# Physics/Dynamics coupling at very high resolution

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Numerical Aspects at ECMWF

September 3, 2013

Increasing resolution in global model
$\Rightarrow$ towards global Convection Resolving Model (CRM)

# Outline

1. Convection-permitting models ?
2. Resolved/subgrid transports

# The basic mechanism of convection

## Convective cloud for dummies

[warming - positive buoyancy- ascent - adiabatic cooling] - condensation/ latent heat release - warming - positive buoyancy - ascent - adiabatic cooling - condensation/ latent heat release - warming - positive buoyancy - ascent etc....

## Non-parametrised moist convection in a numerical model,

- adiabatic cooling in the dynamics "forces" the condensation scheme
- warming by latent heat release "forces" the vertical motion (diagnostic or prognostic) in the dynamics
- $\rightarrow$ the process of non-parametrised moist convection exists thanks to an interaction between physics and dynamics

# What is a convection-permitting model?

A lot of titles in today's programme contain "convection-permitting".

What does "permit convection" mean?
What is needed to permit convection?

Does the current IFS permit convection?
Do we need a non-hydrostatic dynamical core to permit convection?
Anything else?

# H and NH

**Limit of validity of hydrostatic assumption?**

$$\mathcal{H}/\mathcal{L} << 1$$

But what are $\mathcal{H}$ and $\mathcal{L}$? Can we learn something about the limit in term of $\delta x$, $\delta z$ and $\delta t$?
One proposal : If $\mathcal{H} = 10$ km (height of tropopause), then H valid for $\mathcal{L} >> 10$ km.
Following what Nils said yesterday, the IFS "resolves" 8 to $4\delta x$ $\rightarrow$ H valid for $\delta x >> 1.25$ to 2.5 km.

**Let's check...**

LNHDYN=.true./.false. in the IFS (everything else the same, so H is not exactly the operational setting)

# H and NH "Permitted" Dry Convection

Series of warm bubble simulations at different resolutions with both H and NH IFS.

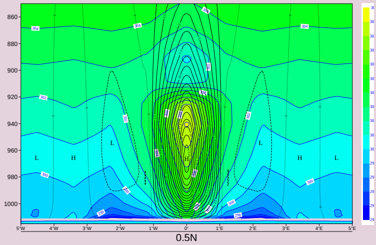
- small planet
- T159, L91
- $\gamma$ from 12 ($\Delta x = 10$ km) to 250 ($\Delta x = 0.5$ km)

Heating with a constant rate of 0.1 K/s for 5 min in one single grid box near the surface.

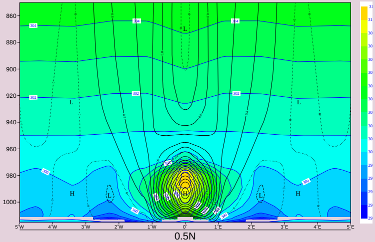
# $\Delta x = 0.5$ km, $\Delta t = 10$ s

## after 8 min of simulation, $\theta$ and $w$

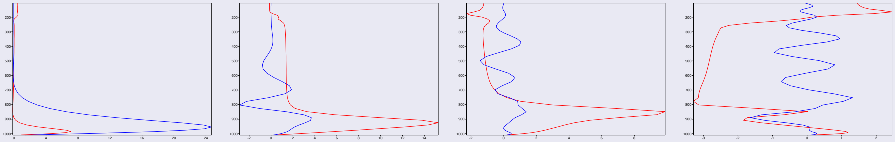
### Hydro




### NH



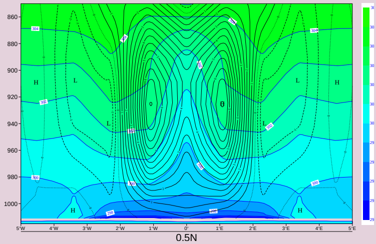

## $w$ for H(blue)/NH(red) after 8, 10,12 and 14 min



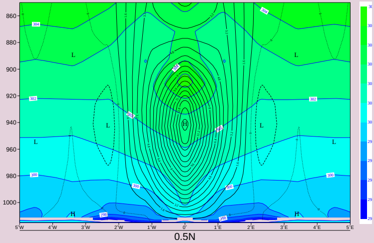
# $\Delta x = 0.5$ km, $\Delta t = 10$ s

## after 10 min of simulation, $\theta$ and $w$

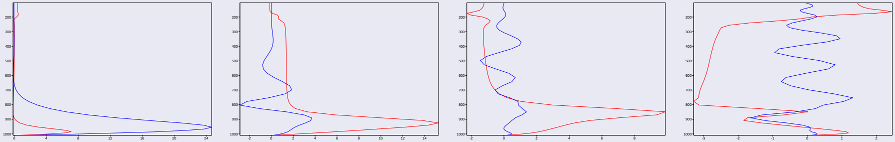
### Hydro




### NH



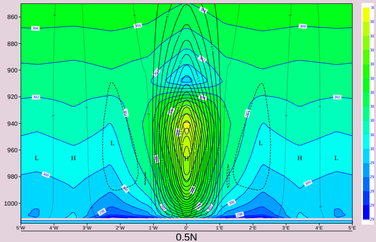

## $w$ for H(blue)/NH(red) after 8, 10, 12 and 14 min



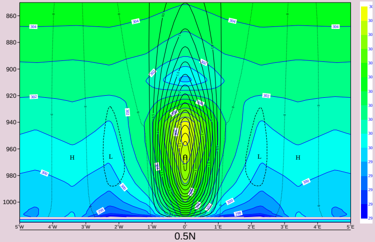
# $\Delta x = 2.5$ km, $\Delta t = 60$ s

## after 30 min of simulation, $\theta$ and $w$

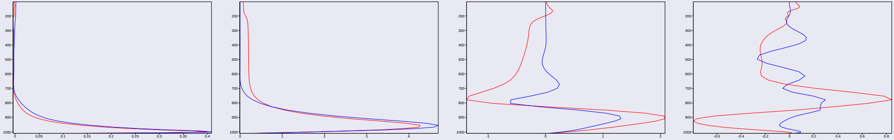
### Hydro




### NH



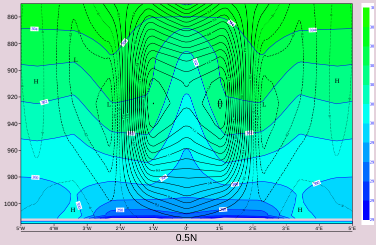

## $w$ for H(blue)/NH(red) after 20, 30, 40 and 50 min



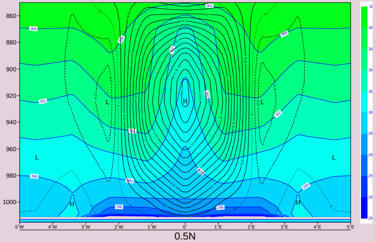
# $\Delta x = 2.5$ km, $\Delta t = 60$ s

## after 40 min of simulation, $\theta$ and $w$

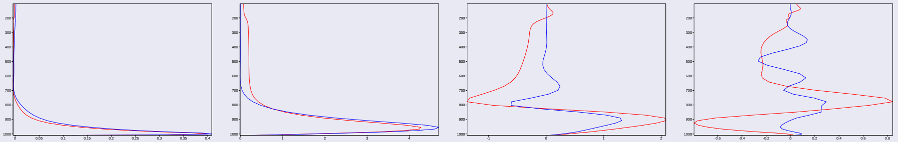
### Hydro



### NH



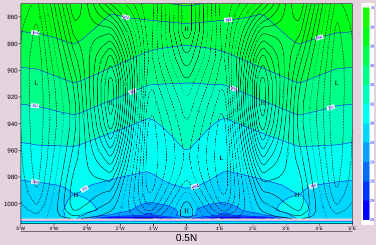
## $w$ for H(blue)/NH(red) after 20, 30, 40 and 50 min



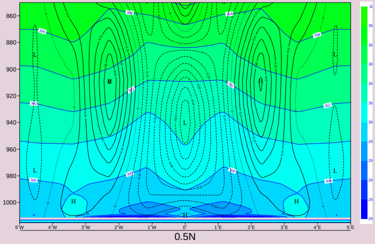
# $\Delta x = 2.5$ km, $\Delta t = 60$ s

## after 50 min of simulation, $\theta$ and $w$

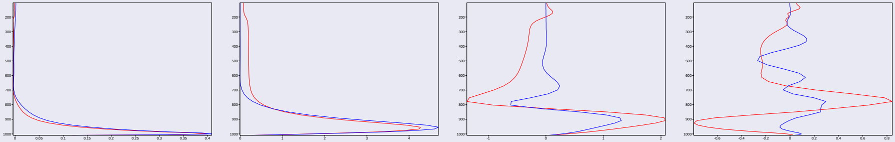
### Hydro




### NH



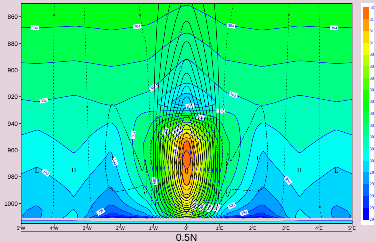

## $w$ for H(blue)/NH(red) after 20, 30, 40 and 50 min



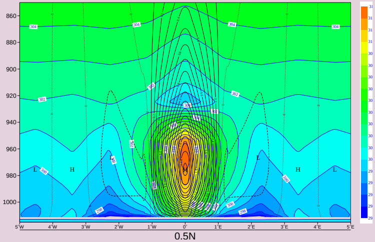
# $\Delta x = 5$ km, $\Delta t = 120$ s

## after 50 min of simulation, $\theta$ and $w$

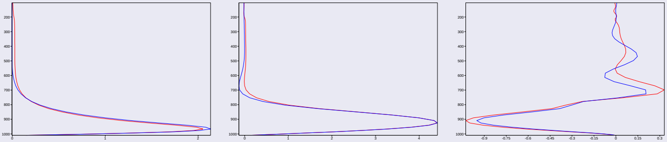
### Hydro




### NH



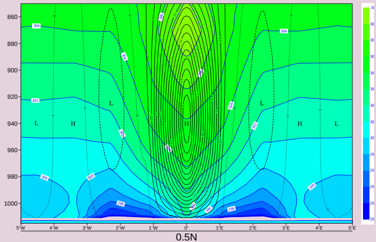

## $w$ for H(blue)/NH(red) after 50, 60 and 80 min



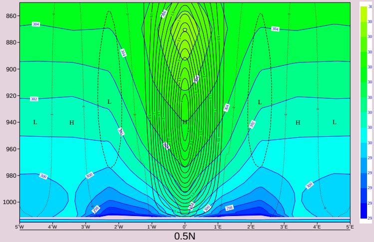
# $\Delta x = 5$ km, $\Delta t = 120$ s

## after 60 min of simulation, $\theta$ and $w$

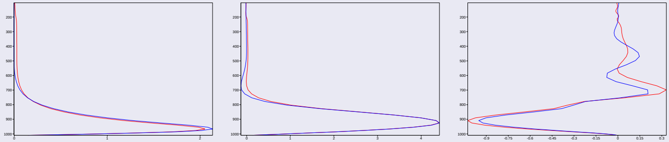
### Hydro




### NH



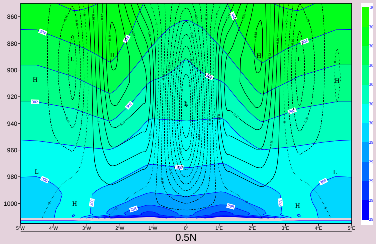

## $w$ for H(blue)/NH(red) after 50, 60 and 80 min



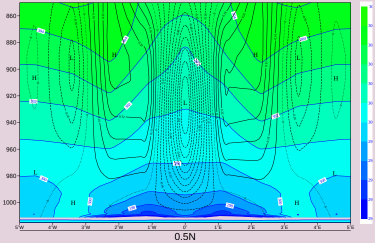
# $\Delta x = 5$ km, $\Delta t = 120$ s

## after 80 min of simulation, $\theta$ and $w$

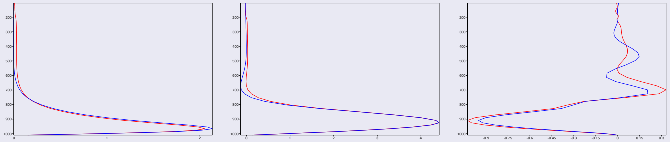
### Hydro




### NH



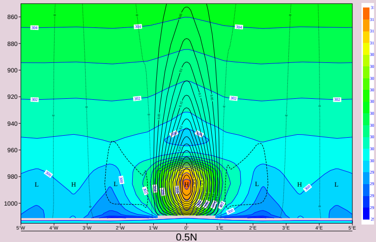

## $w$ for H(blue)/NH(red) after 50, 60 and 80 min



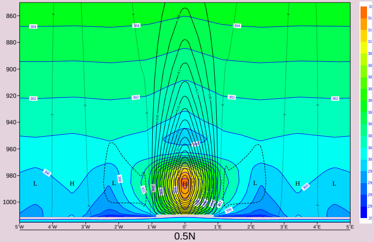
# $\Delta x = 10$ km, $\Delta t = 300$ s

## after 100 min of simulation, $\theta$ and $w$

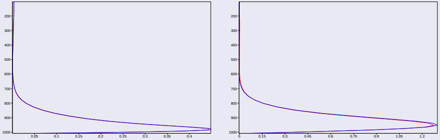
### Hydro




### NH



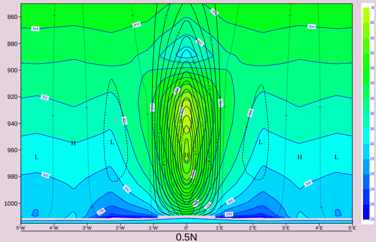

## $w$ for H(blue)/NH(red) after 100, 120 min



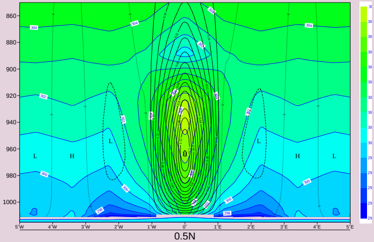
# $\Delta x = 10$ km, $\Delta t = 300$ s

## after 120 min of simulation, $\theta$ and $w$

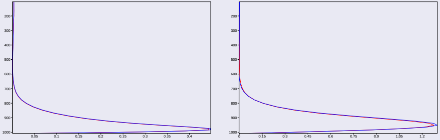
### Hydro




### NH




## $w$ for H(blue)/NH(red) after 100, 120 min



# "Permitting" dry convection?

Buoyancy driven ascents are permitted in the hydrostatic model, even at sub-kilometric resolution. As the vertical momentum equation is not a prognostic equation in the H model, the convection is directly driven by the horizontal pressure gradient force and the mass continuity ($w_H$ is diagnostic $\rightarrow w_H \neq 0$ and $Dw_H/Dt \neq 0$)

## BUT

- Hydrostatic model produces too strong and fast acceleration at very high resolution (higher than about 2 km ?). The gravity waves produced in the dissipation phase are also quite different in both models.
- For lower resolutions, H and NH models give very similar simulations of shallow dry ascents and of their dissipation with gravity wave generation.

# Sensitivity of small scale free convection with respect to numerics

## SETTLS or ICI for the non-linear residual in the RHS

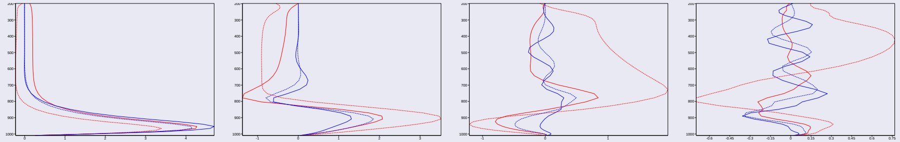
$$\mathcal{N}_{M,t+\Delta t/2} = \frac{1}{2}\left(\mathcal{N}_{D,t} + \underbrace{\mathcal{N}_{A,t+\Delta t}}_{???}\right)$$

$\mathcal{N}_{A,t+\Delta t}$ is not part of the semi-implicit formulation.

It has to be estimated with an extrapolation of the evolution between the 2 previous time steps (SETTLS) or thanks to an iteration (ICI).

## $w$ for H(blue)/NH(red) after 30, 40, 50 and 60 min

$\Delta x = 2.5$ km, $\Delta t = 60$ s Solid line with ICI, dashed line with SETTLS



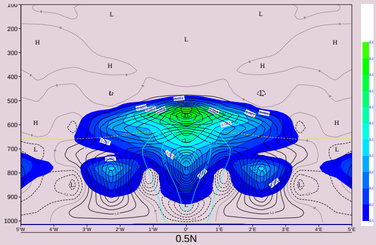
But "convection permitting" is probably anyway more referring to deep convective clouds...

Then, let's add the "resolved cloud scheme" of the IFS physics package (LEPCLD=true) to the IFS dynamics (H or NH).

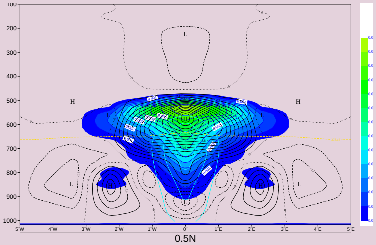
# H versus NH deep cloudy bubbles

$\boxed{\Delta x = 2.5 \text{ km}}$, after 40 min, $q_l$, $w$, iso-0°C

## Hydro



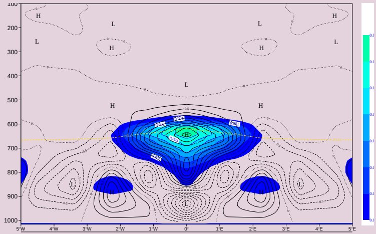

## NH



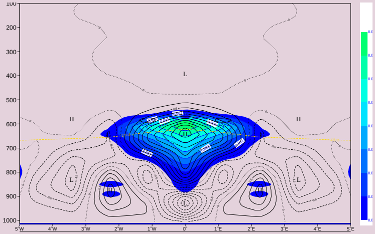
# H versus NH deep cloudy bubbles

## $\boxed{\Delta x = 5 \text{ km}}$, after 35 min, $q_l$, $w$, iso-0°C

### Hydro



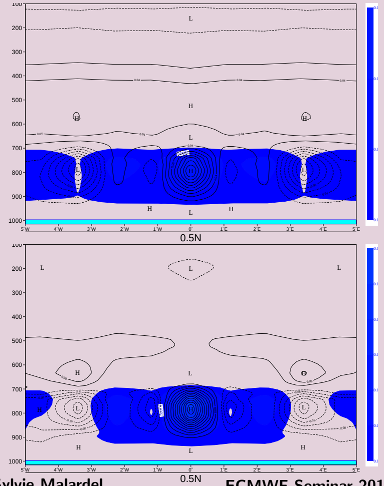

### NH



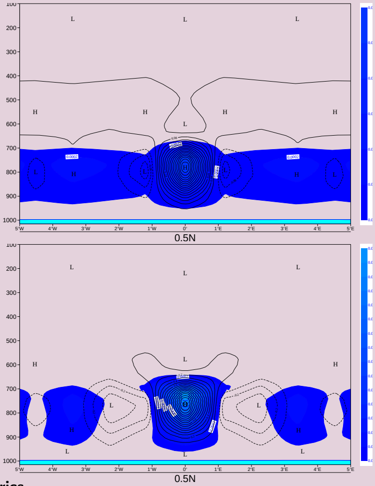
# H versus NH cloudy bubbles embedded in stratiform clouds

## $\boxed{\Delta x = 5 \text{ km}}$, after 35 and 40 min, $q_l$, $w$

### Hydro



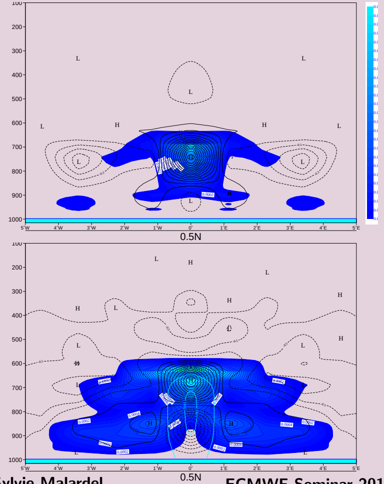

### NH



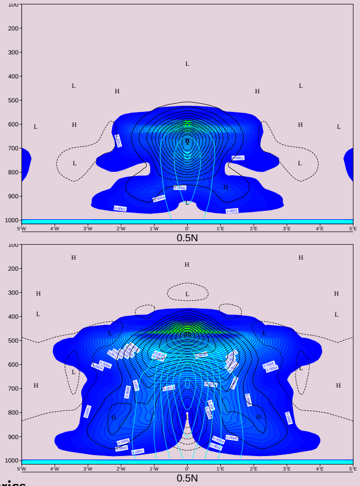
# H versus NH cloudy bubbles embedded in stratiform clouds

## $\boxed{\Delta x = 5 \text{ km}}$, after 50 and 60 min, $q_l$, $w$

### Hydro



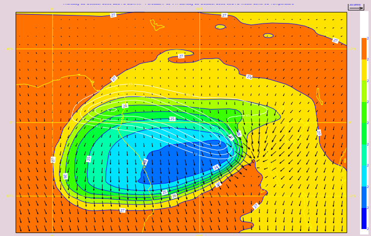

### NH



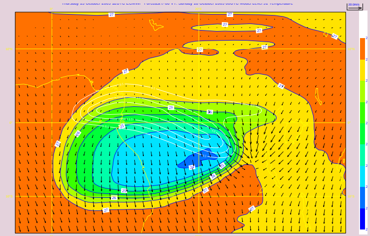
# H versus NH splitting storms (Weisman and Klemp, 1984)

## $\boxed{\Delta x = 5 \text{ km}}$, $T_s$, wind$_s$, LSP

### Hydro



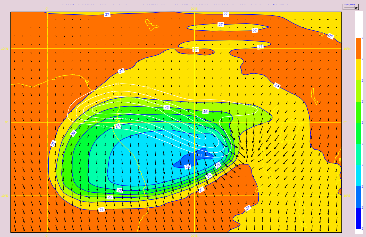
### NH



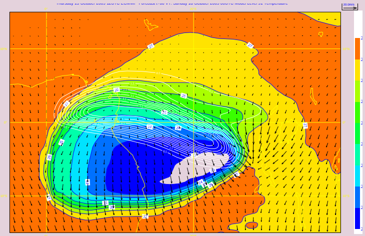
# NH splitting storms: sensitivity to autoconversion rate

## $\boxed{\Delta x = 5\ \text{km}}$, $T_s$, wind$_s$, LSP

### $\tau = 6000s$ as in oper IFS



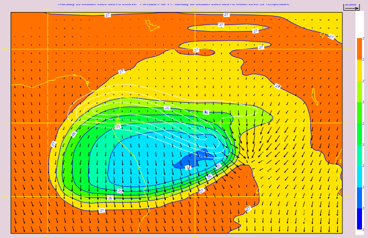
### $\tau = 1000s$ as for most CRM



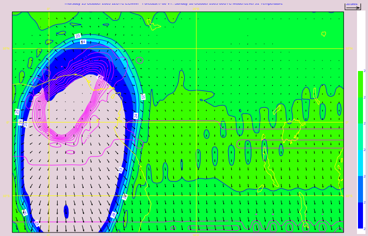
# NH splitting storms with convection scheme off/on

$\boxed{\Delta x = 5 \text{ km}}$, $T_s$, $\text{wind}_s$, LSP/CP

**off**



**on**



# Permitting moist deep convection?

- The IFS hydrostatic dynamics + the IFS prognostic cloud scheme permit deep moist convective ascent (and descent) at high resolution.
- The tuning of the microphysics may change the solution as much as H versus NH.
- There may be conditions where the more realistic description by a NH system of the environment of convective cells is of importance, even for resolution around 5 km.

Are these sensitivities a problem of predictability of convection? Are both H and NH solutions two possible occurrences or is the H model really "deficient"?

# Is a convection permitting model a model without convection schemes?

When the convection scheme is on, the interactive process between the dynamics and the latent heat release which permit "resolved" convection does not happen anymore. As expected, the convection scheme "solves" the process as a subgrid process. But the solution is very different from what is given when the convection scheme is off.
At resolution where grid boxes may "realistically" be buoyant, the non-parametrised convective feedback and the parametrisation scheme are "fighting"!
But, in the grey zone of convection, we would need them to "complement" each other.

# Outline

# Mass flux approach

## Reynolds decomposition

$$\overline{\rho}\frac{D\overline{\psi}}{Dt} = \mathcal{S}_{dyn} - \frac{\partial\overline{\rho w'\psi'}}{\partial z} + \mathcal{S}_{phys}$$

## updraft/environment

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

## $\sigma_u << 1 \rightarrow$ environment $\simeq$ grid box mean

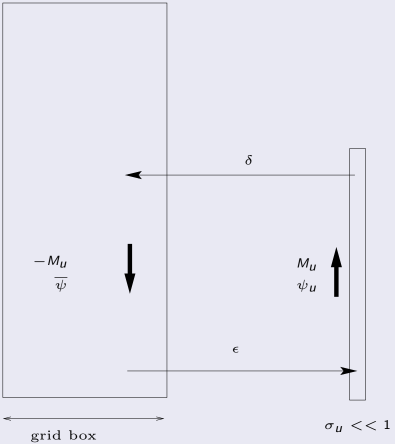
$$-\frac{\partial\overline{\rho w'\psi'}}{\partial z} = -\frac{\partial[\sigma_u\rho(w_u-\overline{w})(\psi_u-\overline{\psi})]}{\partial z}$$

## $w_u >> \overline{w}$

$$-\frac{\partial\overline{\rho w'\psi'}}{\partial z} = -\frac{\partial[\overbrace{(\sigma_u\rho w_u)}^{M_u}(\psi_u-\overline{\psi})]}{\partial z}$$

# Mass flux approach

## Conventional mass flux approach in a graph



# How to generalise the mass flux approach for the grey zone of convection? (1)

## Net advection inside the physics: HYMACS (Kuell, Gassmann and Bott, 2007)

$$\frac{\partial(\rho\psi)}{\partial t})_{conv} = -\frac{\partial(M_u\psi_u)}{\partial z} = -\epsilon_u\overline{\psi} + \delta_u\psi_u$$

The compensating subsidence is not parametrised by the convection scheme $\Rightarrow$ the dynamics is expected to close the budget of $\psi$?

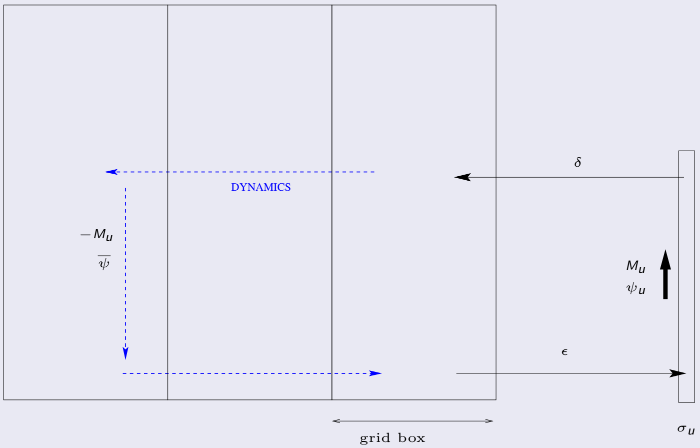
## HYMACS continuity equation ($\psi = 1$)

$$\frac{\partial(\rho)}{\partial t})_{conv} = -\frac{\partial M_u}{\partial z} = -\epsilon_u + \delta_u$$

$$\Rightarrow \frac{D\rho}{Dt} = -\rho\vec{\nabla}.\vec{u} - \frac{\partial M_u}{\partial z}$$

# HYMACS

## HYMACS approach in a graph



# HYMACS mass transport

## Projection of an adiabatic $\rho$ tendencies onto $T$ and $p$ (or $p-\pi$)

$$\frac{\partial T}{\partial t})_{conv} = \frac{1}{c_v}\frac{(RT)^2}{p}\frac{\partial \rho}{\partial t})_{conv}$$

$$\frac{\partial p}{\partial t})_{conv} = \frac{c_p}{c_v} RT \frac{\partial \rho}{\partial t})_{conv}$$

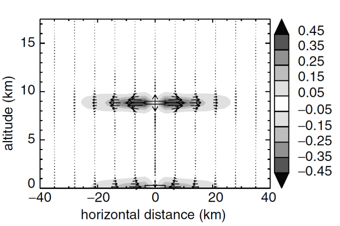
$$\rightarrow \frac{\partial \theta}{\partial t})_{conv} = 0$$

$$\Rightarrow \frac{D(\ln(p/\pi))}{Dt} = -\frac{c_p}{c_v} D_3 - \frac{\omega}{\pi} + \frac{1}{p}\frac{\partial p}{\partial t})_{conv}$$

## Results in the Lokal Model

from Kuell et al, 2007

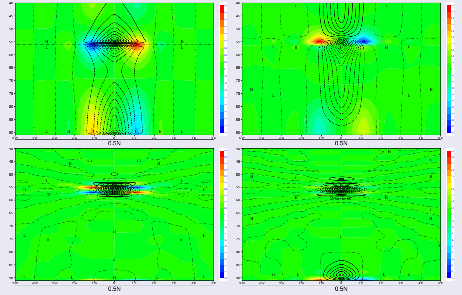
after 30 min of simulation



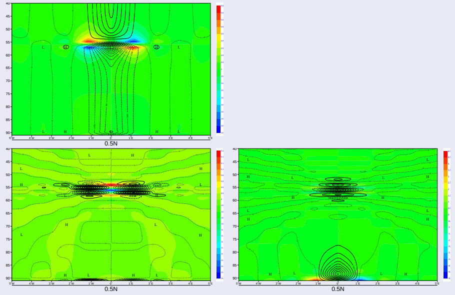
# HYMACS mass transport in the IFS

$u$ (shading) and $w$ (isolines)
after (12 s), 120 s, 30 min, 1 hour of simulation

## $\delta t = 12$ s



## $\delta t = 120$ s



# HYMACS in the IFS?

## "My" interpretation

$\rho$ tendencies projected on $T$ and $p - \pi$ are understood as elastic chocks by the dynamics (which are not "resolved" by the semi-implicit for long time steps) but not as an effective mass transport along the column.
*elastic* : "internal" work of pressure force, without moving the gravity centre of the grid boxes

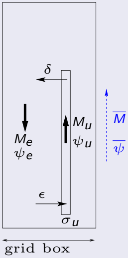
- can we allow the physics to "move" mass? And if yes, how to do it in practice (change $\pi$, $\omega$???)
- and if we manage to change $\rho$ along a convective column, won't we generate buoyancy flows locally?
- isn't it inconsistent to transport $s = cpT + \phi$ as a conservative variable in the cloud model (instantaneous adjustment to (hydrostatic) pressure) but later compute a tendency for $p$?

# How to generalise the mass flux approach for the grey zone of convection? (2)

## Re-integrate the subgrid updraft/downdraft into the grid box

- Arakawa and Wu, 2013
- Aladin community around L. Gerard (CSD: Complement of Resolved Updraft), J.M. Piriou and J.F. Geleyn (3MT)

## In a graph...




$$\overline{M} = \sigma_u M_u + (1-\sigma_u) M_e$$

$$\overline{\psi} = \sigma_u \psi_u + (1-\sigma_u) \psi_e$$

## $\sigma \neq 0$, $\overline{\psi} \neq \psi_e$, $\overline{w} \neq 0$

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

# Summary

What do we really need in the NH? (imagine that we want to parametrise the NH effects, what effects shall we parametrise?)

We need accurate and efficient convection permitting dynamics, but we also need a convection permitting physics (and a consistent interface between them...)

## In the grey zone of convection

- Better understand interactions between dynamics and the parametrisations and between the parametrisations themselves (what is forcing what?)
- Check the consistency between all the different "mono-process" (or small group of processes, i.e. dynamics, ED+MF) implicit solvers? (dream: include linear physics into the TL-SI mentionned by Pierre yesterday!)

# Summary

## For global medium range very high resolution NWP

- revise some (sometime forgotten or hidden) hypotheses made in the physics-dynamics interaction and in the parametrisation themselves to go towards a global CRM,
- use the new degrees of freedom (NH fully compressible, no convection scheme ...) with care,
- should not forget the "large scale" knowledge and check that we still have the large scale balances right when averaging the high resolution results (for ex: convection-radiation balance)