Physics/Dynamics interactions

Split approximations and coupling

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Outline

1 Model = Dynamics+Physics

2 Numerical models : time and space discretisations

3 The Physics/Dynamics Interface

Dynamics versus Physics

Dynamics

- The "resolved" part of the equations
- The "adiabatic" model
- The Meteorology as in "text books"....
- Dynamics = Mathematics and Numerics ?

Physics

- The mean subgrid effects
- The diabatism
- The water phase transitions
- one more difficulty : feedback between subgrid vertical motion and water phase change
- Parametrisation = "Fudging" ?

The Dynamics : the "resolved" processes but....

- The equations in the dynamics looks like the one in a text book, but they are NOT at the scale of the continuum.
- They are the result of an averaging process (time/space resolution of the model). They may also be supposed in "balance" (the time scale of the balance adjustment is then supposed to be much faster than the time step), for example in an hydrostatic model.
- The model variables contain some information about the scales (time and space resolution). For example, if the resolution is about 100 km, then the wind is not far from the geostrophic wind. If the resolution is 1 km, the wind may be very ageostrophic.
- What is "subgrid" or "unresolved" depends on the dynamics (equations and numerics) and of the resolution : for example, for resolution of a few km, we do not need a deep convection scheme.

Physics : the "parametrised" processes

- The parametrisations are little models which have their own hypotheses, own equations, own variables
- "Column" physics : no exchange between the columns ("Eulerian" approach)
- No net mass transport (no hydrostatic pressure tendencies)

- statistical approach (Reynolds decomposition)
- bulk model
- "stationarity" hypothesis
- simplified geometry

Physics/Dynamics Coupling

Model = Dynamics+Physics

Physics/Dynamics interactions

- the Dynamics "forces" the Physics : for example adiabatic cooling $\Rightarrow$ condenstation
- the Physics "forces" the Dynamics : for example latent heat release $\Rightarrow$ divergent circulations/vertical velocity ($\rightarrow$ adiabatic cooling)

Direct tendencies from physics

- diabatic heating (radiation)
- redistributes heat, moisture, momentum (but not mass)
- water phase changes (clouds and precipitation)

Indirect effects

- generate large scale/mesoscale circulations,
- trigger waves (Rossby, Kelvin, gravity)

PDC workshops

- Very First Physics/Dynamics Coupling workshop PDC14 in Dec. 2014, Mexico
- PDC16 : PNNL, Richland campus, Washington, USA.
- PDC18 : ECMWF

For more information and illustrations

⇒ M. Gross, N. Wood, S. Malardel and Ch. Jablonowski, 2015 : Bridging the (knowledge) gap between physics and dynamics, BAMS.

⇒ Beljaars, A., P. Bechtold, M. Kohler, J.-J. Morcrette, A. Tompkins, P. Viterbo, and N. Wedi, 2004 : The numerics of physical parameterization. Proc. ECMWF Workshop on Recent Developments in numerical methods for atmosphere and ocean modelling, European Centre for Medium-Range Weather Forecasts, Reading, U.K., September 2004.

⇒ Dubal, M., N. Wood, and A. Staniforth, 2004 : Analysis of parallel versus sequential splittings for time-stepping physical parameterizations. Mon. Wea. Rev., 132(1), 121-132.

⇒ Lander, J., and B. J. Hoskins, 1997 : Believable scales and parameterizations in a spectral transform model. Mon. Wea. Rev., 125 (2), 292-303.

⇒ Williamson, D. L., 2002 : Time-split versus process-split coupling of parameterizations and dynamical core. Mon. Wea. Rev., 130 (8), 2024-2041.

Outline

1. Model = Dynamics+Physics

2. Numerical models : time and space discretisations

3. The Physics/Dynamics Interface

IFS primitive equations

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\,\nabla_h\pi - f\vec{k}\times\vec{v} + \vec{s}_v$$

$$\frac{DT}{Dt} = \frac{R}{c_p}\frac{T}{\pi}\frac{D\pi}{Dt} + s_T - L\dot{q} + R$$

$$\frac{Dq}{Dt} = s_q + \dot{q}$$

$$\frac{\partial\pi_s}{\partial t} = \int_{bot}^{top} D$$

$$\frac{Dw}{Dt} << [-\frac{1}{\rho}\frac{\partial p}{\partial z} - g] \Rightarrow w \text{ diagnostic}$$

$$p = \pi$$

$$\Rightarrow \text{adjustement to hydrostatic equilibrium}$$

$$\text{faster than a time step}$$

Splitting processes

The model is based on a single set of equations without any splitting of the processes.

But, these equations are split into dynamics and parametrisation 1, parametrisation 2, parametrisation 3 etc in order to be solved numerically.

- Recent observation spectra do not really show any clear scale separation : artificial scale separation between resolved versus parametrised (nightmare in "grey" zones)
- The time split and process split in numerical models are often based more on practical/numerical reasons than theoretical argumentation.

Coupling of split processes

The dynamics and the different parametrisations (or groups of parametrisations) which have been solved independently need to be coupled together in order to restore the initial equations.

Different coupling strategies are possible, depending on the type of model and the choices done for the dynamical core.

For example : One time step in the IFS

Grid Point Space

- Compute the adiabatic Source terms (RHS) of the equations (explicitly)
- Compute the evolution due to the resolved motion (advections)
- $\Rightarrow$ an "adiabatic" and explicit guess of the next time step

Compute the evolution due to a series of physical parametrisations

- from the explicit guess
- and/or from the state at the beginning of the time step

Spectral Space

- Semi-Implicit Correction (for linearized fast term of the dynamics)
- "Numerical" diffusion

Numerical forecast : time stepping on a discrete space

From one time step to the next one

$$\psi @(M, t^+) = \psi @(?, t^-, t) + \mathrm{TEND} @(?, t^-, t, t^+)\Delta t$$

where ψ is a prognostic variable of the model.

Eulerian versus Semi-Lagrangian

Eulerian

$$
\begin{aligned}
\psi @(M, t^+) &= \psi @(M, t^-, t) \\
&+ ADV @(M, t^-, t, t^+)\Delta t \\
&+ S_{Dyn} @(M, t^-, t, t^+)\Delta t \\
&+ S_{Phy} @(M, t^-, t, t^+)\Delta t
\end{aligned}
$$

- The advection term is computed as one of the RHS.
- CFL criteria $U\Delta t < \Delta x$ for advection.

Eulerian versus Semi-Lagrangian

Semi-Lagrangian

$$\begin{aligned}
\psi @(A, t^+) &= \psi @(D, t^-, t) \\
&\quad + S_{Dyn} @(A, D, t^-, t, t^+) \Delta t \\
&\quad + S_{Phy} @(A, D, t^-, t, t^+) \Delta t
\end{aligned}$$

- In a semi-Lagrangian scheme, the transport by the resolved motion (advection) is computed "following" the air at each grid point A backward for one time step (trajectories/interpolation at departure points D).
- In the dynamics, the RHS are averaged between departure point and arrival point.
- There is no CFL stability condition with respect to the advection term (but still for fast waves).

Explicit versus Implicit

Explicit

$$\psi(t^+) = \psi(t) + S(\psi(t))\Delta t$$
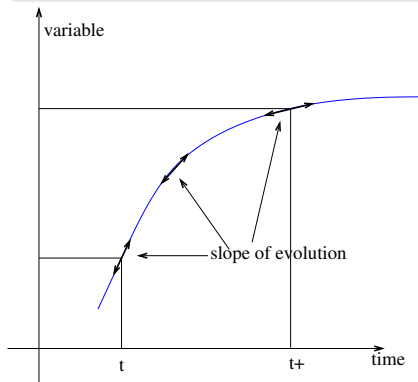
Semi-Implicit

$$\psi(t^+) = \psi(t) + [\alpha S(\psi(t^+)) + (1-\alpha)S(\psi(t))]\Delta t$$

α gives the degree of "implicitness".
In the dynamics, the linear part of the Sources terms which are responsible for the fastest waves are treated implicitly.
In the physics, several processes have an implicit solver.

Sequential/Parallel coupling

Parallel

All the processes are computed independently.

$$d\psi = \frac{\partial \psi_-}{\partial t} \Big|_1 dt + \frac{\partial \psi_-}{\partial t} \Big|_2 dt + ... + \frac{\partial \psi_-}{\partial t} \Big|_i dt + ...$$

The order of the calculation is not important. But, if long time step, time tendencies of fast processes may need "to know" about the evolutions (inside a time step) coming from the slower processes.

Parallel coupling is more often used in model with explicit dynamics (short time step). Parallel coupling is "scalable".

Sequential/Parallel coupling

Sequential

The process i knows about the process $i - 1$

$$d\psi = \frac{\partial \psi_-}{\partial t} \mid_1 dt + \frac{\partial \psi_1}{\partial t} \mid_2 dt + ... + \frac{\partial \psi_{i-1}}{\partial t} \mid_i dt + ...$$

The final result depends on the order of the processes. But if the order is "well chosen" the result is more realistic, in particular if the time scale of the processes are very different. We'll usually start with the "slow" processes (radiation) and finish with the fast ones (adjustments, for example adjustment to saturation).

Physics "along" a trajectory

In the IFS, the coupling between the dynamics and the physics and between the parametrisation is sequential.

The physics computations are done along vertical columns but some physical tendencies are "averaged" along the trajectory of the semi-Lagrangian scheme.

$$\begin{aligned}
\psi_A(t^+) = {} & \psi_D(t) + (Dyn(\psi_D(t), \psi_A(t)))\,\Delta t \\
& + \left(\frac{1}{2}\left[Phy_{rad,conv,cld^\diamond}(\psi_D(t)) + Phy_{rad,conv,cld}(\psi_A(t^*))\right]\right)\Delta t \\
& + \left(Phy_{diff,gwd,cld^\diamond}(\psi_A(t^*))\right)\Delta t + SI_{cor}(\psi_A(t^*), t^+)
\end{aligned}$$

where $\psi_A(t^*)$ is the current guess after the previous processes treated in the time step.

($\diamond$) in the cloud scheme, T and q_v tendencies are averaged but q_l, q_i, q_r and q_s are not.

Sequential/parallel processes inside the Physics

Sequential : order of processes is important

For example, if the radiation "sees" the clouds formed by condensation before rain forms, it "sees" too much clouds (radiation should not be in between the condensation scheme and the microphysics)

Parallel : negatives values

Microphysics transformations have Source Species and Product Species. Before starting to estimate one transformation, you have to check the current reservoir of the Sources Species in order to avoid "negative" values (add a bit of sequentiality..).

The sequence in the IFS

From Slow to Fast (but...)

1. Radiation

2. Gravity Wave Drag (Subgrid Orography)

3. Vertical Diffusion (Boundary Layer)

4. First call of Microphysics and Cloud Scheme

5. Convection (Deep and Shallow)

6. Microphysics and Cloud Scheme

What's forcing what ?

Zonal mean of cumulated U-tendencies for 24h

DYN
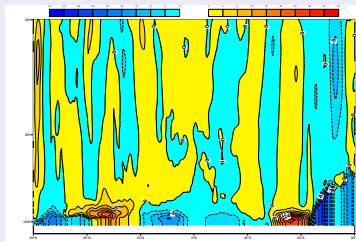
VDIFF
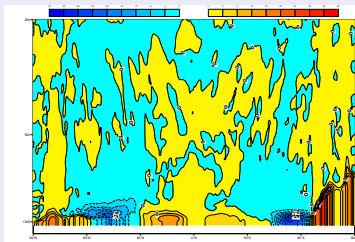
TOTAL
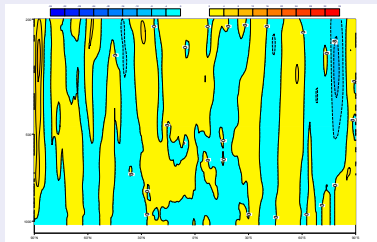
What's forcing what ?
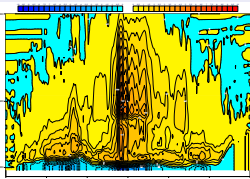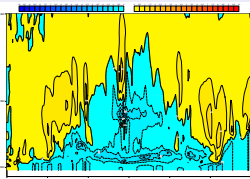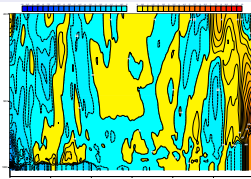
Zonal mean of cumulated T-tendencies for 24h

DYN
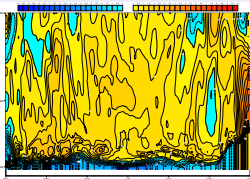
RAD
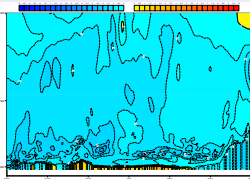
VDIF
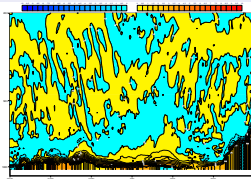
CONV

CLOUD

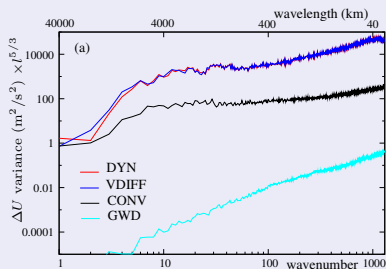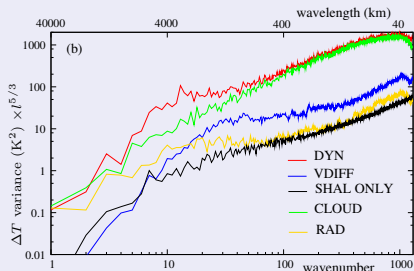TOTAL

Scales and interactions
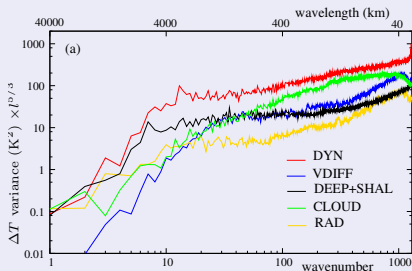
Spectral scale analysis of wind tendencies,
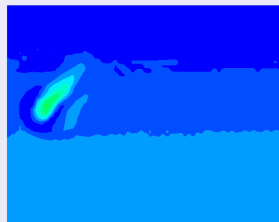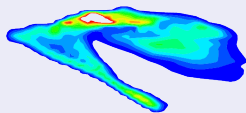950 hPa   200 hPa.
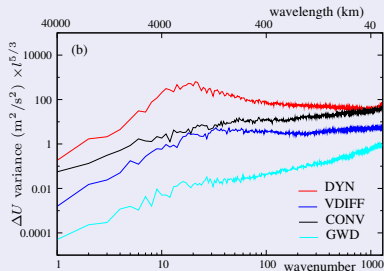
Scales and interactions

Spectral scale analysis of temperature tendencies,
at 700 hPa,
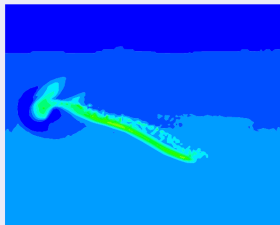with and without deep convection scheme.

Dynamics/Cloud scheme versus Convection scheme in the "grey zone" of convection : academic split storm
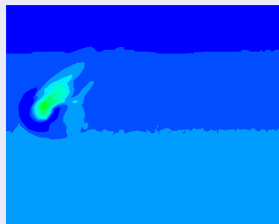
Simulations at 6.5 km resolution without and with convection scheme

First call for convection only

First call for convection + cloud scheme

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1. Model = Dynamics+Physics

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3. The Physics/Dynamics Interface

The role of the interface

- 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.
- The resulting system should in particular assure the conservation of mass, momentum and energy.

Re-projection of "dry" Conservative variables

Implicit "conversion" term (s_z or θ)

- Some parametrisations are using equations for a variable which is conservative with respect to the "internal" pressure work : static energy $s_z = c_p T + \phi$ or potential temperature $\theta = T(p_o/p)^{R/c_p}$.
- The parametrisation computes tendencies for s_z or θ.
- But s_z or θ are not prognostic variables in IFS... These tendencies are projected onto a T physics tendency and the dynamics will later adjust the pressure/geopotential.

Re-projection of "moist" Conservative variables

Implicit water phase transitions (h_z or θ_l)

- In some parametrisations, the water phase transitions do not have to be expressed explicitly thanks to moist conservative variables :
$h_{zil} = c_p T + \phi - L_s q_l - L_i q_i$ or $\theta_l = \theta - -L_s/c_p q_l - L_i/c_p q_i$

- The cloud scheme (condensation/evaporation) gives the final equilibrium between the water phases using the last guess of the atmospheric state after the Dynamics and all the other parametrisations :

$$(h_{zil}, q_t) \Rightarrow (T, q_v, q_l, q_i)$$

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

The tendencies computed in the Physics have to match the equations which have started to be solved by the Dynamics (there are several possible forms for the equation of a given parameter).

For example...

internal energy form :

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

enthalpy form :

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

Dynamics and Physics are not "black boxes"....