Physics/Dynamics Coupling at very high resolution:

permitted versus parametrized convection

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1 Introduction

The resolution increases of the operational Integrated Forecast System (IFS) have been following the increase of performance of the super computers installed at ECMWF in the last 25 years. The next horizontal resolution upgrade of the global IFS is planned for 2015. The current spectral truncation T1279 which corresponds to a resolution of the reduced Gaussian grid of about 16 km will then be replaced by a T2047 and a Gaussian grid with a resolution of about 10 km around the globe. Such a resolution was, 20 years ago, accessible to operational limited area models (LAM) only. Operational LAM are now running with resolutions around 2 km or even higher; resolutions which were used by the research Cloud Resolving Models (CRM) 20 years ago (Weisman and Klemp, 1982, Guichard, 2004). In research mode, it is already possible to run global models with the resolution of the first CRM. Even if it still takes 20 years before we could run operationaly at such very high resolutions, global modelling is entering a new era where convective processes will step by step migrate from the world of parametrized processes to the world of 3D resolved circulations.

This paper addresses the problem of the transition from parametrized to resolved deep convection in a didactic way. Several aspects of the representation of convective motions in atmospheric models are discussed, with a special emphasis on resolutions which are too high for the fundamental hypotheses of the current deep convection parametrisations to be valid but which are not high enough to properly resolve the individual convective cells. The last section gives a brief review of the current research in the climate and NWP communities aiming to improve the representation of deep convection in numerical models in this *grey zone* of convection.

2 Towards convection permitting global model

2.1 What does convection permitting means?

In the atmosphere, *convection* mainly refers to vertical updrafts driven by buoyancy. An easy way to picture convective motion is using warm air parcels (warm bubbles) which will accelerate upwards because they are lighter than the surrounding air. Convection in the atmosphere can be "dry", i.e. the buoyant updrafts reach their level of equilibrium before reaching their level of condensation, or "moist", if the adiabatic cooling of the ascending parcel is enough for the water vapour present inside the parcel to reach saturation. In this case, the latent heat released by the condensation is balancing part of the adiabatic cooling and the parcel remains buoyant (warmer/lighter than its environment) until much higher altitude than in the dry case. Dry convection is usually a shallow and fast process whereas moist convection is deeper and can be associated with complex interactions between the circulation (wind shear, density current, small scale pressure and vorticity anomalies etc) and cloud/precipitation processes such as evaporation, freezing and melting, water loading.

For operational numerical weather prediction (NWP), dry convection is still a small scale and fast process whose overturning effect needs to be parametrized by the vertical diffusion parametrisation and/or by a parametrization of more organised dry thermals in the boundary layer (see for example, the Eddy-Diffusivity Mass-Flux approach (EDMF) in Siebesma et al, 2007 or Pergaud et al, 2009). In atmospheric models, the parametrization of moist cloudy convection is usually split in two, one parametrization for shallow cumulus clouds and one for deep cumulonimbus, their associated thunderstorms or more organised large convective systems.

For low resolution models (we will discuss the limit between low and high resolutions with respect to deep convection in the next sections), the transport and the microphysics associated with moist convection are fully parametrized. But, as the resolution increases, the non-parametrized circulations start to take over the convective transport, i.e. convective parcels of at least the size of a grid box become "buoyant" with respect to the neighbouring grid boxes. In this case, the convective circulation is mostly driven by the horizontal pressure gradient forces in the dynamics and, in the case of moist convection, the buoyancy is maintained by the latent heat released in the buoyant grid boxes by the condensation parametrized in the "resolved" cloud scheme [1]. Freezing/melting, water loading (weight of condensates in air parcels) are also involved in the simulation of convective processes in this case.

When non-parametrized vertical and horizontal circulations start to release convective available potential energy (CAPE), thanks to the positive feedback between the adiabatic cooling (computed in the dynamical core of the model) and the latent heat release (parametrized in the physics package of the model), the model *permits* non-parametrized convection. The NWP community is often referring to *convection permitting model* rather than *convection resolving model* because the current operational NWP models are often working at resolutions such that the details of the convective circulations are not numerically well resolved because the size of most simulated convective updraft is close to the size of the grid mesh. The convective circulations are then permitted but not well resolved by the numerical schemes which are known to have large errors at the smallest scales allowed by the discretisation. When the convection scheme is off and the resolution still too low to sample deep convective cells, the non-parametrized convective updraft often show unrealistically strong updrafts and density currents as well as too intense precipitation rates (Deng and Stauffer, 2006).

In the transition zone at resolutions where the statistical sub-grid approach for the parametrisation of convection is not valid anymore but the sampling of convective cells is not fine enough, the problem is often to find the balance between parametrizing convection and permitting explicit 3D convective circulations as both "compete" to release the CAPE present in the atmospheric state. In order to help address this problem, we'll first analyse what is necessary to permit convection in a model and then investigate some proposals to help the dynamics and the convective parametrisation to interact in a more seamless manner in the grey zone of convection.

2.2 Do we need a non-hydrostatic dynamics to permit convection?

The vertical velocity in a convective updraft may have the same order of magnitude (or even larger) than the horizontal wind. There is then a common belief that updraft driven by positive buoyancy can not be modelized by an hydrostatic model because in the hydrostatic system of equations, the vertical

[1] We call "resolved" cloud scheme the parametrisation of cloud and precipitation microphysical processes mainly triggered by the "resolved" mean (non-parametrized) circulation of the model. In the current IFS, this scheme is a 1 moment bulk microphysics with 5 prognostic water variables advected by the mean wind: water vapour, cloud droplets, cloud ice, rain and snow. The scheme is currently tuned for the current IFS resolutions, but very few parameters need re-tuning when the scheme is used in a "convection permitting mode"

acceleration is neglected when compared to the gravity or the buoyancy force in the vertical momentum equation. However, it is an error to think that the vertical velocity in an hydrostatic model is necessarily small. When the hydrostatic approximation is done, the vertical velocity is not a prognostic variable anymore, but it is a diagnostic parameter which is controlled by the horizontal circulation and the continuity of the fluid. Then, if the horizontal acceleration is mainly cross-isobaric (ageostrophic), the circulation is highly convergent/divergent and it will "force" a very large hydrostatic vertical velocity.

The refinement given by a non-hydrostatic (NH) model is rather in the finer description of the acceleration phase and the transient state towards the hydrostatic balance unlike the hydrostatic system which supposes an "instantaneous" (or much faster than a time step) hydrostatic adjustment (in the hydrostatic system, the hydrostatic adjustment is seen as a non resolved sub-time step process which involves "implicit" global mass redistribution).

But from which time/space scales and for which model resolutions do we need to resolve the transient non-hydrostatic states in order to get the correct evolution of the processes studied or simulated?

A common answer found in the literature resulting from scale analysis or linear internal gravity wave studies says that the hydrostatic approximation remains a good approximation if:

$$\mathscr{H}/\mathscr{L} << 1 \tag{1}$$

where $\mathscr{H}$ and $\mathscr{L}$ are the vertical and horizontal characteristic sizes (or wavelengths) of the process of interest. For deep convection, $\mathscr{H}$ is the height of the tropopause, i.e. about 10 km. Then, according to equation 1, convective processes with $\mathscr{L} <<$ 10 km have to be modelized with a non-hydrostatic system.

But how are $\mathscr{L}$ and $\mathscr{H}$ related to the horizontal and vertical resolution of a numerical model? The answer is probably different depending on the numerics of the model. With the IFS numerics, the wavelengths which are accurately resolved are between 4 to 8 times the grid size which means the hydrostatic approximation would collapse for resolution higher than 2.5 to 1.25 km.

The IFS can be used as a laboratory to check this theoretical guess as it can be run in hydrostatic and non-hydrostatic mode with only minimal changes in the numerics. A series of academic warm bubble simulations has been run at different resolutions with both the hydrostatic and non-hydrostatic IFS with the small planet configuration (Wedi et al, 2009). The spectral resolution for all experiments is T159. The vertical levels are the 91 levels used in operation at ECMWF until June 2013. The grid size of the reduced Gaussian grid is given by the reduction factor of the planet radius γ and goes from $\Delta x = 10$ km for $\gamma = 12$ to $\Delta x = 0.5$ km for $\gamma = 250$.

In each case, the simulations are initialised by a steady state (no wind) and vertical profiles of T and q from the sounding used for the study of storm dynamics by Klemp and Wilhemson (1978). A heating with a constant rate of 0.1 K/s is switched on for 5 min in one single grid box near the surface.

At 0.5 km resolution and a time step of 10 s, the hydrostatic model produces quickly very large vertical velocities and the bubble reaches its level of equilibrium about twice earlier than in the non-hydrostatic model (figure 1). At this resolution, the hydrostatic approximation clearly reaches its limit. But, the vertical acceleration diagnosed by the hydrostatic system is not too small as often thought, but much too large and the vertical velocities reached by the bubble are too strong to be realistic.

At 2.5 km resolution and a time step of 60 s (not shown), the ascending phase of the bubble is quite similar in both hydrostatic and non-hydrostatic models, with again a slightly larger maximum vertical velocity at the beginning of the ascent in the hydrostatic model. The dissipation phase of the bubble into horizontally propagating gravity waves is however quite different in the hydrostatic and non-hydrostatic models with again, waves propagating faster in the hydrostatic model than in the non-hydrostatic one.

At 5 km resolution and a time step of 120 s (figure 2) and lower resolution (not shown here), both the ascending phase and the dissipation phase remain similar in the hydrostatic and non-hydrostatic models.

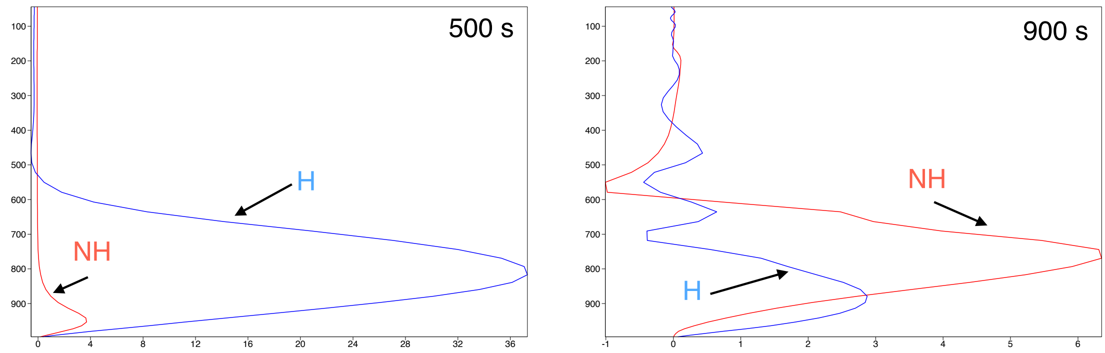

Figure 1: Simulation of a warm bubble ascent at 500 m resolution (dt =10 s). Vertical profiles of vertical velocity in the centre of the bubble after 500 s and 900 s. Hydrostatic results in blue, non-hydrostatic results in red.

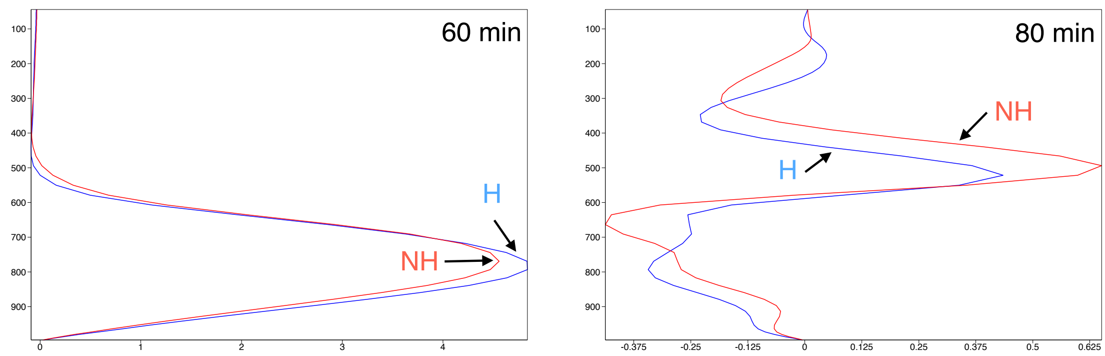

Figure 2: As figure 1 but at 5 km (dt =120 s) resolution and after 60 min and 80 min.

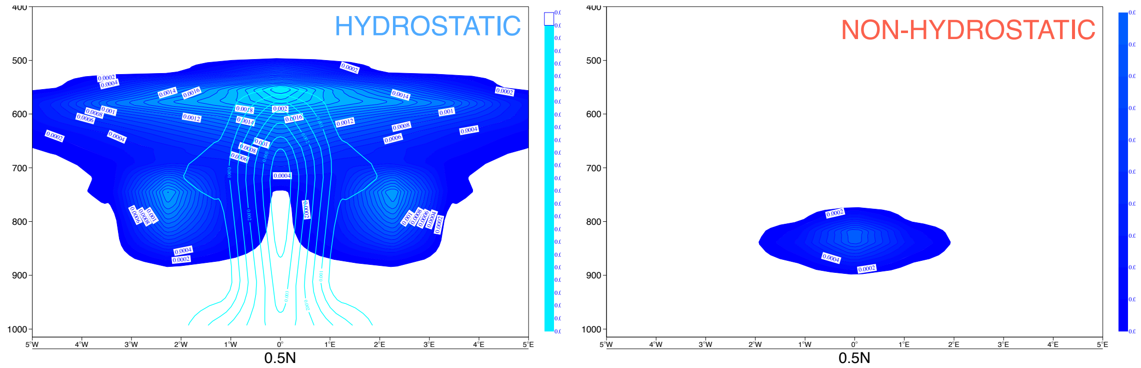

Figure 3: Moist simulations at 0.5 km resolution (dt =10 s) of a moist single grid box bubble. Zonal-vertical cross-section across the bubble after 15 min of cloud (liquid+ice) specific content (shading) and rain specific content (cyan isolines) in the hydrostatic case (left panel) and non-hydrostatic case (right panel).

This series of simulations is very academic, but they show that both the hydrostatic and non-hydrostatic dynamical core of the IFS are permitting dry convection of grid scale bubbles at resolution from 0.5 to 10 km. The larger the bubble, the longer the time scale needed to reach the equilibrium level. For sub-kilometric resolutions, the hydrostatic model shows significatively larger vertical accelerations at the beginning of the evolution compared to the non-hydrostatic solution. For resolution equal or lower than 5 km, the difference between hydrostatic and non-hydrostatic becomes very small. For this range of resolutions, the sensitivity of small scales (with respect to grid scale) to other numerical "tuning", especially numerical diffusion but also time discretisation of fast processes, is much higher than the differences between the hydrostatic and the non-hydrostatic core simulations.

The same bubble experiments can be re-run with the "resolved" cloud scheme switched on. The model runs then in some kind of CRM mode. In these cases, the warm bubbles start their ascent as in the dry cases, but they reach their level of condensation before reaching their equilibrium level. The feedback between the warming by latent heat release and the adiabatic ascent/cooling creates a deep convective cloud above the initial heating.

At 0.5 km resolution (time step 10 s), the evolution of the hydrostatic cloud is much faster than in the non-hydrostatic case (figure 3). As in the dry case, diagnostic hydrostatic vertical velocities largely over-estimate the prognostic vertical velocities of the non-hydrostatic model (figure 4). Rain appears much sooner in the hydrostatic model generating subsiding motion already after 15 minutes of simulation, at a time where the autoconversion has not yet created any rain in the the non-hydrostatic cloud. At 1 km resolution (time step 30 s), the hydrostatic cloud still grows significantly faster than the non-hydrostatic one. But at 2.5 km (time step 60 s) and 5 km (time step 120 s) resolutions, the differences between the two cloud simulations are small. In these cases, the differences between hydrostatic and non-hydrostatic are much less than differences obtained with a different tuning in the cloud scheme, for example changing from the operational autoconversion rate to an autoconversion rate in better agreement with what is used in CRM (figure 5).

The small planet configuration of the IFS is also suitable to study the development of more complex convective organisations. For example, the setting proposed in Weisman et al (1990) for an academic squall line has been adapted for the small planet. In this case, the squall line is triggered by an initial 2.5 km deep cold pool with a maximum potential temperature deficit of 8 K near the surface. A strong wind shear in the first 2.5 km above the surface brings the easterly wind from 17.5 m/s at the surface to zero above 2.5 km. The results shown in figure 6 come from simulations on a small planet at a resolution of about 3 km (T255 with a reduction factor $\gamma = 25$) with only the "resolved" cloud scheme

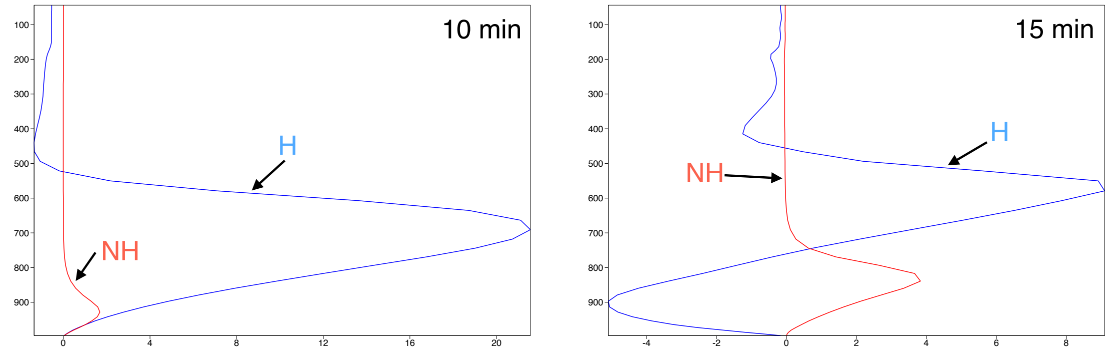

Figure 4: Moist simulations at 0.5 km resolution (dt =10 s) of a moist single grid box bubble. Profiles of vertical velocity at the centre of the bubble after 10 and 15 min of simulation (blue line for hydrostatic, red line for non-hydrostatic).

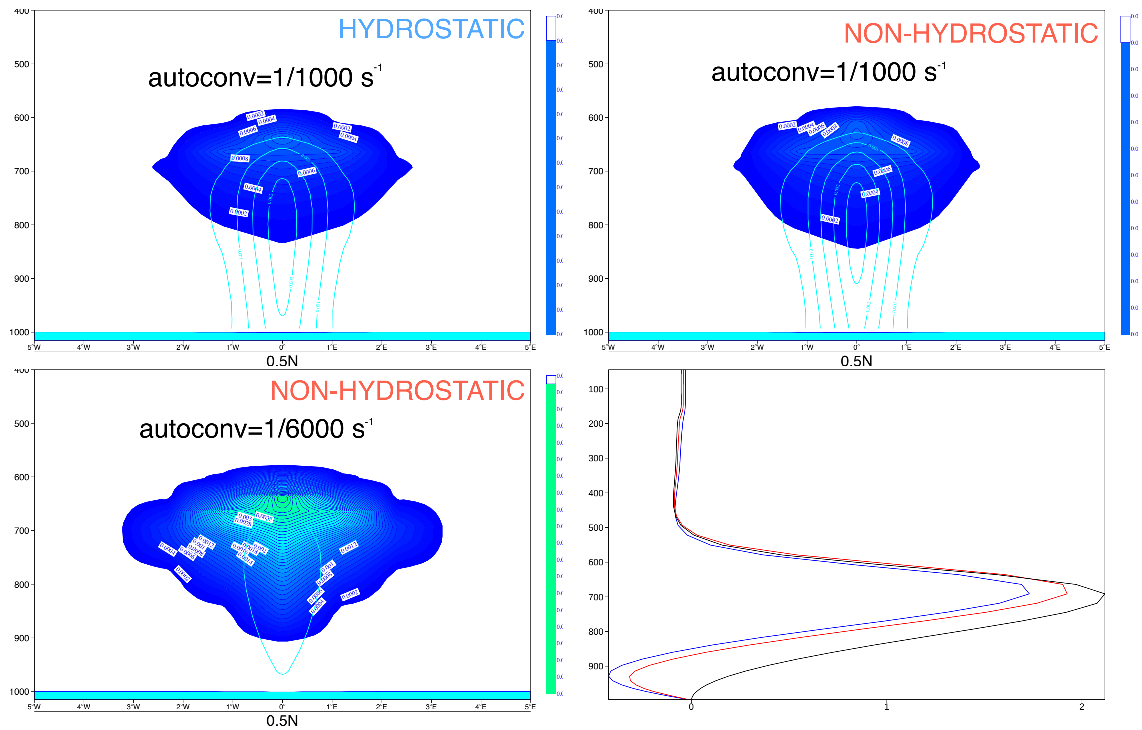

Figure 5: Moist simulations at 5 km resolution (dt =120 s) after 100 min of moist convective motion of a single grid box bubble. Zonal-vertical cross-section across the bubble of cloud (liquid+ice) specific content (shading) and rain specific content (cyan isolines) in the hydrostatic case (top left panel) and non-hydrostatic case (top right panel). The bottom left panel shows the cloud in a non-hydrostatic simulation with the current operational autoconversion rate 1/6000 s^{-1} instead of the autoconversion rate more classically used in CRM of 1/1000 s^{-1}. In this case, the amount of air-borne cloud droplet is much higher as the rain formation is delayed. The subsidence below the cloud due to rain evaporation is then also delayed as seen on the bottom right picture showing profiles of w for the hydrostatic (blue), the non-hydrostatic (red) and the non-hydrostatic with operational autoconversion rate (black).

on (all the other parametrisations in the physics package are off). In both the hydrostatic and non-hydrostatic simulations, the system is quasi-stationary. A line of convective cells develops at the front edge of the cold pool. The mesoscale rear flow which is characteristic of this type of squall line (Houze, 1993) descends under the trailing stratiform clouds and finally reaches the base of the convective cells where it reinforces the convergence near the leading gust front. Unlike what is suggested in Weisman et al (1997), the vertical velocity in both the hydrostatic and non-hydrostatic models simulated by the IFS on a Gaussian grid with a resolution of about 3 km is still of similar maximum amplitude (figure 7).

2.3 Can we permit convection with a deep convection scheme on?

Resolutions around 5 km are not very far from being accessible to global models (it is actually already possible with the IFS, even so still very expensive). We've seen in the previous section that, even at such resolutions, single column deep convective cells can be simulated by both the hydrostatic and the non-hydrostatic models. However, such small scale structures are not well resolved by the numerics which is not designed to deal accurately with near grid scale structures. On the other hand, at these resolutions, fundamental hypotheses made in the convection scheme also reach their limit (Yano et al, 2012, Gerard et al, 2007). These limitations will be discussed with more details in the next section.

We use here the academic simulation of a squall line described in the previous section to illustrate the problem of the representation of deep convection and its interaction with the larger scales at resolutions in the so-called grey zone of convection.

As in section 2.2, the squall line is simulated on a small planet. The resolution of the Gaussian grid is now 5 km (T159, $\gamma = 22,5$). In a first simulation, the non-hydrostatic dynamical core is coupled to the "resolved" cloud scheme only and in a second simulation, it is coupled to both the "resolved" cloud scheme and the convection scheme of the IFS physics package. Figure 8 shows the cross-sections along the equator of the developing squall line after 2 and 6 hours of simulation without or with convection scheme on. The simulations of the academic squall line at 5 km resolution when the convection scheme is off is very similar to the 3 km resolution simulations shown in the previous section. But, when the convection scheme is on, results are quite different (figure 8). The convection scheme release the convective instability very quickly. Light convective precipitation is produced everywhere around the planet with slightly stronger rates at the leading edge of the initial cold pool during the first 2 hours of simulation. The high level ice clouds detrained by the convection scheme at the beginning of the simulation are not able to initiate the feedback between the microphysics and the dynamics which generates the mesoscale rear flow in the case where the convection scheme is switched off.

As expected, the convection scheme release convective energy. But it does it with a feedback on the mean model variables which is very different from the 3D response found in the case without convection scheme. When the convection is treated in the parametrisation scheme, the instability is released in a single vertical column. The convective circulation does not "feel" the wind shear of the environment which should create an up-shear tilt of the convective clouds. Without this key factor, the simulation with the convection scheme on completely misses the development of the squall line.

3 Generalisation of the mass flux approach for high resolution

One of the main objective when moving towards high resolution is to improve the representation of convection in NWP models. As the resolution is increasing but when computer resources are not yet enough to reach sub-kilometric resolutions at which it starts to be more realistic to run without a deep convection scheme, it is interesting to revisit the hypotheses made in the convection schemes which have been designed when the scale separation between the scale of deep convective clouds and the scale of

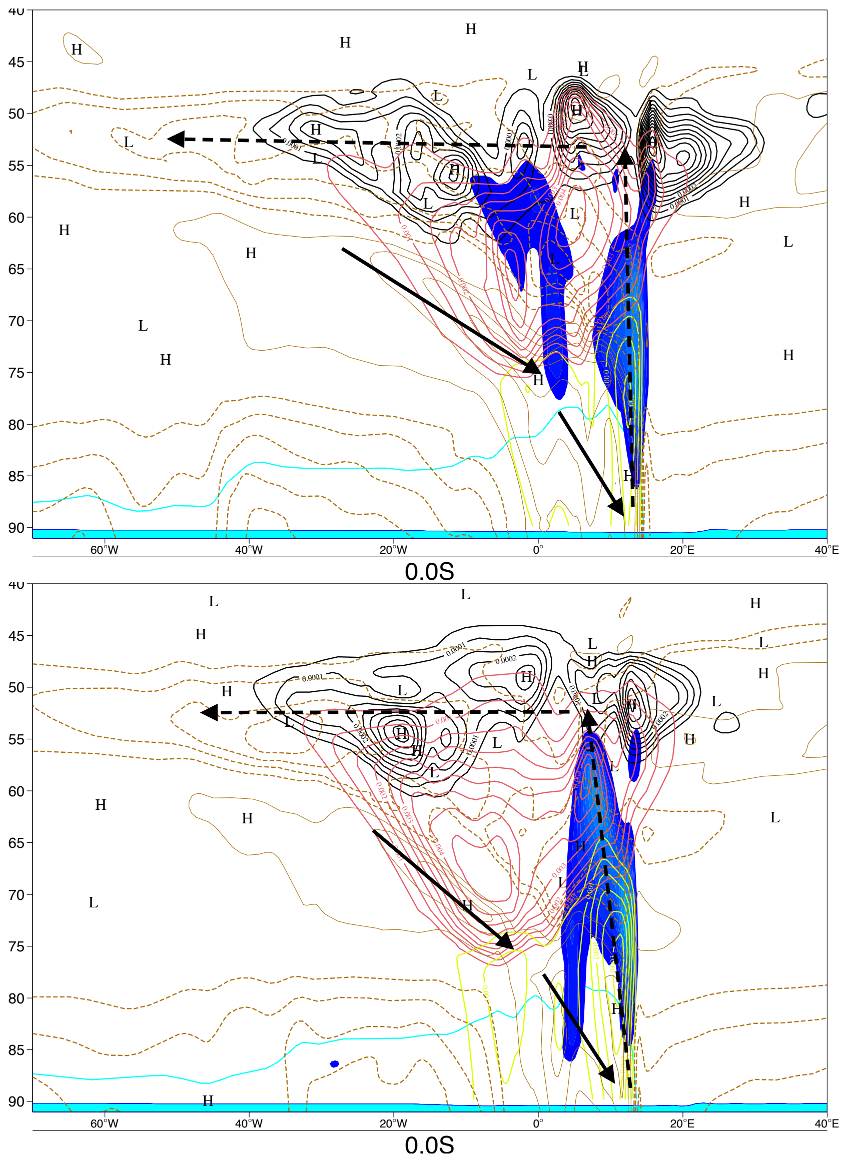

Figure 6: Squall line simulation on the small planet. 5 hours IFS hydrostatic (top) and non-hydrostatic (bottom) simulations at 3 km resolution. Cross-section along the equator of the small planet across the squall line. Brown lines for zonal wind (every 5 m/s, dashed line for easterly wind). The cyan line is the $\theta = 300$ *K iso-line which represent the edge of the cold pool. Shading for cloud droplet, black lines for cloud ice, pink lines for snow and green lines for rain specific contents. The black arrows emphasise the mesoscale circulation characteristic of the squall line.*

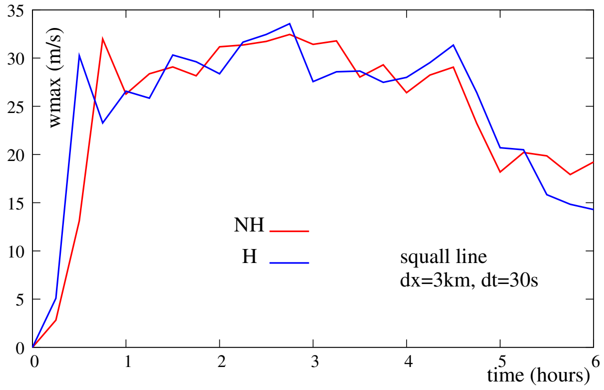

Figure 7: Maximum vertical velocity in the squall line simulations with the hydrostatic and non-hydrostatic IFS at 3 km resolution.

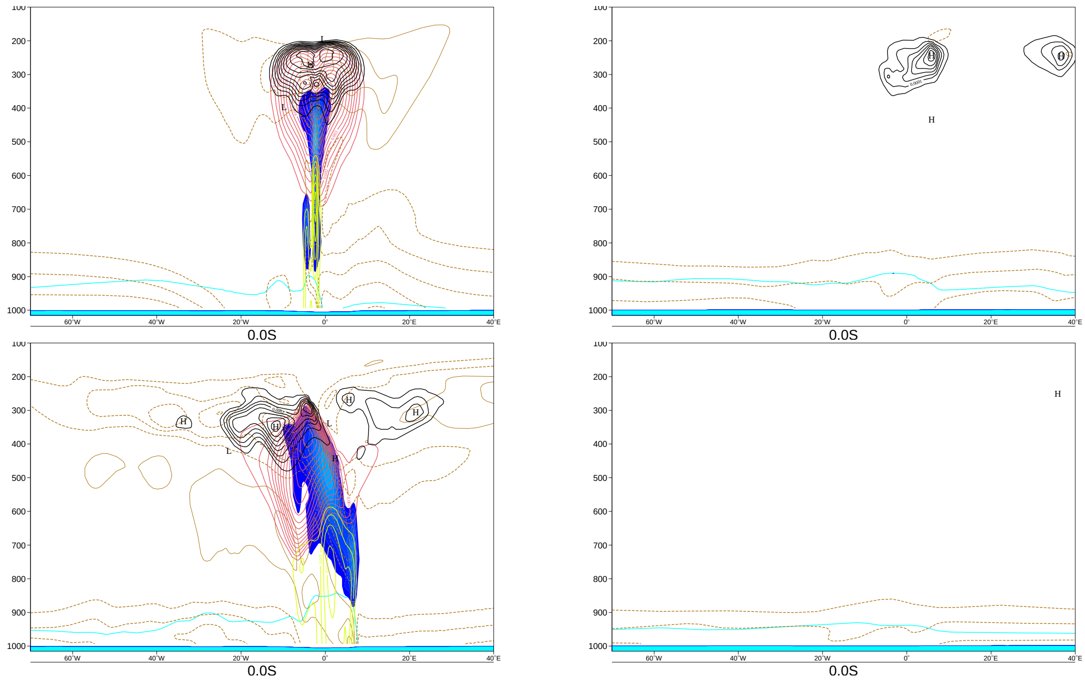

Figure 8: Squall line simulation on the small planet. 2 and 6 hours IFS NH simulation at 5 km resolution without (left) and with (right) convection scheme on. Cross-section along the equator of the small planet across the squall line. Iso-lines as in figure 6.

the resolved processes was clear.

Work started in the LAM community more than 10 year ago for models which could access resolutions around 5 km but no yet more (Gerard and Geleyn, 2005). Most LAM models have now jumped to resolutions of about 2 km or less and run without deep convection scheme. But global models are already experimenting at resolutions in the grey zone of convection and the problem of improving the convection scheme for resolutions between 10 and 2 km may regain interest.

3.1 Parametrized transport in convection schemes

The classical starting point for the parametrisation of sub-grid transport is a Reynold decomposition of the prognostic variables of the model equations. For a prognostic variable per unit mass ψ, the evolution of the mean prognostic variable $\overline{\psi}$ is given by an equation which can be written as:

$$\overline{\rho\psi} = \mathscr{S}_{dyn} - \overline{\rho w'\psi'} + \mathscr{S}_{phys} \tag{2}$$

where $\mathscr{S}_{dyn}$ is the "resolved" source terms of the adiabatic equations, $-(\overline{\rho w'\psi'})$ is the sub-grid vertical transport of fluctuation of ψ by the fluctuation of vertical velocity w' (the horizontal contribution of sub-grid transport is still often neglected in NWP model) and $\mathscr{S}_{phys}$ represents the diabatic sources parametrised in the physics package (radiation, microphysics). Note that one of the difficulty for the design of parametrisation is that there is no "separability" between the sub-grid transport and the diabatic sources. For instance, in a convection scheme, the fluctuation of vertical velocity is clearly dependent of the condensation and vice versa.

In the following, we will concentrate on the formulation of the sub-grid transport, forgetting for the moment the problem of condensation and its feedback on the transport.

In the mass flux formulation, the surface of the grid is divided into two fractions. The fraction σ_u is supposed to be covered by the convective updrafts and the rest of the grid, $(1-\sigma_u)$ is covered by the environment of the updrafts. The sub-grid transport term on the RHS of equation 2 can then be expressed as :

$$-\overline{\rho w'\psi'} = -[\sigma_u\rho(w_u-\overline{w})(\psi_u-\overline{\psi})] - [(1-\sigma_u)\rho(w_e-\overline{w})(\psi_e-\overline{\psi})] \tag{3}$$

$w_{u/e}$ are the mean vertical velocities in the updraft/environment fractions and $\psi_{u/e}$ are the mean values of the variable ψ on the updraft/environment fractions. According to the Reynold decomposition, the mean of the fluctuation is zero, for instance:

$$\overline{w'} = \overline{(\sigma_u(w_u-\overline{w})+(1-\sigma_u)(w_e-\overline{w}))} = 0$$

which is equivalent to:

$$\overline{w} = \sigma_u w_u + (1-\sigma_u)w_e \tag{4}$$

In most conventional convection schemes, it is supposed that the updraft fraction is very small compared to the size of the grid box ($\sigma_u << 1$). The second term on the RHS of expression 3 is then neglected, and the sub-grid transport simplifies to :

$$-\overline{\rho w'\psi'} = -[\sigma_u\rho(w_u-\overline{w})(\psi_u-\overline{\psi})]$$

Once this approximation is done, the very small fraction of updraft does not directly contributes to the mean values of the grid box unlike what is suggested by equation 4. It is rather considered as an "external" mechanism which takes some input from the mean "resolved" state and returns the mean effects of the sub-grid processes on the mean "resolved" state which is also supposed to be the environment of the updraft.

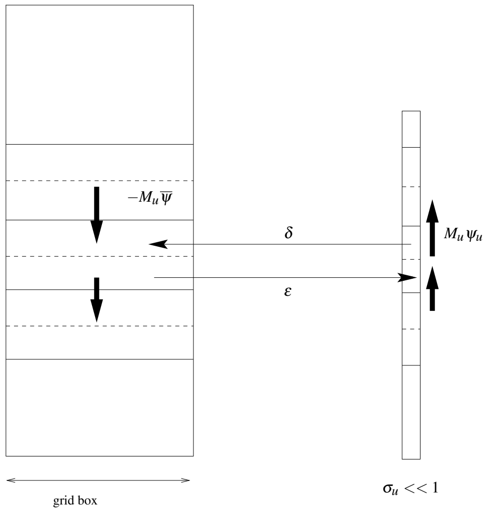

Figure 9: Schematic representation of the conventional mass flux approach.

Most parametrisations go even further in the approximations as it is usually supposed that $w_u >> \overline{w}$ and the mass flux transport is then written as:

$$\overline{\rho\Psi}_{conv} = -\overline{\rho w'\psi'} = -[\overbrace{(\sigma_u\rho w_u)}^{M_u}(\psi_u - \overline{\psi})] \tag{5}$$

where $M_u = \sigma_u\rho w_u$ is the mean convective *mass flux* across a section of the vertical column.

When applied to mass transport, ψ is the mass per unit mass, then $\psi = \overline{\psi} = \psi_u = 1$ and $\psi' = 0$. According to equation 5, there is no mean sub-grid transport of mass by the convection scheme which means that, in each grid box, the buoyant air which is lifted to the grid box above with the thermodynamics characteristics of the updraft is immediately replaced by exactly the same amount of subsiding air coming from above but with the thermodynamics characteristics of the mean atmospheric state above (figure 9). The hydrostatic pressure inside the grid boxes is not changing but the temperature is changing, so is the density, i.e. the volume occupied by the same amount of air. In practice, in an hydrostatic model, the geopotential of the pressure levels will change.

In most convection schemes, the exchanges between the "external" deep convective cloud and the grid box are given by vertical profiles of entrainment of air from the grid box (environment) into the updraft and detrainment of air from the updraft toward the grid box. The mass of the convective flux is then changing along the vertical thanks to entrainment of environmental air (air "from the model grid" integrated into the updraft) and detrainment of updraft air toward the environment (figure 9):

$$M_u = \varepsilon_u - \delta_u$$

$$M_u\psi_u = \varepsilon_u\overline{\psi} - \delta_u\psi_u$$

The rate of change of variable $\overline{\psi}$ due to convective mixing is then computed as the rate of change due to exchanges with the updraft plus the mixing due to the compensating subsiding mass flux:

$$\overline{\Psi}_{conv} = -\overline{\rho w'\psi'} = \underbrace{-\varepsilon_u\overline{\psi} + \delta_u\psi_u}_{-(M_u\psi_u)} - (-M_u\overline{\psi}) \tag{6}$$

A convection scheme is much more complex than just a vertical transport. But this simple development shows well some of the main hypotheses done in most convection schemes:

- the area fraction of the “composite” single updraft is very small compared to the size of the grid.
- as a consequence of the first assumption, the mean grid box variables are not any more the area weighted average between the updraft state and the state of its environment, they are the environment.
- the vertical velocity of the composite updraft is treated as a “perturbation” of vertical velocity with respect to the vertical mean flow ($\overline{w}$ is then implicitely supposed to be zero).
- the mass flux does not modify the mass inside a grid box (no convection tendency on the continuity equation). The updraft mass flux is always compensated by a subsiding flux of the same mass but of air with the thermodynamics properties of the mean grid scale state instead of the properties of the buoyant updraft.
- the mean flow is supposed stationary when the updraft is built up from the surface (this is part of the well know “quasi-equilibrium” assumption of Arakawa and Shubert (1974) and both the updraft, the precipitation and the compensating subsidence happens in a single column (no interaction between the wind shear and the updraft for example).

Other assumptions related to the microphysics and its interaction with the updraft and mean flows should also be analysed, but this would go father than the simple didactic scope of this paper. In the next sections, we present some proposals which are aimed to generalise the conventional mass flux formulation used in most deep convection schemes.

3.2 How to release hypotheses in the mass flux formulation for the grey zone of convection

3.2.1 Sharing the mass transport between dynamics and physics?

We have seen in the previous section that in the mass flux formulation used by most deep convection schemes, the sub-grid transport is composed of two fluxes, a convective buoyant updraft mass flux M_u and a compensating subsiding mass flux $-M_u$, both occurring in the same vertical column. As the resolution increases, the hypothesis that the updraft fraction is small compared to the grid size will become less and less valid. But the conceptual model where the compensating subsidence happen in the same single column than the updraft has to be revisited even earlier as the compensating subsidence occurs at a scale much larger than the scale of the convective updraft .

Kuell et al (2007) designed a new mass flux scheme, HYMACS, such that the sub-grid transport in the convection scheme includes only the updraft part of the convective mixing. The compensating subsidence is not parametrised by the convection scheme and then should be taken care of by the dynamics in order to fulfil mass conservation (figure 10). In such a case, the physics does a net transport of mass which has to be integrated as a sub-grid transport into the continuity equation:

$$(\rho)_{)conv} = -M_u = -\varepsilon_u + \delta_u \tag{7}$$

For a variable ψ, the convective transport in the HYMACS approach is given by:

$$(\rho\psi)_{)conv} = -(M_u\psi_u) = -\varepsilon_u\overline{\psi} + \delta_u\psi_u$$

Note that, in this case, the sub-grid transport is not derived from a Reynold formulation anymore ($\overline{w'} \neq 0$).

The implementation of this kind of formulation is not trivial in a model like the IFS with a mass vertical coordinate (vertical coordinate derived from the hydrostatic pressure) and a vertically integrated continuity equation for the surface pressure.

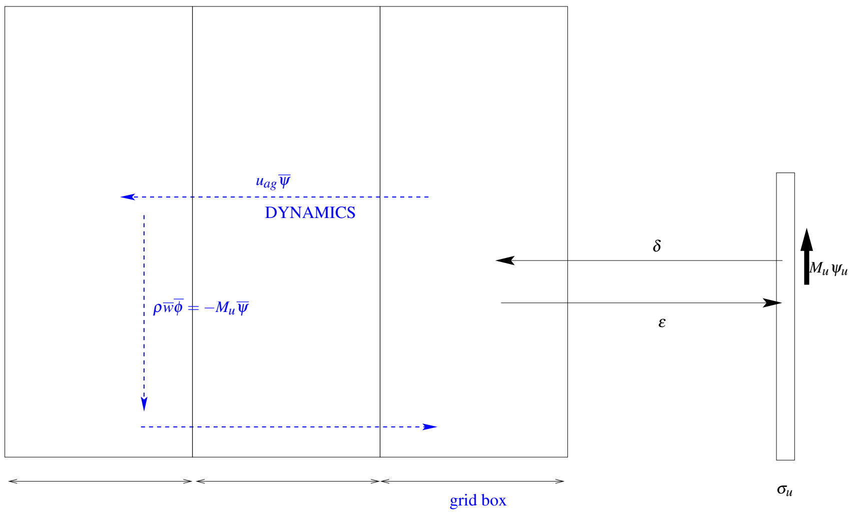

Figure 10: Schematic representation of the HYMACS approach.

Kuell et al (2007) met a similar problem when they implemented their idea in the Lokal modell. They then proposed to project the sub-grid ρ tendency (equation 7) onto adiabatic tendencies of temperature and pressure of the fully compressible equations using the gas law $\rho = p/(RT)$:

$$\left.\begin{array}{lll} T)_{conv} & = & c_v \frac{(RT)^2}{p} \rho)_{conv} \\ p)_{conv} & = & \frac{c_p}{c_v} RT \rho)_{conv} \end{array}\right\} \theta)_{conv} = 0 \tag{8}$$

In the non-hydrostatic IFS, the projection of the ρ tendency has to be done on the prognostic variable of the compressible model $\ln(p/\pi)$ where p is the true pressure and π is the hydrostatic pressure:

$$\Rightarrow (\ln(p/\pi)) = -\frac{c_p}{c_v} D_3 - \frac{\omega}{\pi} + pp)_{conv}$$

where $\omega = \pi$.

Academic tests have been set up in the IFS as proposed in Kuell et al (2007). But unlike what is shown for the lokal modell, the non-hydrostatic IFS dynamics does not understand the parametrised density tendency projected on T and $p - \pi$ as an effective mass transport. The IFS dynamics interprets it as an elastic shock and the numerics very quickly brings back the state of the atmosphere towards a resting balanced state without generating any compensating large scale circulation. In order to parametrise a net mass transport in the IFS, the physics would need to provide a tendency for the hydrostatic pressure, i.e. for the diagnostic computation of $\omega = \pi$. This is a delicate operation which needs a careful implementation as the stability of the numerics may be deteriorated (see for example Wedi and Cullen, 2001 for a similar experimentation). In fact, when the continuity equation if modified, the whole system of equations of the IFS should be carefully revisited as, for consistency, most equations should then see the parametrized net sub-grid mass transport (see the list of most useful advices in Yano, 2013).

3.2.2 Re-integrate the sub-grid updraft inside the grid box

The recent paper of Arakawa and Wu (2013) is also revisiting the traditional hypotheses done on the mass flux formulation used in most convection scheme with the perspective of the transition from parametrised to resolved convection. One of the main consequences of coming back to a less approximated mass flux form equation would be to re-integrate the updraft into the definition of the mean model parameters as originally express by equation 4 for instance (figure 11).

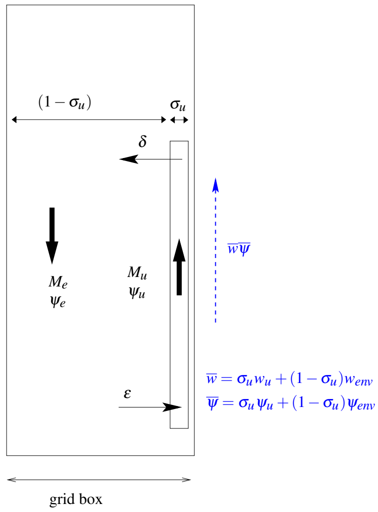

Figure 11: In the original formulation of the mass flux formulation derived from the Reynolds decomposition, the updraft is part of the model mean state.

The same type of reflexion started about 10 years ago in the LAM community. Different approaches have been proposed and coupled with the LAM version of the IFS dynamics called ALADIN. The 3MT approach has been developed for several years in the “ALARO” model (Gerard et al, 2009). More recently, Gerard (2012) presented an other formulation of this idea in which the convection scheme is designed to be only a complement of the convective adjustment already done by the non parametrised equations (CSD: Complement of Resolved Updraft).

Work along this line is in progress and may help the community along its journey through the grey zone of convection.

4 Conclusion

Computer ressources are now such that global models can be run in research mode with grid meshes around 5 km. It may be still more than 10 years before global operational models can reach such a high resolution, but evaluation of the current systems has started in this range of resolutions where the scale separation between the resolved flow and the convective circulations becomes fuzzy.

The limit of the hydrostatic approximation in the IFS has been investigated with a series of academic convective cases. These simulations show that the hydrostatic approximation usually holds very well until resolutions around 2-3 km. At higher resolution, the hydrostatic model produces too large vertical velocities and the response of the convection in term of gravity waves becomes quite different in the hydrostatic and non-hydrostatic models. But for resolutions around 5 km, the hydrostatic model is perfectly able to produce diagnostic vertical velocities which are permitting buoyant non-parametrized convective updrafts very similar to the ones simulated by the non-hydrostatic version of the model.

At resolutions around 5 km, several LAM models showed however that explicit simulations of convection (deep convection scheme swithed off) produce irrealistic convective structures with exagerated precipitation rates and very intense density currents. On the other hand, academic simulation of MCS with the IFS and LAM simulations of organized mesoscale systems in the tropics (see for instance Beucher et al, 2013 for simulations during the AMMA period) benefit from the explicit simulation of convection at 5-3 km resolutions. In this range of resolutions, the traditional hypotheses done in the deep convection parametrizations actually reach their limit as the mean effect of convection cannot be represented by a statistical representation of clouds whose total cloud fraction remains much smaller than the grid area. The single column representation of convective circulation in the parametrizations and the quasi-equilibrium hypothesis do not allow the key interaction between the convective circulation and the mean flow which produces the mesoscale circulations which are characteristic of squall lines and other mesoscale convective systems.

Some attempts to revisit the mass flux scheme often used in convection schemes have started mainly in the LAM community more than 10 years ago. At resolutions where convection becomes partly resolved partly parametrized, a common effort from both the parametrisation community and the dynamical core developers is necessary to get a better understanding of the interaction between the convective updrafts and their environment and between the physics and the dynamics of numerical models. Such an effort will hopefully accelerate the design of a next generation of convection parametrizations which will be more suitable for the grey zone of convection.

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