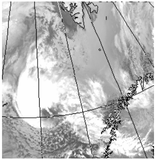
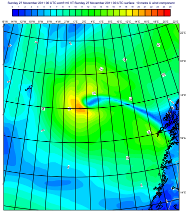
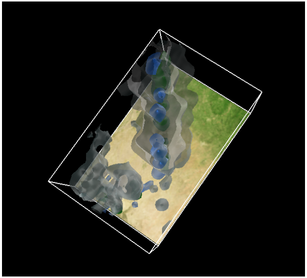
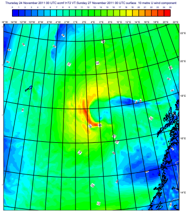
Towards
very high resolution
global
Numerical Weather Prediction

Sylvie Malardel



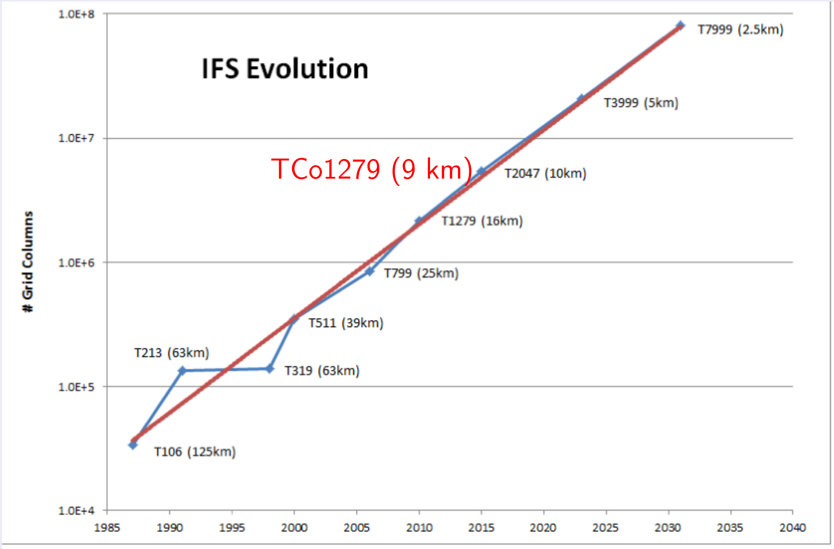






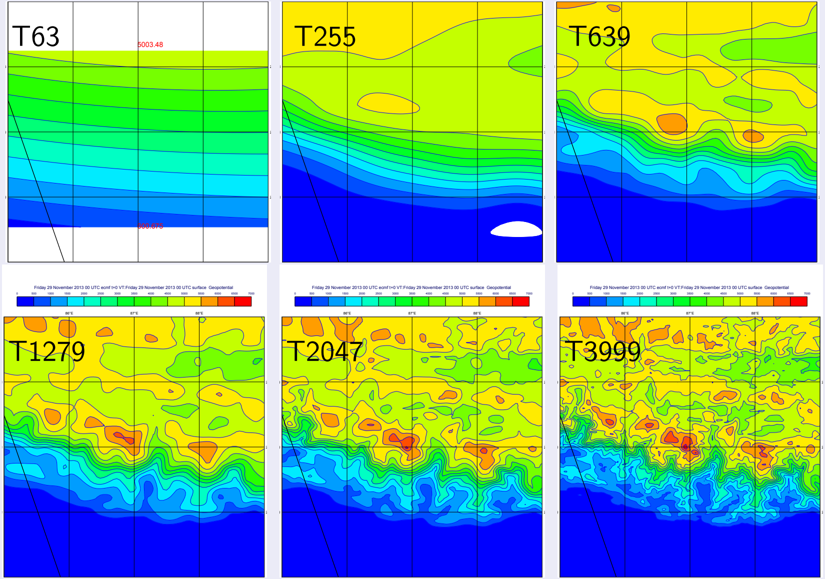
About resolution...

Towards very high resolution global NWP model



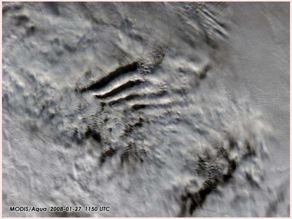
Why higher and higher resolutions?

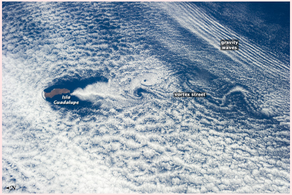
More details, more realism: z_s around Mount Everest

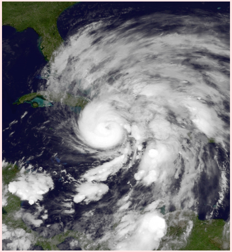


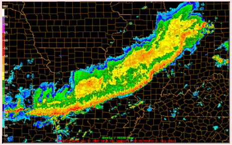
Why higher and higher resolution?

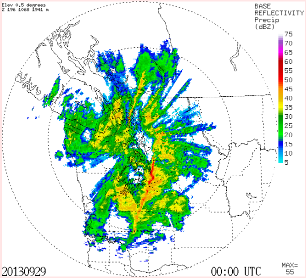
Resolve more processes

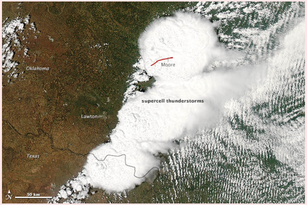












Why higher and higher resolution?

BUT, at the same time, it is important for a global model to:

- keep the large scale balances correct,
- improve the large scale/medium range forecast,
- improve the interaction between the scales.

What do we need to run with higher resolution?

- a more powerful computer (in Bologna?),
- a more scalable code (“scalability” project),
- faster/more efficient solvers (towards a grid-point solver, cf PanraRhei).

What do we need to run with higher resolution?

finer “climate” files from even finer global data sets:

- orography,
- land/sea mask,
- surface parameters (albedo, LAI, soil, vegetation).

What do we need to run with higher resolution?

New equations (non-hydrostatic?)?

New parametrizations (scale-aware?)?

New coupling between Physics and Dynamics?

What do we need to run with higher resolution?

The horizontal resolution of the atmospheric system has to be

- consistent with the vertical resolution
- consistent high resolution assimilation
- consistent high resolution coupled systems (surface, ocean)
- consistent high resolution products
- consistent high resolution verification

Last resolution upgrade for the IFS: March 2016

From:

4DV: TL1279/TL255-255-255
HRES: TL1279
EDA: TL399
ENS: TL639/TL319 (d1-10/d11-30)

To:

4DV: TCo1279/TL255-319-399
HRES: TCo1279
EDA: TCo639
ENS: TCo639/TCo319 (d1-10/d11-30)

Reanalyses

ERA-interim at TL255, L60 to ERA5 at TL639, L137

What does TCo mean?

IFS spectral representation

Idea

To "fit" a discrete representation of a field on a grid by a continuous function (compute derivatives, solve/inverse linear systems)

IFS

- fit discrete values with global functions
- series of spherical harmonics with a "triangular" truncation

$$\psi(\lambda, \mu) \simeq F(\lambda, \mu) = \sum_{l=0}^{NSMAX} \sum_{-l \leq m \leq l} \psi_{l,m} Y_{l,m}(\lambda, \mu)$$

The spectral coefficients $\psi_{l,m}$ are computed from the values known at each point $A_i(\lambda_i, \mu_i)$ of a Gaussian grid on a sphere by a Fast Fourier Transform (zonal) followed by (Slow/Fast) Legendre transform (meridional).

$NSMAX$ is the spectral truncation.
Currently, in the IFS, $NSMAX = 1279$.

IFS grids

Gaussian grids: Gaussian latitudes along meridians (conservation of global integrals between SP and GP spaces)

- regular (full): same number of points along each latitude circle (i.e. crowded near the poles)
- reduced: number of points per latitude circle decreases towards the poles
  - "isotropic" grid: $dx \simeq dy$ (i.e. quasi-regular grid spacing, uniform CFL)
  - new Octahedral (or Collignon) mesh "à la IFS"

Linear, quadratic or cubic resolutions

Pairing grid/truncation

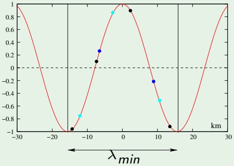
linear: the smallest wavelength $\lambda_{min} = (\pi * RA)/NSMAX$ is sampled on the grid, along a meridian, by 2 points $\Rightarrow NLAT_{lin} \simeq NSMAX$

quadratic: by 3 points $\Rightarrow NLAT_{quad} \simeq 3/2 * NSMAX$

cubic: by 4 points $\Rightarrow NLAT_{cub} \simeq 2 * NSMAX$

$$T1279 \Rightarrow \begin{array}{l} NLAT_L = 1280 \\ NLAT_Q = 1920 \\ NLAT_C = 2560 \end{array}$$

$$NLAT = 1280 \Rightarrow TL1279 \text{ or } TC639$$



Linear, quadratic or cubic grids

History

IFS had to use a quadratic grid before the introduction of the semi-Lagrangian scheme as the Eulerian advection scheme generates a lot of aliasing on a linear grid.
1999: $NLAT = 320 (\Delta y = 63 \text{ km})$ but $TQ213 \Rightarrow TL319$

Why linear, quadratic, cubic?

quadratic : no aliasing for quadratic terms (product of 2 variables)
cubic : no aliasing for cubic terms (product of 3 variables)

Linear, quadratic or cubic grids

- If no operation is done in GP space or in SP space: equivalence between the spectral representation $T(NSMAX)$ and the representation on the associated linear grid ($\simeq$ same number of degrees of freedom, for storage for ex.).
- GP computations (often non-linear) benefits from the higher resolution of the cubic grid (no aliasing, less numerical diffusion, more realistic surface fields...)
- Only VOR, DIV, T_v, p_s have a spectral representation. The other parameters (moisture, cloud variables, tracers, surface fields) only have a grid point representation.

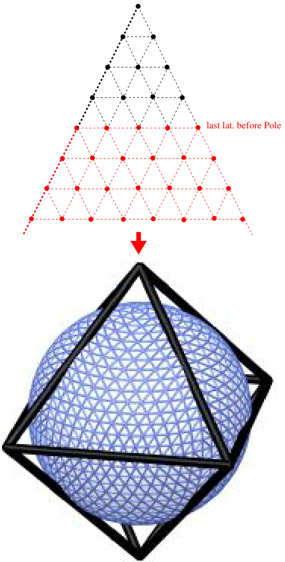
What is the octahedral grid?

It is a reduced Gaussian grid with the same number of latitude circles (*NLAT*) than the standard Gaussian grid (↔ Gaussian weights) but with a new rule to compute the number of points per latitude circle.

Number of points per latitude

NLOEN(lat_N)=20 → Poles
NLOEN(lat_i)=NLOEN(lat_{i-1})+4

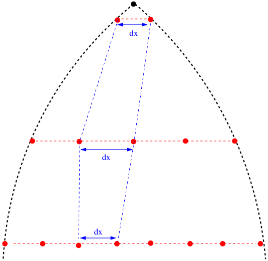
TL1279 :2.14 Mpoints
TC1023 :5.45 Mpoints
TC1279 :8.51 Mpoints
TCo1279 :6.59 Mpoints

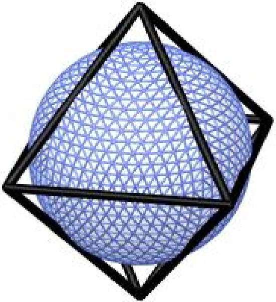


What is the octahedral grid?

- more continuous reduction of NLOEN(lat_i), no more jump between blocks of latitudes of constant NLOEN
- abandon FFT992 (NLOEN factor of 2*3*5) for the public domain FFTW

With this new rule, the zonal resolution varies more with the latitude than for the standard reduced Gaussian grid.

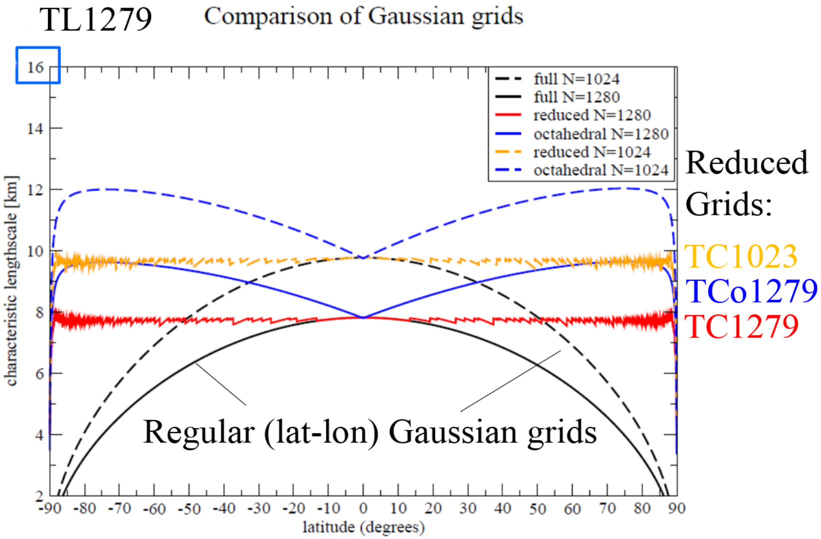




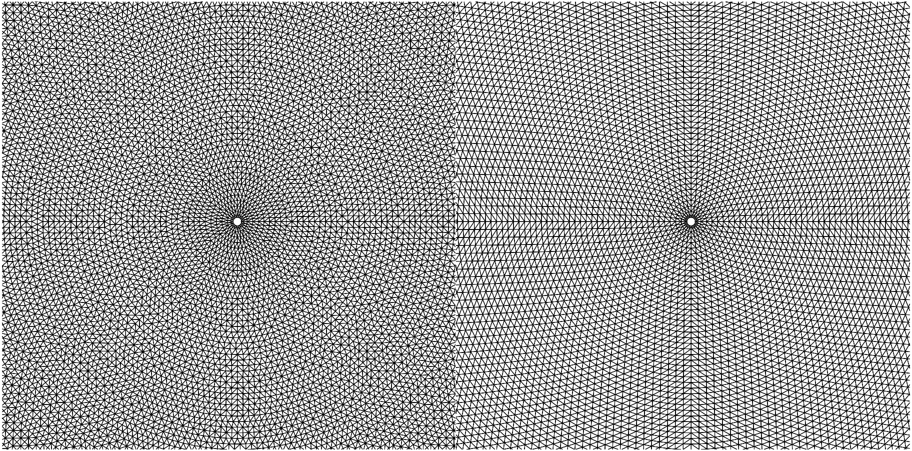
Resolution of the octahedral grid?

In theory, the octahedral grids could be used for linear, quadratic or cubic resolutions but, IN PRACTICE, the rtables and the climate files exist only for cubic resolutions: TCo1279.

Resolution of the octahedral grid?



Resolution of the octahedral grid?

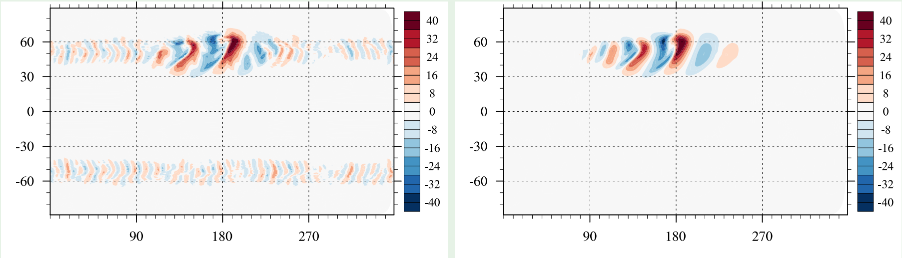


Standard Reduced Gaussian grid   Octahedral Reduced Gaussian grid

TCo for Grid Point Only numerics option in a future IFS

- improve GP local derivative calculation on a reduced Gaussian grid
- available in Atlas library (enters the IFS from CY41R2)

Baroclinic instability with PantaRhei (Christian Kühnlein)



Standard Reduced Gaussian grid

Octahedral Reduced Gaussian grid

What does horizontal resolution mean?

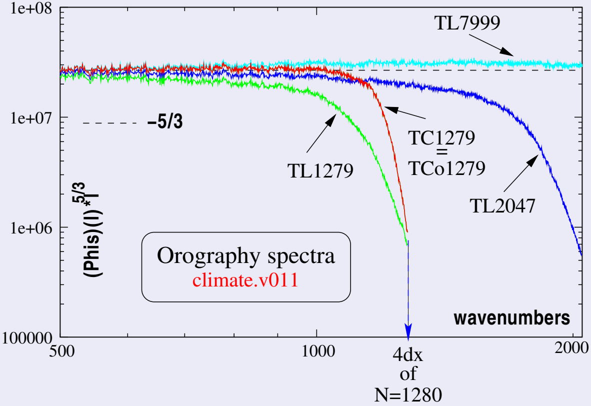
Horizontal resolution upgrade?

- increase the number of wavenumbers but keep the same grid: what we did in 1999,
- add new wavenumbers in the series of $Y_{l,m}$, keeping the same pairing rule ($NSMAX \nearrow$, $NLAT \nearrow$): what we did in the last 15 years,
- keep the same number of wavenumbers and resolve them better in grid point space ($NSMAX = cste$, $NLAT_{lin} \Rightarrow NLAT_{cub}$): what we have done for the next resolution upgrade.

What does horizontal resolution mean?

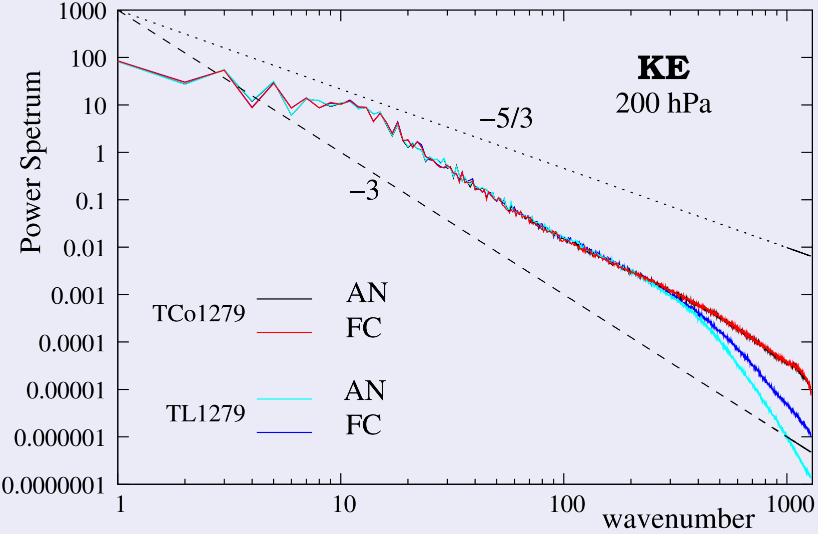
Resolve more processes (finer description of the surface, filter and parametrise less, use NH...)

IFS spectral orography



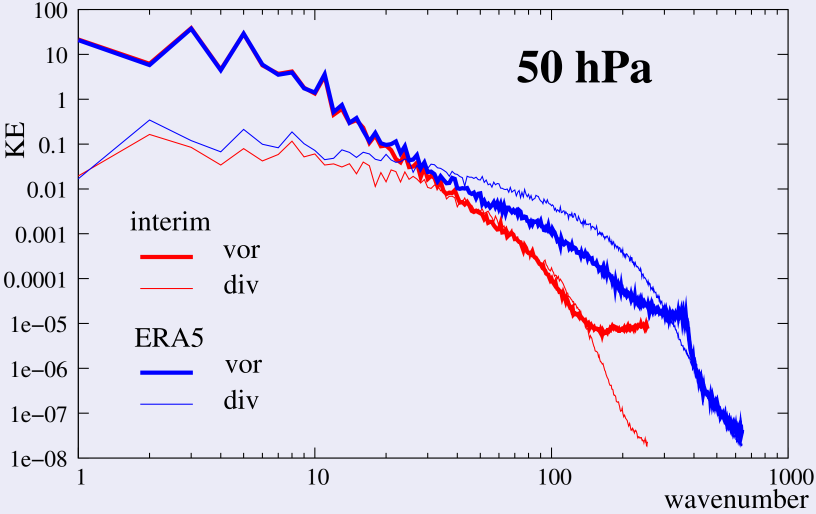
What does horizontal resolution mean?

KE spectra at TL1279, TCo1279



What does horizontal resolution mean?

KE spectra at 50 hPa for ERA5 (CY41r2,TL639) and ERA-interim (CY31r2,TL255)



Do we need a non-hydrostatic IFS yet?

Validity of the hydrostatic approximation

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

If $\mathcal{H} = 10$ km (height of tropopause), then hydrostatic valid for

$$\mathcal{L} >> 10 \text{ km}$$

Common interpretation : Hydrostatic valid for $\Delta x > 10$ km

With TCo1279 $\Rightarrow \Delta x \simeq 9$ *km*, do we need a NH model?

Hydrostatic approximation

$$\begin{aligned}\frac{Dw}{Dt} &<< [-\frac{1}{\rho}\frac{\partial p}{\partial z} - g] \Rightarrow w \text{ diagnostic} \\ p &= \pi \\ & \Rightarrow \text{adjustement to hydrostatic equilibrium} \\ & \text{faster than a time step}\end{aligned}$$

- vertical velocity is not zero in an hydrostatic model, it is diagnostic (i.e. w constrained by the (hydrostatic) evolution of the other variables),
- vertical acceleration is not zero either
- the hydrostatic asumption remains valid when w diagnosed by the hydrostatic system remains similar to w prognosed by the NH system. If the vertical accelation becomes very large in the hydrostatic model, the solution given by the hydrostatic model differs from the NH solution.

What is it we want to capture with a NH model that we don't have with an hydrostatic model?

Hydrostatic model

In an hydrostatic model, the adjustement to hydrostatic balance is supposed to be much faster that the time step.
Sub-time step, unresolved transient processes have been active to restore the balance. These unresolved processes involve mass redistribution, i.e. convergent/divergent ageostrophic wind and vertical velocity acceleration driven by small scale NH pressure gradient forces. The “resolved” state of the atmosphere never sees them explicitly as it is always supposed to be in hydrostatic balance.

Non-hydrostatic model

A NH model is able to resolve explicitly these transient processes if the space and time resolutions of the model are fine enough to resolve them. If not, the NH model must give the same results as the hydrostatic model.

H and NH versions of the IFS

Operational dynamical core: primitive equation

Operational version of the IFS: Primitive equations (hydrostatic), spectral semi-implicit, semi-Lagrangian, reduced Gaussian grid, hybrid vertical levels $p(\eta) = \pi(\eta) = A(\eta)\pi_{oo} + B(\eta)\pi_s$, IFS physics package

Euler equations

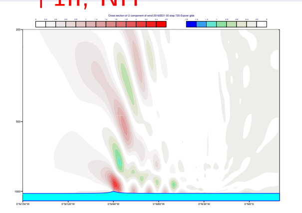
A non-hydrostatic fully compressible set of equations has been developed for the limited area version of the IFS dynamical core ALADIN/AROME/HARMONIE (Bubnova et al, 1995) which has been adapted for the global dynamical core (Wedi et al, 2009): spectral semi-implicit, semi-Lagrangian, reduced Gaussian grid, hybrid vertical levels $p(\eta) = A(\eta)\pi_{oo} + B(\eta)\pi_s$ where π is the hydrostatic part of the true pressure p, IFS physics package.

- 2 more prognostic variables, w (in practice, the vertical term of the 3D divergence) and the NH pressure departure $\ln(\frac{p-\pi}{\pi})$
- predictor/corrector scheme: double cost of dynamics

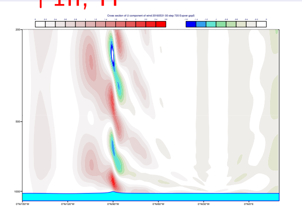
Academic Mountain waves

Montain waves on small planet (γ=200), $\Delta x = 250$ m

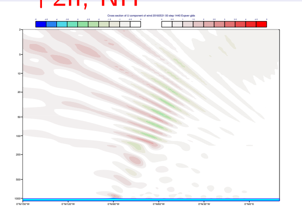
+1h, NH



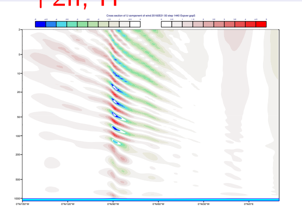
+1h, H



+2h, NH



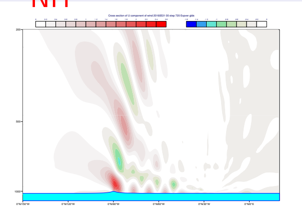
+2h, H



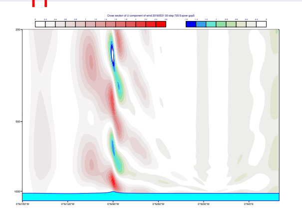
Academic Mountain waves

Montain waves on small planet (γ=200), Δx = 250 m

NH

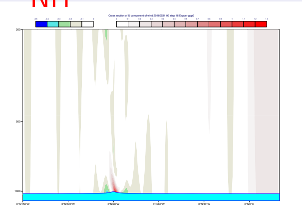


H

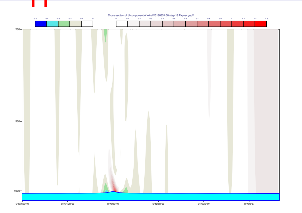


Montain waves on small planet (γ=5), Δx = 10 km

NH

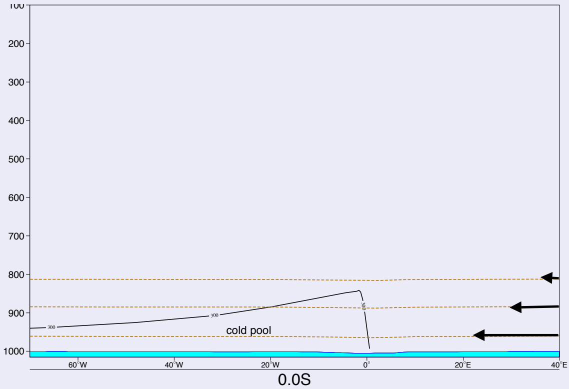


H



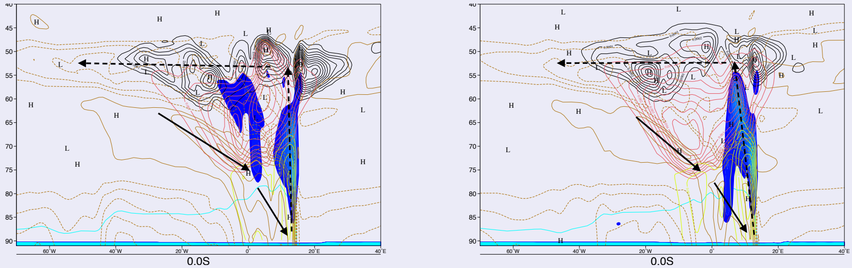
Academic explicit squall line - Initial conditions

Weisman et al (1990): Cold pool in a wind shear environment



Explicit squall line simulations on the small planet at 3 km resolution

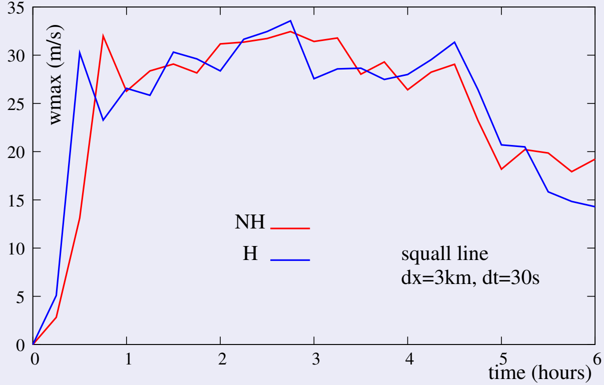
after 5 hours of hydrostatic (left) and NH (right) simulations



The black arrows emphasise the mesoscale circulation characteristic of the squall line.

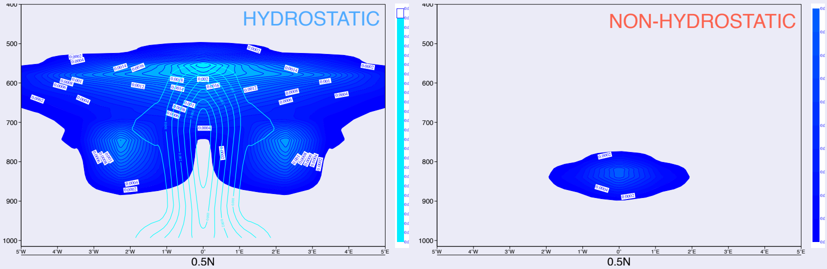
Explicit squall line simulations on the small planet at 3 km resolution

Maximum vertical velocity

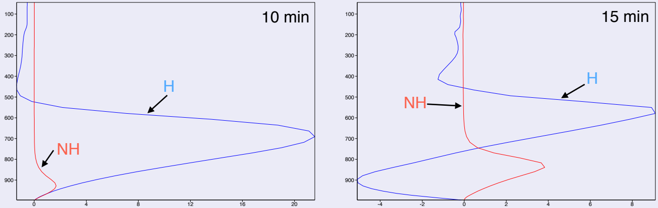


Explicit convective cloud at 500 m resolution

$q_l + q_i$ (shading) and q_r (cyan isolines) after 15 min



vertical velocity at the centre of the bubble

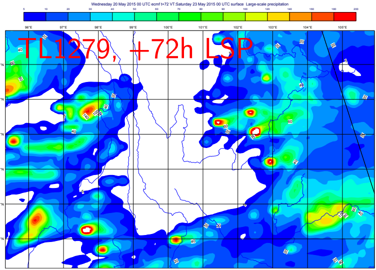


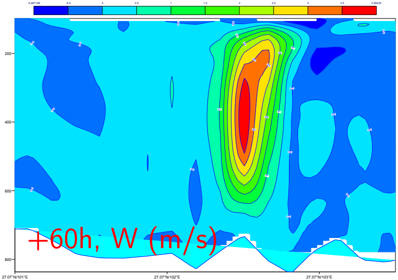
- The IFS hydrostatic dynamics + the IFS prognostic cloud scheme permit deep moist convective ascent (and descent) which are very similar to the NH ones until resolutions of 5 (maybe 3) km.
- The tuning of the model physics and dynamics may change the solution as much as H versus NH.

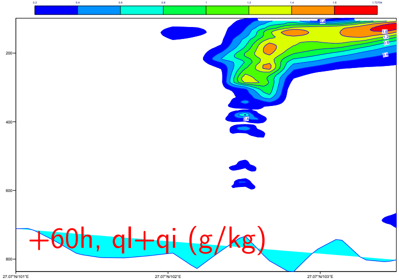
TCo1279 $\Rightarrow \delta x \simeq 9\ km$.
Hydrostatic IFS is able to simulate large vertical velocity.

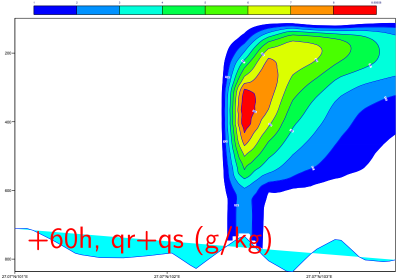
Do we start resolving deep convection at TCo1279 in the IFS?

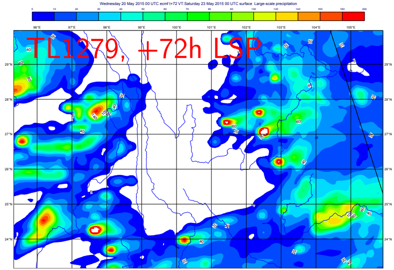
Actually, we already do sometimes at $\Delta x = 16$ km. But it is by accident!



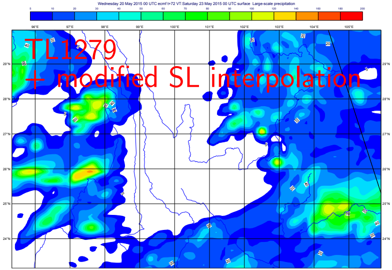




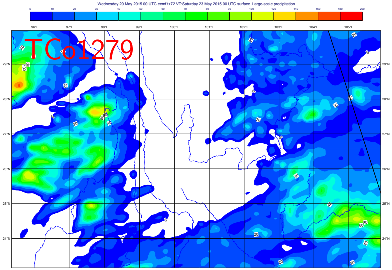




TL1279, +72h LSP



TL1279
+ modified SL interpolation



TCo1279

Impact of resolution on intense convective system simulation

Severe event near Cannes on Oct. 3rd 2015 at 21UTC