Outline

1. 1 Model = Dynamics+Physics
2. Splitting and Connections inside the Physics
3. The Interface Physics/Dynamics

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 sugrid effects
- The diabatism
- The water phase transitions
- Parametrisation = "Fudging" ?

The Dynamics

- 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 exemple in an hydrostatic model.
- They are only one part of a more complex system.
- We have to be carefull with the meaning of the pronostic variabless... 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" is Dynamics and resolution dependent (need of "adaptative" Physics).

What do we do in the Dynamics in IFS ?

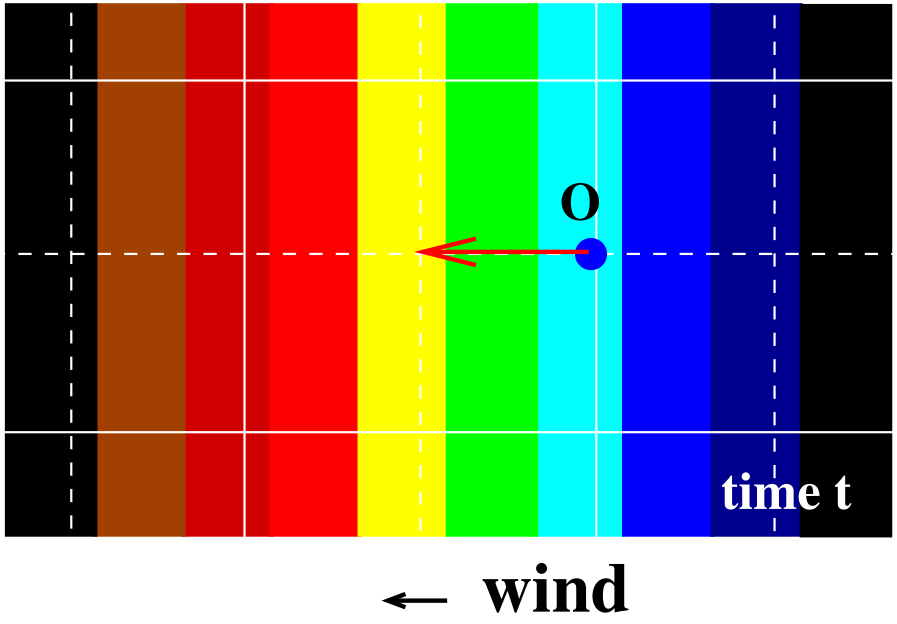
Grid Point Space

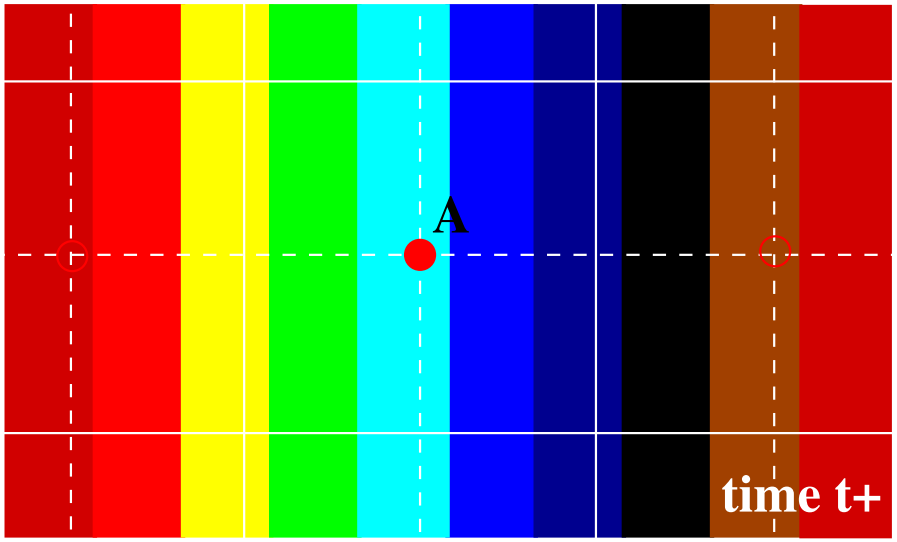
- Compute the adiabatic Source terms (RHS) of the equations (explicitly)
- Compute the evolution due to the resolved motion (advections)
- $\Rightarrow$ an "adiabatic" and explicit guess of the next time step
- Compute the evolution due to the physical parametrisations

Spectral Space

- SI Correction
- "Numerical" diffusion

Semi-Lagrangian





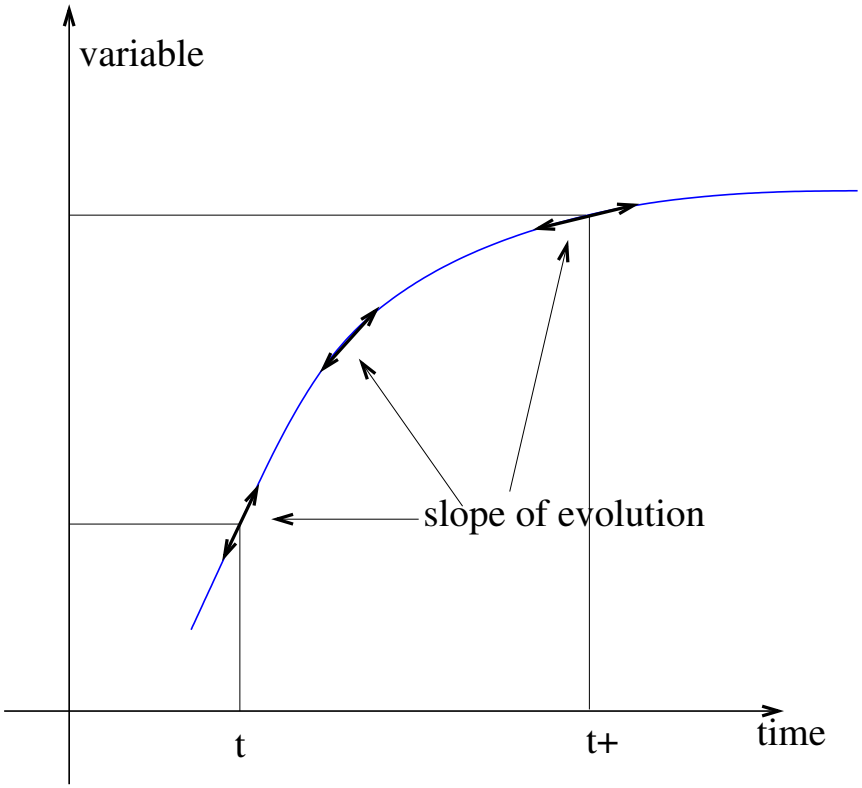
In a semi-Lagrangian scheme, the transport by the resolved motion (advection) is not a Source term as in an Eulerian scheme, but it is computed "following" the air backward from one time step back to the previous one (trajectories/interpolation at Origin points).

$$\phi_A(t^+) = \phi_O(t) + Sources(A?, O?, t?, t^+?)\Delta t$$

Explicit versus Implicit

Explicit

$$\psi(t^+) = \psi(t) + S(\psi(t))\Delta t$$



Semi-Implicit

$$\begin{aligned}\psi(t^+) &= \psi(t) + [\alpha S(\psi(t^+)) \\ &\quad +(1-\alpha)S(\psi(t))]\Delta t\end{aligned}$$

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.

Splitting between NA and PA sections....

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

- Recent observation spectra do not really show any clear scale separation (cf Anton's introduction)
- The splitting between the Dynamics and the Physics is more a practical/numerical solution.
- Inside the physics, the parametrisation of the processes also results of a splitting of the full atmospheric evolution.

Sequential/Parallel spliting

Parallel

All the processes are modelised independantly.

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

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) linked with slower processes.

Sequential/Parallel spliting

Sequential

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

$$d\psi = \frac{\partial \psi_-}{\partial t}\,|_1\; dt + \frac{\partial \psi_1}{\partial t}\,|_2\; dt + ... + \frac{\partial \psi_{i-1}}{\partial t}\,|_i\; dt + ...$$

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 (adjustements, for example adjustement to saturation).

Explicit/Implicit resolution and equilibrium

In an implicit formulation, the "Source" (RHS) depends on the the results itself (the "slope" of the evolution is implicitly changing). A sequential splitting makes the evolution even more "implicit" (as the RHS knows already one part of the evolution).
An implicit formulation of process i in a sequential splitting often results in a balance between the tendencies of i and the tendencies of the previous processes.

An implicit formulation of a process i in a parallel splitting may prognose a wrong time slope for t^+ because the evolution "sees" only the one given by the process i.

Explicit and parallel treatment are better suited for slow processes (with respect to the time step).

Illustration

The Numerics of Physical Parametrization, Beljaars A. et al, ECMWF Seminar Proceedings, 6-10 Sept 2004, pp113-134

How are the Physics and the Dynamics connected in IFS

- The Physics is done **after** the "explicit part" of the dynamics, before the semi-implicit correction (done in spectral space) and the splitting is "sequential"
- Some physical tendencies are "adveraged" along the trajectory of the semi-Lagrangian scheme (mixture between the physical tendencies at time t at arrival point and physical tendencies at time $t - dt$ at Origin point).

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

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

Some consequences of the Physics/Dynamics splitting

- The original set of equation is not solved in one go (one part of the evolution has to be computed without knowing of the other part...)
- Forcing/Response relashionship (cause/effect) $\Rightarrow$ for ex. vertical advection is the main cause of condensation toward a large scale balance.
- Some parametrisations can be seen as an adjustment (instantaneous or with a prescibed time scale) toward an equilibrium. They produce the energy and momentum transferts or conversions which are done by smaller scale processes or diabatic processes inside a column $\Rightarrow$ vertical diffusion, convection, condensation
- In theory, all variables may be affected by both the dynamics and the physics processes. But, in the current physics for example, mass reorganisation is not allowed in the physics (no surface pressure tendencies).

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Classical Hypotheses in the parametrisation packages

- The parametrizations are little models which have their own hypotheses, own equations, own variables $\rightarrow$ Hard work for the dynamics/Physics Interface !
- "Column" physics : not exchange between the columns ("Eulerian" tendencies)
- pressure = mass of the column : no surface pressure/mass tendencies

Time discretization and numerics in the Physics

- The parametrizations are little models which have their own numerics.
- The time evolution of each parametriszation is seen as a "partial" time evolution. The time scheme treats the physical process solved by the parametrisation only, knowing (sequential) or not (parallel) about the effect of the previous processes treated previously in the time step.
- The stability problems are solved separatly for each parametrization (or group of, for ex : EDMF).
- Further instabilities or strange behaviour may come from the splitted treatment of the processes in the physics.

CFL ctriterium for vertical advection

Mass flux schemes

A Mass Flux Form equation

$$\frac{\partial \psi}{\partial t} = -\frac{1}{\rho} \frac{\partial M(\theta_{up} - \theta)}{\partial z}$$

is an "hiddden" vertical advection equation.

Precipitation sedimentation

In explicit microphysics schemes, the sedimentation of the precipitations is an advective process which may affect the stability of the Physics.

Implicit method (IFS), Time splitting (smaller sub-time step) or statistical "semi-lagrangian" techniques are usefull solutions to stabilize the model.

Time discretisation of diffusion equations

In the turbulence scheme, after the closure in K-coefficient, equations looks like a "heat" equation :

$$\frac{\partial \psi}{\partial t} = K \frac{\partial^2 \psi}{\partial z^2}$$

Stability condition for an explicit discretisation

An explicit discretisation

$$\psi_j^{n+1} = \psi_j^n + \frac{K \Delta t}{\Delta z^2} \left(\psi_{j+1}^n - 2\psi_j^n + \psi_{j-1}^n \right)$$

is stable if

$$\frac{K \Delta t}{\Delta z^2} < \frac{1}{2}$$

with $K \simeq 5$ m^{2}s^{-1} and $\Delta z \simeq 50$ m $\Rightarrow \Delta t < 250$ s (6 min).

Implicit time scheme for diffusion equations

Semi-Implicit discretisation

$$\begin{aligned}\psi_j^{n+1} &= \psi_j^n + \frac{K\Delta t}{\Delta z^2}[\alpha[\psi_{j+1}^{n+1} - 2\psi_j^{n+1} + \psi_{j-1}^{n+1}] \\ &\quad +(1-\alpha)[\psi_{j+1}^n - 2\psi_j^n + \psi_{j-1}^n]]\end{aligned}$$

is a more stable time scheme but it needs a tridiagonal matrix inversion.

Over-implicit resolution for EDMF

In the EDMF parametrisation, the Exchange Coefficients K and the Mass Fluxes are not constant. They are computed in an explicit way. An over-implicit scheme efficiently remove spurious oscillations (fibrillations) linked with the non-linear dependency of K and M.

Implicit coupling with the surface

The computation of the surface fluxes (boundary condition for the turbulent fluxes) are in between the downward and upward sweeps of the tridiagonal matrix for better stability and better representation of the quick (compared to the time step) response of the surface processes.

Sequential/parallel processes inside the Physics

Sequential : order of processes is important

For example, if the radiation "sees" the cloud before rain forms, it "sees" too much cloud (radiation should not be in between the cloud scheme and the micrphysics)

Parallel : negatives values

Micropysics transformation 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. Convection (Deep and Shallow)
5. Microphysics and Cloud Scheme

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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 equation 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 pronostic variables in IFS... These tendencies have to be transformed into T tendencies and ???

- In the hydrostatic model, p is the hydrostatic pressure, it is computed in the Dynamics from p_s and the definition of the hybrid levels and ϕ is diagnostic (hydrostatic integration).
- The "column" physics is not changing p and ϕ and the physics tendencies of s_z are "projected" on a tendency of temperature only (this is in agreement with the "no mass redistribution" by the Physics).

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"....