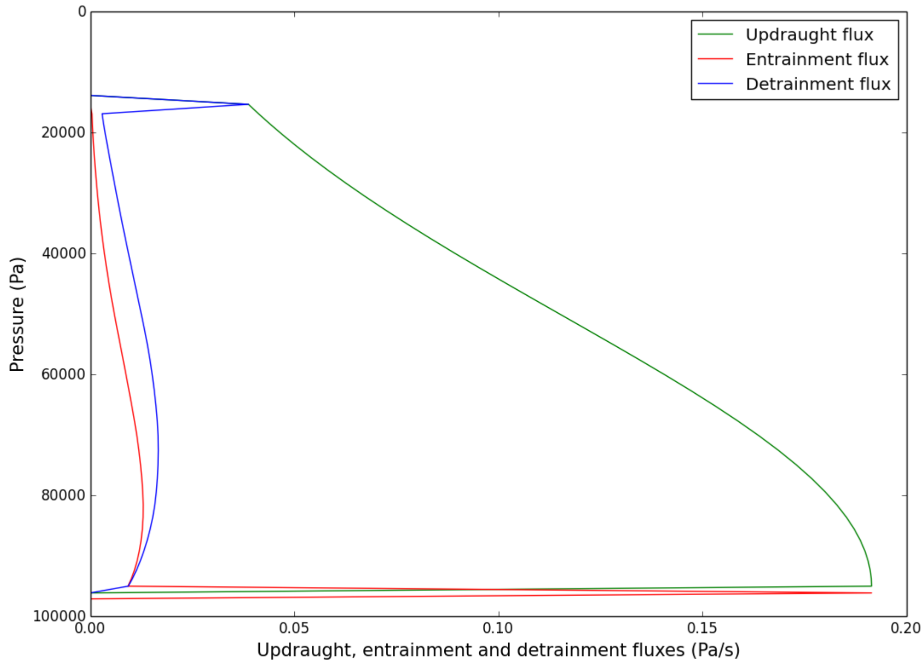


Figure 5: Mass, entrainment and detrainment flux profiles as a function of pressure for a given cloud base and top.

The entrainment flux (Pa/s) can then be calculated as:

$$E_k = \epsilon M_k \Delta p_k \tag{10}$$

Generally a much larger entrainment flux is needed for the pressure layer that includes the cloud base.

For detrainment, the UM calculates rates and fluxes of both mixing and forced detrainment. The first type of detrainment is associated with mixing and evaporative cooling at the cloud edges and is estimated in the UM as a function of relative humidity. Forced detrainment is instead due to loss of buoyancy of the core updraught and its estimation involves the calculation of the excess buoyancy, i.e. the difference between the virtual potential temperature of a rising air parcel and that of the environment (e.g. Stirling and Stratton, 2012 and Derbyshire et al., 2011).

The new convective scheme in NAME does not use the UM approach to calculate the detrainment rate. Instead, the detrainment flux is calculated using the continuity equation (eq. 3) after calculating M_k, M_{k+1} and E_k. Whenever a negative detrainment flux is encountered, a correction is made to enforce zero detrainment and to increase the entrainment flux at the corresponding pressure level. Figure 5 illustrates the resulting profiles of mass, entrainment and detrainment fluxes for an example of convective cloud: the biggest entrainment flux occurs in the pressure layer containing the cloud base then decreases with height, whilst the detrainment flux has a maximum in the layer including the top of the cloud.

3.3 Scheme for vertical displacement

The scheme implemented for vertical transport, based on mass fluxes, is similar to the one described in Collins et al. (2002) for convective transport of chemical species. The transport of particles inside the convective cloud is represented as follows. At the beginning of each time step, particles are distributed in the environment. Then, the fluxes described in the previous section are used to estimate how many particles entrain in a given cloud layer and, once entrained, how many particles move upward and detrain via a set of probabilities, defined as:

$$P_{ent,k} = \frac{\Delta t E_k}{\Delta p_k}, \quad P_{up,k} = \frac{M_{k+1}}{(M_k + E_k)}, \quad P_{det,k} = 1 - P_{up,k}. \tag{11}$$

$P_{ent,k}$, $P_{up,k}$ and $P_{det,k}$ are respectively the probability to entrain, move upwards and detrain for a given layer k, Δt is the model timestep, typically ranging from 300 s to 900 s in NAME and Δp_k is the depth of the layer.

The probability of moving in an updraught is evaluated by estimating the fraction of mass that moves upwards with respect to the mass that enters into the cloud column. The probability of detrainment is calculated in a similar way.

These probabilities are designed to be consistent with the mass fluxes imposed. For example, for every pressure layer, the probability of entrainment is calculated as the weight of air entrained ($E_k \Delta t \Delta x \Delta y$) divided by the weight of air in the layer ($\Delta p_k \Delta x \Delta y$), assuming hydrostatic balance. The only restriction imposed on the timestep is that it must be ensured that the probability of entrainment is always less than unity (and for accuracy should be much less than this).

To compensate for upward motion, a subsidence flux equal to the updraught flux is applied to all the particles, so that the resulting particle pressure (p_{new}) is larger than the one in place before applying subsidence (p_{old}), as equation (12) illustrates:

$$p_{new,i} = p_{old,i} + M_i \Delta t \tag{12}$$

where M_i is obtained by interpolating the updraught top and bottom level mass fluxes at the i-th particle position.

Lastly, the scheme has been tested and shown to correctly fulfill the well mixed condition (Thomson, 1987). More details on the scheme for vertical displacement can be found in Meneguz and Thomson (2014).

It is also worth noticing that 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 updraughts and are therefore neglected by some authors (e.g., Collins et al., 2002).

4 Technical information for users

4.1 How to set up a run with convection in NAME

Since the release of this document for NAME version 6.4, the user can choose whether to implement the old convective scheme (described in section 2) or the new scheme by editing the Input file. This means that there are now three acceptable options to enter below the keyword: *Deep Convection?* under the block *Sets of Dispersion Options*, namely:

- *No*

  this means that no convective scheme is active in the run.

- *Old*

  To activate the "old" convection scheme described in section 2.

- *New*

  To activate the new convection scheme described in the remainder of this document.

It is worth mentioning that if the user chooses to run a version of NAME antecedent to 6.4, then only two options are available, i.e.: *No* and *Yes*, where the second activates the 'old' convection scheme mentioned in section 2. In version 6.4, the keyword *Yes* is not accepted anymore (as it would generate confusion about which convective scheme to activate) and if chosen by the user an error message will appear on the screen and the run will be automatically stopped.

If the user chooses to run with a convection scheme turned on, then it might be useful to request *Convective Cloud Base* and *Convective Cloud Top* under the block *Output Requirements - Fields:*. These diagnostics have been made available for output in version 6.4. The values are returned in m agl and can give an idea of the vertical extent of the convective cloud diagnosed at a given location of interest, which can in turn be revealing of the strength of convection.

The call to the subroutine for the new convection scheme is activated in NAME for each individual particle only when the amount of convective precipitation interpolated at the particle position is non-zero (otherwise the criterium for choosing the cloud base mass flux in equation (8) would fail). In theory, it would be useful for the user to request also the amount of convective precipitation under the block *Output Requirements - Fields:*. However, the only diagnostic currently available for output is *Precipitation rate (mm/hr)* which includes both dynamic and convective precipitation.

4.2 Met data and limitations of the scheme

When running NAME with the new convection scheme, attention must be paid to the resolution of met data read into the model. The scheme is designed to work with Global met data or with any met data with horizontal resolutions sufficient to guarantee that convection is not explicitly represented.

If the user wishes to run the new scheme with met data other than those provided by the UM, it is strongly recommended to make sure that convective precipitation (in mm/hr) and convective cloud diagnostics (convective cloud base and top) are available and provided as input into NAME. Failure to provide these variables will result in failure to run NAME with the new convection scheme.

Currently, the option to run NAME with the new convection scheme in Backwards mode has been disabled (an error message will appear on the screen and the run will be stopped if the user attempts to request it). This is because the scheme has not been yet designed for running backwards but this limitation will soon be addressed.

In terms of run-time, preliminary tests suggest that the new convection scheme has a negative impact on NAME performance, and the estimated delay depends on the number of particles employed in the run. However, when run in parallel delays seem to be nearly neglegible. The user is invited to test the performance of NAME with the new convection scheme and report feedback to ADAQ staff (in particular Elena Meneguz, Dave Thomson or Andrew Jones).

5 Test case

The performance of the new convection scheme has been tested running NAME (with global met data PT2) on a deep convective episode that took place over parts of France between the 8-9 of June 2014. Many parts of France were on alert for severe storms for three days and a moderately active Spanish Plume situation evolved in the night of 8 June: just before midnight a cumulonimbus (Cb) cluster, a typical manifestation in the plume, started to grow over the Gironde estuary in south west France. On Sunday night (8 June) damaging winds gusted to over 110 km/h and large hailstones battered areas near Paris, tennis-ball sized hail was reported around the country and in the southern Paris suburb of Mormant building roofs were damaged by hail.

NAME runs have been set up releasing 10,000 particles per hour at Saint-Ciers-du-Taillon, near the Gironde Estuary, where convective cloud extents reached a maximum over 10,000 km (minimum cloud base: 1796.01 m agl, maximum cloud top: 12025.42 m agl) over the night of the 8 June. To capture the base of the cloud, particles are released between 1500-2500 m agl.

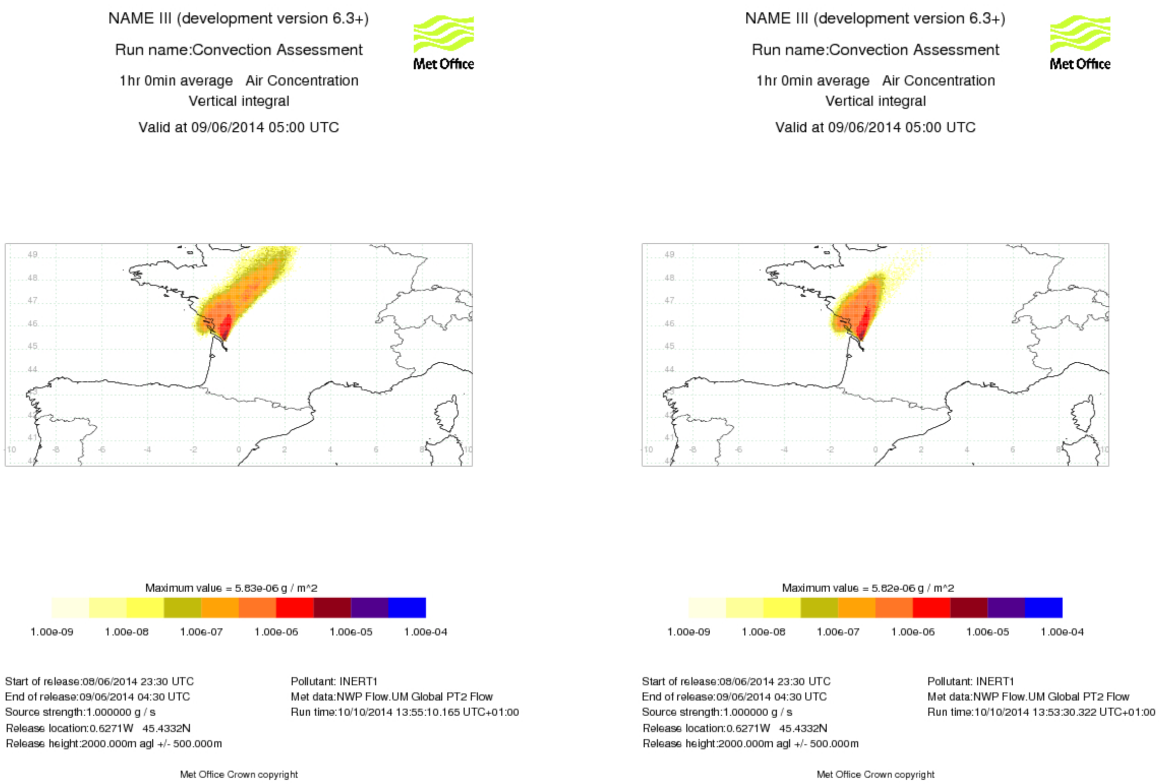
Air Concentration output files have been produced every hour from 09/06/2014 00:00

UTC to 09/06/2014 07:00 UTC integrating over the vertical column. Simulations have been conducted with:

(a) The new convection scheme activated.

(b) The old convection scheme activated.

(c) No convection scheme activated.



(a) (b)

Figure 6: NAME output plots valid at 09/06/2014 at 05:00 UTC for cases (a), left side, and (b), right side.

Figures 6 and 7 illustrate results valid at 09/06/2014 at 05:00 UTC for cases (a), (b) and (c). It is clear that the implementation of the new convective scheme results in more particles displaced higher in the atmosphere, as the shape of the plume in case (a) is significantly different to that of case (c). It also possible to notice that the output produced by the old convection scheme is very similar to that produced without any convection scheme.

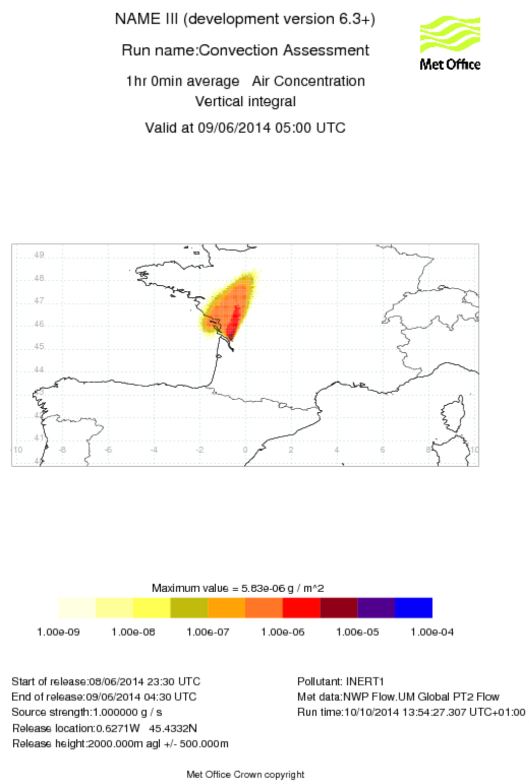


Figure 7: NAME output plots valid at 09/06/2014 at 05:00 UTC for case (c), i.e. simulation without any convective scheme.

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