Physics/Dynamics coupling

Sylvie Malardel

ECMWF

November 8, 2010

Coupling between Physics and Dynamics for "convection permitting" models

The explicit convection results from a complex feed-back between the buoyancy force (Dynamics) and the condensation/evaporation (Physics).

Dynamical cores and Physical packages are often developed quite independently.

- The role of the physics/dynamics interface is to connect both parts in order to restore the main processes described by the complete set of equations at the time and space resolutions of the model.
- The resulting system should in particular assure the conservation of mass, momentum and energy.

Coupling between Physics and Dynamics

Why do we revisit the Phys/Dyn Interface in the context of the NH/"convection permitting" developments?

1. Equations
2. Characteristic Times of the processes with respect to the time step
3. Conservations

1- Equations

- Dynamics/Physics splitting
  - cause/effect or forcing/response (adiabatic cooling/condensation) : impact on the design of the parametrization?
  - separate implicit solvers, with the physics "in the middle" of the semi-implicit?
  - what about the physics in the predictor/corrector scheme?
  - coherence between the dynamics and the physics
- Multiphasic precipitating system (J.F. Geleyn's talk)
  - $p = \rho R_h T = \rho R_d T_v$: need to know which part of the total mass is gas
  - c_{p_h}, c_{v_h} ?
  - resolved buoyancy/latent heat release/water loading
  - mass, energy and momentum transports by precipitation

2- Characteristic times versus smaller time steps

Resolved/sub-time step

- slow or fast with respect to the time step?
- new processes becomes important (prognostic microphysics)
- change of "philosophy" of a parametrization ("resolved" condensation)

- parallel/sequential (order of the processes)
- explicit/implicit treatment (common implicit solver)
- adjustment to saturation : where, how many time etc?
- physics adveraged along the SL trajectories
- phys/dyn+si_1/si_2 or dyn+si_1/phys/si_2? (and PC?)

3- Conservations

- global $\rightarrow$ local conservation
- conservative parameters
  - essential in the parametrization of subgrid mixing processes (J.F.'s talk)
  - but what about the re-projection onto the prognostic variables of the dynamics?
  - usefull in the dynamics (advection)?

Coherence between the equations in the Dynamics and the tendencies from the physics

Dynamics

- Internal energy form (NH IFS) :

$$\frac{DT}{Dt} + \underbrace{\frac{1}{c_v} RTD_3}_{e-\text{conversion term}} = 0$$

- Enthalpy form (hydro IFS) :

$$\frac{DT}{Dt} - \underbrace{\frac{1}{c_p} \frac{RT}{p} \frac{Dp}{Dt}}_{h-\text{conversion term}} = 0$$

Physics

$$\frac{\partial T}{\partial t}|_\varphi = \frac{Q}{c_p}$$

$$D_3 = \vec{\nabla}.\vec{u} = -\frac{1}{\rho}\frac{D\rho}{Dt}$$

Thermodynamics

If no change in the physics and in the interface :

$$\frac{DT}{Dt} + \boxed{\frac{RT}{c_v} D_3} = \frac{Q}{c_p}$$

$$\frac{D\hat{q}}{Dt} + \boxed{\frac{c_p}{c_v} D_3 + \frac{\dot{\pi}}{\pi}} = 0 \qquad \hat{q} = \ln(\frac{p}{\pi}) \qquad \left(\frac{Dp}{Dt} + \boxed{p \frac{c_p}{c_v} D_3} = 0 \right)$$

(equivalence with an anelastic approximation (Thurre et Laprise, 1992))

instead of

$$\frac{DT}{Dt} + \boxed{\frac{RT}{c_v} D_3} = \frac{Q}{c_v}$$

$$\frac{D\hat{q}}{Dt} + \boxed{\frac{c_p}{c_v} D_3 + \frac{\dot{\pi}}{\pi}} = \frac{Q}{c_v T} \qquad \left(\frac{Dp}{Dt} + \boxed{p \frac{c_p}{c_v} D_3} = \frac{pQ}{c_v T} \right)$$

Validation in the Hydrostatic Regime

One single 10 days forecast in T255

3 experiments

"Anelastic" coupling (default)

$$\begin{aligned} \frac{DT}{Dt} + \frac{RT}{c_v} D_3 &= \frac{Q}{c_p} \\ \frac{D\hat{q}}{Dt} + \frac{c_p}{c_v} D_3 + \frac{\dot{\pi}}{\pi} &= 0 \end{aligned}$$

Hydro

$$\frac{DT}{Dt} - \frac{RT}{c_p p} \frac{Dp}{Dt} = \frac{Q}{c_p}$$

and $p = \pi$ diagnosed following the hydrostatic balance

"Compressible" coupling

$$\begin{aligned} \frac{DT}{Dt} + \frac{RT}{c_v} D_3 &= \left[\frac{Q}{c_p} \right] * \frac{c_p}{c_v} \\ \frac{D\hat{q}}{Dt} + \frac{c_p}{c_v} D_3 + \frac{\dot{\pi}}{\pi} &= \left[\frac{Q}{c_p} \right] * \frac{1}{T} * \frac{c_p}{c_v} \end{aligned}$$

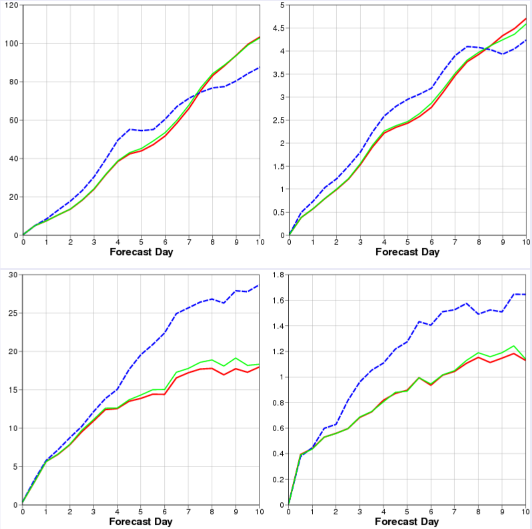
Validation in the Hydrostatic Regime

RMS "error" of geopotential (left) and temperature (right) in the NH (lat> 20^o, top) in the tropics (bottom).

Anelastic coupling : Red curve

Compressible coupling : Blue curve

hydro : Green curve



Validation in the Explicit Convection Regime

Academic experiments only

- Small Planet Testbed in the IFS (Wedi and Smolarkiewicz, 2009)
  - r=a/100 ($\simeq$ 63 km) , T159 $\Longrightarrow$ $\Delta x \simeq 1.3$ km
  - NH and dynamics setup from IFS
- Simplified parametrizations
  1. constant heating
  2. reversible adjustment to condensation

Constant heating near the surface

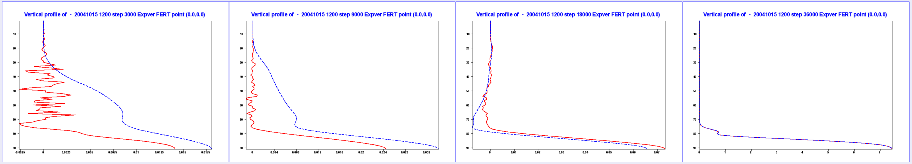
Well resolved "gaussian" heating (characteristic radius of 5km, 100m in the vertical) during 15 min.

Comparison between :

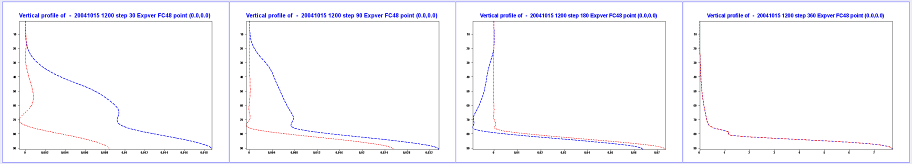
- Compressible coupling (red)
- Anelastic coupling (blue)
- Hydrostatic equations (cyan)

Constant heating near the surface

$dt = 0.1s$ PD after 5, 15, 30 and 60 minutes

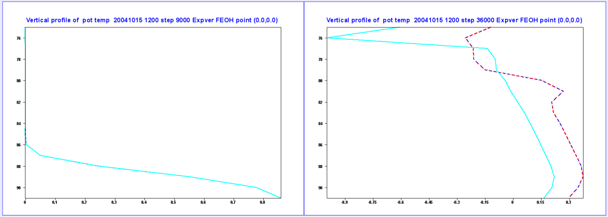


$dt = 10s$ PD after 5, 15, 30 and 60 minutes

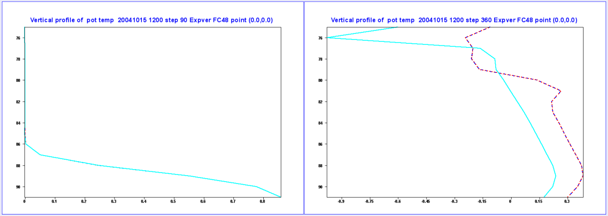


Constant heating near the surface

$dt = 0.1s$ $\theta - \theta_{t=0}$ after 15 and 60 minutes

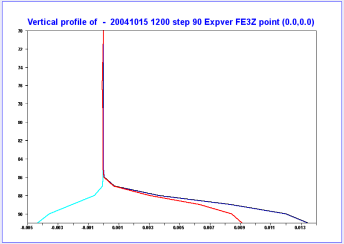


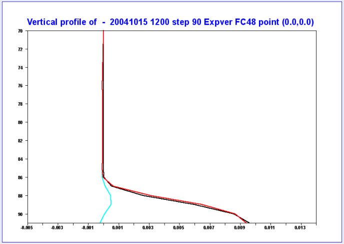
$dt = 10s$ $\theta - \theta_{t=0}$ after 15 and 60 minutes



Constant heating near the surface, $dt = 10s$

T-tendency from the dynamics (cyan), the physics (black) and the sum (red) at t=15 min for the "compressible" coupling (top) and the "anelastic" coupling (bottom)





Elastic Adjustment

Compressible coupling

$$\frac{DT}{Dt} = -\boxed{\frac{RT}{c_v}(\overline{D}_3 + \hat{D}_3)} + \frac{Q}{c_v}$$

$$\frac{D\hat{q}}{Dt} = -\boxed{\frac{c_p}{c_v}(\overline{D}_3 + \hat{D}_3) + \frac{\dot{\pi}}{\pi}} + \frac{Q}{c_v T}$$

$$\Rightarrow \hat{D}_3 = -\frac{c_v}{c_p}\frac{D\hat{q}}{Dt} = \frac{Q}{c_p T}$$

$$\Rightarrow -\frac{RT}{c_v}\hat{D}_3 = \frac{Q}{c_p} - \frac{Q}{c_v}$$

Anelastic coupling

$$\frac{DT}{Dt} = -\boxed{\frac{RT}{c_v}\overline{D}_3} + \frac{Q}{c_p}$$

$$\frac{D\hat{q}}{Dt} = -\boxed{\frac{c_p}{c_v}\overline{D}_3 + \frac{\dot{\pi}}{\pi}}$$

Reversible Adjustment to Saturation

An iterative procedure to find the thermodynamic equilibrium between the 3 water phases (q_v,q_l,q_i) and the temperature T

- guess for the condensates : $q_{cond} = q_{tot} - q_{sat}(T^*)$
- Adjustement of the mass of condensates : $\frac{\partial q_l^*}{\partial t} = q_l^* - q_{cond}$
- Update of the temperature, but how?

Condensation at constant p

$$\frac{\partial T^*}{\partial t} = \frac{1}{c_p}\left(L(T^*)\frac{\partial q_l^*}{\partial t}\right)$$

$$\frac{\partial \hat{q}}{\partial t} = 0$$

Condensation at constant v

$$\frac{\partial T^*}{\partial t} = \frac{1}{c_v}\left(L(T^*)\frac{\partial q_l^*}{\partial t}\right)$$

$$\frac{\partial \hat{q}}{\partial t} = \frac{\left(L(T^*)\frac{\partial q_l^*}{\partial t}\right)}{c_v T}$$

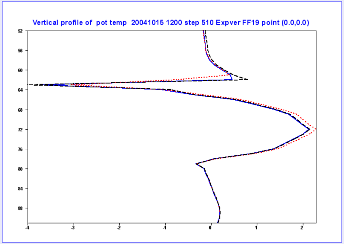
Adjustment to saturation

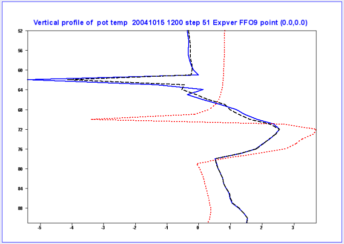
3 solutions

	Interface	Physics
Blue	Anelastic coupling	Adjustment at constant p
Red	Compressible coupling	Adjustment at constant p
Black	Compressible coupling	Adjustment at constant v

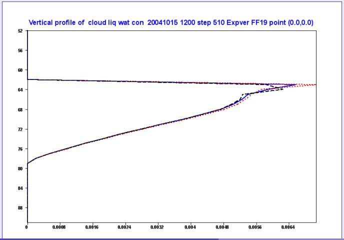
Adjustment to saturation

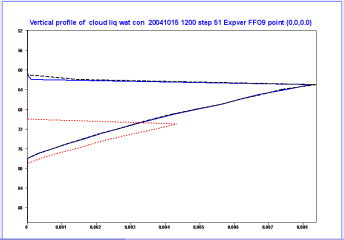
$\theta - \theta_{t=0}$, $dt = 10s$ (left) and $dt = 100s$ (right)





q_l (bottom), $dt = 10s$ (right) and $dt = 100s$ (left)





Adjustment to saturation

3 solutions

	Interface	Physics
Blue	Anelastic coupling	Adjustment at constant p
Red	Compressible coupling	Adjustment at constant p
Black	Compressible coupling	Adjustment at constant v

- With the "red" solution, the distribution between sensible and latent heats obtained in the adjustment at constant p is broken by the compressible phys/dyn interface and the projection on $\hat{q}$ is not able to compensate (non linearity in the physics, non conservation of moist entropy?)
- With the "blue" solution, it is implicitly supposed that the "elastic" part of the work of the pressure force has "already" been used to change the volume
- With the "black", solution the dynamics computes explicitly the evolution of volume (D_3)

Summary

- Thanks to a NH option, a prognostic microphysics and a "small planet" configuration, the IFS can be run in the "convection permitting" regime for idealized cases.
- Testbed to revisit hypotheses usually adopted for the physics/dynamics coupling in the IFS
  - "Anelastic coupling" if physics at constant pressure coupled with the NH dynamics without changing the interface.
  - For long time steps, T-tendencies computed at "constant pressure" in the physics can not be re-projected on the compressible equations in the phys/dyn interface.

- multiphasic equations (new microphysics)
- average along the SL trajectories
- conservative variables (static energy $c_p T + \phi$ in NH? re-projection onto non conservative variables?)