# LMDZ

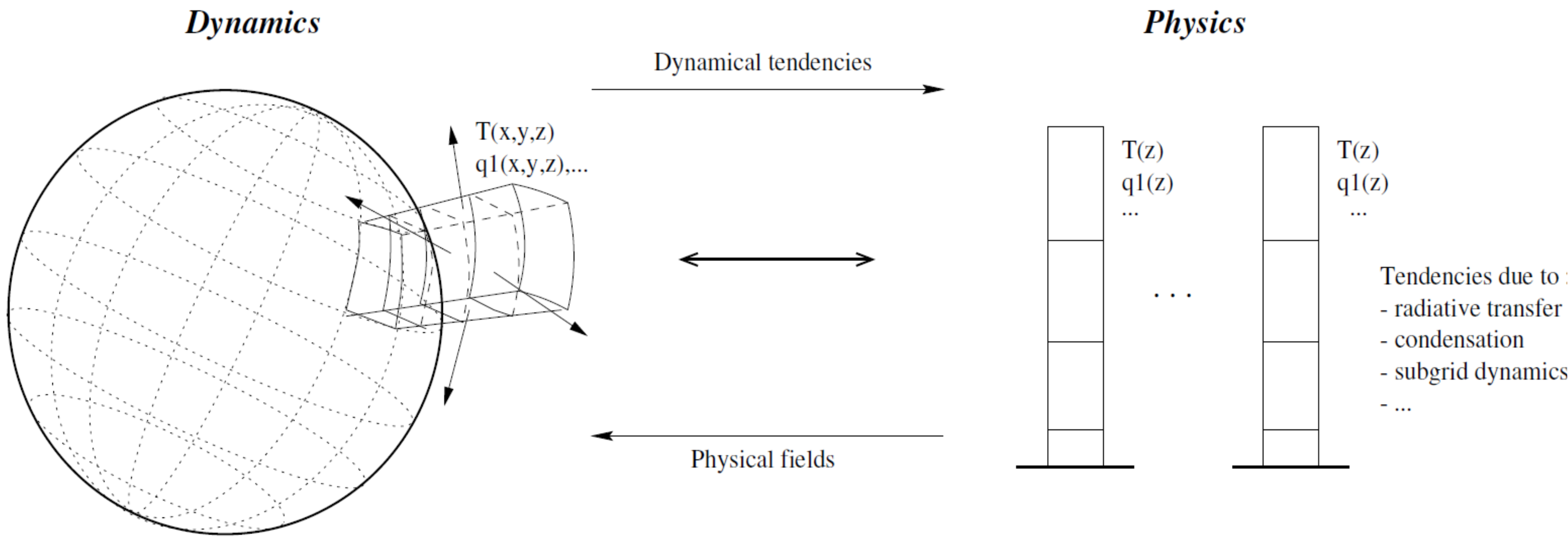
Dynamics/physics organization,
Grids,
Time stepping,
Dissipation...

LMDZ courses, December 10 2021

# Overview of course topics

- Grids:
  - Horizontal grids in the physics & dynamics
  - Vertical discretization
- Time marching:
  - Generalities about time marching schemes
  - What is used in LMDZ
  - Longitudinal polar filter
- Lateral diffusion and sponge layer:
  - Energy cascade
  - Illustrative example of diffusion
  - Sponge layer near model top

# Grids in LMDZ



Separation between physics and dynamics:

- “dynamics”: solving the GFD equations on the sphere; usually with the assumption of a hydrostatic balance and thin layer approximation. Valid for all terrestrial planets.
- “physics”: (planet-specific) local processes, local to individual atmospheric columns.

# Horizontal grids in LMDZ

## Grid dimensions specified when compiling LMDZ:

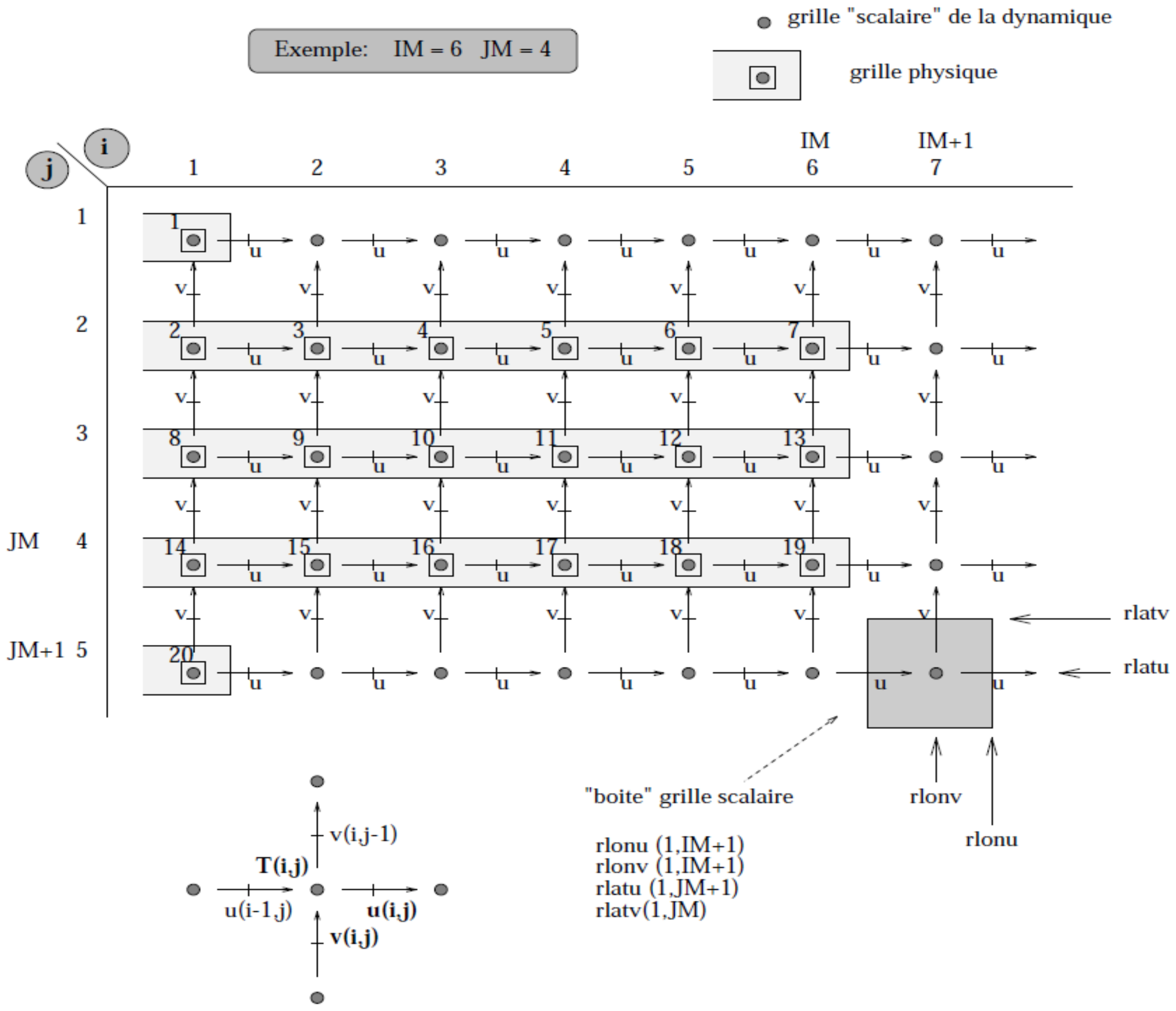
makelmdz[_fcm] -d iimxjjmxllm ...

## In the dynamics:

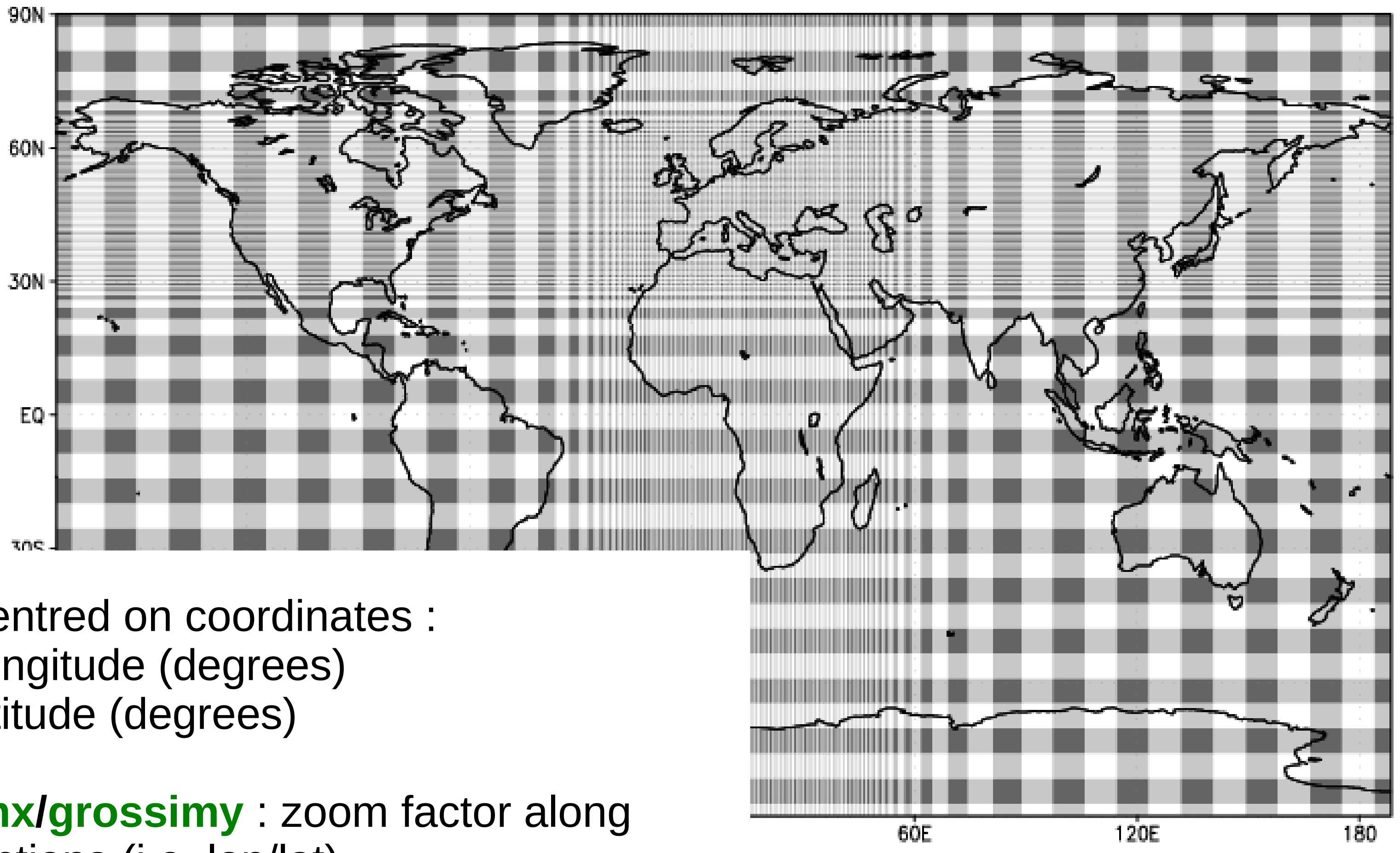
- Staggered grids, u, v and scalars (temperature, tracers) are on different meshes
- Global lonxlat grids with redundant grid points
  - at the poles
  - in longitude

## In the physics:

- Collocated variables
- No global lonxlat horizontal grid, columns are labelled **using a single index** (from North Pole to South Pole)



# LMDZ, Z for Zoom

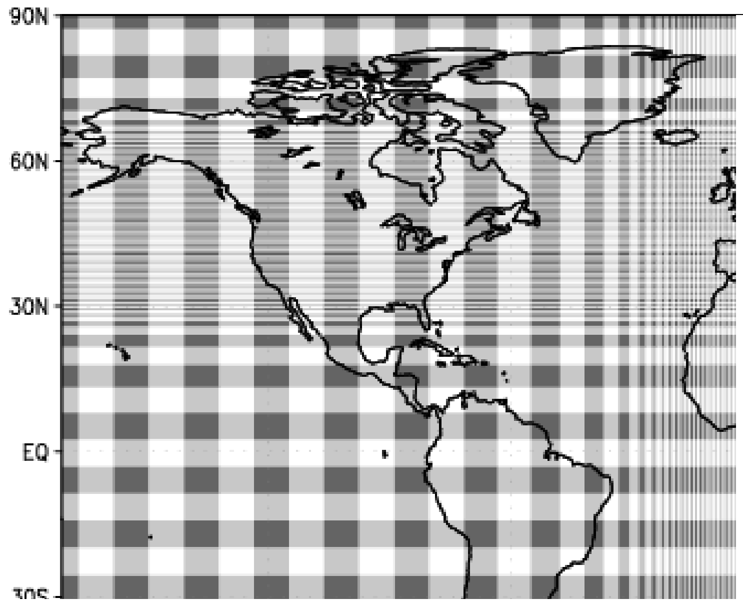


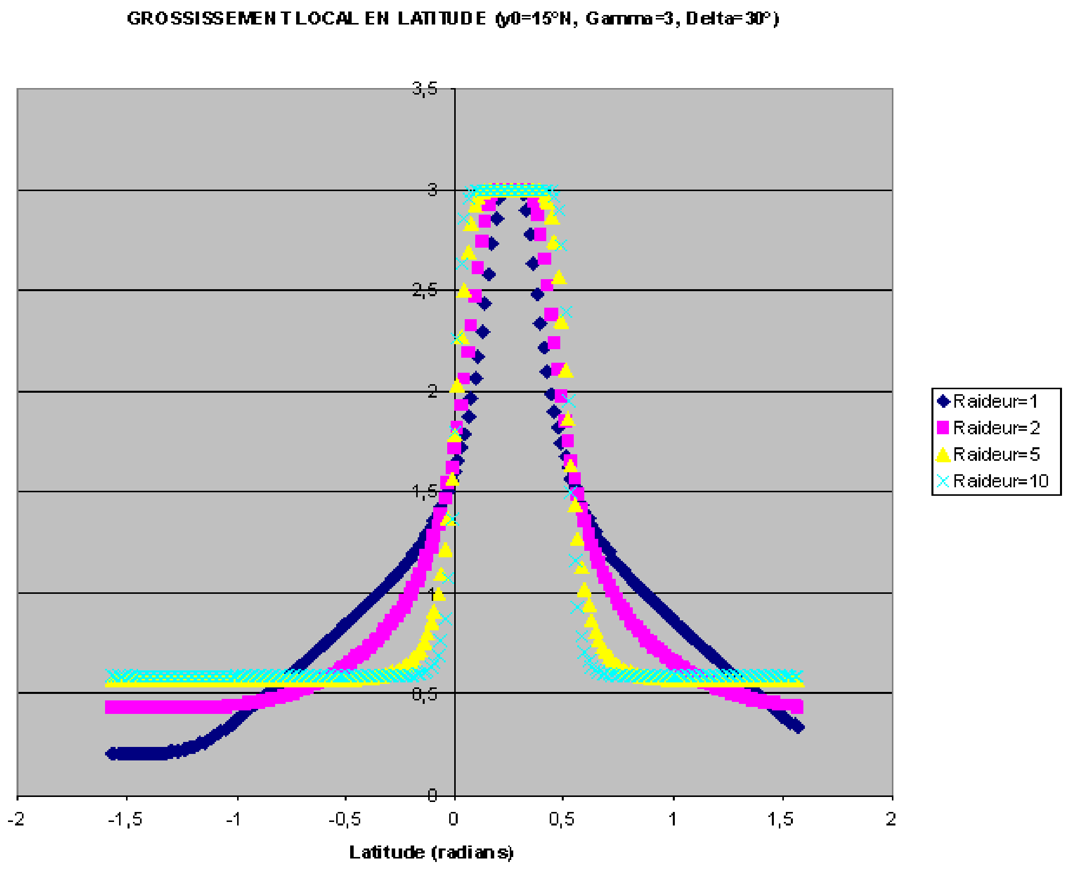
Zoom centred on coordinates :
**clon** : longitude (degrees)
**clat** **:** latitude (degrees)

**grossimx/grossimy** : zoom factor along
x/y directions (i.e. lon/lat)
Computed as the ratio of the smallest mesh (I.e. in the zoom), compared to the mesh size for a global regular grid with the same total number of points.

**dzoomx/dzoomy** : fraction of the grid containing the zoomed area: dzoom*360° by dzoomy*180°

# LMDZ, Z for Zoom





Zoom centred on coordinates :
**clon** : longitude (degrees)
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**grossimx/grossimy** : zoom factor along
x/y directions (i.e. lon/lat)
Computed as the ratio of the smallest mesh (I.e. in the zoom), compared to the mesh size for a global regular grid with the same total number of points.

**taux/tauy** : steepness of the transition between inner zoom and outer zoom meshes (typically one tries to avoid sharp transitions; tau ~ 3 is a reasonable value)

# Nudging in LMDZ

$$\frac{\partial u}{\partial t} = \frac{\partial u}{\partial t}_{GCM} + \frac{u_{analyse} - u}{\tau}$$

$$\frac{\partial v}{\partial t} = \frac{\partial v}{\partial t}_{GCM} + \frac{v_{analyse} - v}{\tau}$$

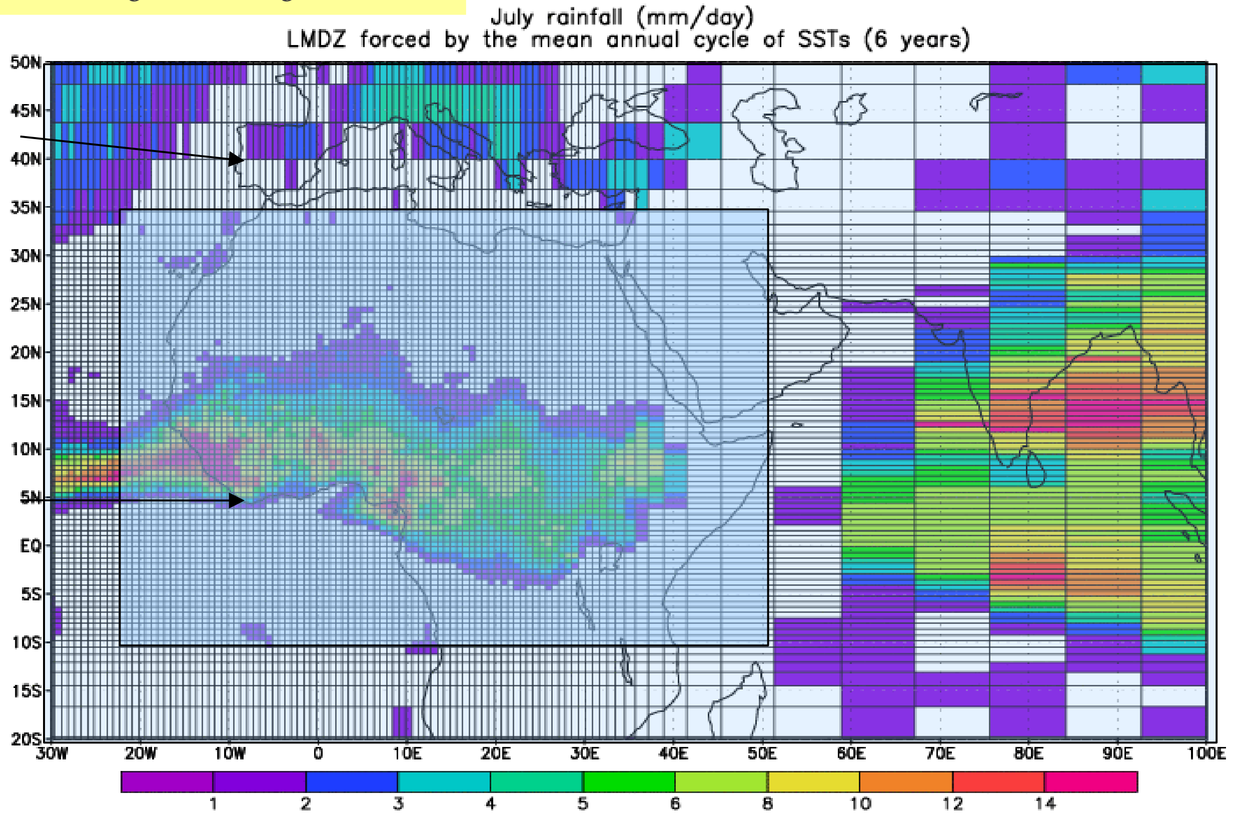
Nudging towards analyses or reanalyses with given time constants
$u_{analyse}$ $v_{analyse}$

**Example of nudging parameters**:

ok_guide = y
guide_T = n , guide_p = n , guide_q = n
guide_u = y , guide_v = y
tau_min_u = 0.0208333 (days)
tau_max_u = 10 (days)
tau_min_v = 0.0208333 (days)
tau_max_v = 10 (days)

Strong nudging ($\tau$=30min)

Weak to moderate nudging ($\tau$=10 days)



# Vertical discretization in LMDZ

- Model levels are hybrid sigma-pressure levels:

  **P**(level,time) = **ap**(level) + **bp**(level) . **Ps** (time)

  hybrid coordinates **ap**(k) and **bp**(k) are fixed for a given model run

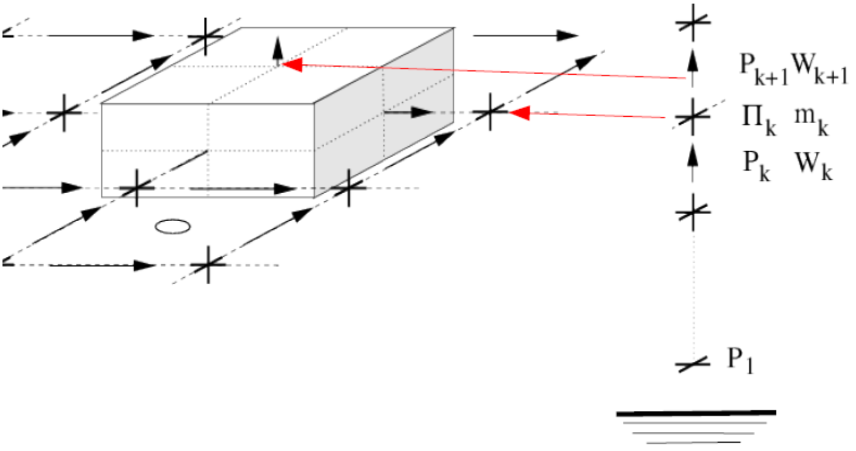
  Surface pressure **Ps**(t) varies during the run

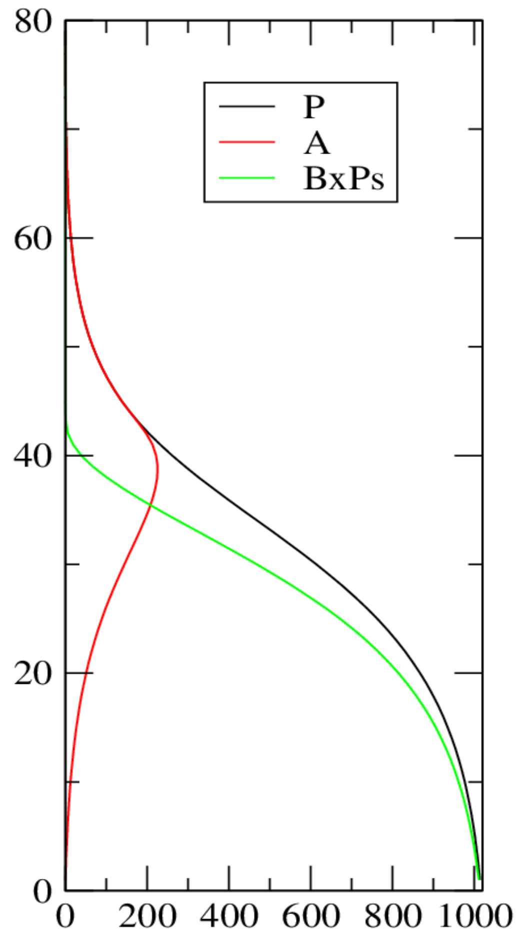
- Near the surface ap ~ 0

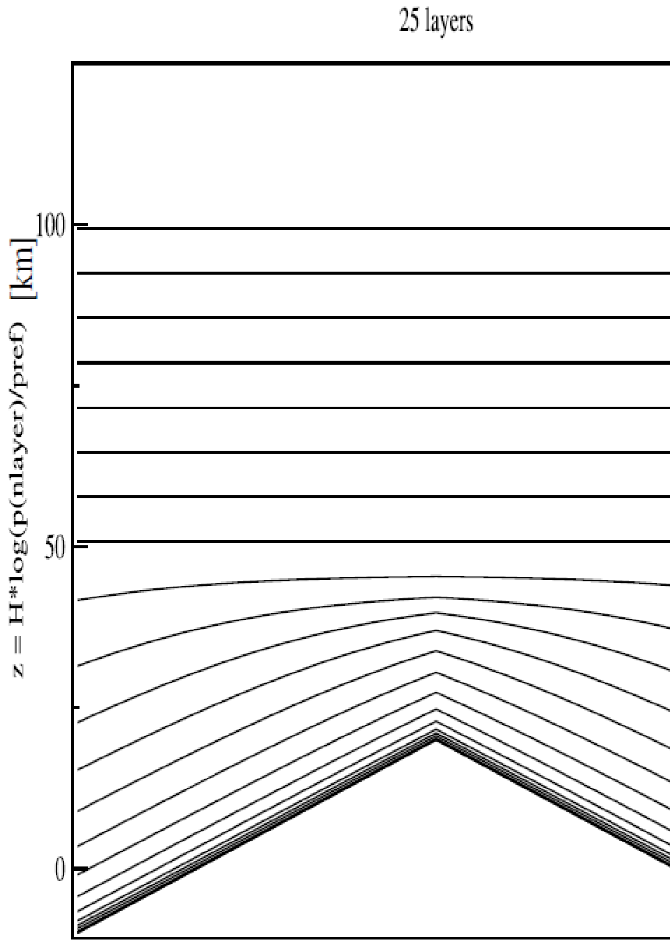
  => bp(k) ~ P/Ps

- At high altitudes , bp ~ 0

  => ap(k) ~ P







# Vertical discretization in LMDZ

- Setting model levels via the def files (also a function of number of vertical levels) :

  **vert_sampling = strato_custom** : customable (via other parameters in .def file; see next slide) discretization for stratospheric extensions.

  Multiple other possibilities from this “default”:

  vert_sampling = strato : a default for stratospheric extensions

  vert_sampling = sigma : automated generation of purely sigma levels

  vert_sampling = param : load values from a “sigma.def” file

  vert_sampling = tropo : a default  for tropospheric simulations

  vert_sampling = read : read ap() and bp() from file “hybrid.txt”

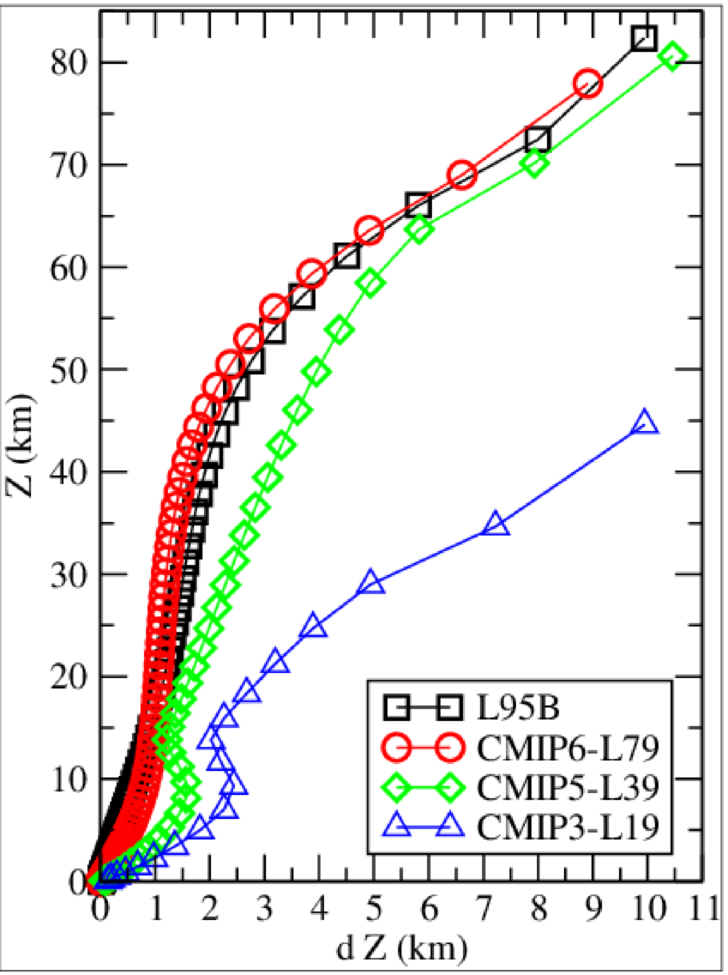
  => Typically you don't need to mess with the vertical discretization,

  **the default behaviour most likely matches your needs**.

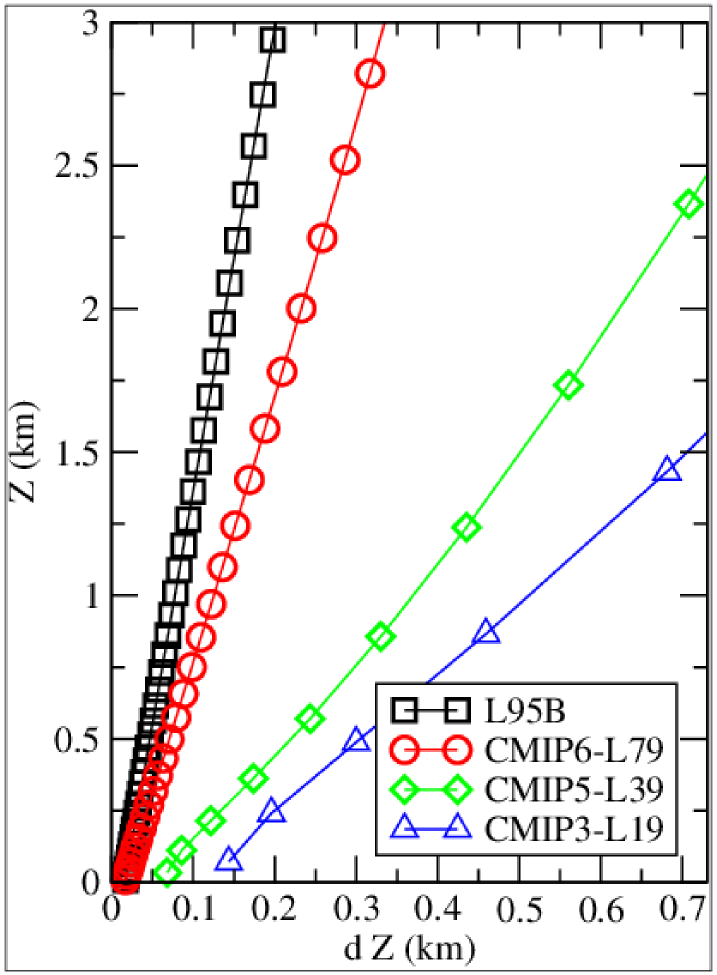
  => Check out routine dyn3d_common/disvert.F90

# Vertical discretization in LMDZ

Illustration of typical altitudes and layer thickness of L19/L39/L79/L95 grids



Over the whole atmosphere
0 < z < ~80 km



Near the surface
0 < z < 3 km

**“Standard” CMIP6 L79 settings (see DefLists/vert_L79.def)**

```
vert_sampling=strato_custom

vert_scale=7.
vert_dzmin=0.017
vert_dzlow=1.
vert_z0low=8.7
vert_dzmid=2.
vert_z0mid=70.
vert_h_mid=20.
vert_dzhig=11.
vert_z0hig=75.
vert_h_hig=20.
```

Questions ?

## Time marching schemes

- **The big picture**: you want to solve

$$\begin{aligned}\frac{df(t)}{dt} &= R(f,t)\\ f(t=0) &= f_0\end{aligned}$$

- And it is all about using a time marching scheme, built on Taylor expansion for evaluation of the time derivative, and choosing at which time level t=n.dt the right hand side term R[f(t),t] is to be evaluated

## Time marching schemes

- Explicit Euler scheme (1st order in time):

$$\begin{aligned} \frac{df(t)}{dt} &\simeq \frac{f_{n+1}-f_n}{\delta t} \\ R(f,t) &\simeq R(f(t_n),t_n) \end{aligned}$$

- Implicit Euler scheme (1st order in time):

$$\begin{aligned} \frac{df(t)}{dt} &\simeq \frac{f_{n+1}-f_n}{\delta t} \\ R(f,t) &\simeq R(f(t_{n+1}),t_{n+1}) \end{aligned}$$

- Crank-Nicholson scheme (2nd order in time):

$$\begin{aligned} \frac{df(t)}{dt} &\simeq \frac{f_{n+1}-f_n}{\delta t} \\ R(f,t) &\simeq \frac{R(f(t_{n+1}),t_{n+1})+R(f(t_n),t_n)}{2} \end{aligned}$$

## Time marching schemes

- Matsuno scheme: a predictor-corrector (Euler explicit-Euler Implicit) scheme (1st order):

$$\begin{aligned}\frac{df(t)}{dt} &\simeq \frac{f_{n+1}-f_n}{\delta t}\\ f^p(t_{n+1}) &= f(t_n)+\delta t.R(f(t_n),t_n)\\ R(f,t) &\simeq R(f^p(t_{n+1}),t_{n+1})\end{aligned}$$

- Leapfrog scheme: use encompassing time steps to evaluate the derivative (2nd order):

$$\begin{aligned}\frac{df(t)}{dt} &\simeq \frac{f_{n+1}-f_{n-1}}{2\delta t}\\ R(f,t) &\simeq R(f(t_n),t_n)\end{aligned}$$

# Time marching schemes

- Illustrative example, on a decay equation

$$\frac{dq(t)}{dt} = -\frac{1}{\tau}q(t) \longrightarrow q(t) = q_0 e^{-\frac{t}{\tau}}$$

- Building Euler explicit (E) & implicit (I) schemes:

$$\begin{aligned} \frac{dq(t)}{dt} &= -\frac{1}{\tau}q(t) \\ \Rightarrow \frac{q^{n+1}-q^n}{\delta t} &\simeq -\frac{1}{\tau}q^n \qquad \text{(E.E.)} \\ \Leftrightarrow q^{n+1}-q^n &= -\frac{\delta t}{\tau}q^n \\ \Leftrightarrow q^{n+1} &= \left[1-\frac{\delta t}{\tau}\right]q^n \end{aligned}$$

$$\begin{aligned} \frac{dq(t)}{dt} &= -\frac{1}{\tau}q(t) \\ \Rightarrow \frac{q^{n+1}-q^n}{\delta t} &\simeq -\frac{1}{\tau}q^{n+1} \qquad \text{(E.I.)} \\ \Leftrightarrow q^{n+1}-q^n &= -\frac{\delta t}{\tau}q^{n+1} \\ \Leftrightarrow \frac{\tau+\delta t}{\tau}q^{n+1} &= q^n \\ \Leftrightarrow q^{n+1} &= \frac{1}{1+\frac{\delta t}{\tau}}q^n \end{aligned}$$

# Time marching schemes

- Illustrative example, on a decay equation

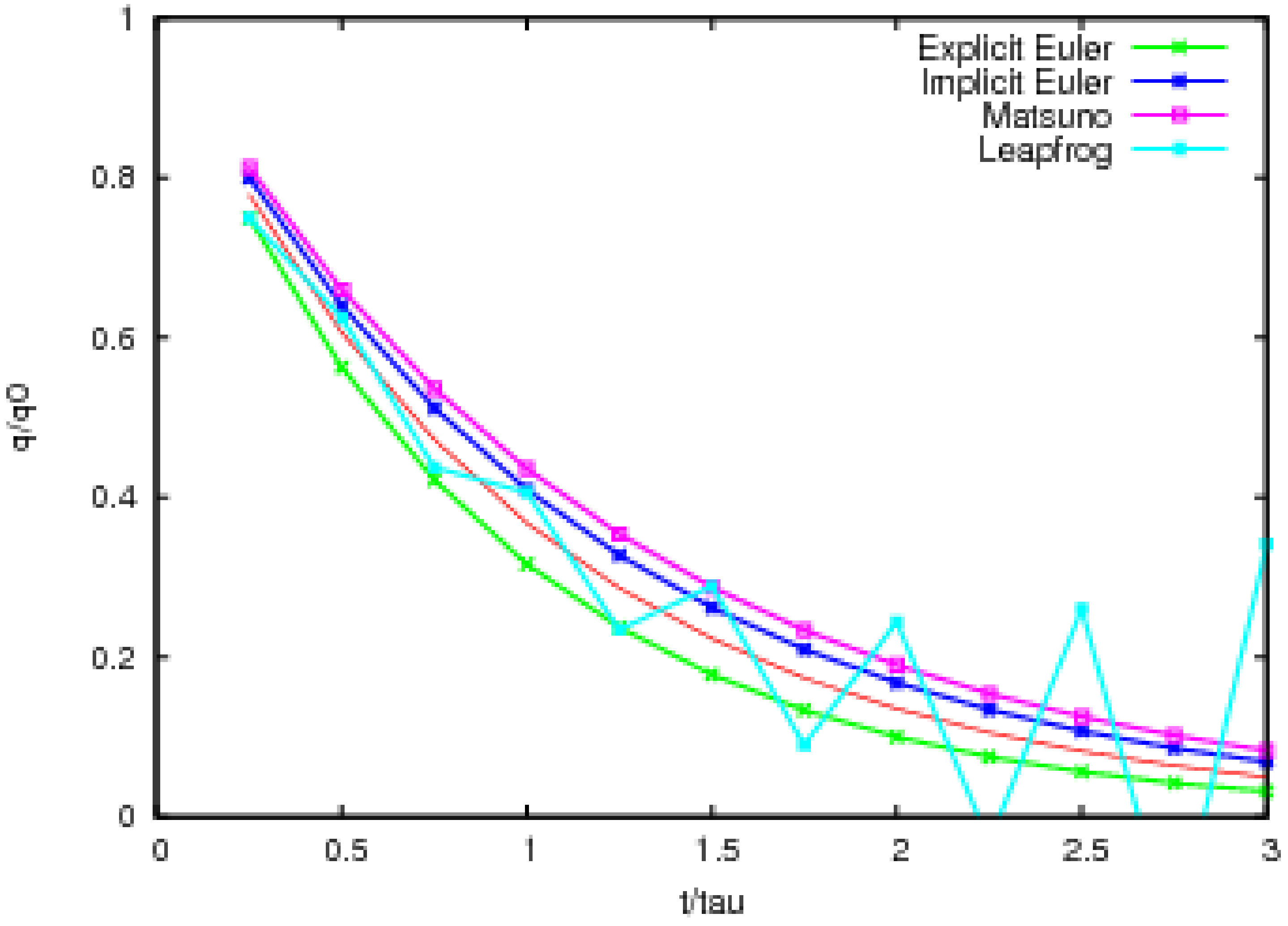
$$\frac{dq(t)}{dt} = -\frac{1}{\tau} q(t) \longrightarrow q(t) = q_0 e^{-\frac{t}{\tau}}$$

- Resulting integration schemes:

$$\begin{aligned}
\mathrm{EE}: \quad q^{n+1} &= \left[1 - \frac{\delta t}{\tau}\right] q^n \\
\mathrm{EI}: \quad q^{n+1} &= \left[\frac{1}{1 + \delta t/\tau}\right] q^n \\
\mathrm{CN}: \quad q^{n+1} &= \left[\frac{1 - \delta t/(2\tau)}{1 + \delta t/(2\tau)}\right] q^n
\end{aligned}$$

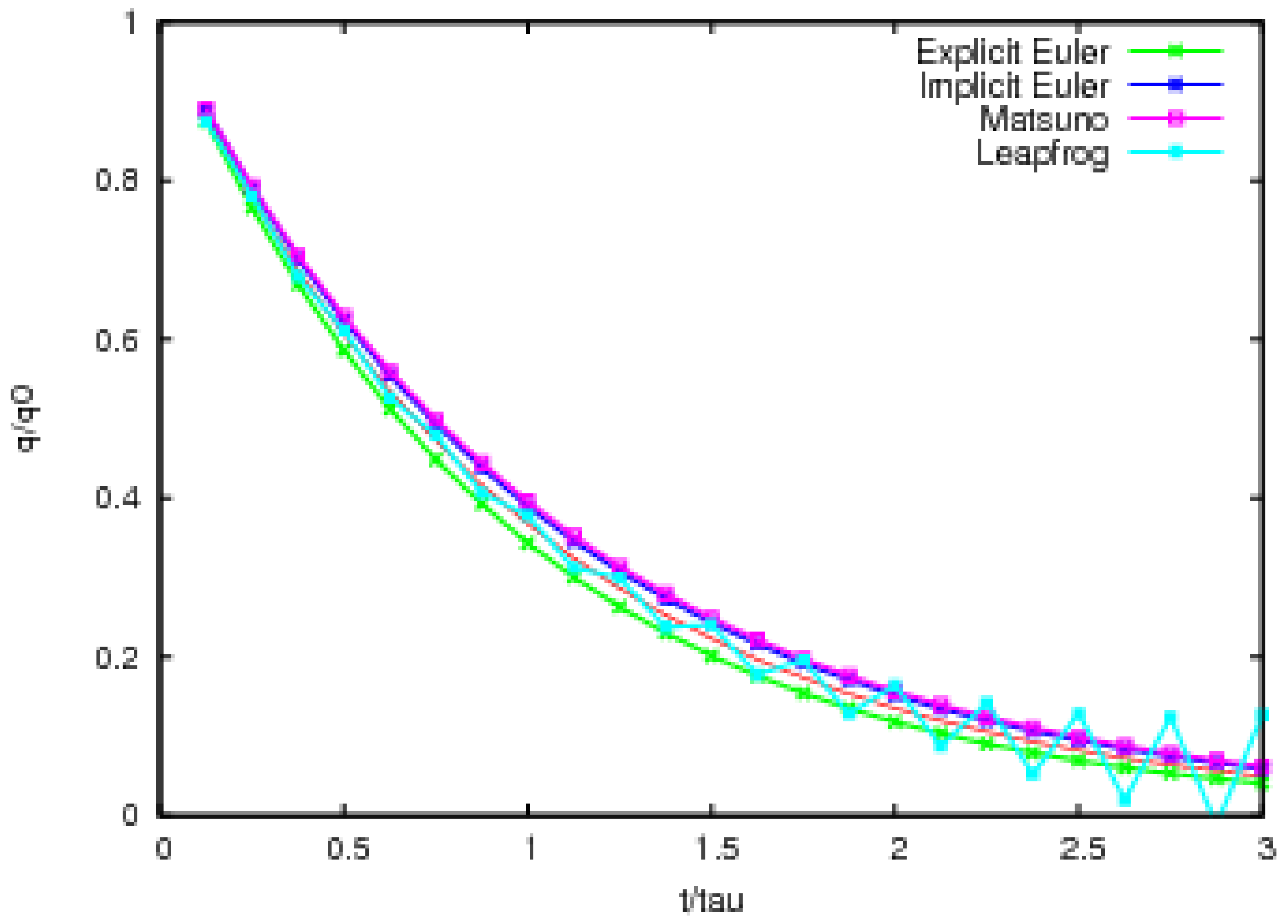
- Stability requirement (CFL) for EE : dt/tau < 2

# Time marching schemes



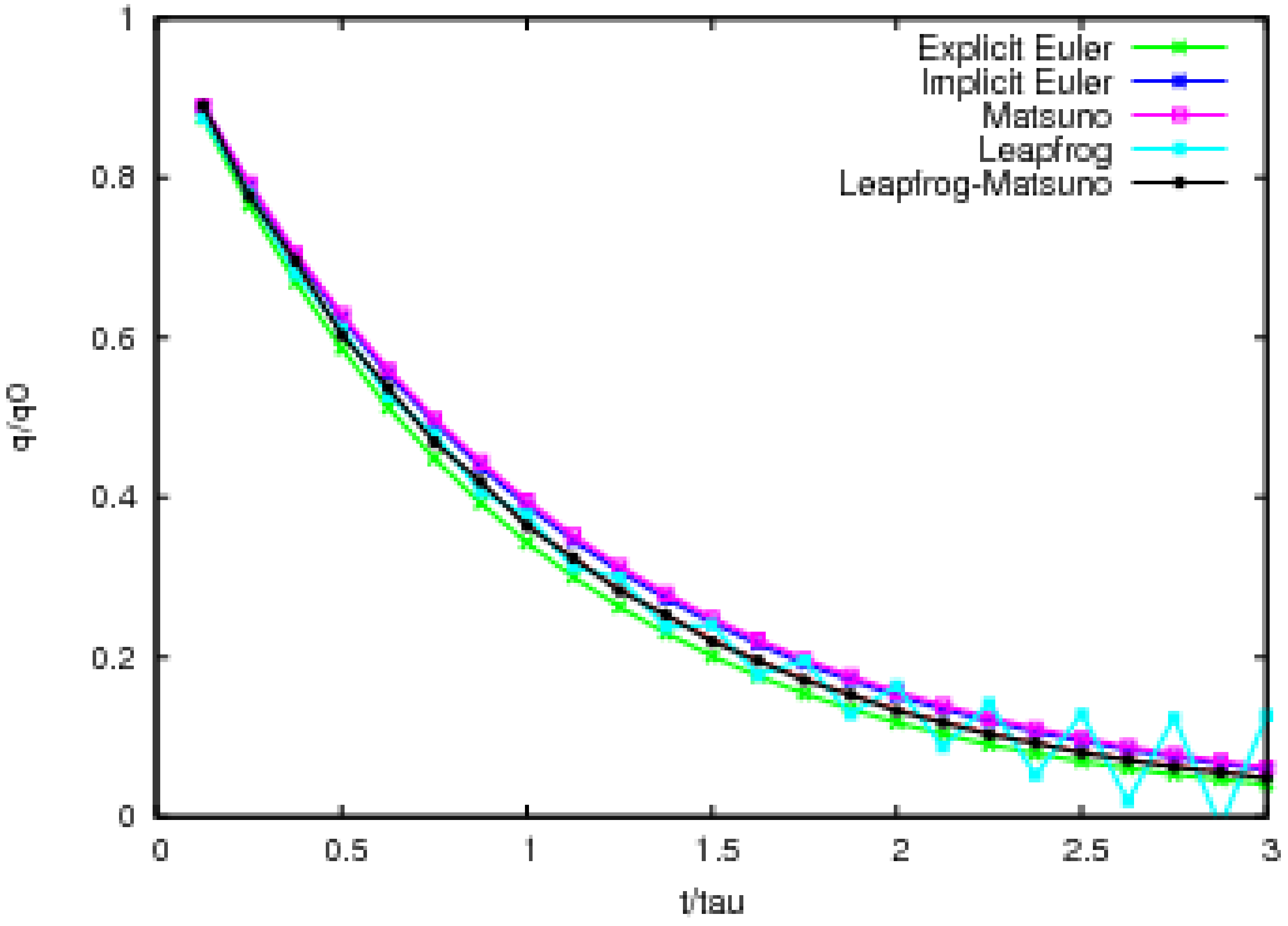
- 4 integration steps per unit of t/tau

# Time marching schemes



- 8 integration steps per unit of t/tau

## Time marching schemes



- 8 integration steps per unit of t/tau

# Time marching in LMDZ

Time splitting between physics/dynamics/dissipation:

$$\frac{\partial\psi}{\partial t} = Dyn(\psi) + Phy(\psi) + Dissip(\psi)$$

- Dynamics : Leapfrog-Matsuno scheme

  Using day_step dynamical steps per day

  Leapfrog steps with a Mastuno step every iperiod step
- Physics : Explicit Euler

  Every iphysiq dynamical steps (multiple of iperiod)
- Dissipation: Explicit Euler

  Every dissip_period dynamical steps (multiple of iperiod)

## Side note about explicit or implicit time marching schemes

Even when solving linear spatio-temporal boundary-value problems, e.g.:

$$\frac{dA}{dt} = \kappa \frac{\partial^2 A}{\partial x^2}$$

The explicit Euler approach leads to a straightforward expression for grid point values (but with stability constraints) :

$$\frac{A_i^{k+1} - A_i^k}{\delta t} = \frac{\kappa}{h^2}\left[A_{i-1}^k - 2A_i^k + A_{i+1}^k\right]$$

Whereas the implicit Euler approach leads to a (tridiagonal) system of equations to solve:

$$\frac{A_i^{k+1} - A_i^k}{\delta t} = \frac{\kappa}{h^2}\left[A_{i-1}^{k+1} - 2A_i^{k+1} + A_{i+1}^{k+1}\right]$$

=> requires more computations, but may be necessary if time-stepping constrains require using large time steps.

## Side note about tridiagonal system solving

When needing to solve a tridiagonal system of the form:

T.x=y , T tridiagonal matrix, x & y vectors

Rather than invert T (costly!) to generate $T^{-1}$ (dense matrix) and compute $x=T^{-1}.y$ (matrix-vector product)

Use the LU decomposition (Gaussian elimination) of T to split the problem into two very simple sub-problems:

1) L.U=T , L and U are bidiagonal (lower/upper) matrices

2) Solve L.z=y for vector z (forward substitution step)

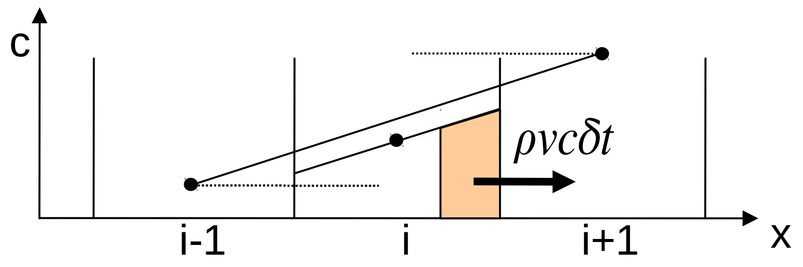
3) Solve U.x=z for vector x (backward substitution step)

# Tracer advection in LMDZ

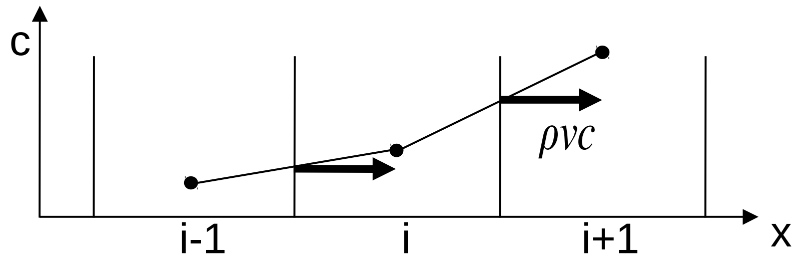
Use of the Van Leer I scheme (1977), a second order finite volume scheme with slope limiters (e.g. MUSCL, MINMOD)  (Hourdin et Armengaud, 1999).

Guaranties of fundamental physical properties of transport : conservation of the total quantity, postitivity, monotony, non amplification of extrema, weak numerical diffusion

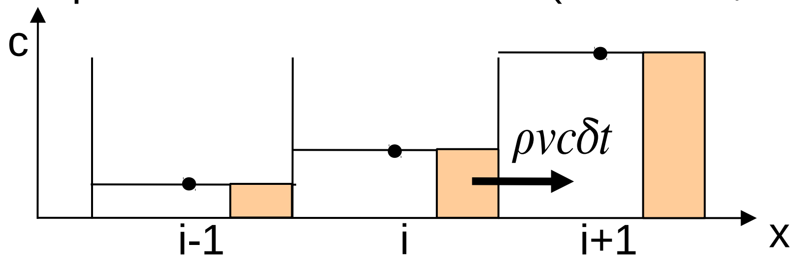
Scheme I by Van Leer (1977)



Centered finite differences (second order)



Upwind first order scheme (Godunov, 1952)



- CFL requirement, for an advection velocity Umax : Umax.(dt/dx) = cte , with cte ~ 0(1)

# Tracer advection in LMDZ

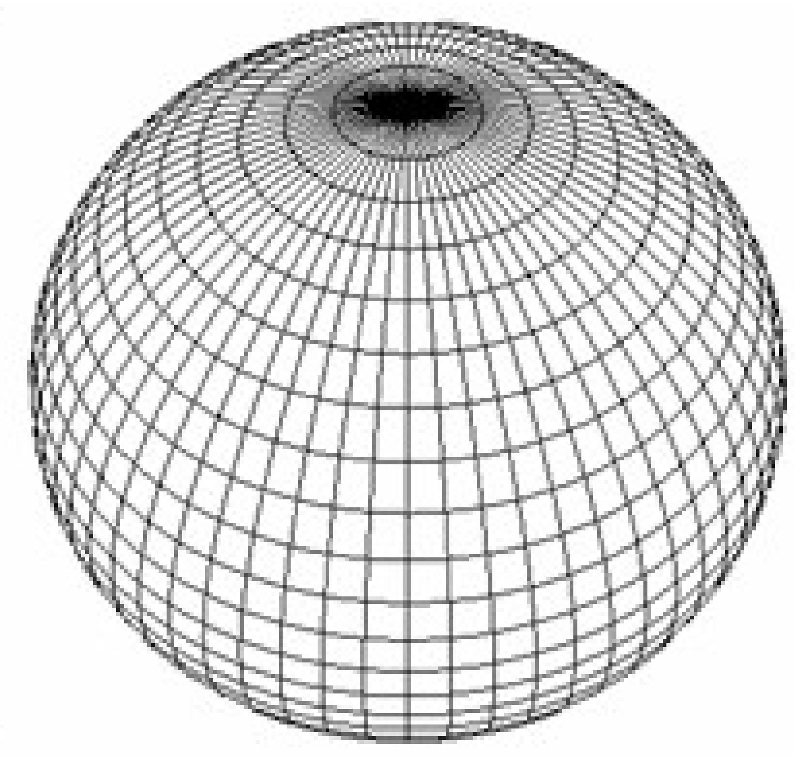
- In practice: Tracer names and advection schemes are set in the traceur.def file. e.g.:

  ```
  5                   <- Total number of tracers
  14 14 H2Ov          <- Tracer advection scheme and name
  10 10 H2Ol          <- Tracer advection scheme and name
  10 10 H2Oi          <- ...
  10 10 RN
  10 10 PB
  ```

- Scheme “10” : Van Leer scheme
- Scheme “14” : Specific modified scheme for water vapor
- Other (experimental) schemes are coded; see dyn3d/advtrac.F90

Questions ?

# The longitudinal polar filter



- A lon-lat grid implies that the meshes tighten dramatically as the pole is approached.
- CFL conditions there would dictate using an extremely small time step for the time marching scheme.

- Longitudinal (Fourier) filtering, removing high spatial frequencies, is used to enforce that resolved features are at the level of those at ~60°
- In addition near the poles there is some longitudinal grouping of meshes (applied to the divergence of air transport) by bunches of $2^{ngroup}$ (typically ngroup=3) which implies that the number of points along longitudes of the GCM must be a multiple of $2^{ngroup}$!

# Energy spectra and lateral dissipation

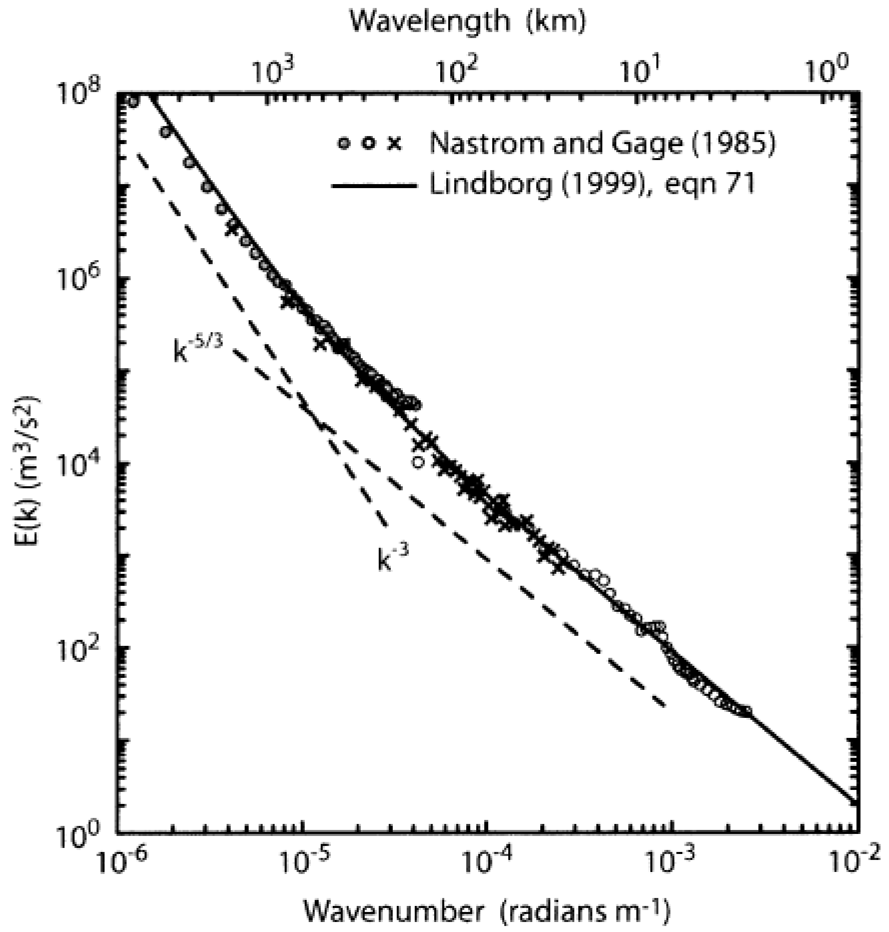


FIG. 1. Nastrom and Gage (1985) spectrum derived from the GASP aircraft observations (symbols) and the Lindborg (1999) functional fit to the MOZAIC aircraft observations.

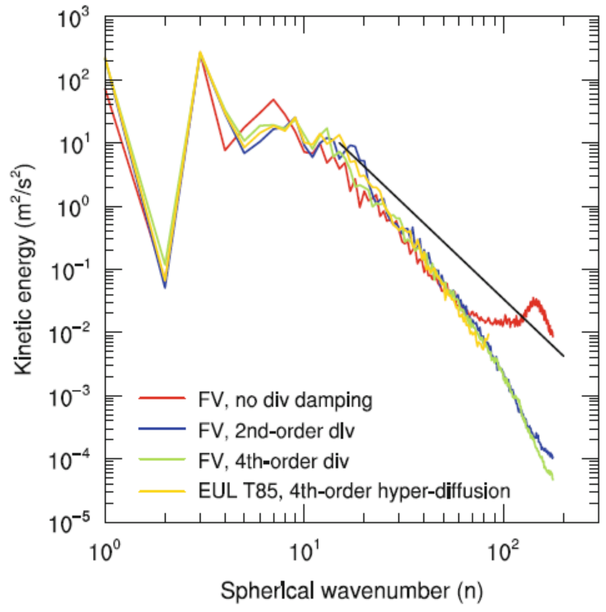
- Observations (Nastrom & Gage 1985, Lindborg 1999) collected over length scales from a few to thousands of km display a characteristic energy cascade (from Skamarock, 2004).

- In order to fulfil the observed energy cascade from resolved scales to unresolved scales in GCMs, a dissipation term is added:

$$Dissip(\psi) = \frac{(-1)^{q+1}}{\tau} \nabla^{2q} \psi$$

# Lateral dissipation in GCMs as a tool to pin the energy cascade

From *Numerical Techniques for Global Atmospheric Models, Lauritzen et al. (eds), 2010*



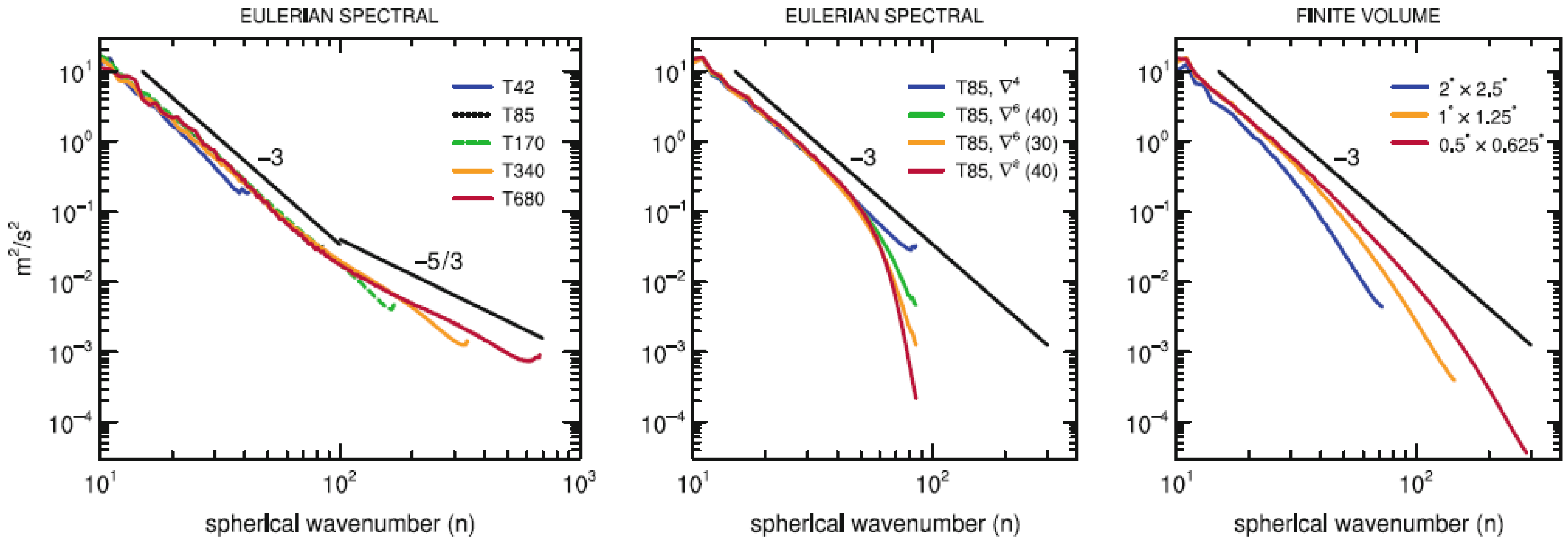


**Fig. 13.4** 250 hPa kinetic energy spectra as a function of the spherical wavenumber ($n$) in aqua-planet simulations from (*left*) CAM Eulerian spectral dynamical core with $\nabla^4$ diffusion for different resolutions, (*center*) T85L26 Eulerian spectral dynamical with $\nabla^4$, $\nabla^6$ and $\nabla^8$ diffusion, and (*right*) CAM Finite Volume (FV) dynamical core for different *lat* × *lon* resolutions in degrees and 26 levels

## Illustrative example of dissipation

- Simple 1D diffusion equation toy model:

$$\frac{dA}{dt} = \nu \frac{\partial^2 A}{\partial x^2}$$

- Von Neumann (Fourier mode) analysis

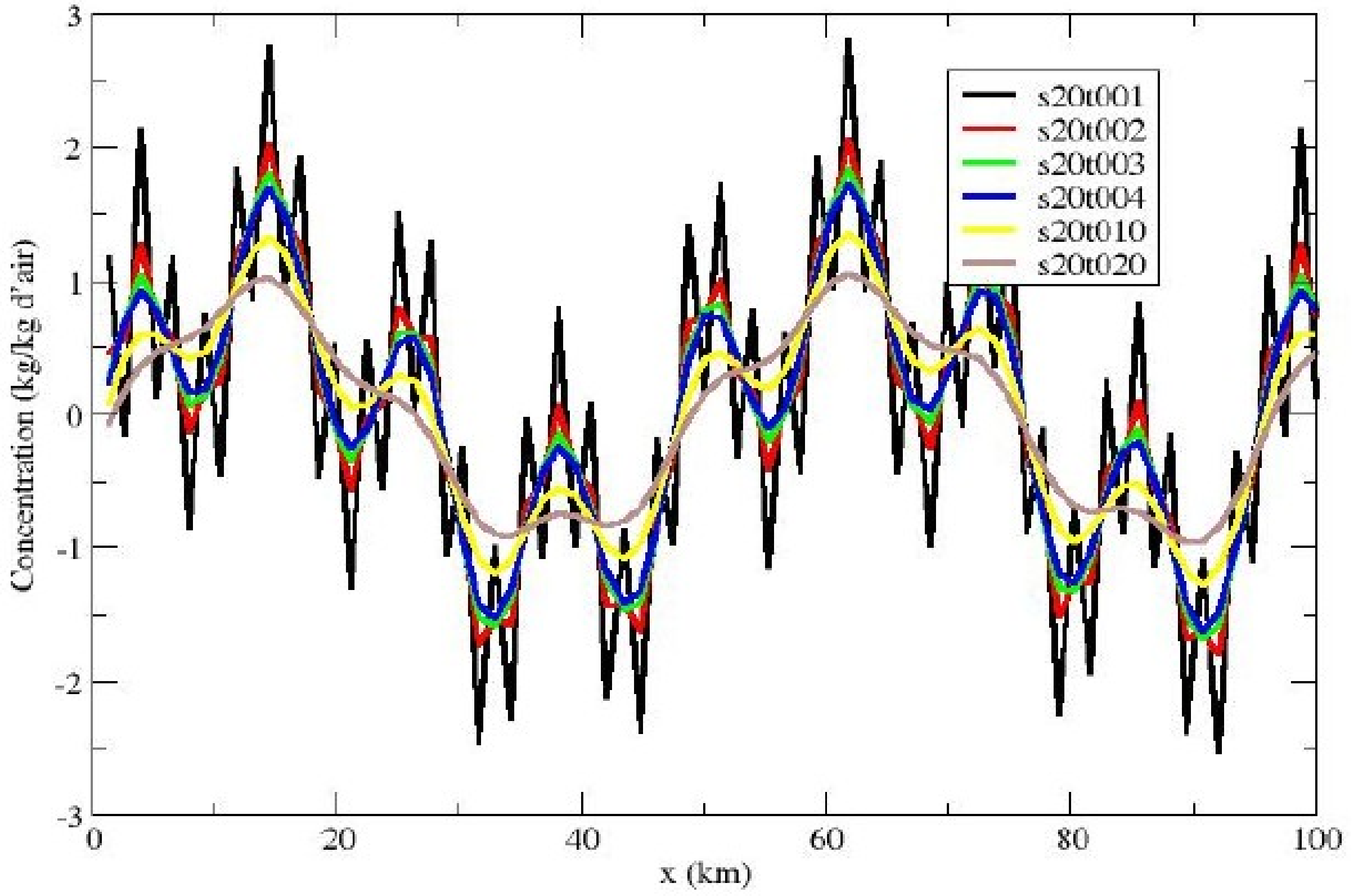
$$A_k(t) = a_k(t).sin(kx)$$

- Explicit Euler time marching (with stability condition!):

$$a_k^{n+1} = \left(1 - \nu k^2 \Delta t\right) a_k^n$$

Note that mode damping is stronger for large k

# Illustrative example of dissipation



- Temporal evolution, from an initial condition consisting of 2 sine modes and an extreme (2 grid points wavelength) “numerical mode”

# Controlling dissipation in LMDZ

- Parameters in file gcm.def:

  **dissip_period**: Apply dissipation every dissip_period dynamical steps (or **specify 0 to let model pick an appropriate value**)

  **nitergdiv**: number of iterations on velocity dissipation operator grad.div

  **nitergrot**: number of iterations on velocity dissipation operator grad.rot

  **niterh**: number of iterations on temperature dissipation operator div.grad

  **Usual values:** nitergdiv=1, nitergrot=2, niterh=2

  **tetagdiv**: dissipation time scale (s) for smallest wavelength for u,v (grad.div component)

  **tetagrot**: dissipation time scale (s) for smallest wavelength for u,v (grad.rot component)

  **tetatemp**: dissipation time scale (s) for smallest wavelength for potential temperature (div.grad)

  **values depend on horizontal resolution**

## Controlling dissipation in LMDZ

- Parameters in file gcm.def:

  **tetagdiv**: dissipation time scale (s) for smallest wavelength for u,v (grad.div component)

  **tetagrot**: dissipation time scale (s) for smallest wavelength for u,v (grad.rot component)

  **tetatemp**: dissipation time scale (s) for smallest wavelength for potential temperature (div.grad)

  optimal teta values depend on horizontal resolution

- Moreover there is a multiplicative factor for the dissipation coefficient, which increases with model levels (see dyn3d_common/inidissip.F90), which can be controlled by flag “vert_prof_dissip”

# The sponge layer

- In addition to lateral dissipation, it is necessary to damp vertically propagating waves (non-physically reflected downward from model top).
- The sponge layer is limited to topmost layers (usually 4) and added during the dissipation step.
- Sponge modes and parameters (gcm.def):

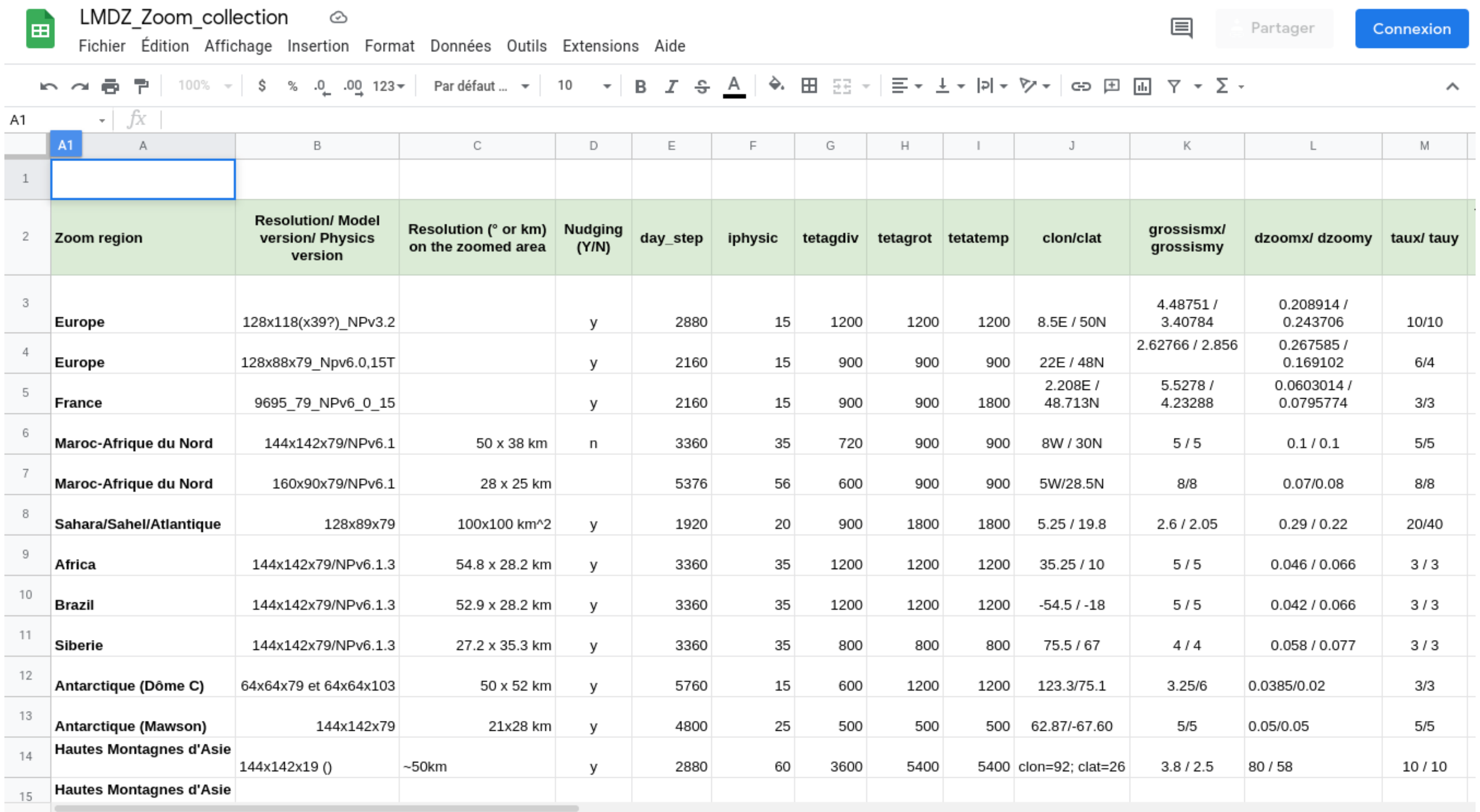
  **iflag_top_bound**: 0 for no sponge, 1 for sponge over 4 topmost layers, 2 for sponge from top to 100 times topmost layer pressure

  **mode_top_bound**: 0 for no relaxation, 1 to relax u,v to zero, 2 to relax u,v to their zonal mean, 3 to relax u,v and potential temperature to their zonal mean.

  **tau_top_bound**: inverse of characteristic time scale at the topmost layer (halved at each successive descending layer)

# Where to get typical values of the run.def/gcm.def parameters

- Check out the various examples of gcm.def_* files located in the **LMDZ/DefLists** subdirectory
- Some examples of specific cases of Zoomed simulation setups are detailed in a collaborative document; get the link by searching “Zoom collection” on LMDZPedia : https://lmdz-forge.lmd.jussieu.fr/LMDZPedia



LMDZ_Zoom_collection
Fichier Édition Affichage Insertion Format Données Outils Extensions Aide
Partager
Connexion
100%
Par défaut ...
10
A1

| Zoom region | Resolution/ Model version/ Physics version | Resolution (° or km) on the zoomed area | Nudging (Y/N) | day_step | iphysic | tetagdiv | tetagrot | tetatemp | clon/clat | grossismx/ grossismy | dzoomx/ dzoomy | taux/ tauy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Europe** | 128x118(x39?)_NPv3.2 | | y | 2880 | 15 | 1200 | 1200 | 1200 | 8.5E / 50N | 4.48751 / 3.40784 | 0.208914 / 0.243706 | 10/10 |
| **Europe** | 128x88x79_Npv6.0,15T | | y | 2160 | 15 | 900 | 900 | 900 | 22E / 48N | 2.62766 / 2.856 | 0.267585 / 0.169102 | 6/4 |
| **France** | 9695_79_NPv6_0_15 | | y | 2160 | 15 | 900 | 900 | 1800 | 2.208E / 48.713N | 5.5278 / 4.23288 | 0.0603014 / 0.0795774 | 3/3 |
| **Maroc-Afrique du Nord** | 144x142x79/NPv6.1 | 50 x 38 km | n | 3360 | 35 | 720 | 900 | 900 | 8W / 30N | 5 / 5 | 0.1 / 0.1 | 5/5 |
| **Maroc-Afrique du Nord** | 160x90x79/NPv6.1 | 28 x 25 km | | 5376 | 56 | 600 | 900 | 900 | 5W/28.5N | 8/8 | 0.07/0.08 | 8/8 |
| **Sahara/Sahel/Atlantique** | 128x89x79 | 100x100 km^2 | y | 1920 | 20 | 900 | 1800 | 1800 | 5.25 / 19.8 | 2.6 / 2.05 | 0.29 / 0.22 | 20/40 |
| **Africa** | 144x142x79/NPv6.1.3 | 54.8 x 28.2 km | y | 3360 | 35 | 1200 | 1200 | 1200 | 35.25 / 10 | 5 / 5 | 0.046 / 0.066 | 3 / 3 |
| **Brazil** | 144x142x79/NPv6.1.3 | 52.9 x 28.2 km | y | 3360 | 35 | 1200 | 1200 | 1200 | -54.5 / -18 | 5 / 5 | 0.042 / 0.066 | 3 / 3 |
| **Siberie** | 144x142x79/NPv6.1.3 | 27.2 x 35.3 km | y | 3360 | 35 | 800 | 800 | 800 | 75.5 / 67 | 4 / 4 | 0.058 / 0.077 | 3 / 3 |
| **Antarctique (Dôme C)** | 64x64x79 et 64x64x103 | 50 x 52 km | y | 5760 | 15 | 600 | 1200 | 1200 | 123.3/75.1 | 3.25/6 | 0.0385/0.02 | 3/3 |
| **Antarctique (Mawson)** | 144x142x79 | 21x28 km | y | 4800 | 25 | 500 | 500 | 500 | 62.87/-67.60 | 5/5 | 0.05/0.05 | 5/5 |
| **Hautes Montagnes d'Asie** | 144x142x19 () | ~50km | y | 2880 | 60 | 3600 | 5400 | 5400 | clon=92; clat=26 | 3.8 / 2.5 | 80 / 58 | 10 / 10 |
| **Hautes Montagnes d'Asie** | | | | | | | | | | | | |

# Rules of thumb for run.def parameters

- Time steps in LMDZ:

  dynamical time steps: dtvr = daysec / day_step

  physics time step: dtphys = iphysiq * dtvr

  dissipation time step: dtdiss = dissip_period * dtvr

  tracer advection time step: dtvrtrac = iapp_trac * dtvr

- Constraints to be aware of:

  dtvr limited by CFL for waves: Cmax.dt < min(dx,dy)

  dtrtrac limited by advection CFL: Umax.dt < min(dx,dy)

  iphysiq, dtvrtrac, dissip_period should be multiples of iperiod

## Rules of thumb for run.def parameters

- Constraints to be aware of (continued):

  dissipation time step should be much smaller than dissipation timescales:

  dtdiss << tetatgdiv, tetagrot, tetatemp

- Changing time step with resolution on a regular grid:

  day_step(max(iim,jjm)=N) ~ day_step(max(iim,jjm)=M) * M/N

- Time step for a zoomed simulation, compared to regular grid:

  day_step(zoom) ~ day_step(regular)*max(grossismx,grossismy)