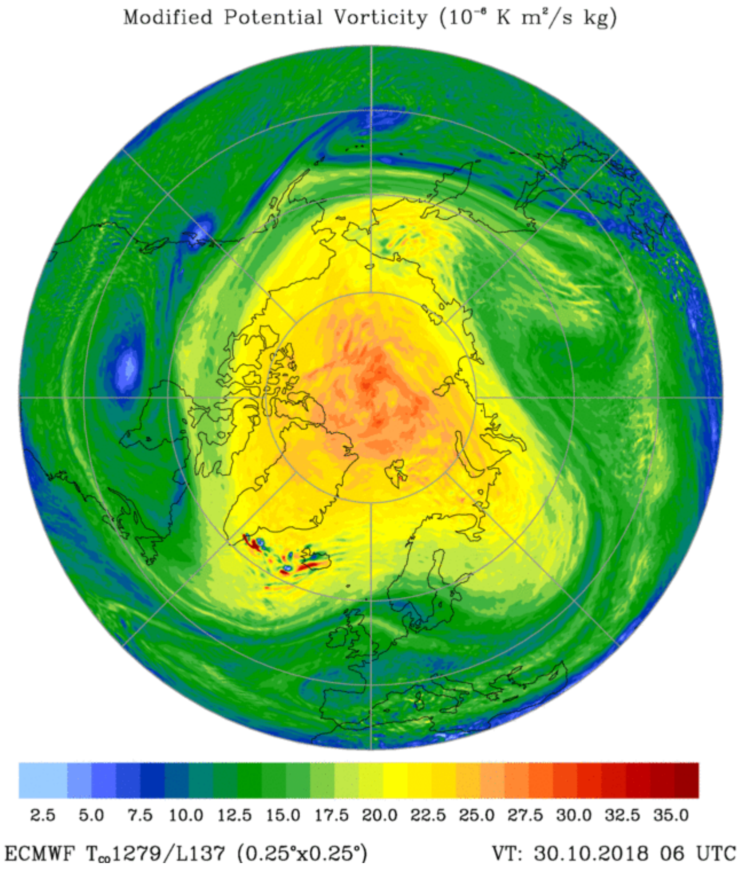
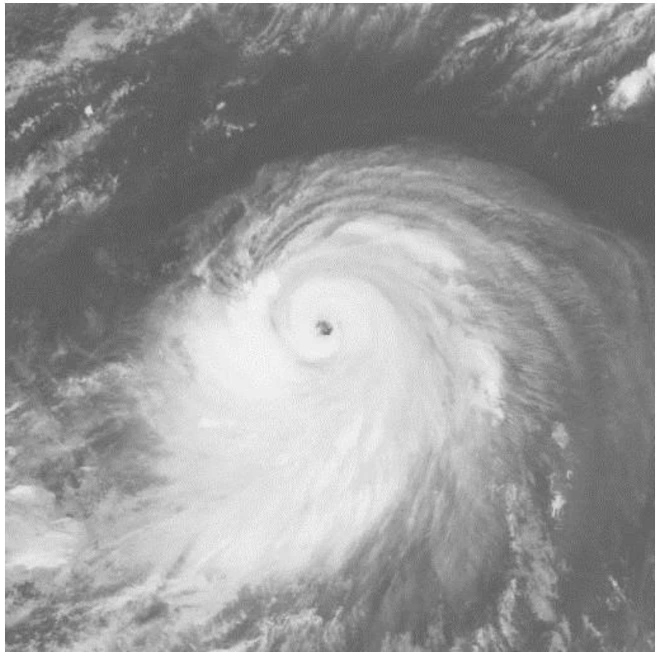
Resolution, hydrostatic and non-hydrostatic dynamics and resolved convection



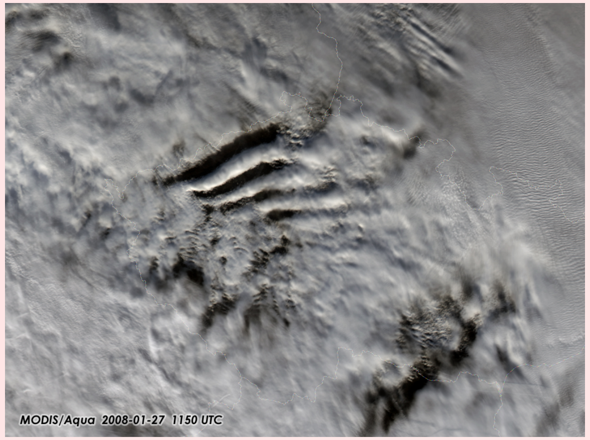
Inna Polichtchouk

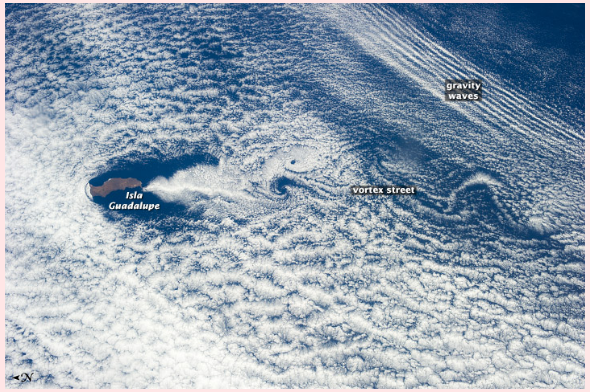
With thanks to: Sylvie Malardel, Jozef Vivoda and Jan Masek

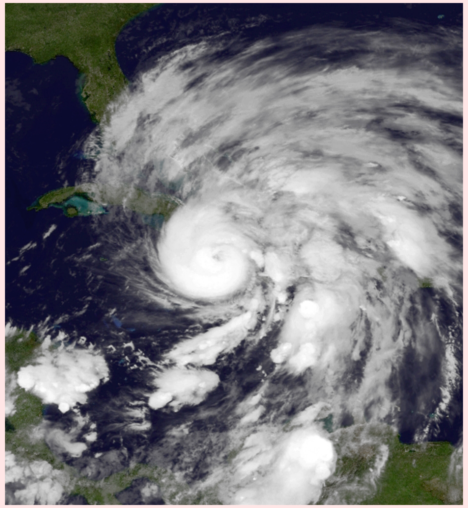


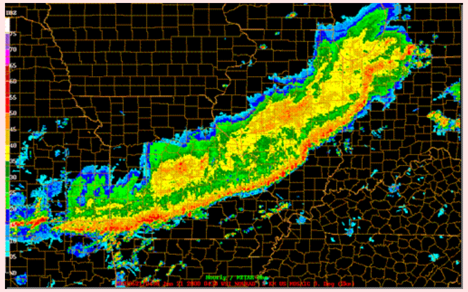
Why higher and higher resolution?

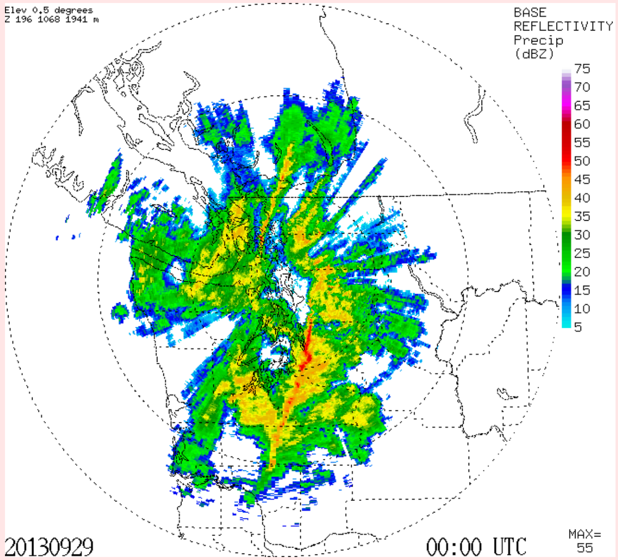
Resolve more processes → Important for impacts

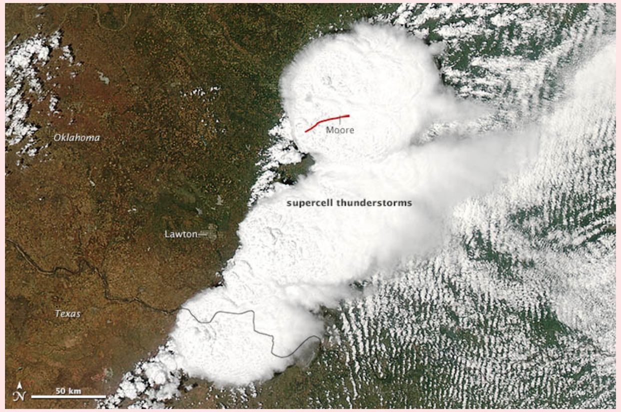




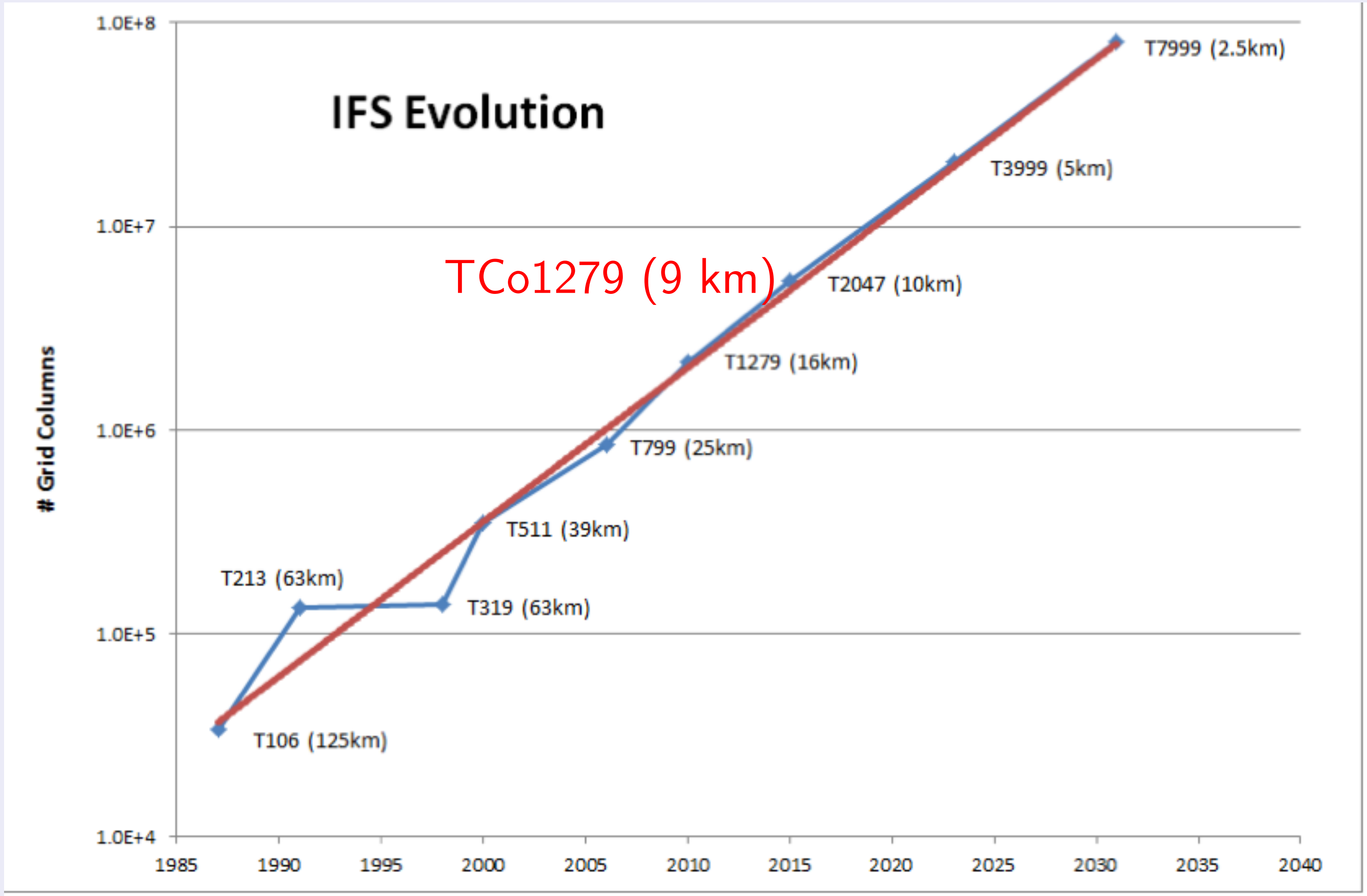








Towards very high resolution global NWP model



What do we mean by horizontal resolution?

A bit about spectral semi-Lagrangian IFS

Integrated Forecast System (IFS) dynamical core

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

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, $NSMAX = 1279$.

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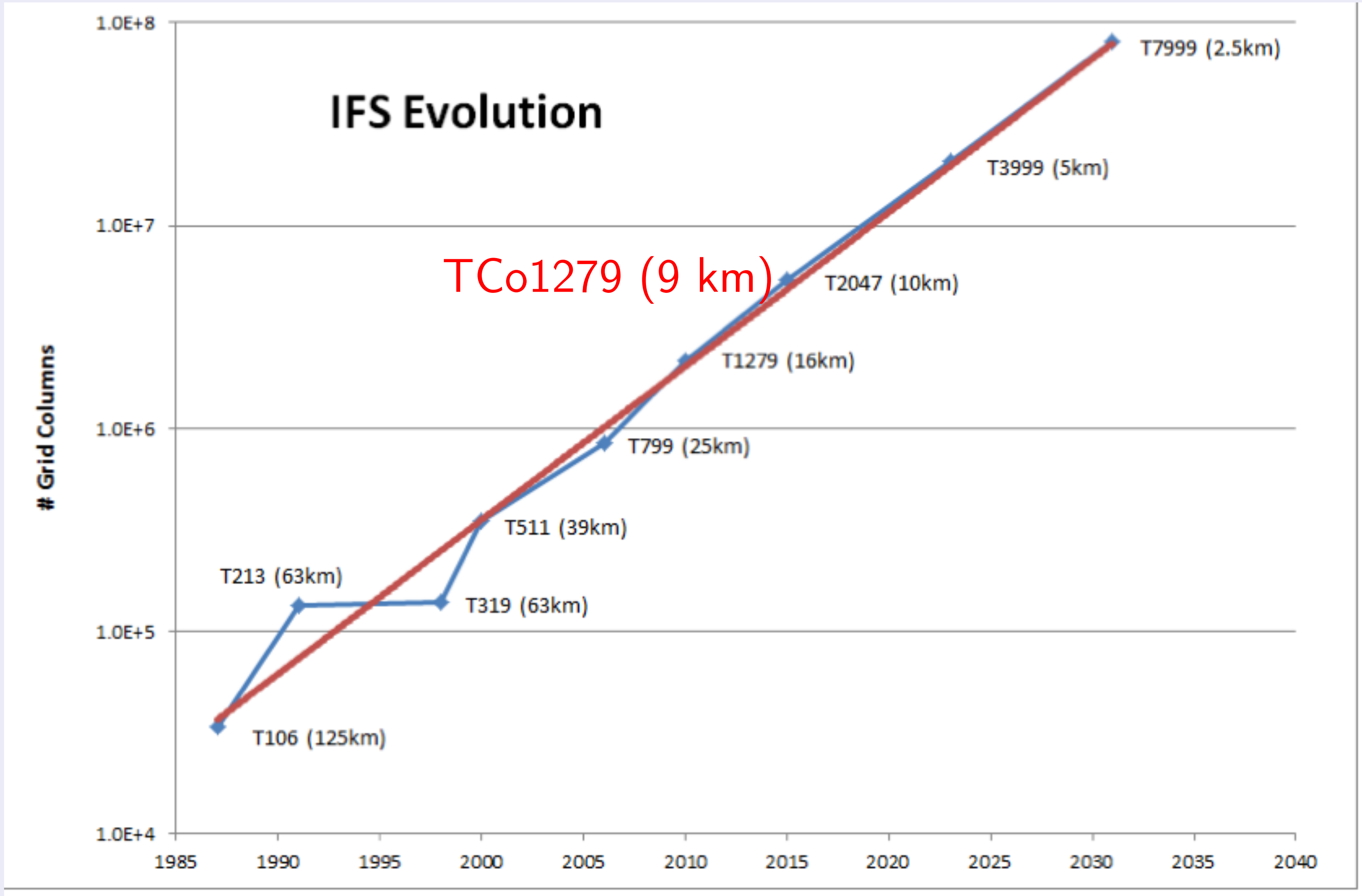
$NSMAX$ is the spectral truncation. **This is the 'T' in T1279 etc.**

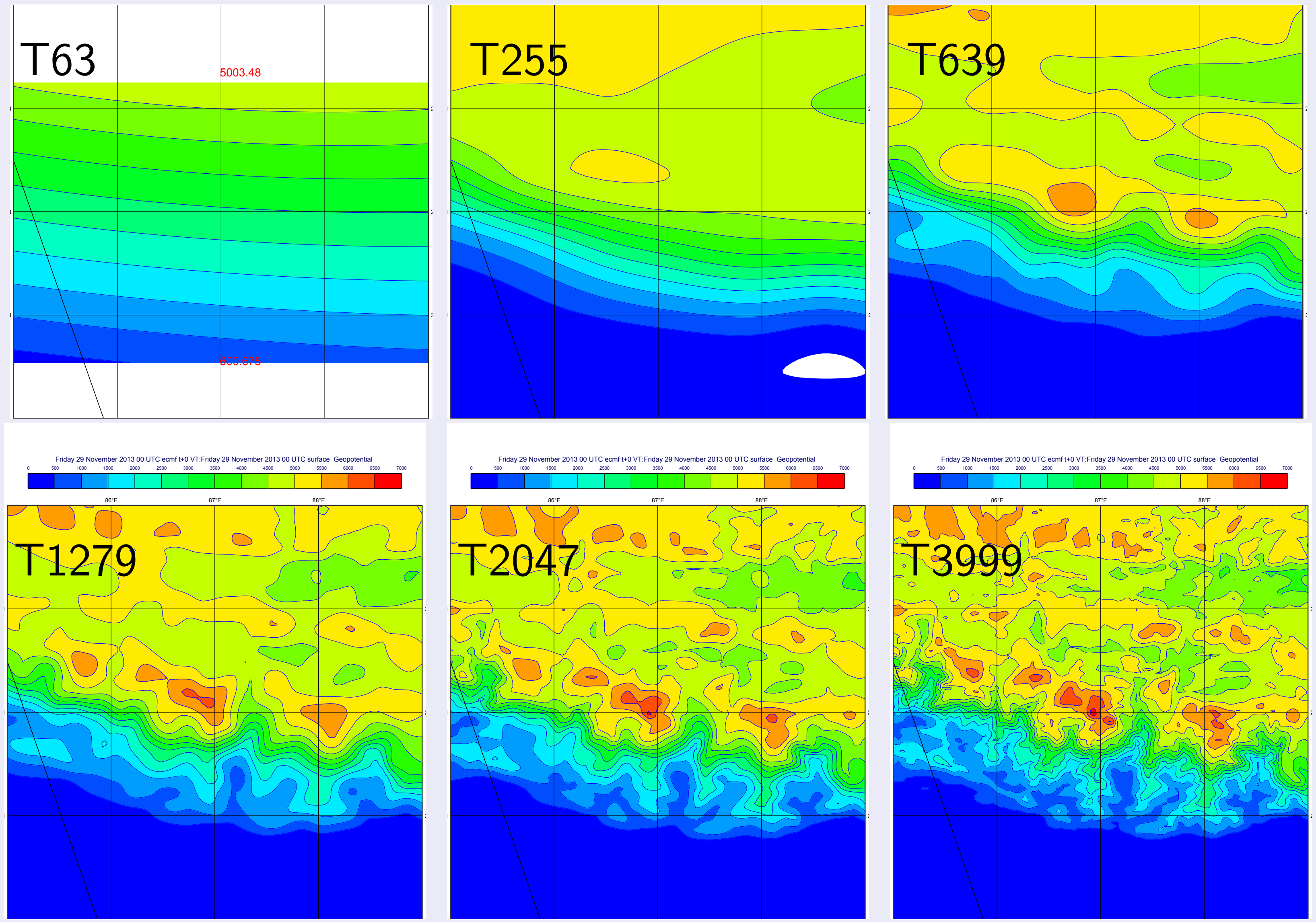
Currently, in the IFS, $NSMAX = 1279$.

Towards very high resolution global NWP model



Why higher and higher resolutions?

More details, more realism: z_s around Mount Everest



Spectral vs. grid point representation in the IFS

- **Derivatives, dissipation and semi-implicit solver** calculated in **spectral** space. Only VOR, DIV, T_v and p_s have spectral representations.

- **Nonlinear terms and semi-Lagrangian advection** calculated in **grid-point** space. Also physical parametrizations applied in grid-point space. → Need a grid to convert from spectral space.

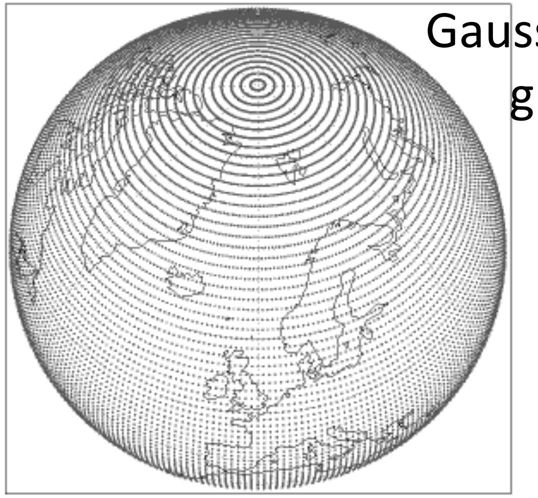
- For every spectral truncation there is a **physical space grid**.

  Next, a bit about physical space grids in IFS….

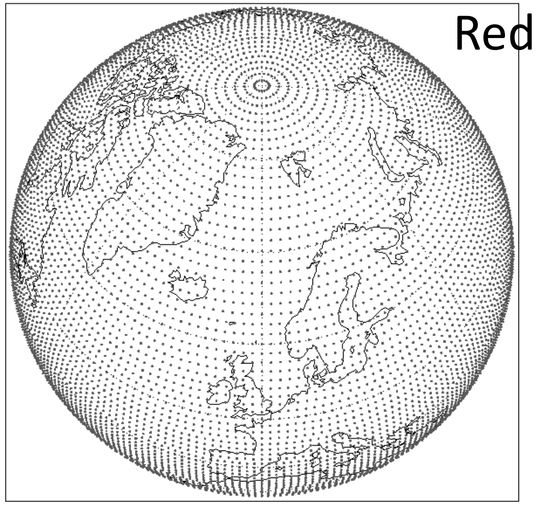
IFS grids

Gaussian grids

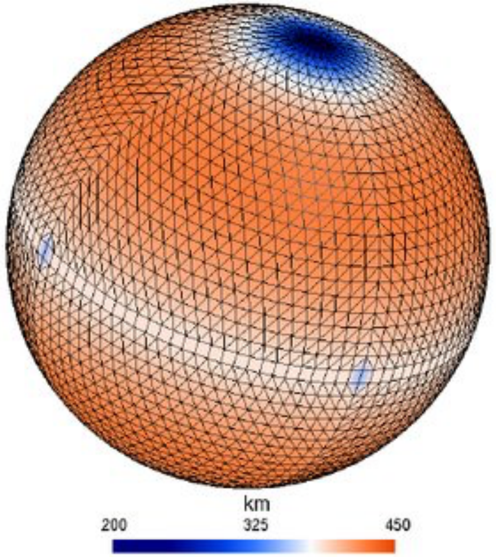
- regular (full): same number of points along each latitude circle (i.e. crowded near the poles)
- reduced: number of points per latitude circle decreases towards the poles
  - current "isotropic" grid: $dx \simeq dy$ (i.e. quasi-regular grid spacing, uniform CFL)
  - new Octahedral (or Collignon) mesh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



Gaussian grid



Reduced grid



Octahedral grid

Linear, quadratic or cubic resolutions

Pairing grid/truncation

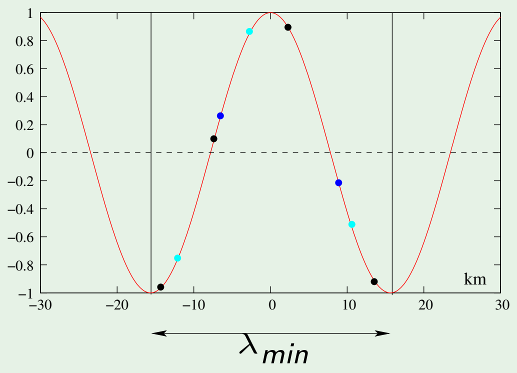
linear: the smallest wavelength $\lambda_{min} = (2 * \pi * RA)/NSMAX$ is sampled on the grid, along the equator, by 2 points $\Rightarrow NDLON_{lin} \simeq 2 * NSMAX$

quadratic: by 3 points $\Rightarrow NDLON_{quad} \simeq 3 * NSMAX$

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

$$T1279 \Rightarrow \begin{array}{l} NDLON_L = 2560 \\ NDLON_Q = 3840 \\ NDLON_C = 5120 \end{array}$$

$NDLON = 2560 \Rightarrow TL1279$ 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.

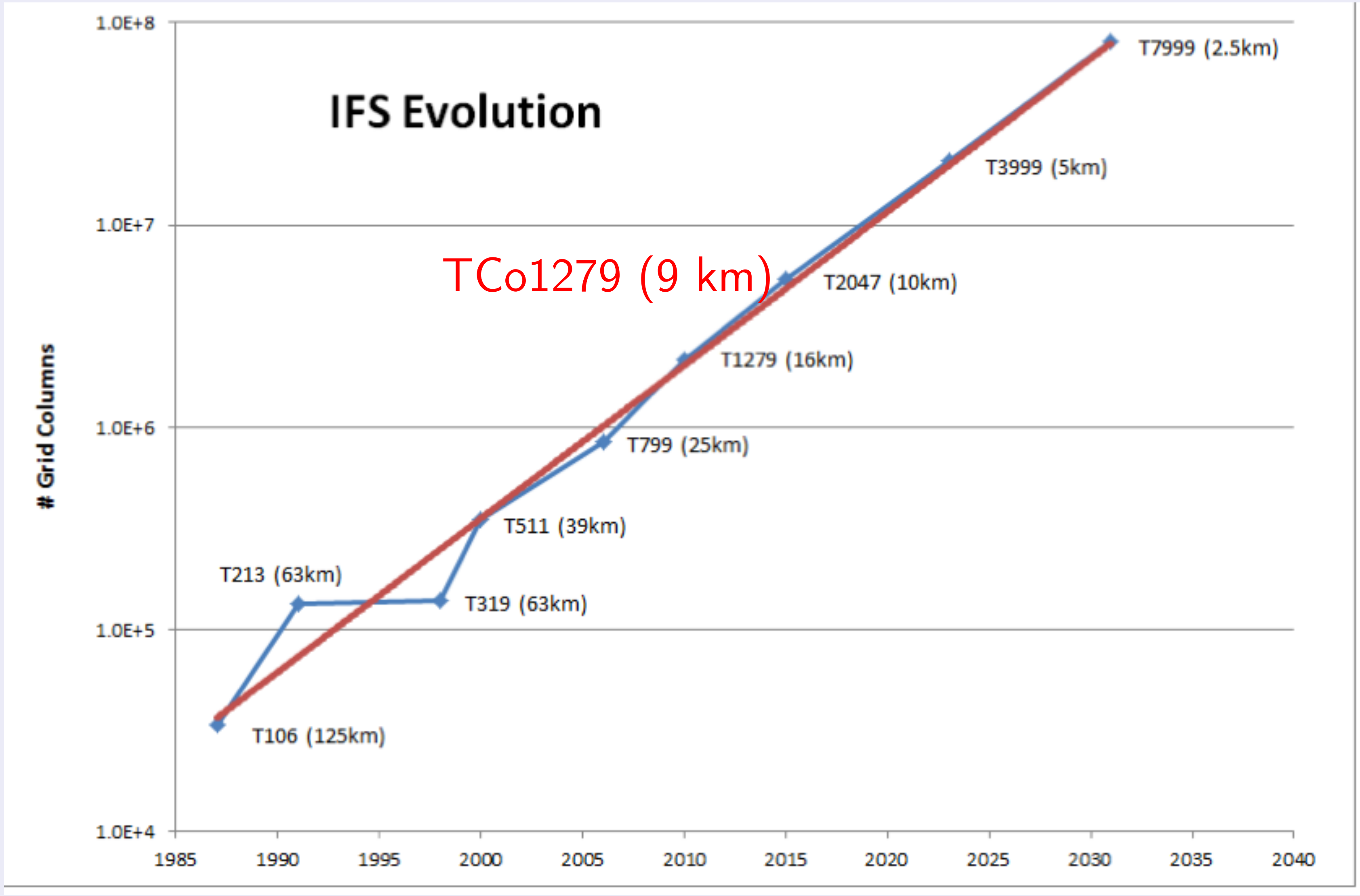
1999: $NDLON = 640 (\Delta x = 63$ km$)$ but $TQ213 \Rightarrow TL319$

Why linear, quadratic, cubic?

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

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

Towards very high resolution global NWP model



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 does horizontal resolution mean?

Horizontal resolution upgrade?

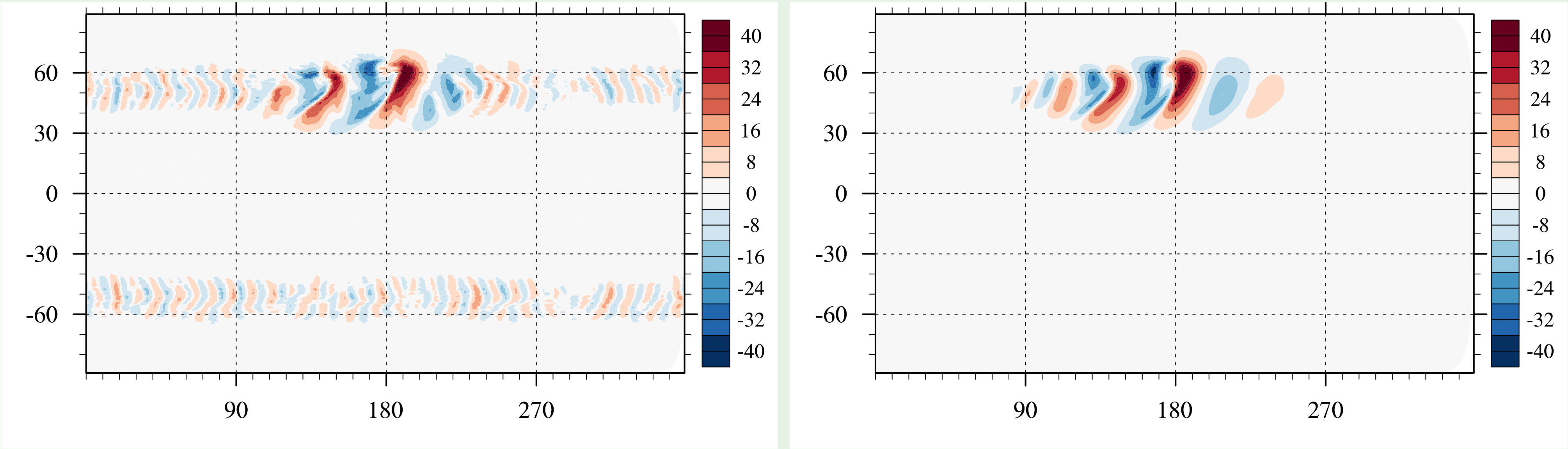
- increase the number of wavenumbers but keep the same grid: what we did in 1999,
- add new wavenumbers in the series of $Y_{l,m}$ according to a fixed type of resolution ($NSMAX \nearrow$, $NDLON \nearrow$): what we did in the last 15 years,
- keep the same number of wavenumbers and resolve them better in grid point space ($NSMAX = cste$, $NDLON_{lin} \Rightarrow NDLON_{cub}$):

This is what is currently done

TCo for Grid Point Only numerics option

- 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

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

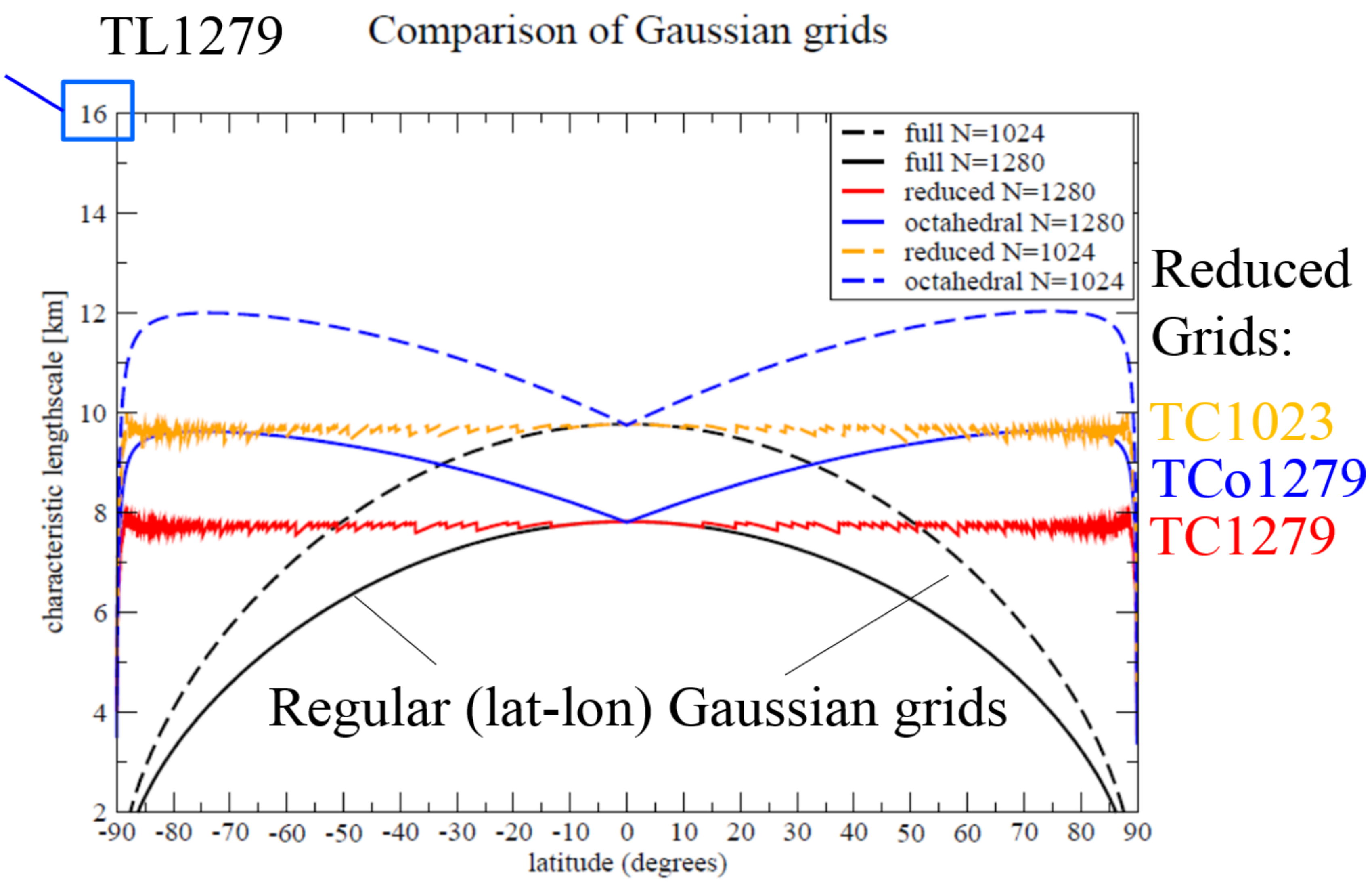
HRES: TCo1279

EDA: TCo639

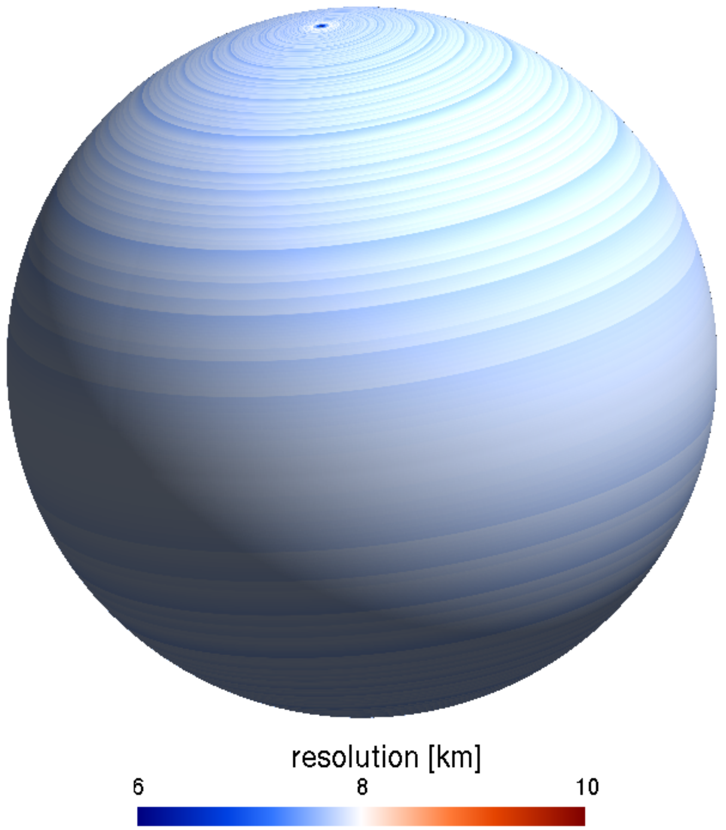
ENS: TCo639/TCo319 (d1-10/d11-30)

What does TCo mean?

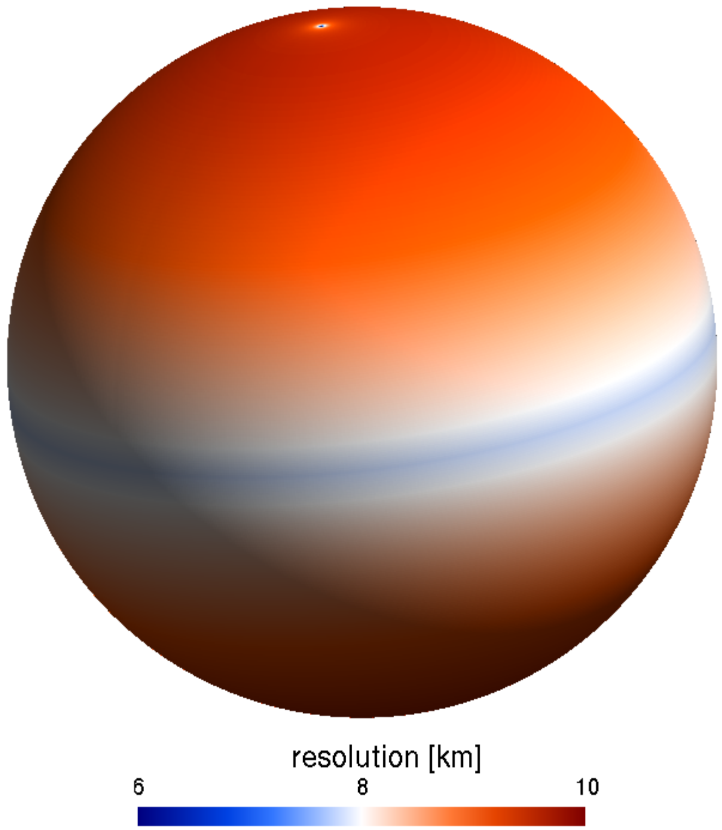
Resolution of the octahedral grid?



Resolution of the octahedral grid?



Standard Reduced Gaussian grid



Octahedral Reduced Gaussian grid

Why higher and higher resolution?

BUT, at the same time,

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

- a more powerful computer,
- a more scalable code,
- faster/more efficient solvers.

finer "climate" files

- 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?)?

Hydrostatic approximation

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

- 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.

Do we need a non-hydrostatic IFS yet?

Validity of the hydrostatic approximation

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

scale height

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?

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

Validity of hydrostatic approximation: Example 1

Convection is a good example to test hydrostatic assumption:

Convection is caused by local imbalance between pressure gradient force (buoyancy) and gravity → likely that hydrostatic approximation will distort evolution of explicitly resolved convective systems

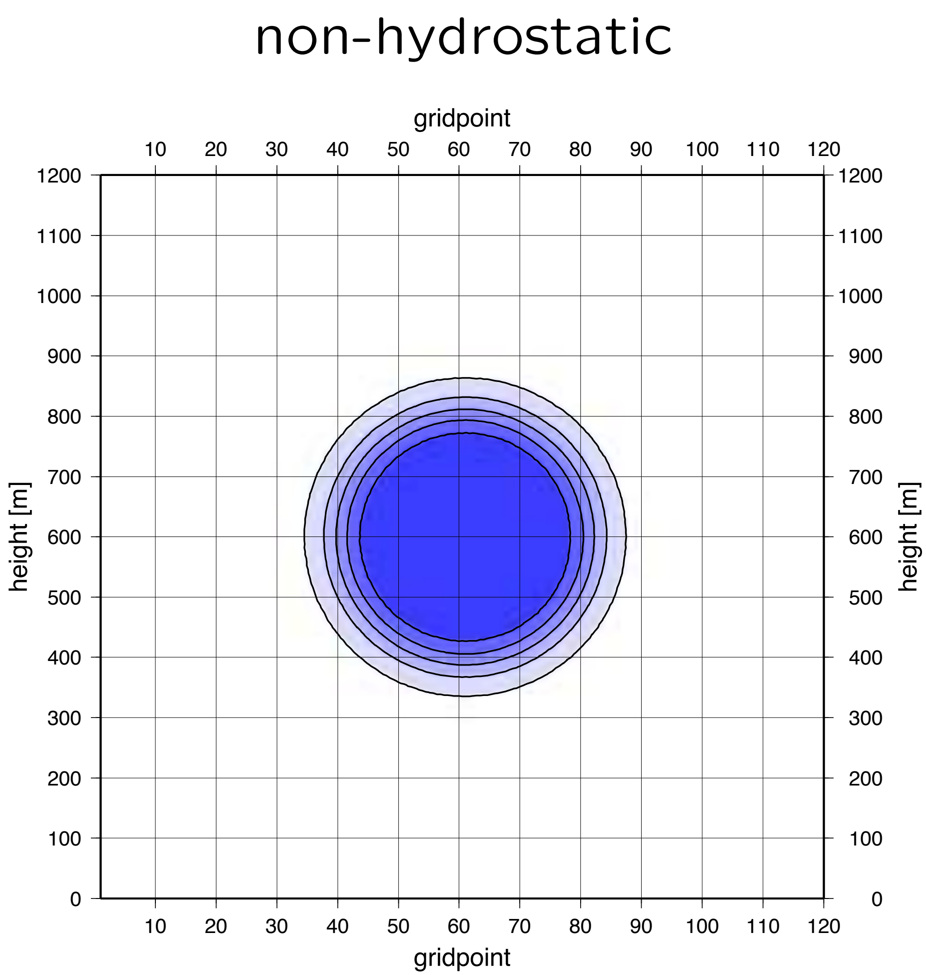
Use the cold bubble test case for convection in 2D-plane with flat orography:

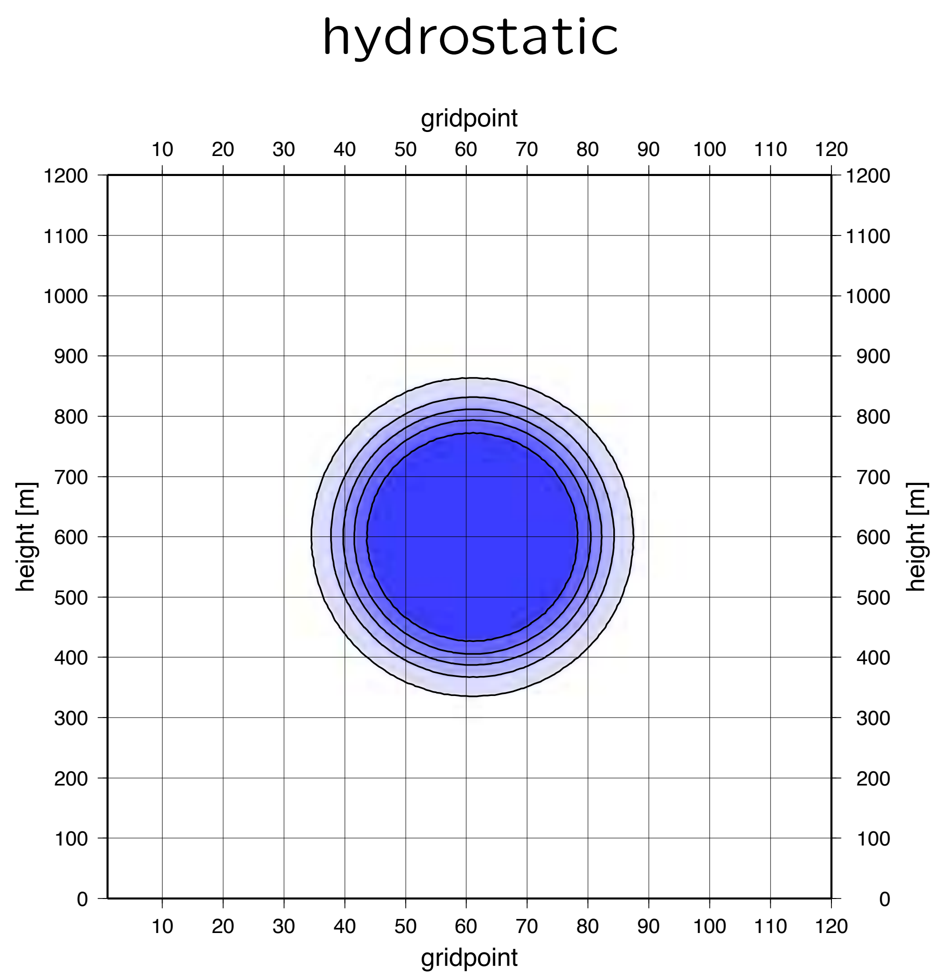
- initial state of rest (u, w = 0), constant surface pressure
- neutral background stratification (θ = const)
- bubble perturbation in initial θ field (θ = θ + θ')
- Size of bubble 100m

Perform numerical simulations with hydrostatic (H) and non-hydrostatic (NH) model at different horizontal resolutions: 1) 10m and 2) 5m.

Simulation results courtesy of: Jozef Vivoda and Jan Masek

perturbation of potential temperature $\theta - \overline{\theta}$

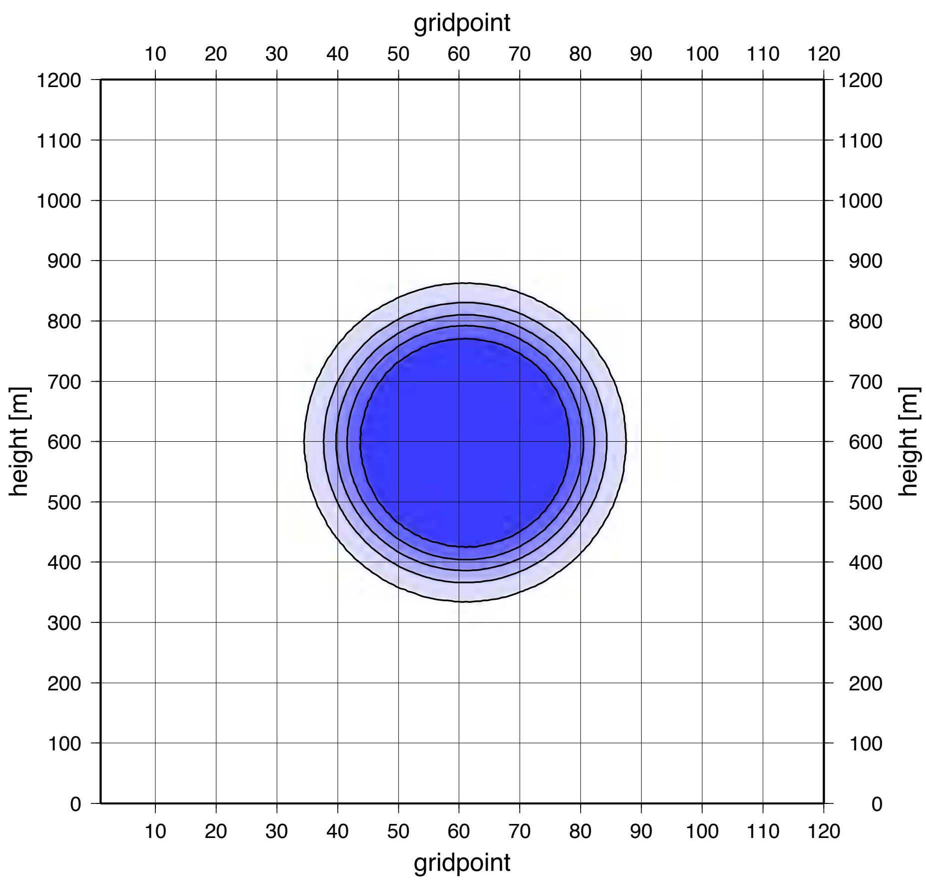




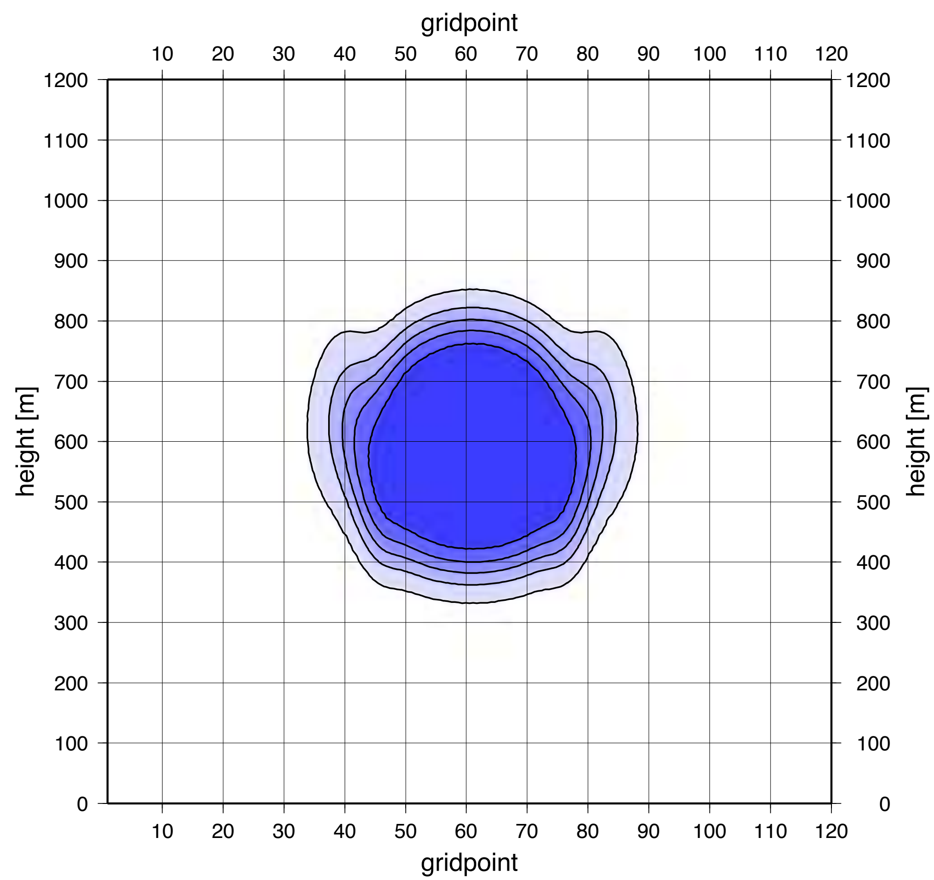
$\Delta x = 10\,\text{m},\ t = 0\,\text{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



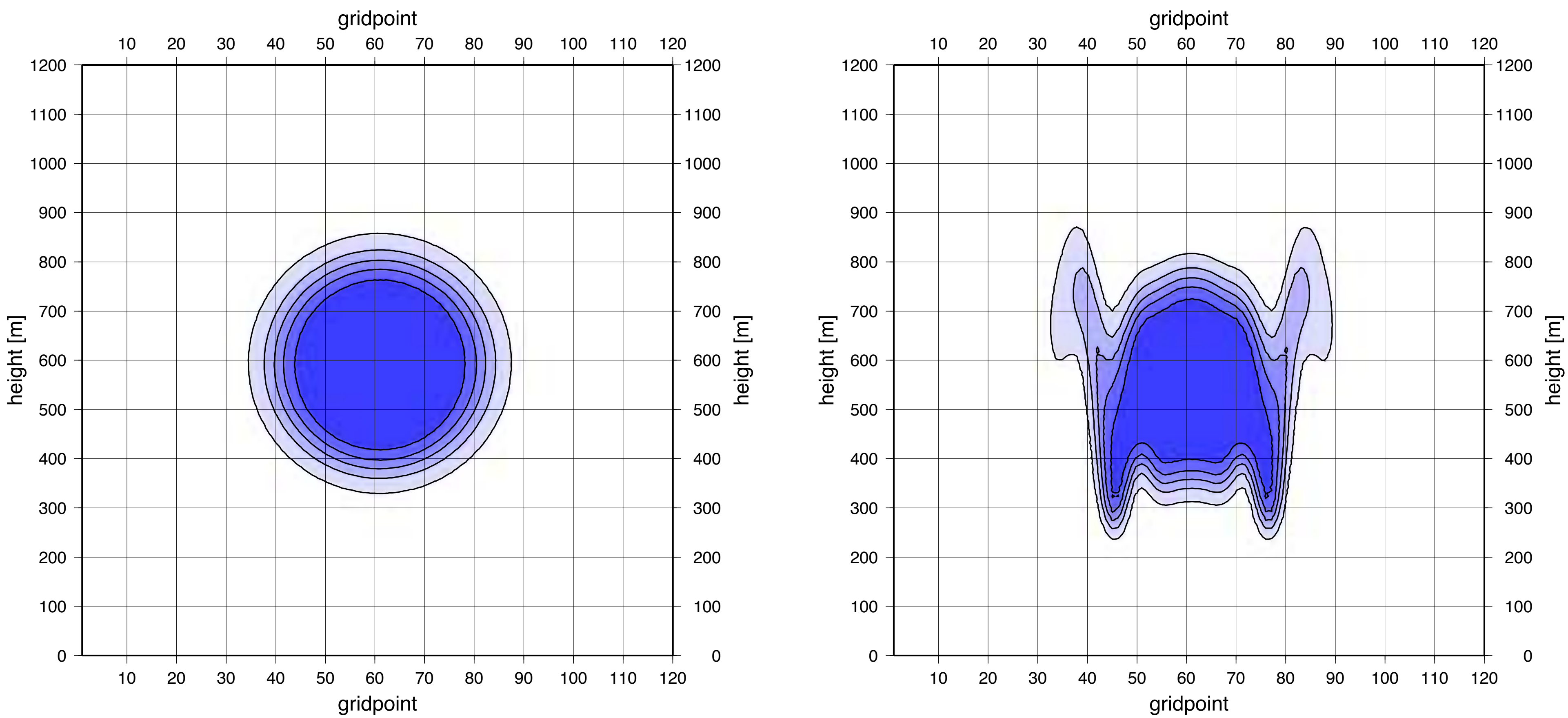
hydrostatic



$\Delta x = 10\,\mathrm{m},\ t = 20\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

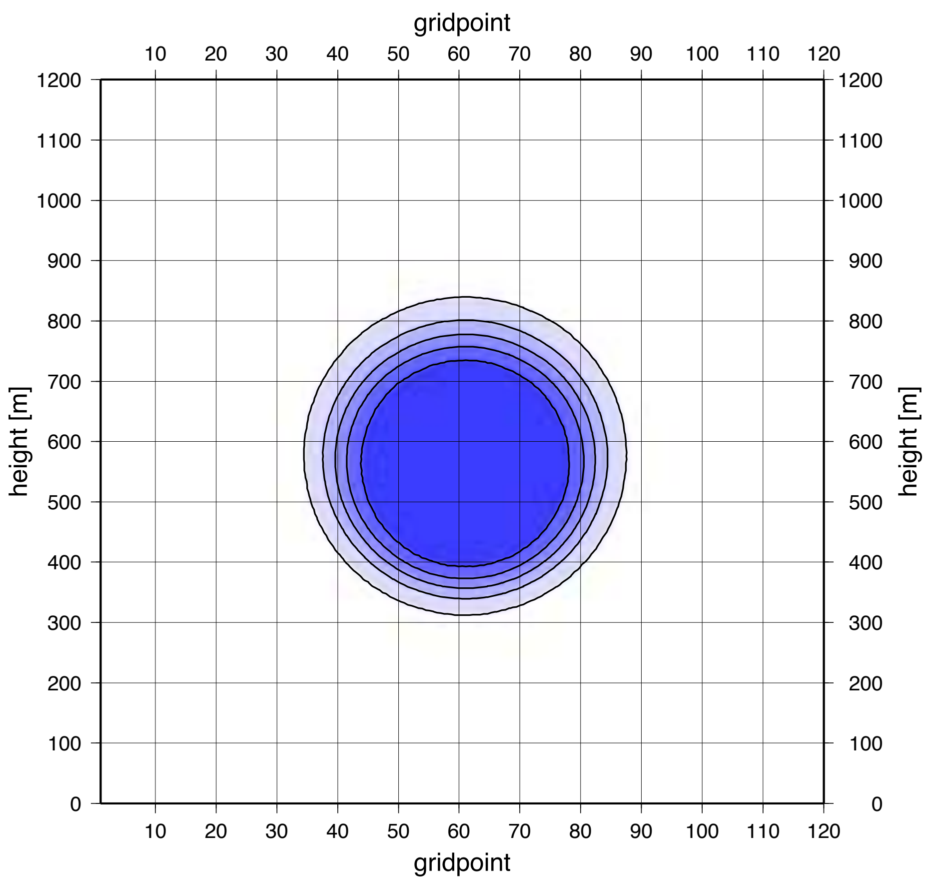
non-hydrostatic | hydrostatic



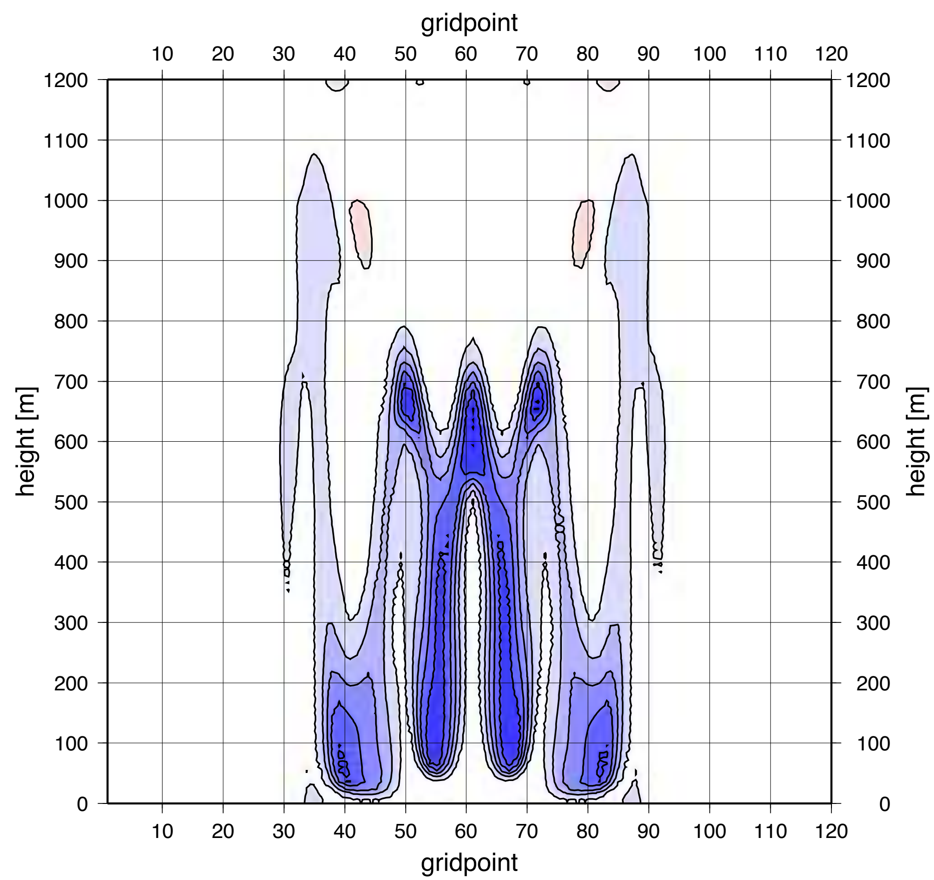
$\Delta x = 10\,\text{m}, \; t = 50\,\text{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic

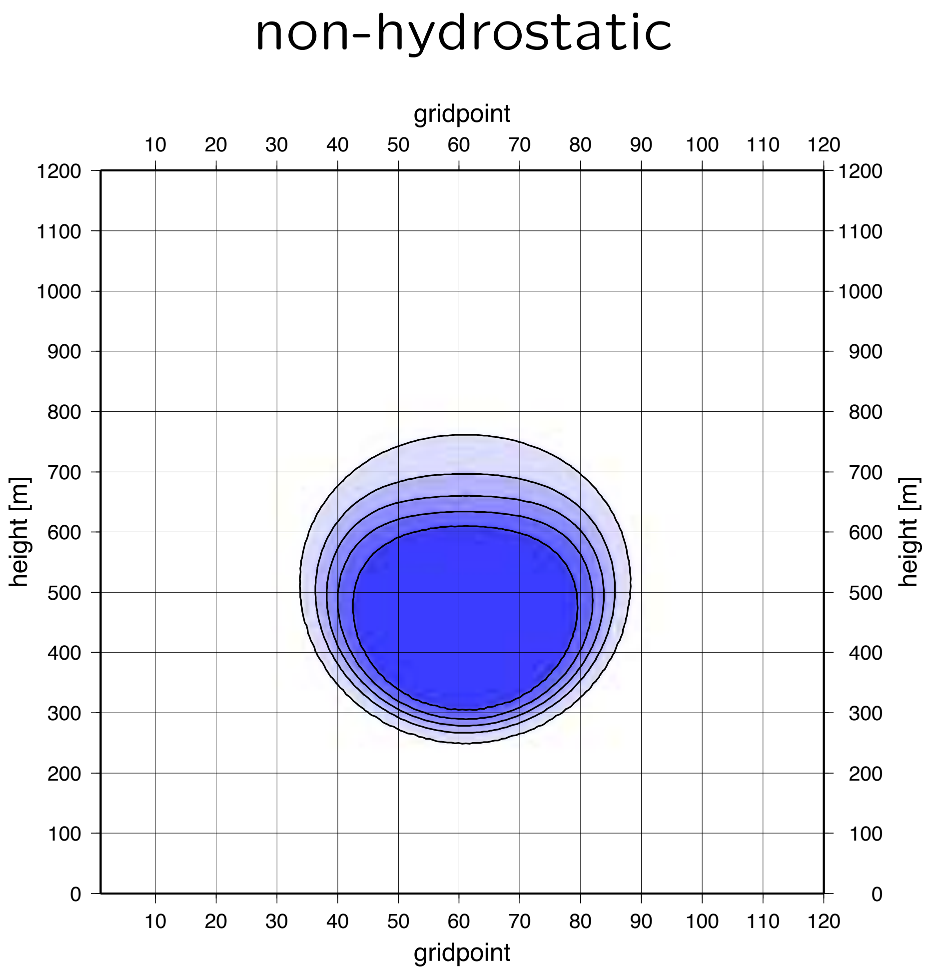


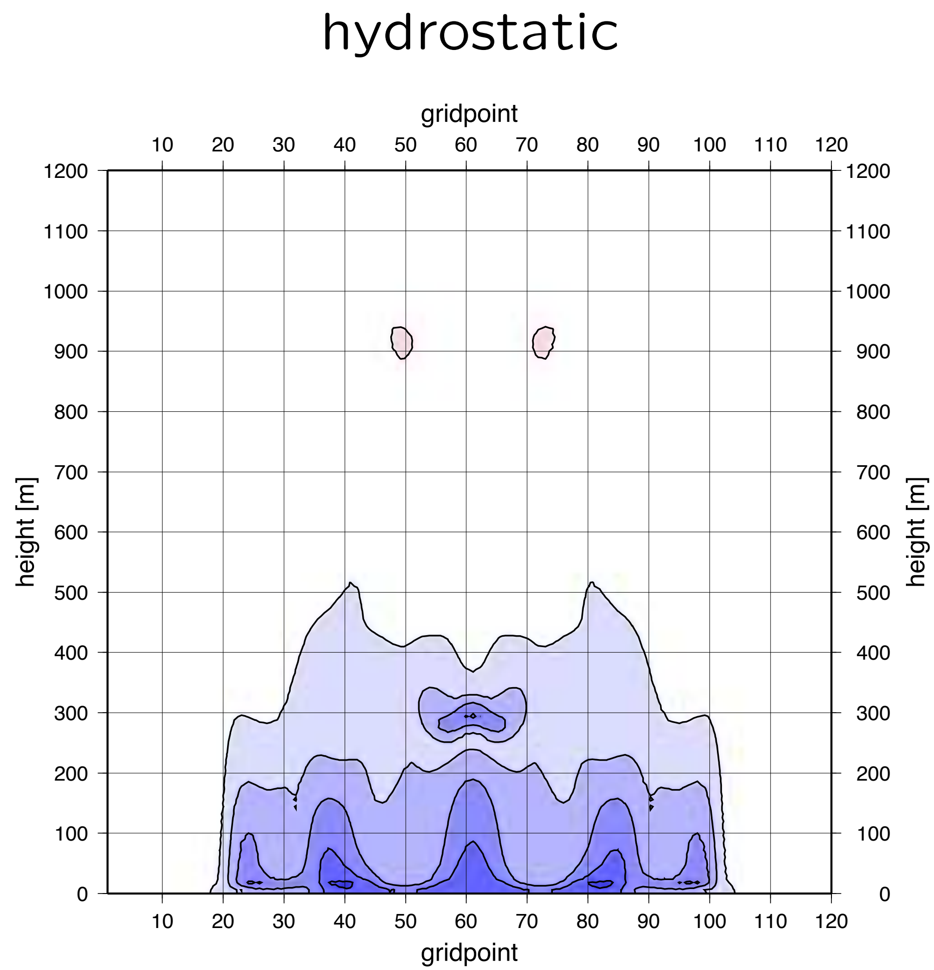
hydrostatic



$\Delta x = 10\,\mathrm{m},\ t = 100\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

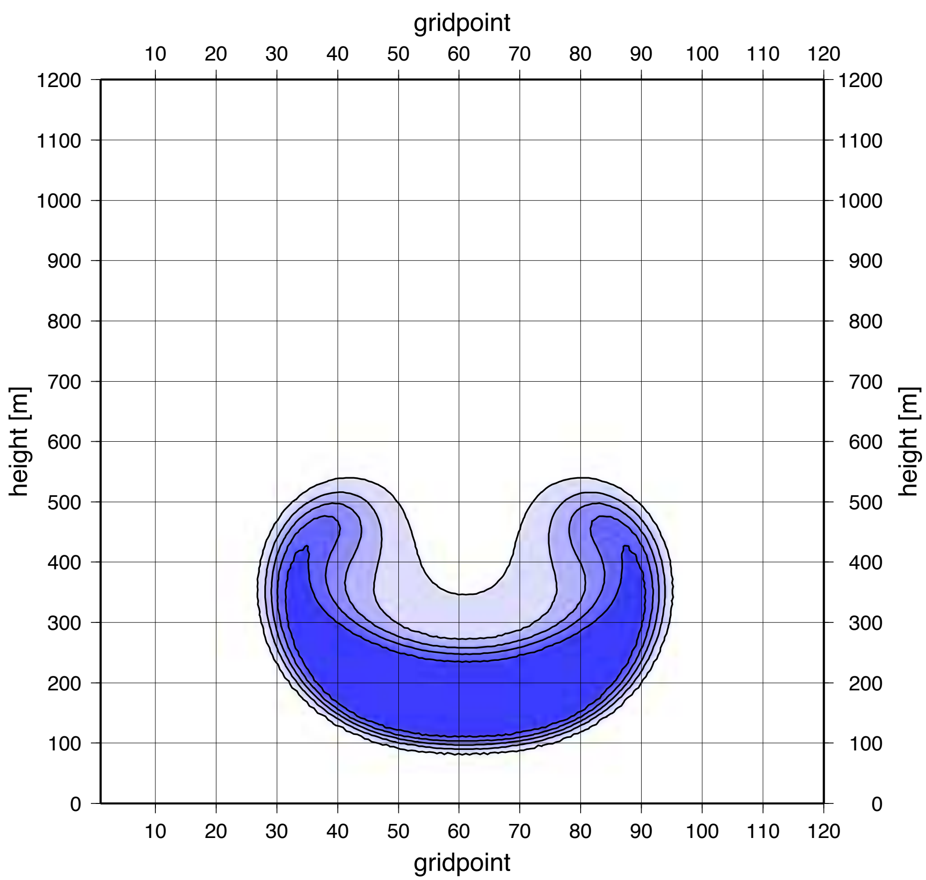




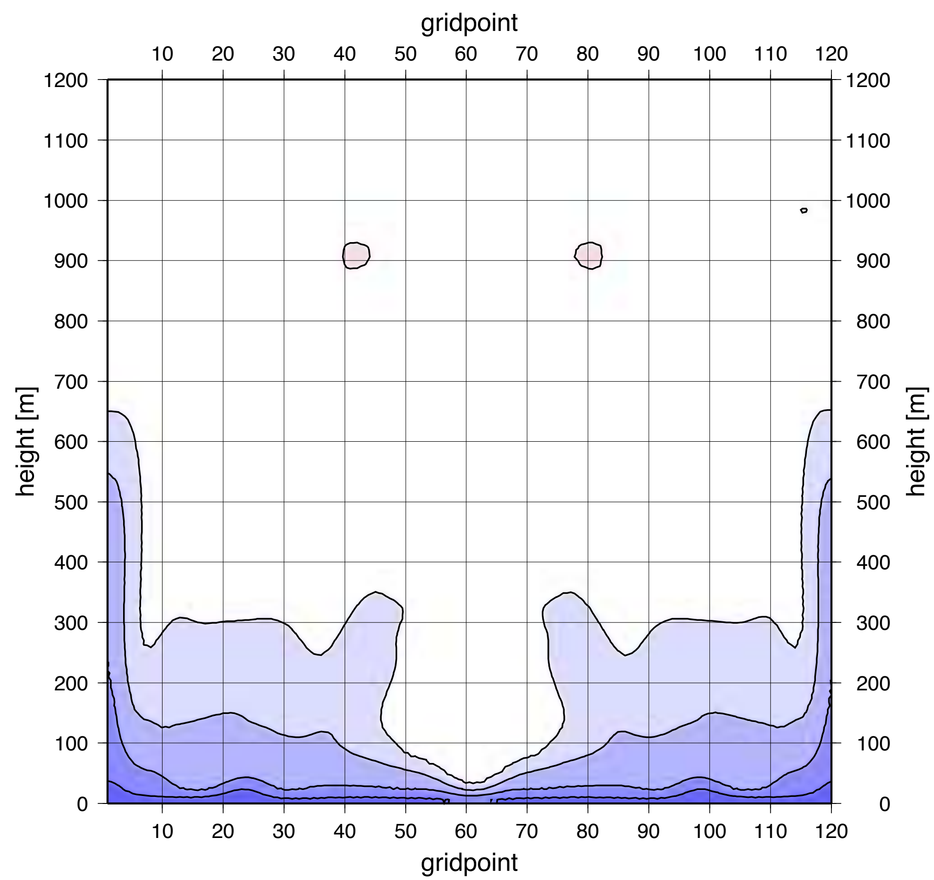
$\Delta x = 10\,\mathrm{m},\ t = 200\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



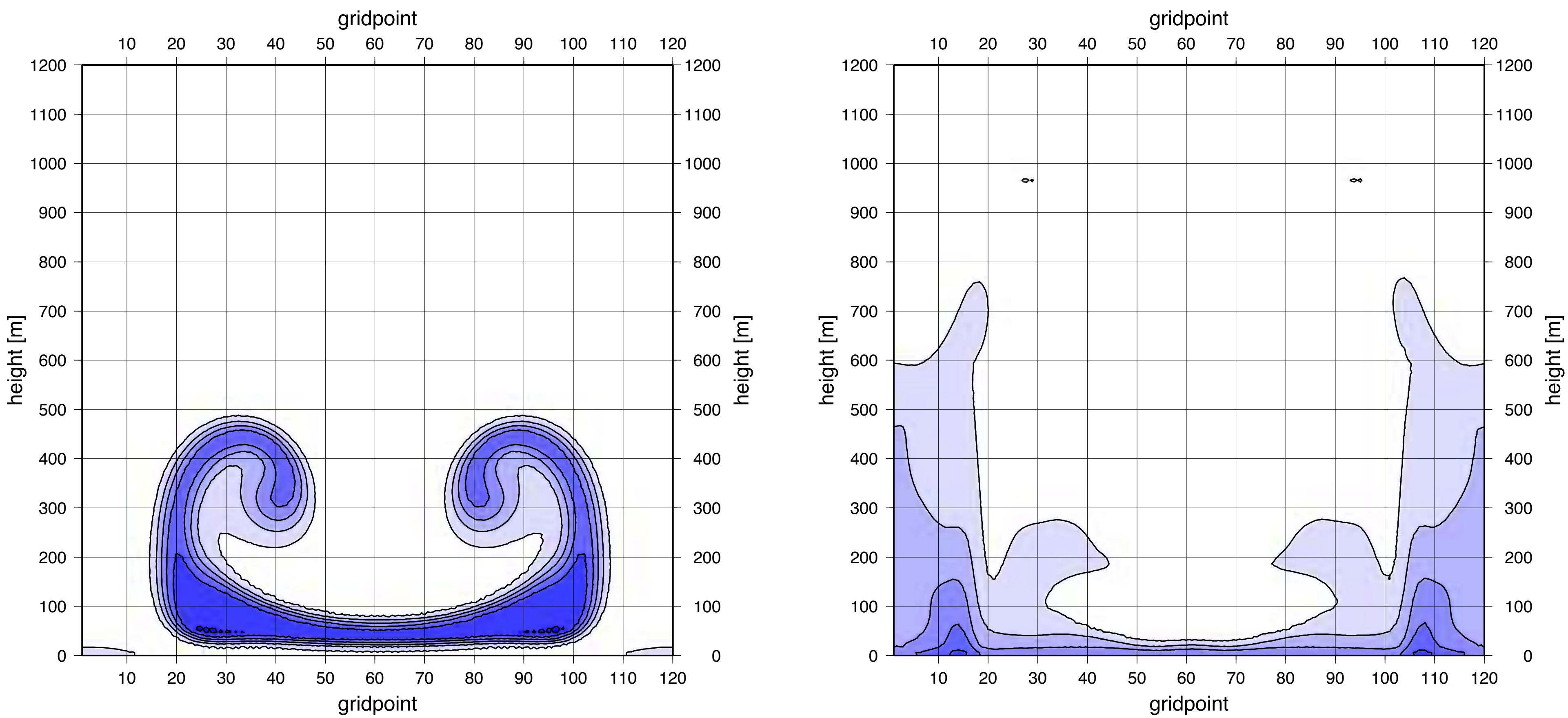
hydrostatic



$\Delta x = 10\,\mathrm{m},\ t = 400\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic | hydrostatic



$\Delta x = 10\,\mathrm{m},\ t = 600\,\mathrm{s}$

Validity of hydrostatic approximation: Example 1

At 10m horizontal resolution, differences between H and NH considerable.

NH model realistically represents descent of cold bubble, while in H model the descent is too fast.

However, despite the inability to appropriately evolve the bubble, H simulation tends to meaningful final state, with stabilized stratification.

Test for convergence with horizontal resolution: Example 1

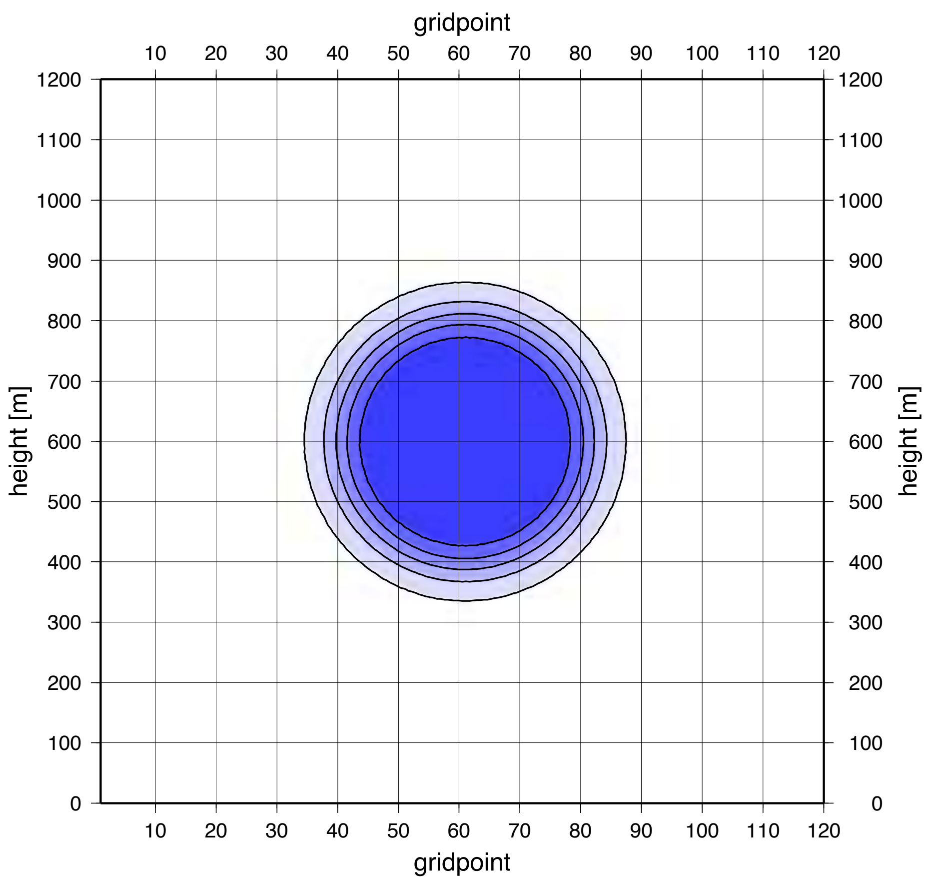
Convection (like turbulence) is a non-linear phenomena consisting multiple scale interactions

Simple test to judge if going to finer and finer resolution leaves the NH results unaltered is to increase horizontal resolution and redo the simulation

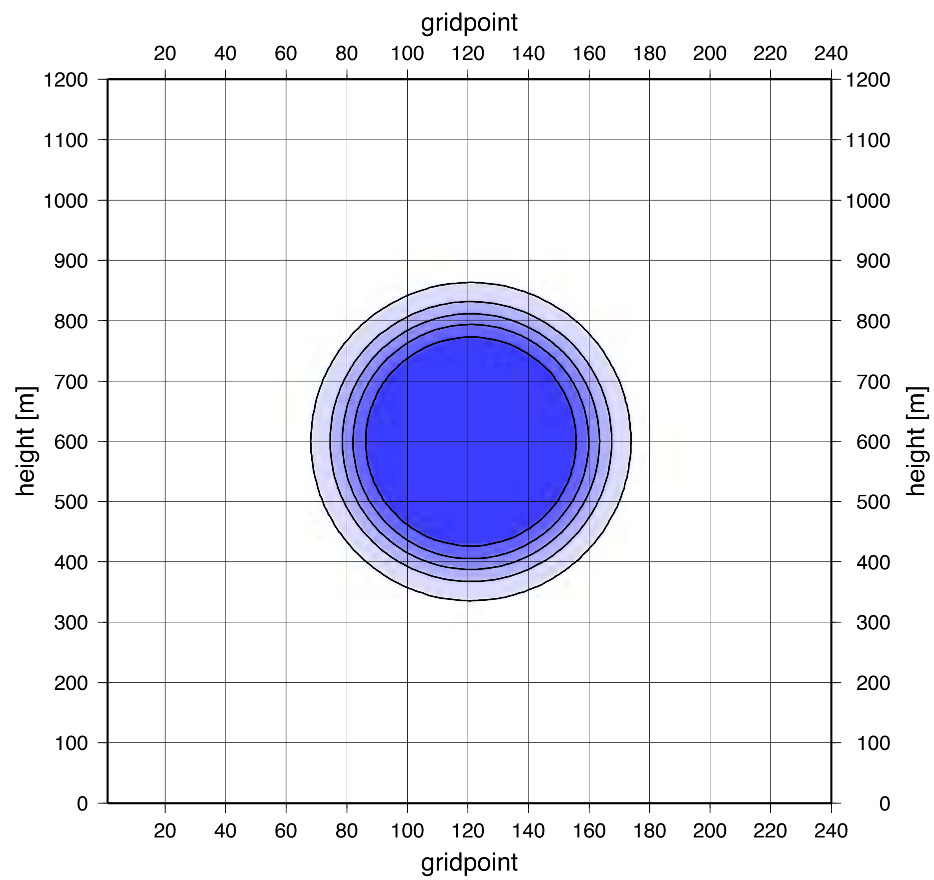
If the results are not changed dramatically, influence of sub-grid convective scales is weak, i.e. there is no need for their parameterization → This is indeed the case at 5m resolution.

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$



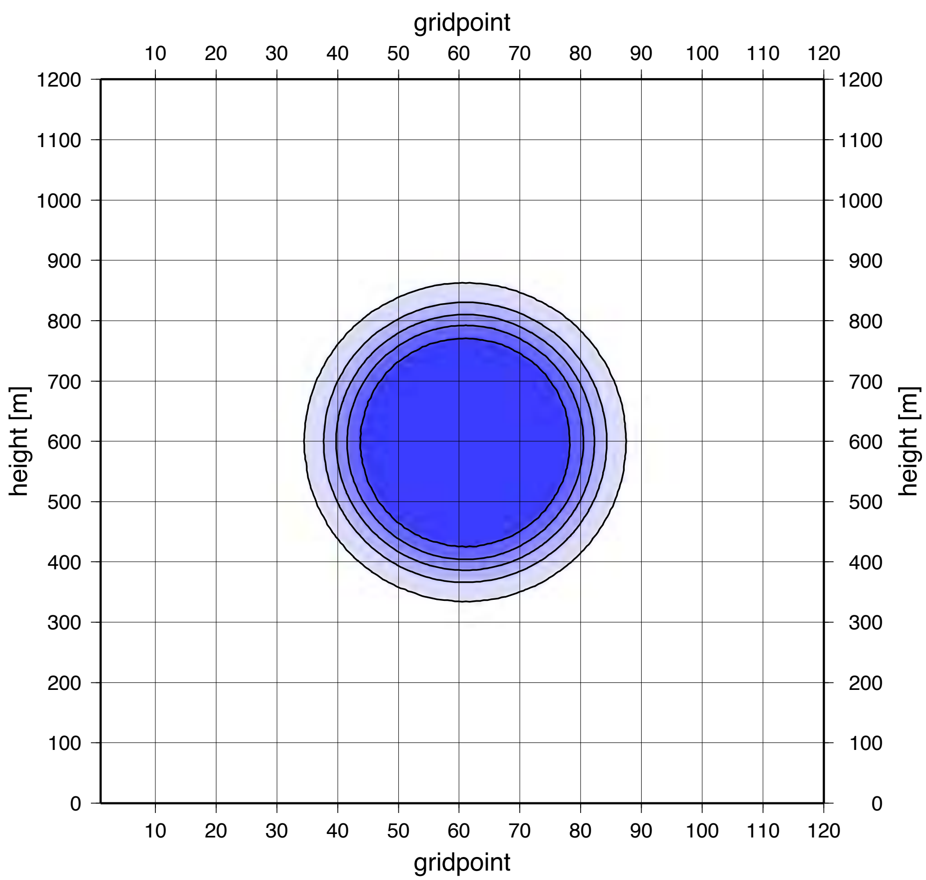
$\Delta x = 5\,\mathrm{m}$



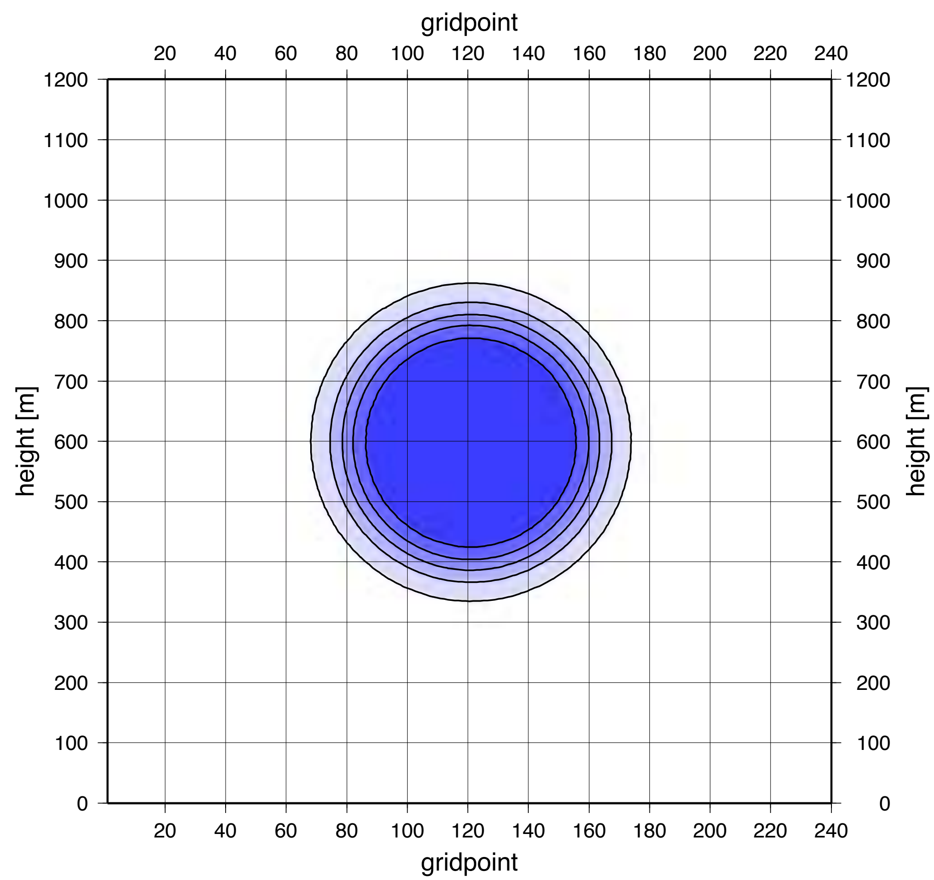
non-hydrostatic run, $t = 0\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\text{m}$



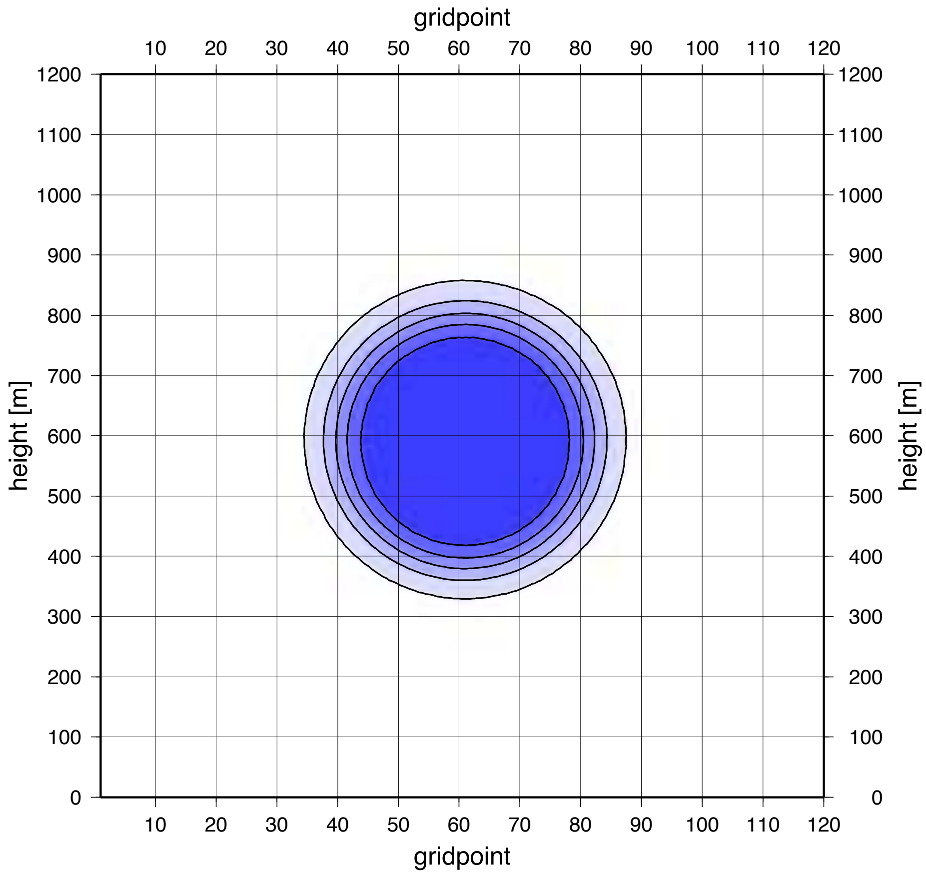
$\Delta x = 5\,\text{m}$



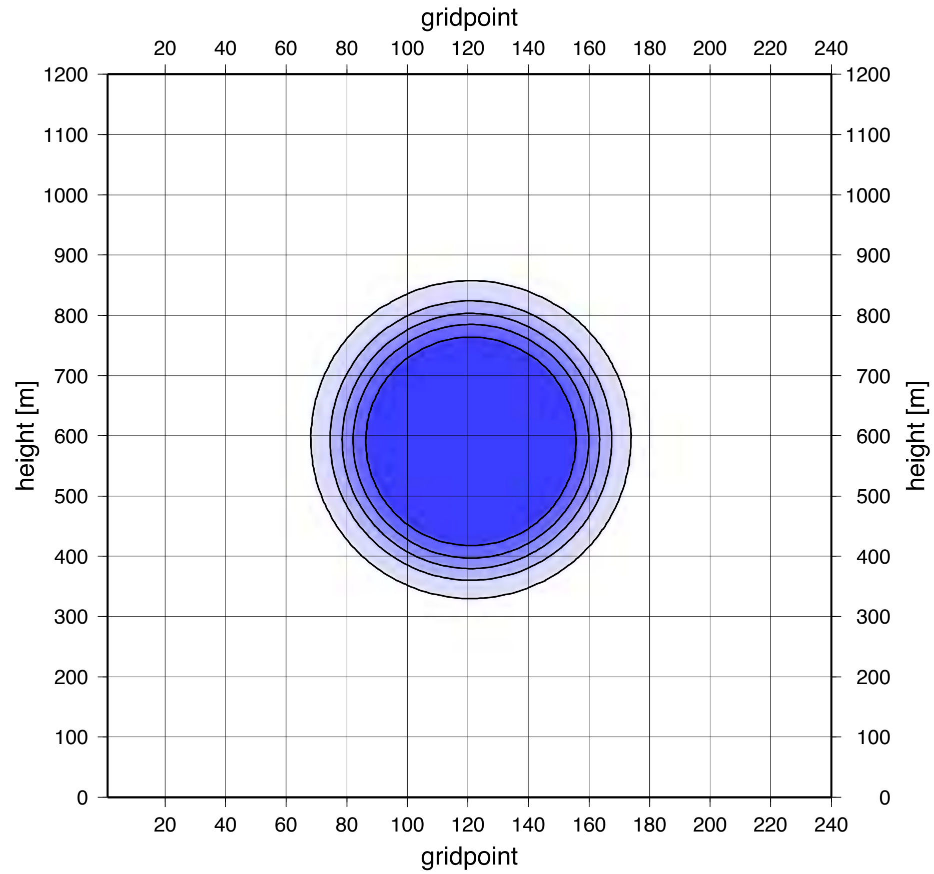
non-hydrostatic run, $t = 20\,\text{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\text{m}$



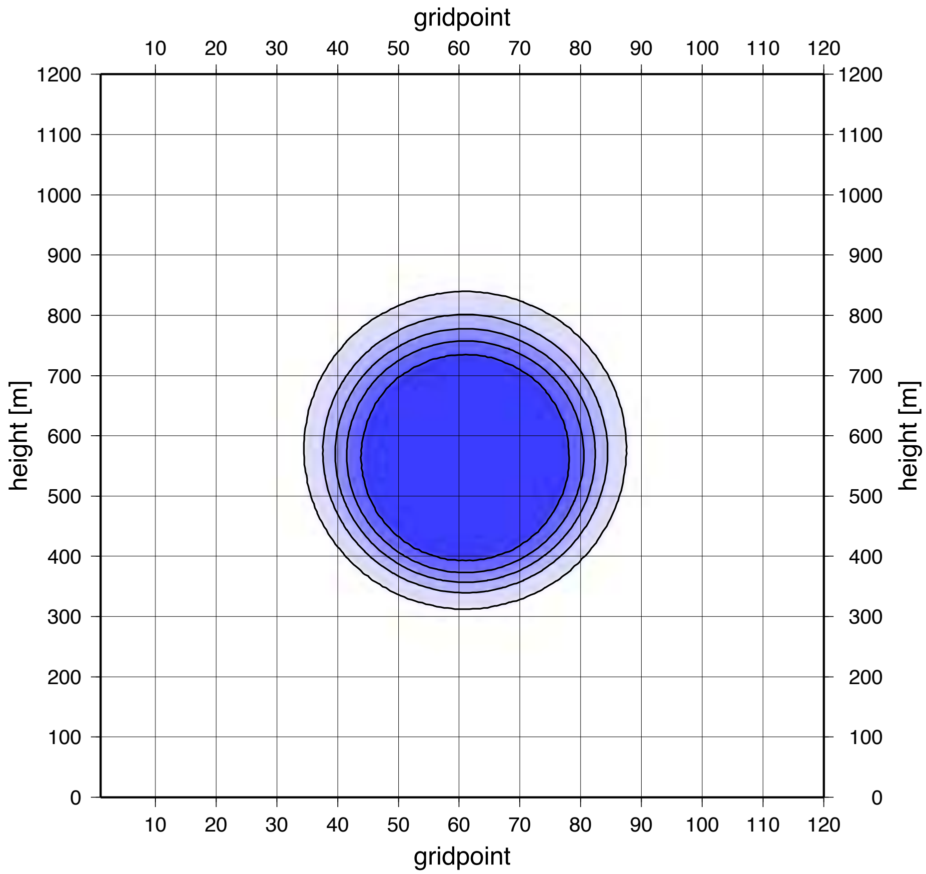
$\Delta x = 5\,\text{m}$

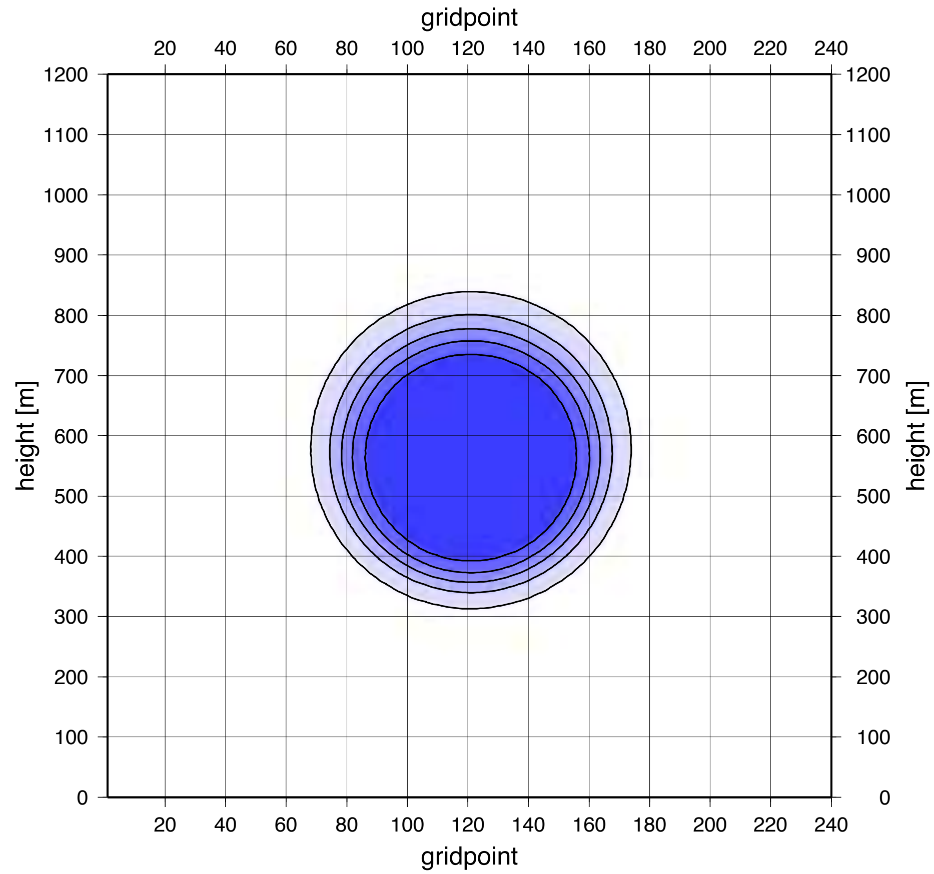


non-hydrostatic run, $t = 50\,\text{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$ | $\Delta x = 5\,\mathrm{m}$

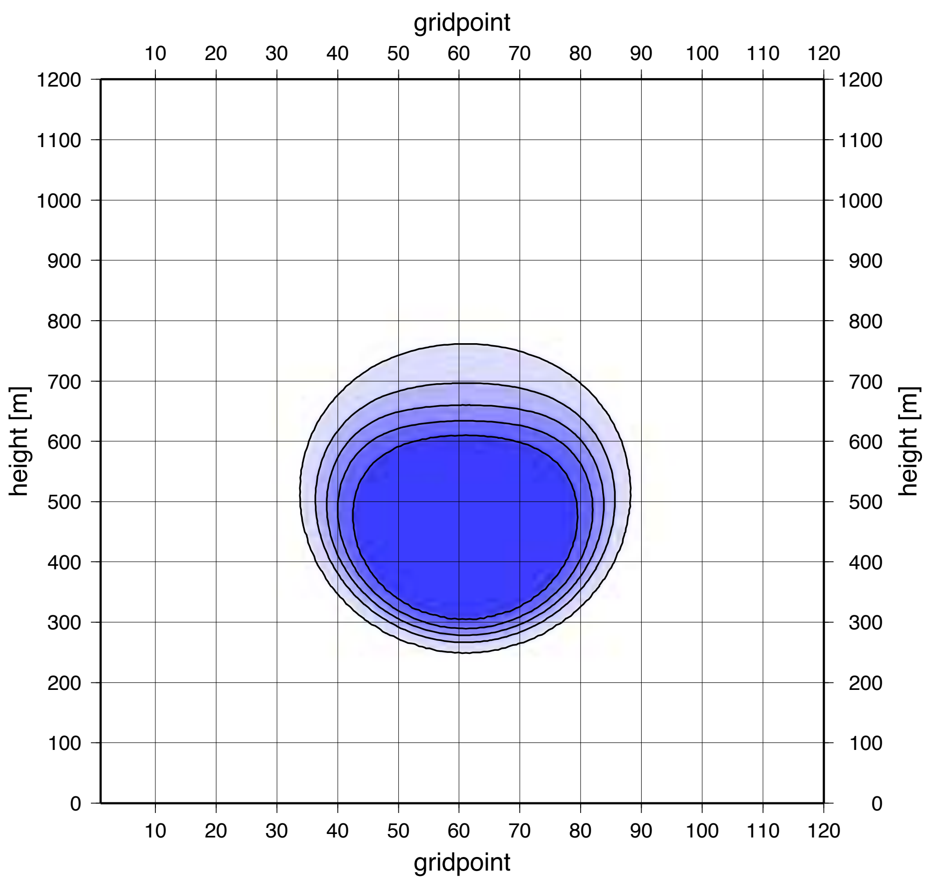




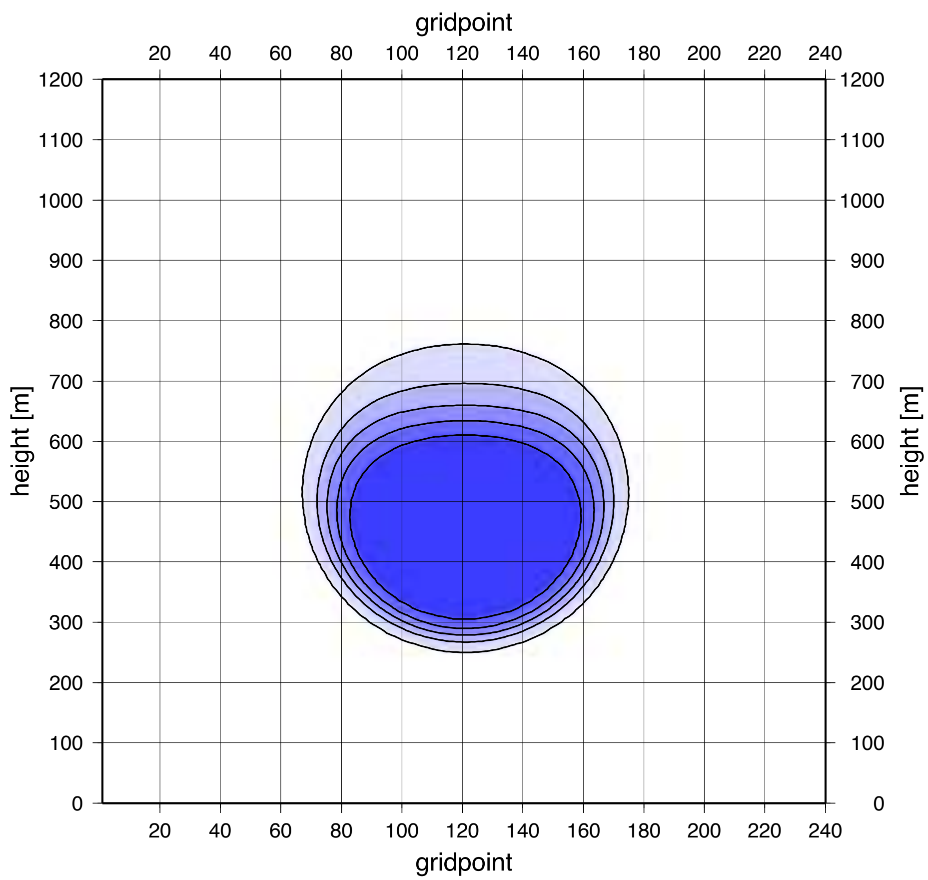
non-hydrostatic run, $t = 100\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\mathrm{m}$

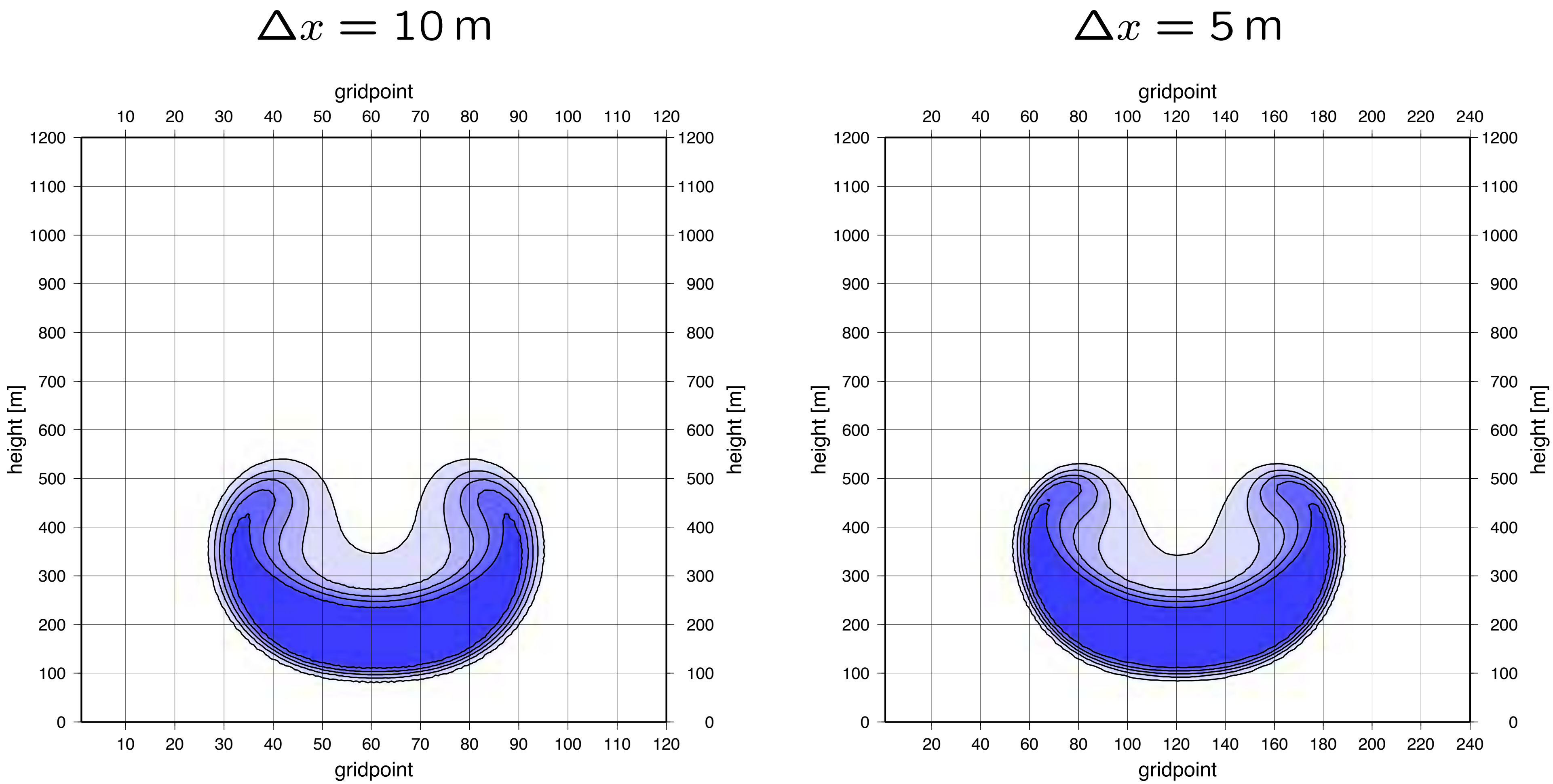


$\Delta x = 5\,\mathrm{m}$



non-hydrostatic run, $t = 200\,\mathrm{s}$

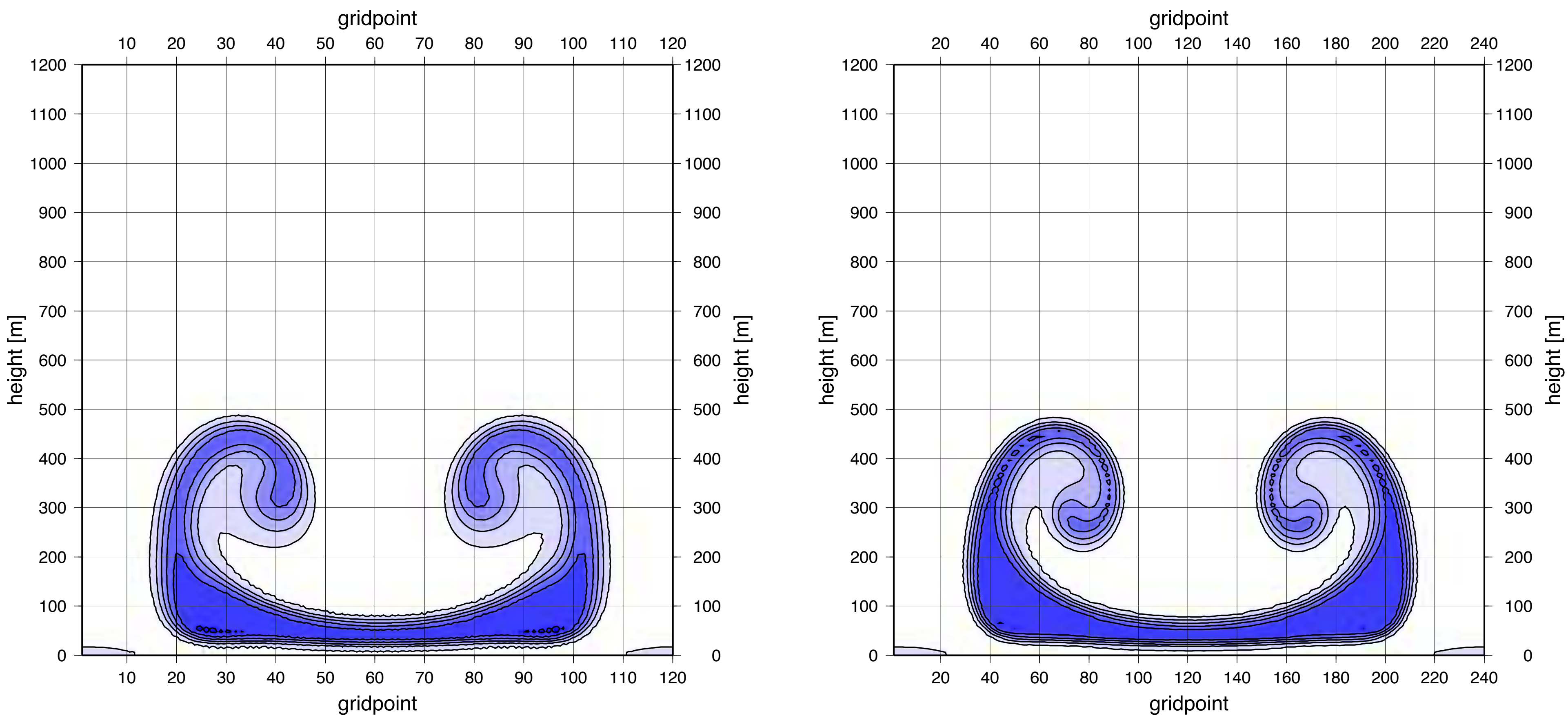
perturbation of potential temperature $\theta - \overline{\theta}$



non-hydrostatic run, $t = 400\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

$\Delta x = 10\,\text{m}$ $\Delta x = 5\,\text{m}$



non-hydrostatic run, $t = 600\,\text{s}$

Test for convergence with horizontal resolution: Example 1

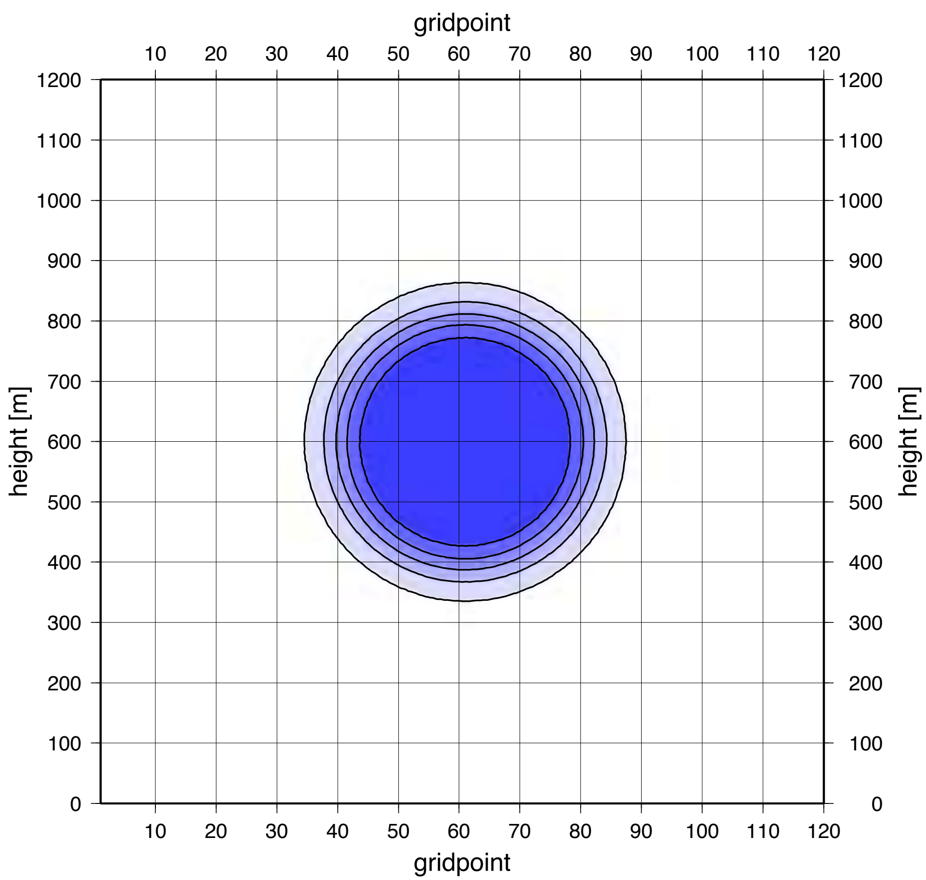
What happens if the size of bubble is increased to 1.5km?

Evolution is slower, it takes longer for bubble to drop down to the surface

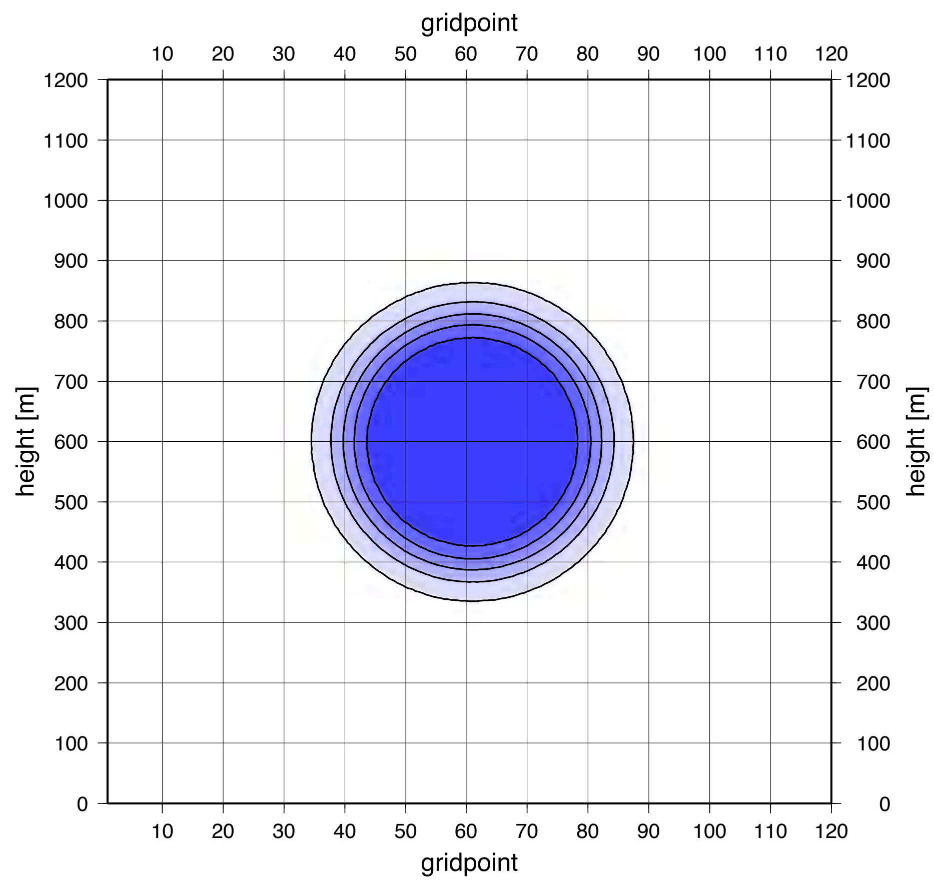
Differences between H and NH are smaller, but still there.

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



hydrostatic

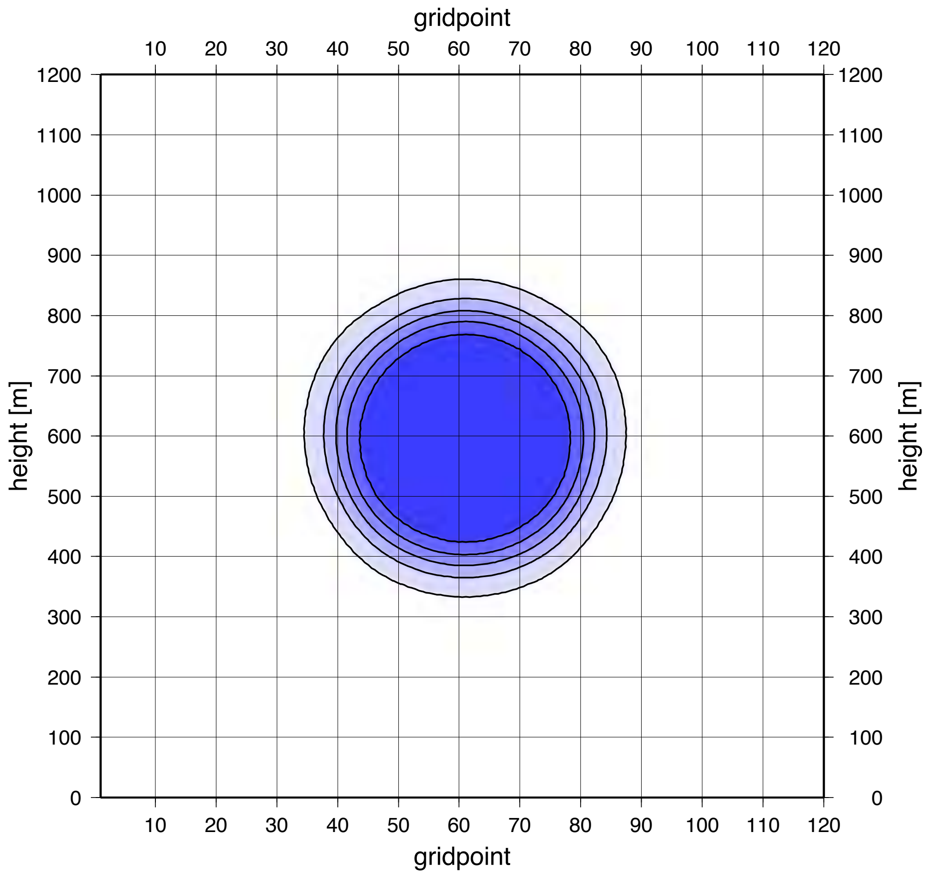


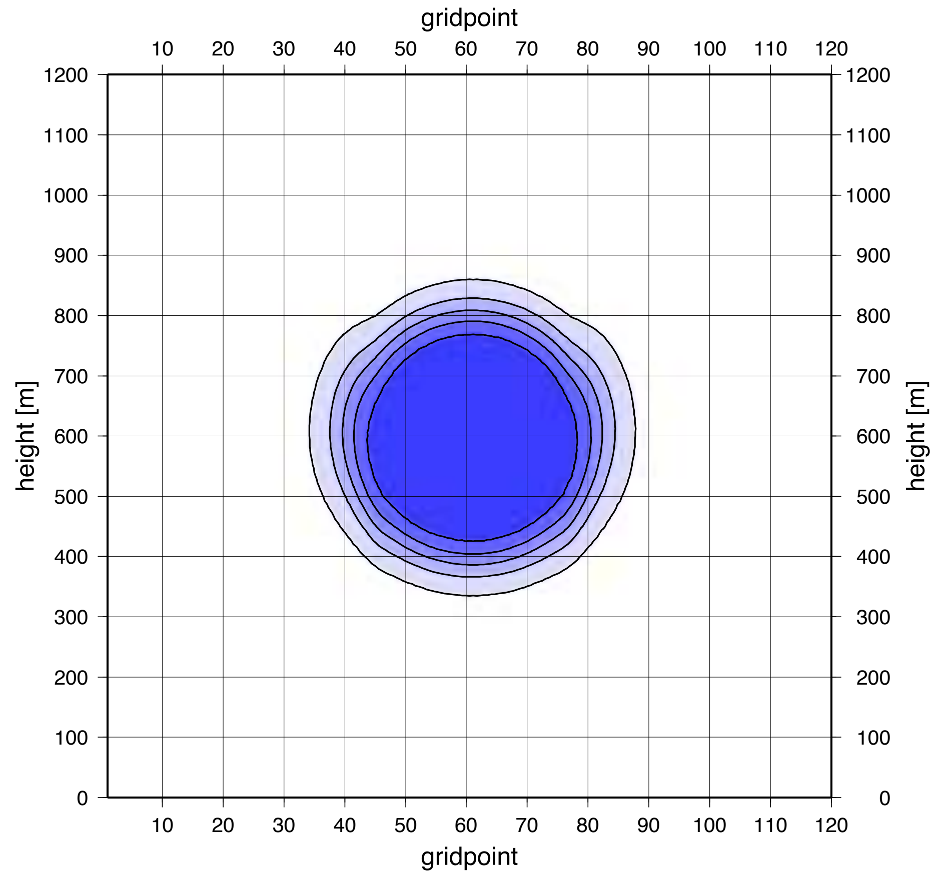
$\Delta x = 100\,\mathrm{m}$, $t = 0\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic

hydrostatic

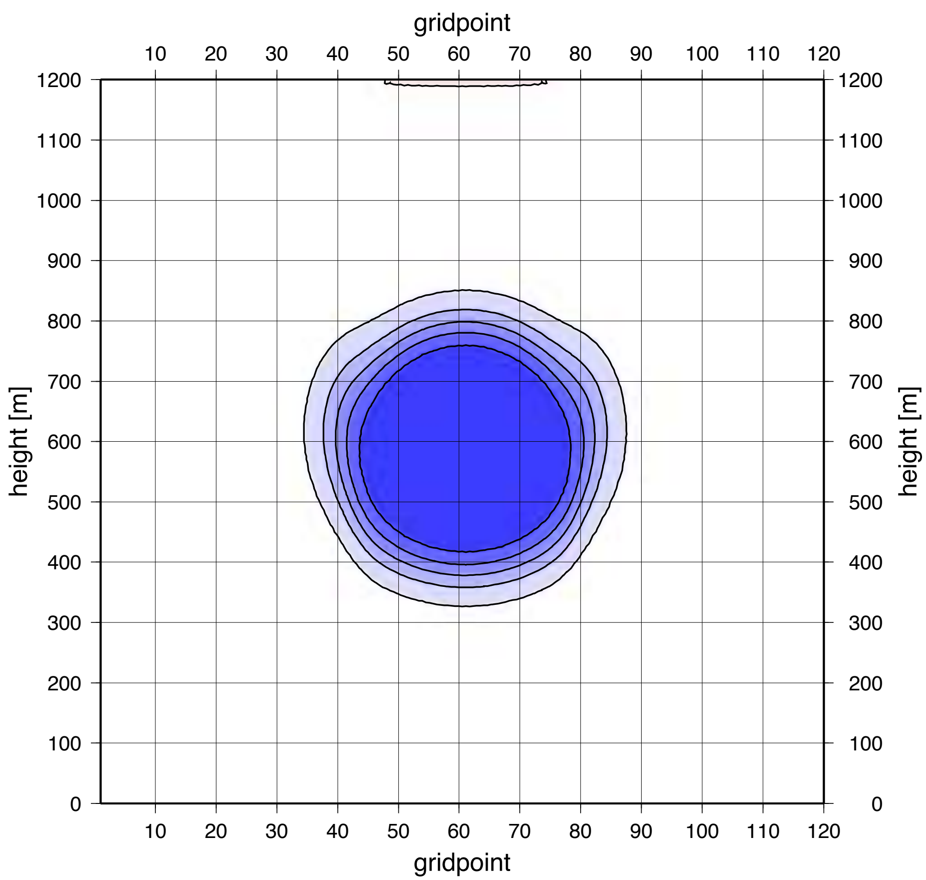




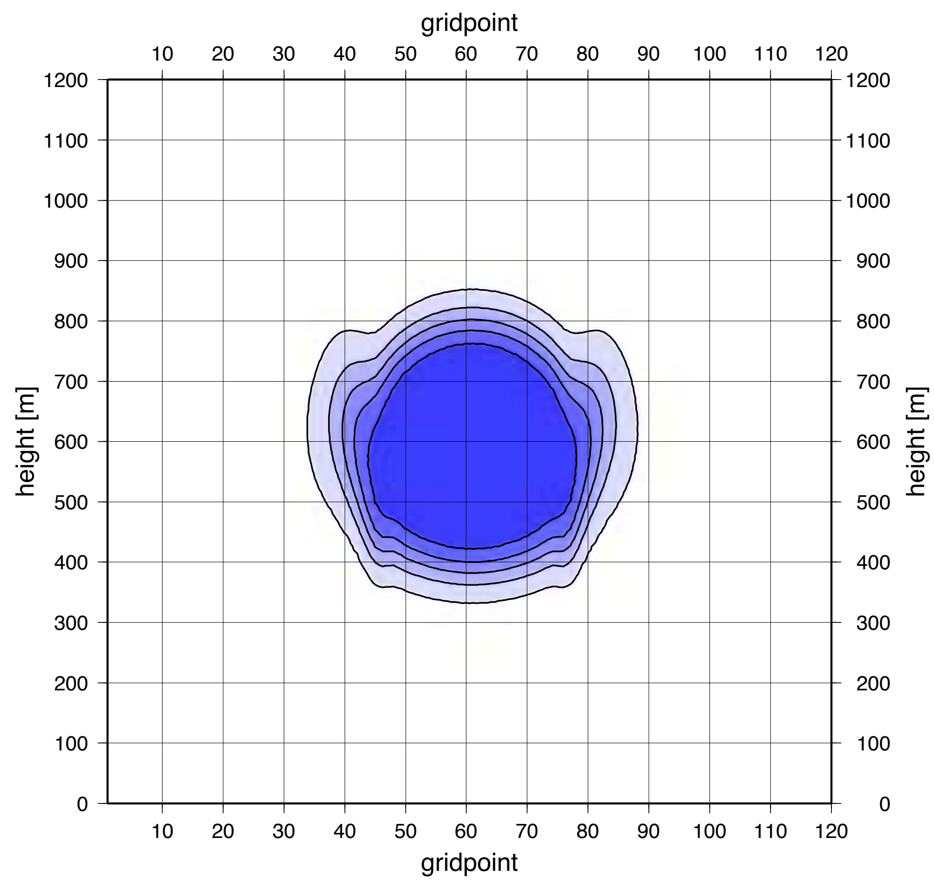
$\Delta x = 100\,\mathrm{m},\ t = 100\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



hydrostatic

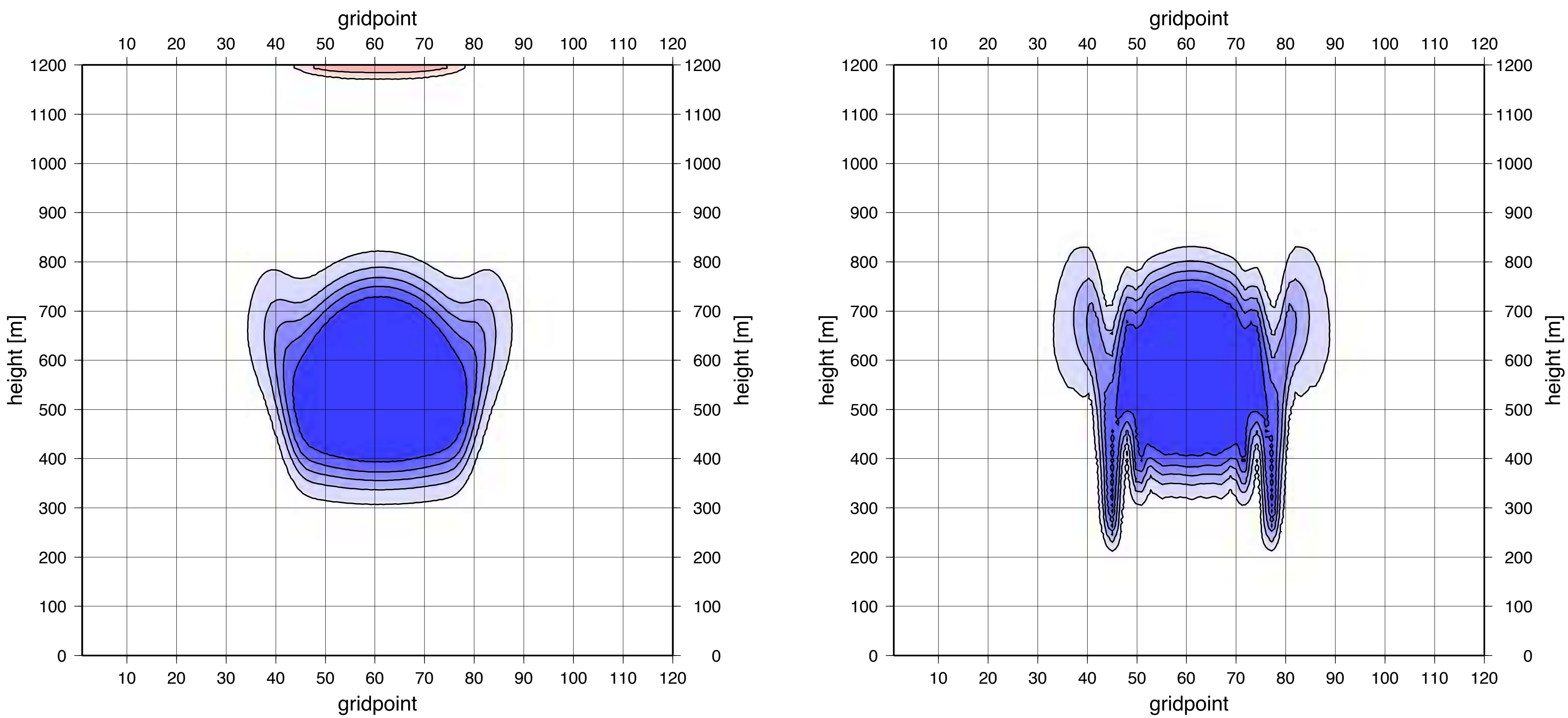


$\Delta x = 100\,\mathrm{m},\ t = 200\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic

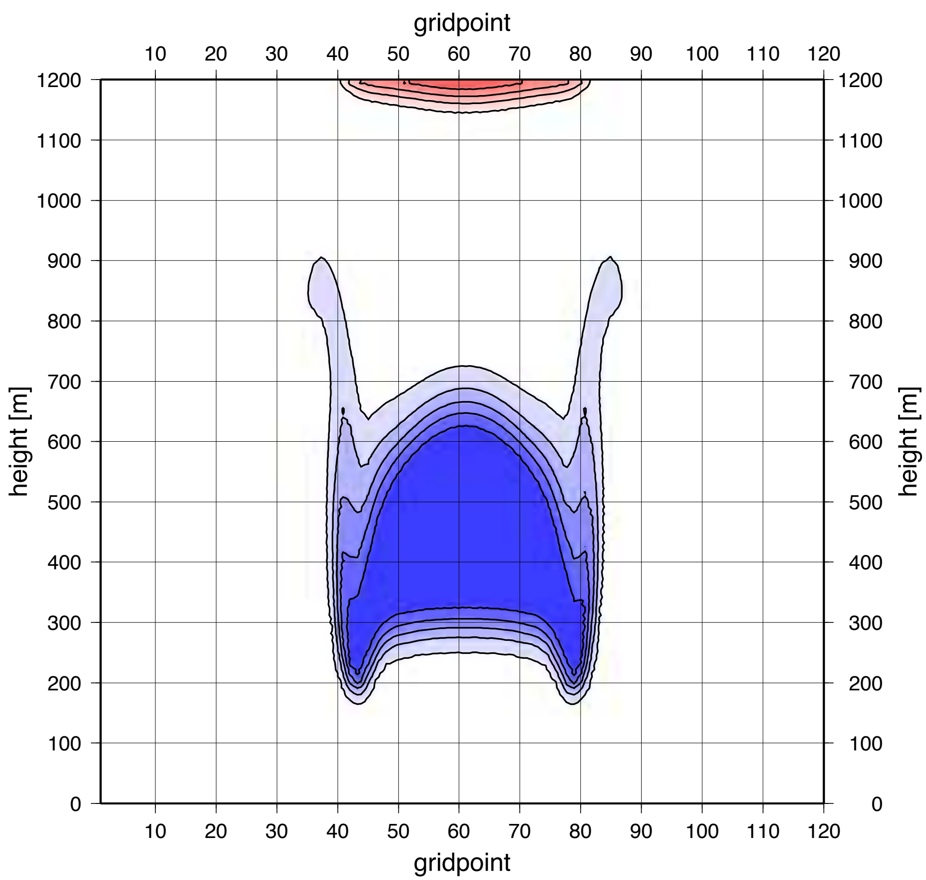
hydrostatic



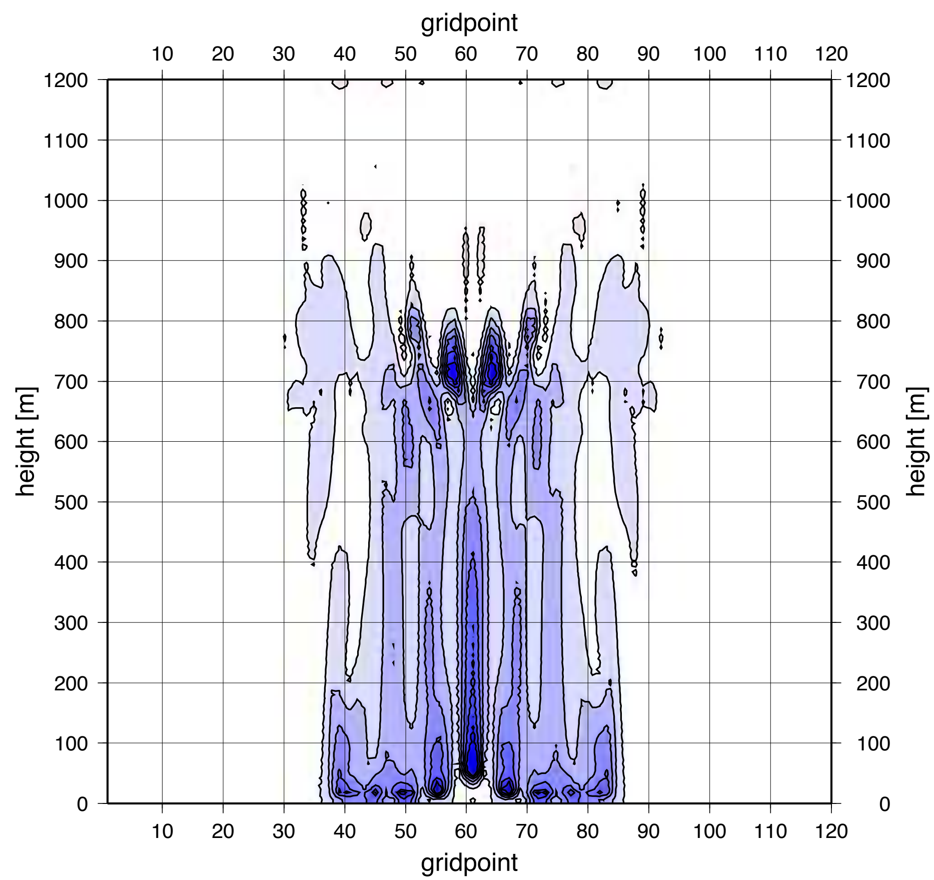
$\Delta x = 100\,\text{m},\ t = 400\,\text{s}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic

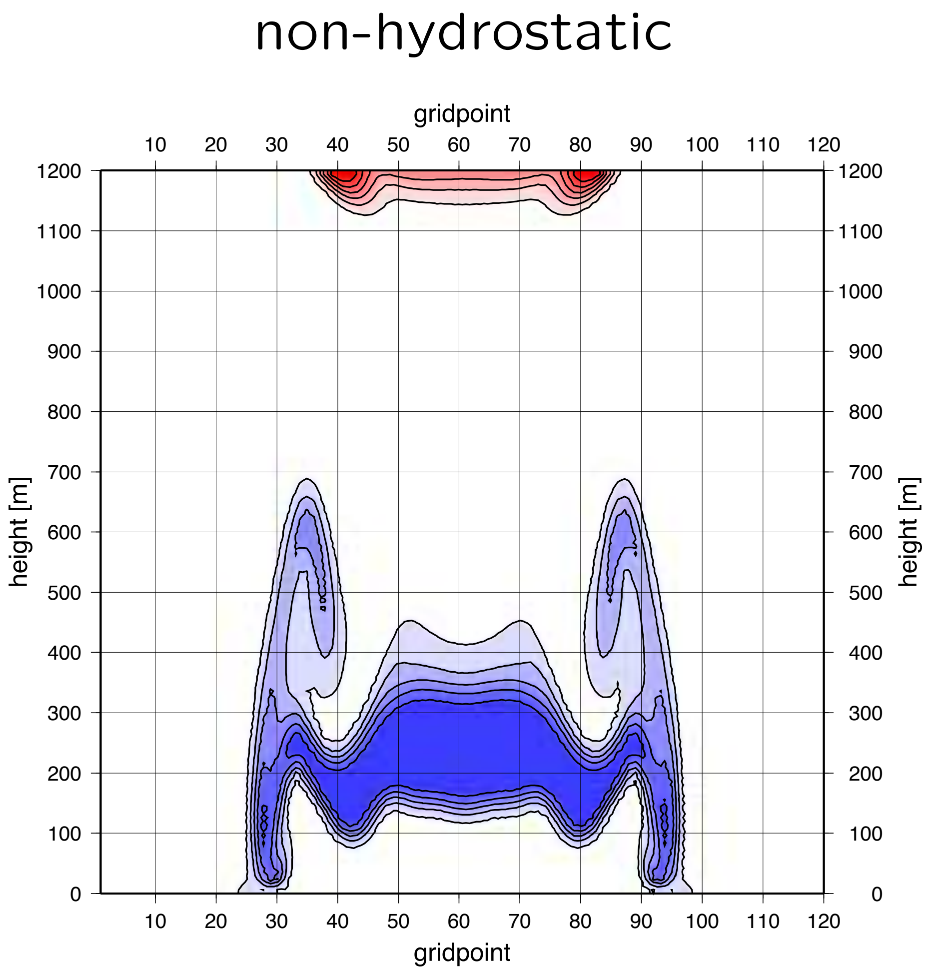


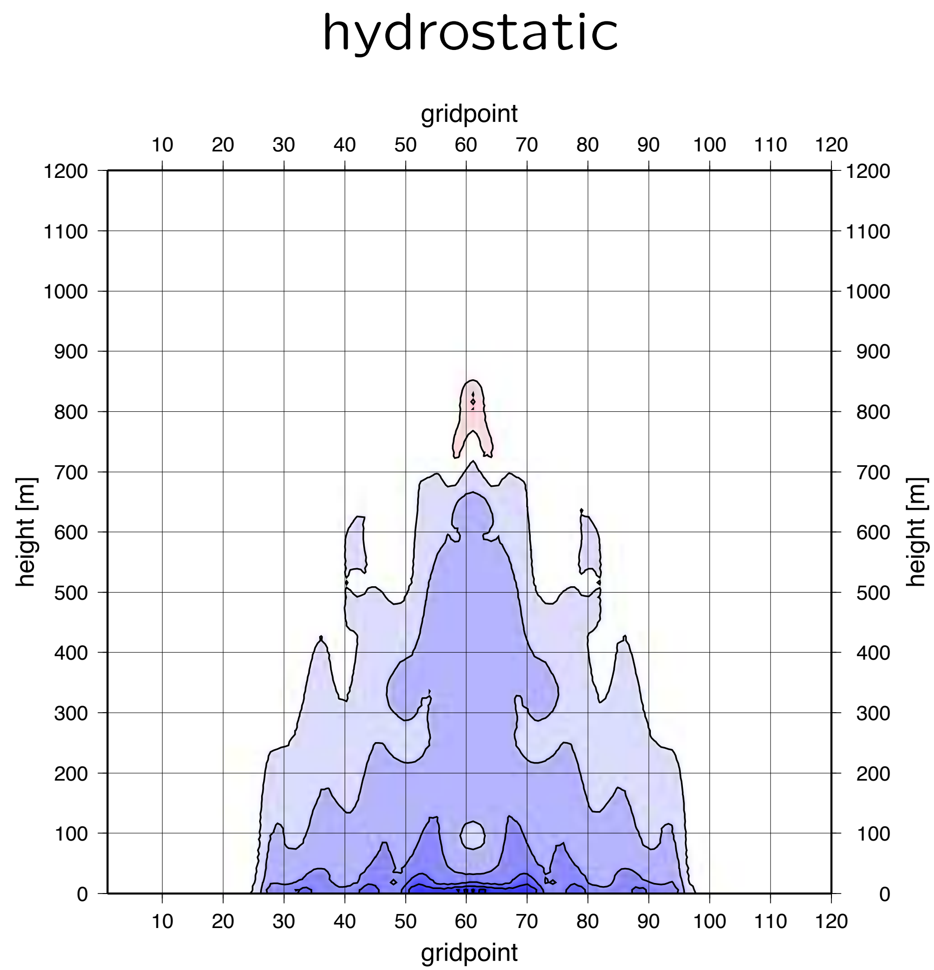
hydrostatic



$\Delta x = 100\,\text{m},\ t = 800\,\text{s}$

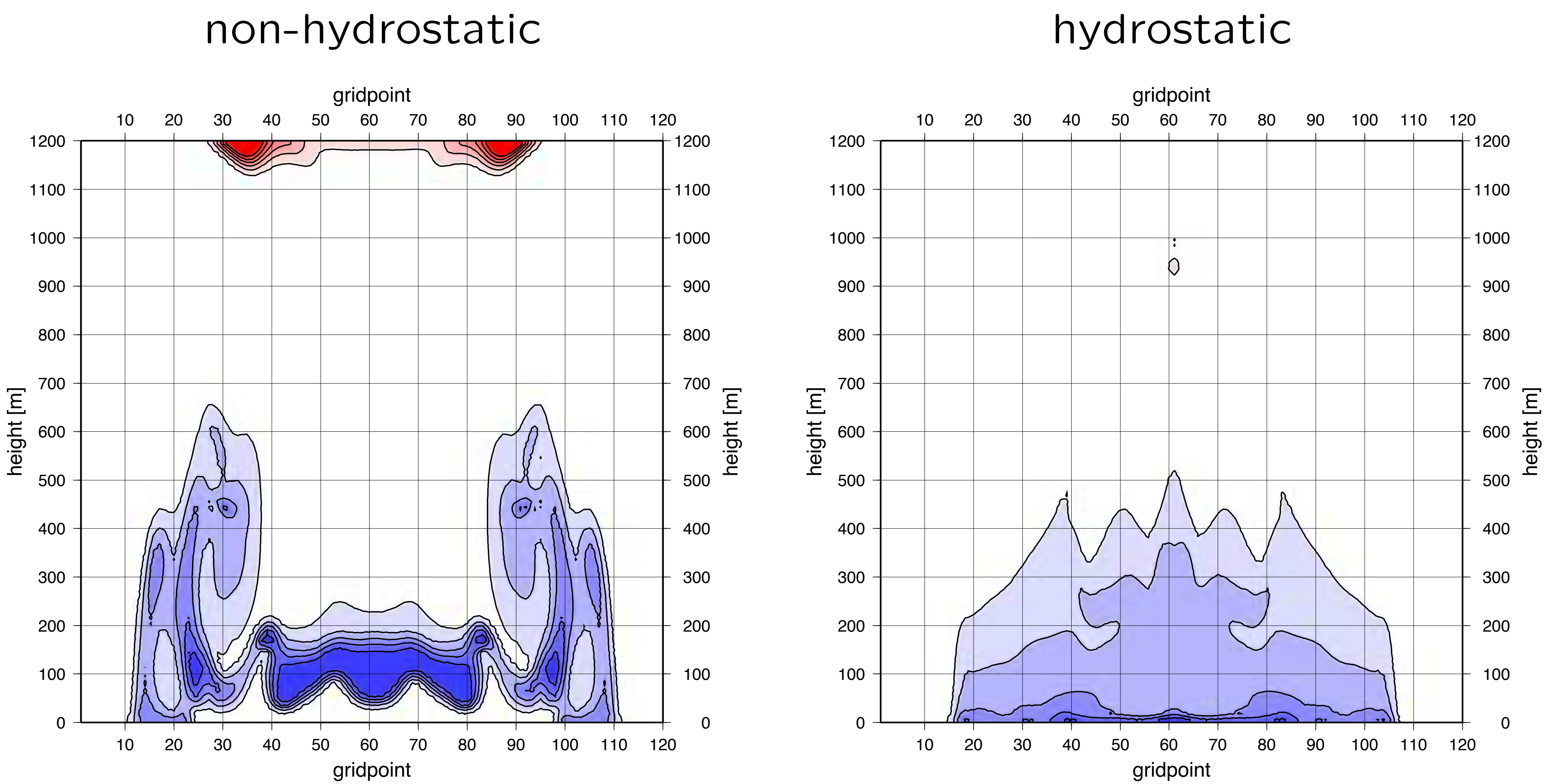
perturbation of potential temperature $\theta - \overline{\theta}$





$\Delta x = 100\,\mathrm{m},\ t = 1600\,\mathrm{s}$

perturbation of potential temperature $\theta - \overline{\theta}$



$\Delta x = 100\,\mathrm{m},\ t = 2400\,\mathrm{s}$

Test for convergence with horizontal resolution: Example 1

What happens if the size of bubble is increased further to 15km?

Evolution is even slower.

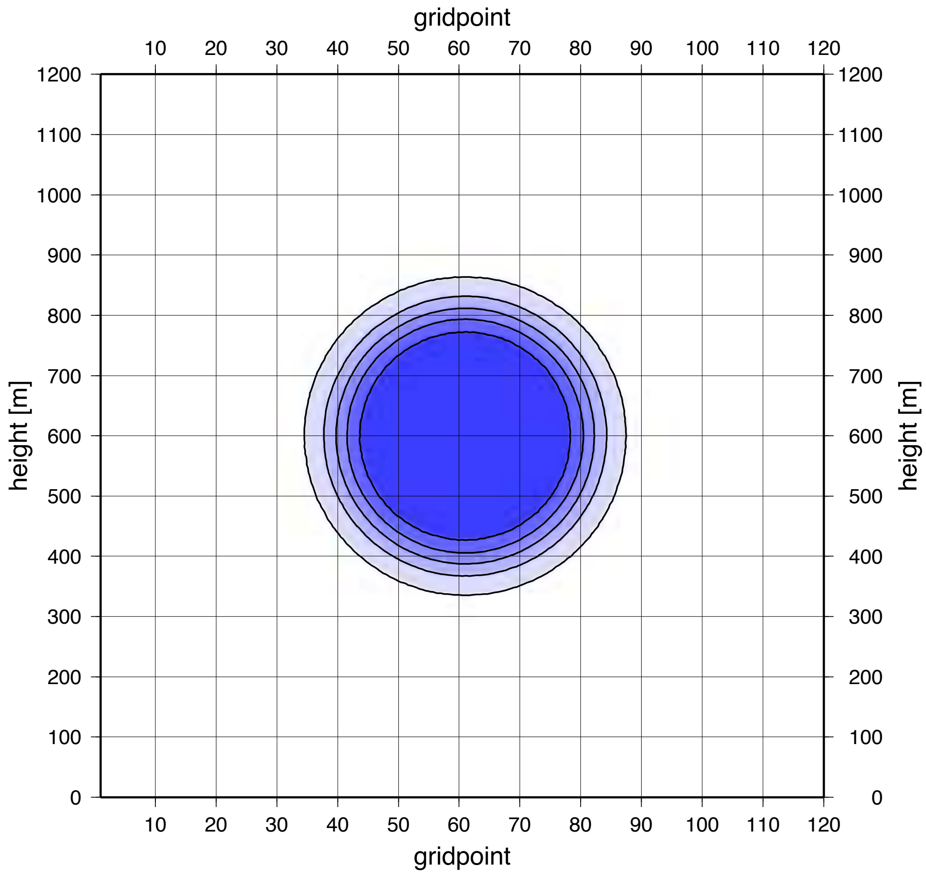
Now H and NH agree very well → Subgrid-scales for convection important → Need to parametrize convection.

Results from this test case suggest that non-hydrostatic dynamics is not important for horizontal scales larger than 1km.

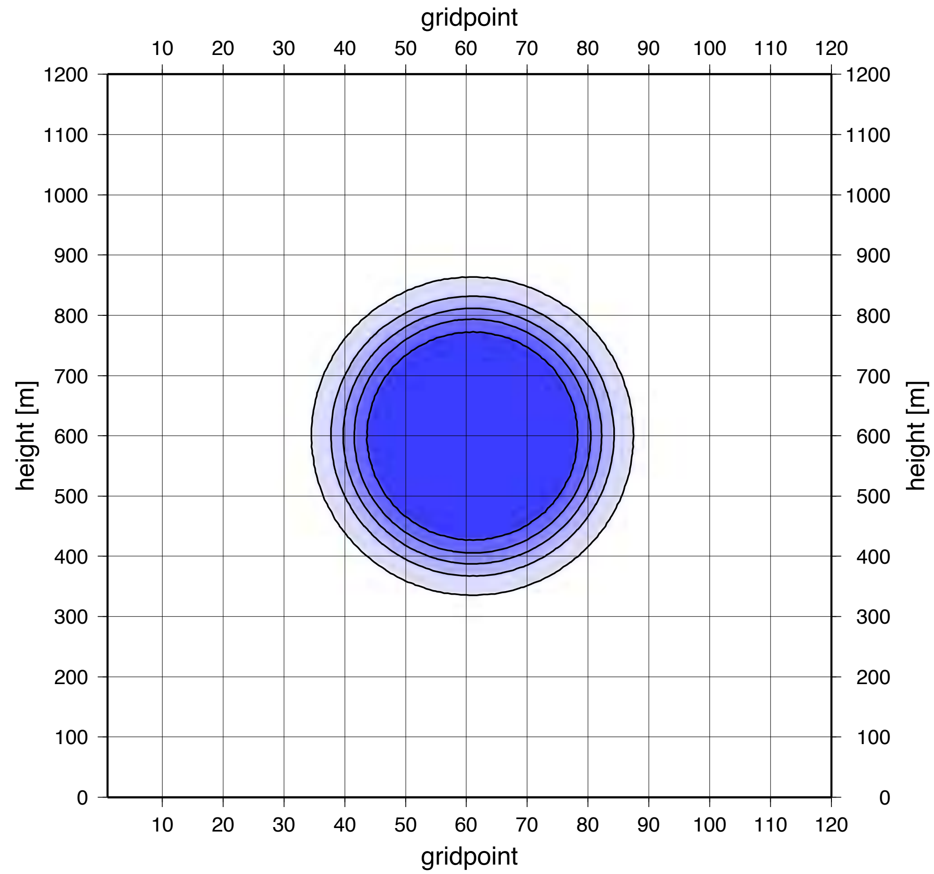
Conclusion: At horizontal resolutions of ~1km NH and H give comparable results.
At higher horizontal resolutions, NH and H diverge → need for NH model.
Only at very high 10m horizontal resolution convection can be resolved explicitly in NH model.

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



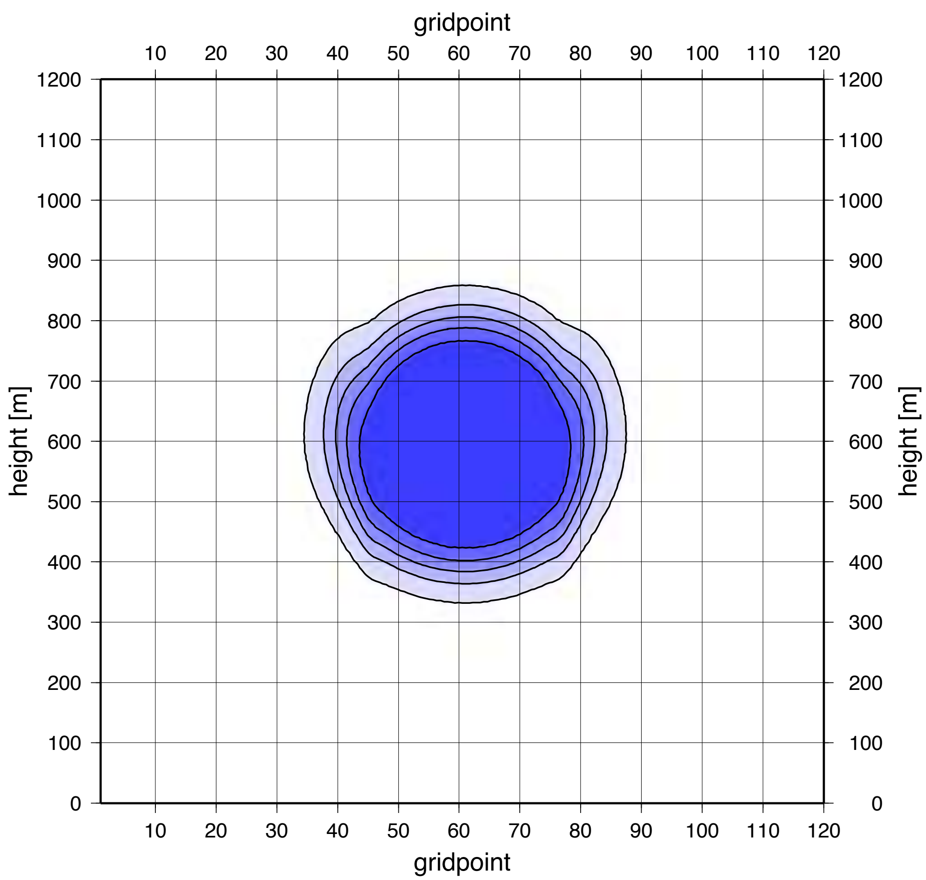
hydrostatic



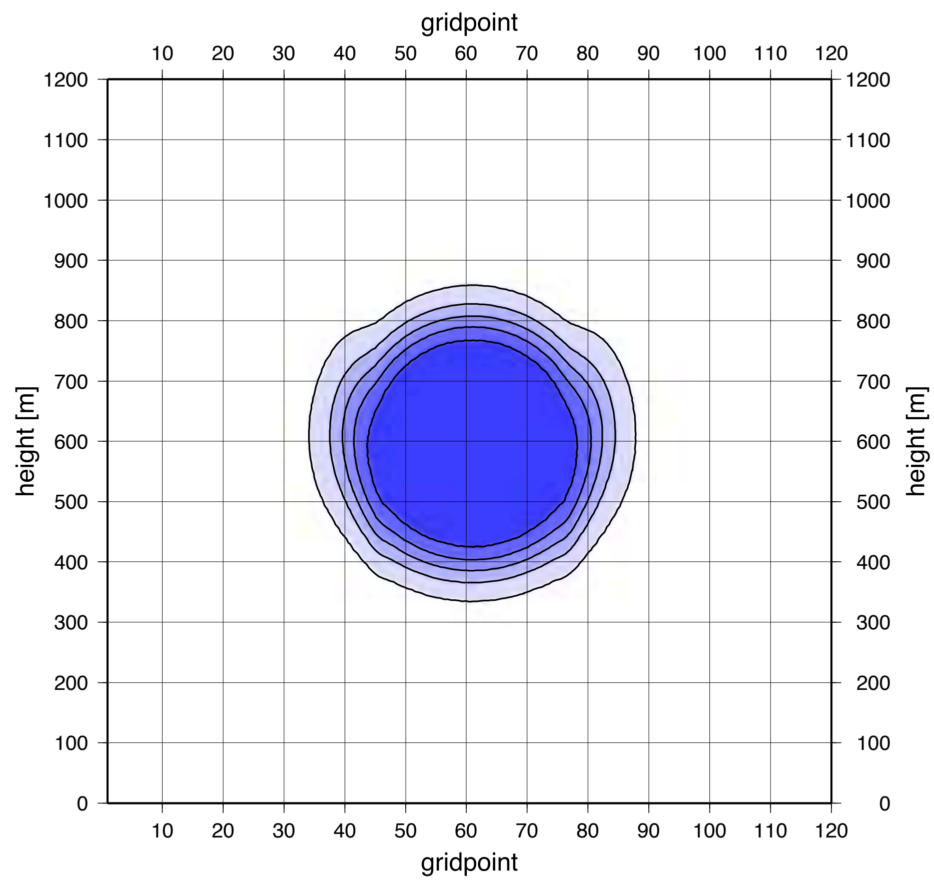
$\Delta x = 1\,\text{km},\ t = 0\,\text{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic

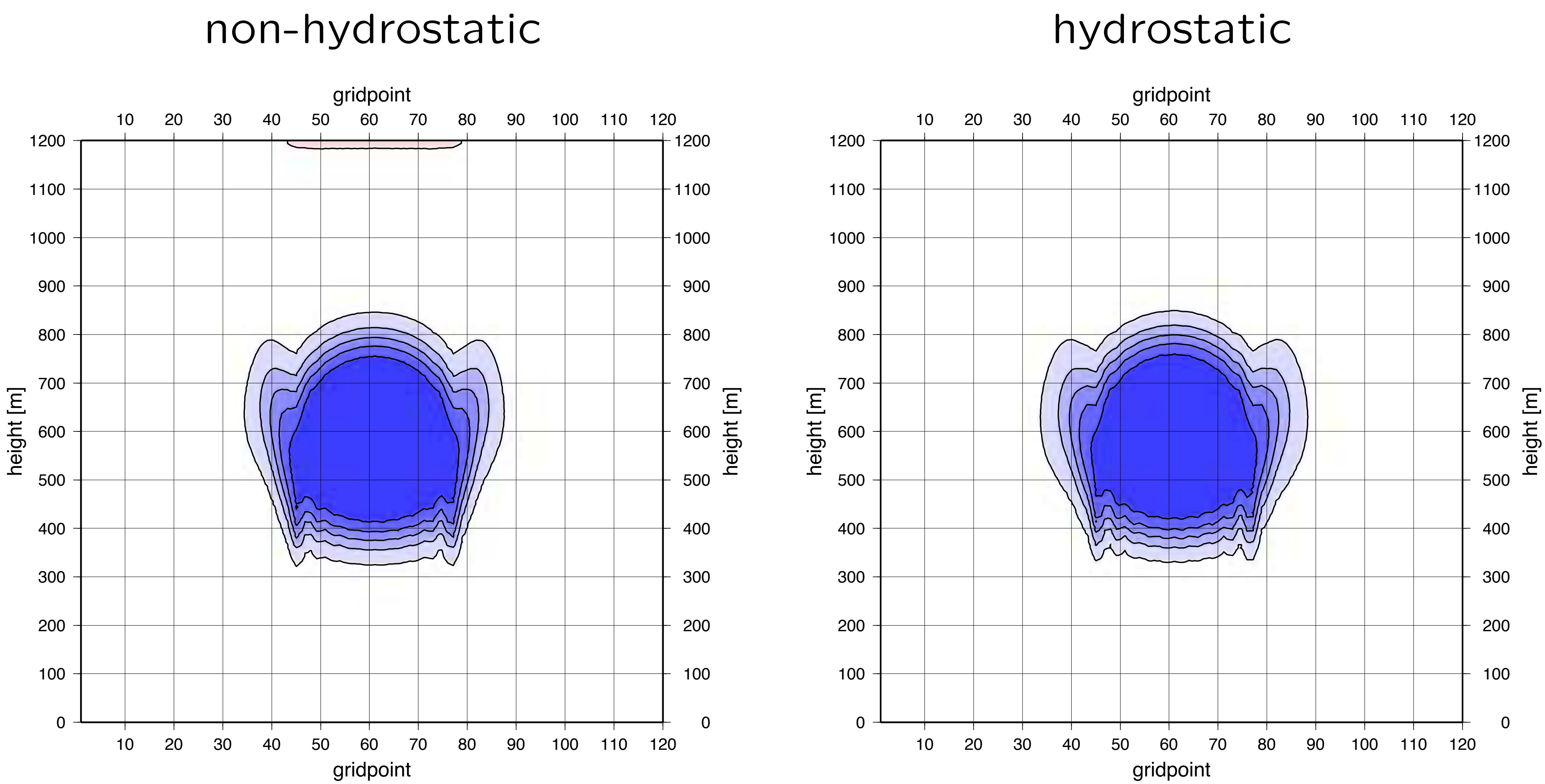


hydrostatic



$\Delta x = 1\,\text{km},\ t = 20\,\text{min}$

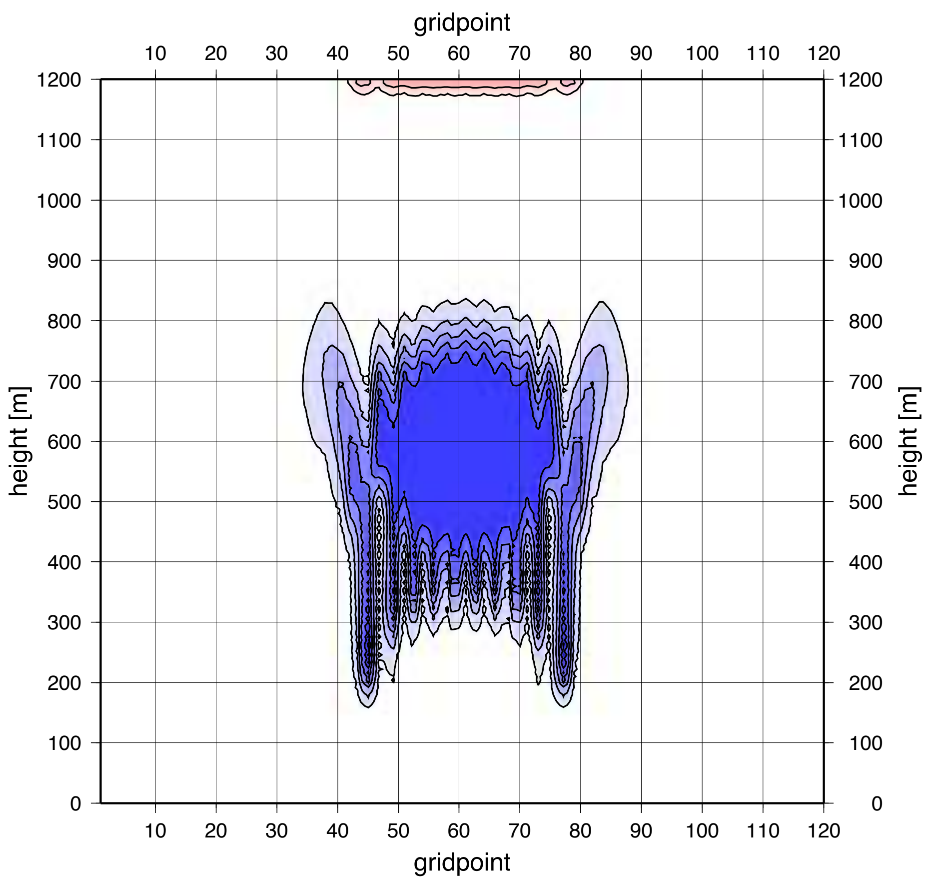
perturbation of potential temperature $\theta - \overline{\theta}$



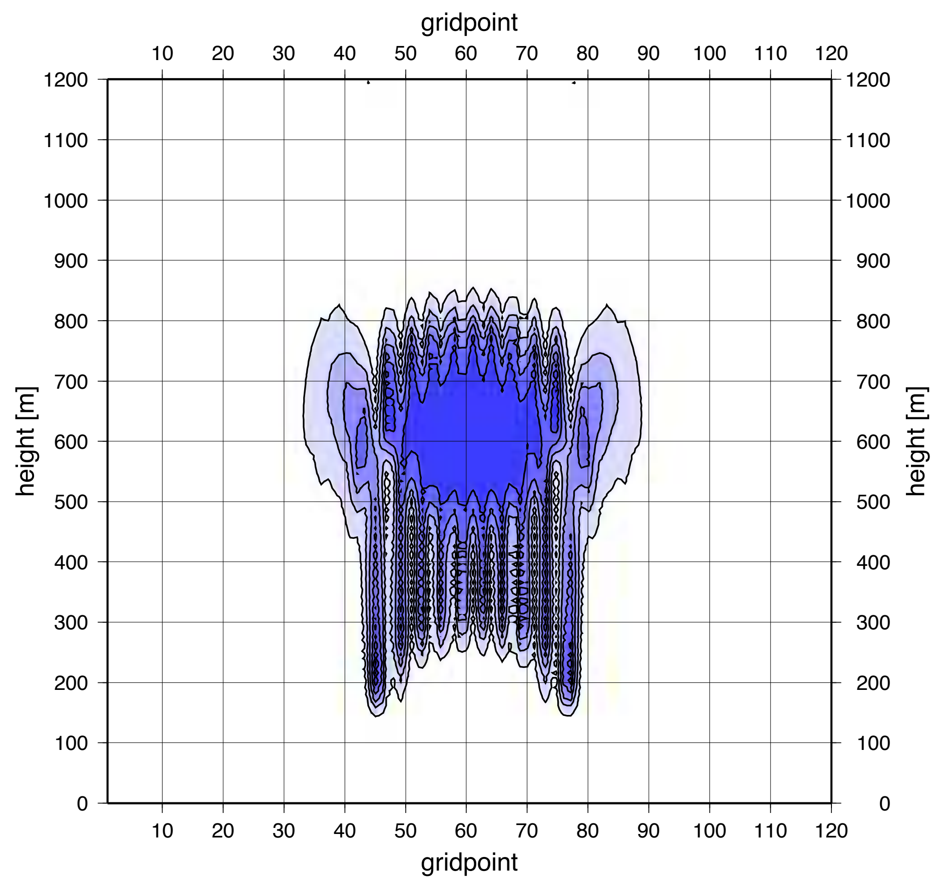
$\Delta x = 1\,\text{km},\ t = 40\,\text{min}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic

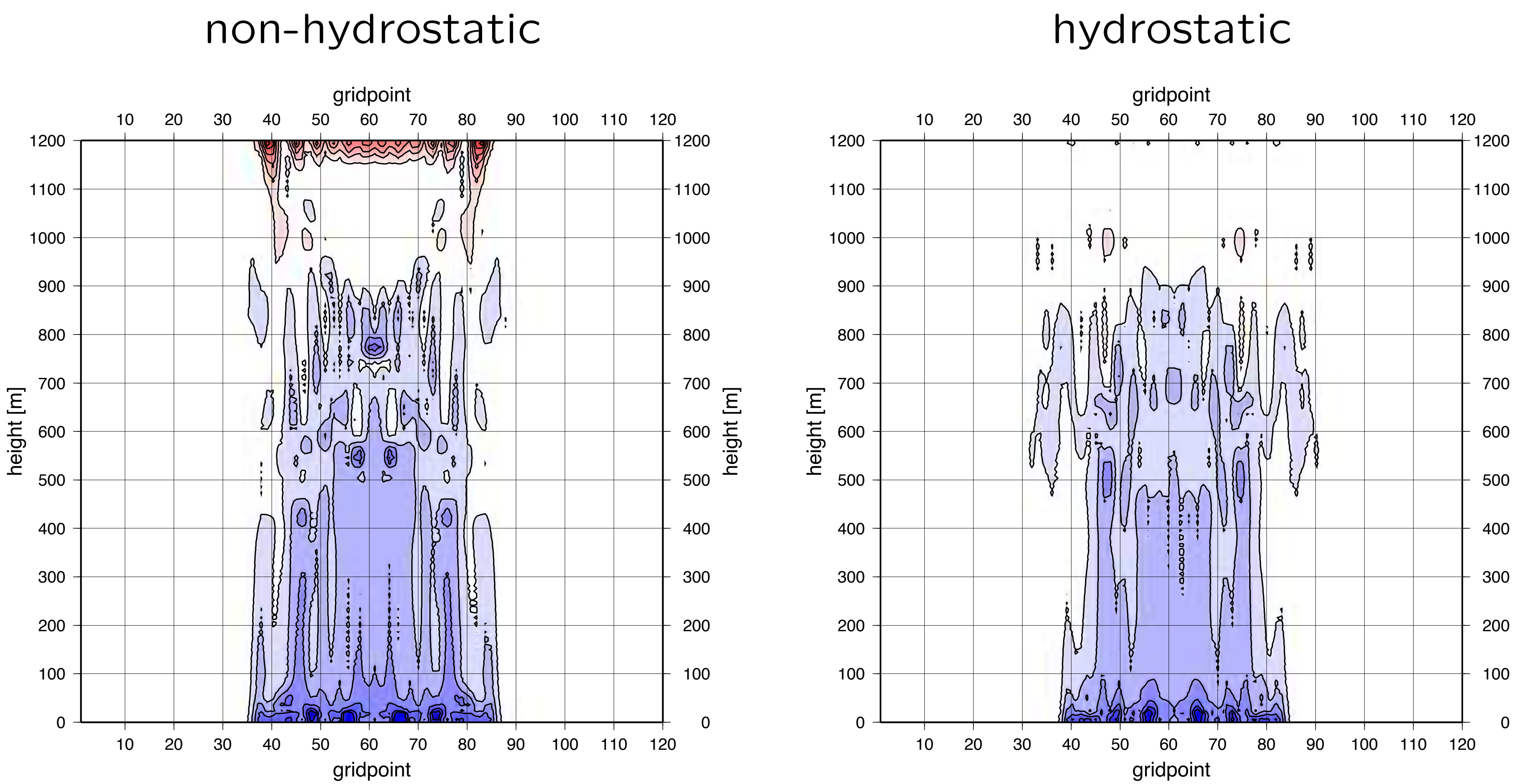


hydrostatic



$\Delta x = 1\,\text{km},\ t = 1\,\text{h}$

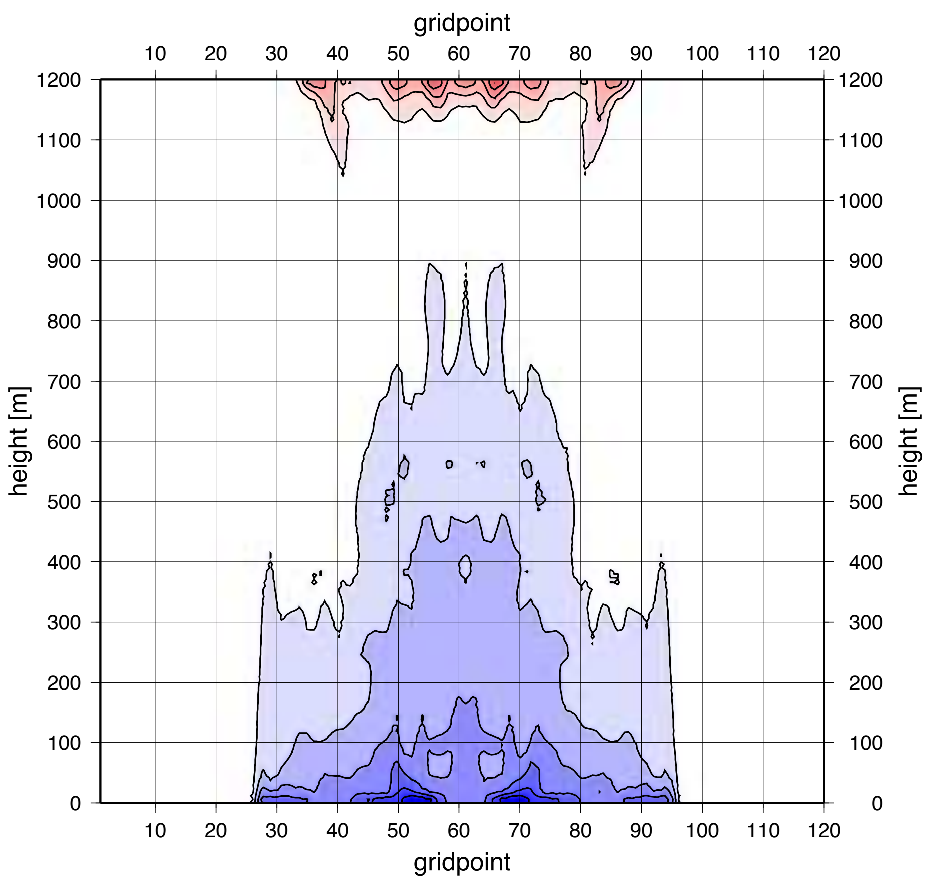
perturbation of potential temperature $\theta - \overline{\theta}$



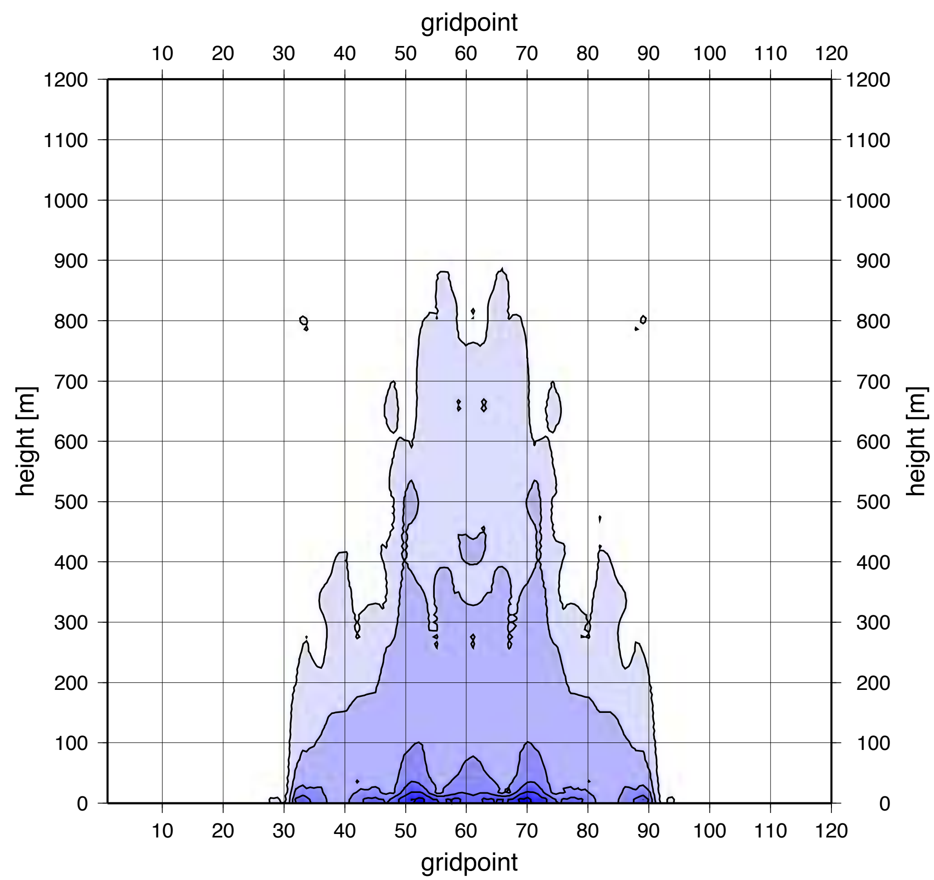
$\Delta x = 1\,\mathrm{km},\ t = 2\,\mathrm{h}$

perturbation of potential temperature $\theta - \overline{\theta}$

non-hydrostatic



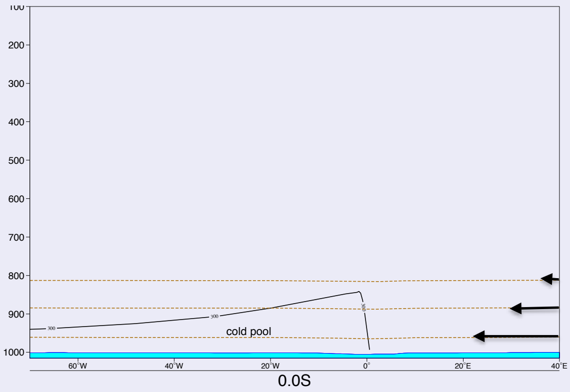
hydrostatic



$\Delta x = 1\,\text{km},\ t = 4\,\text{h}$

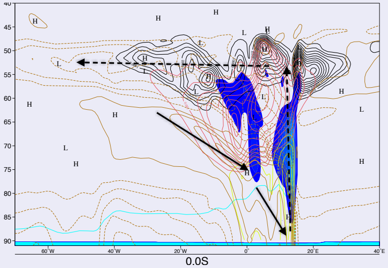
Academic explicit squall line - Initial conditions

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



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

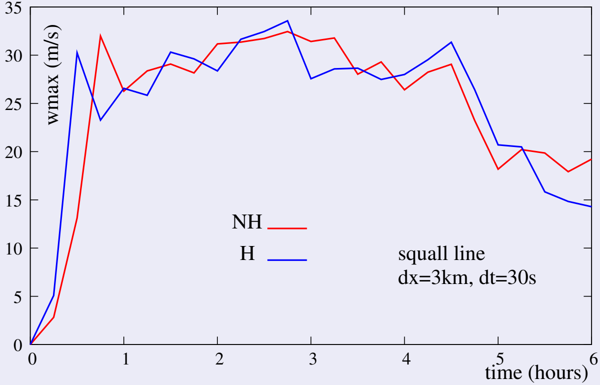
after 5 hours of hydrostatic (left) and NH (right) simulations



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

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

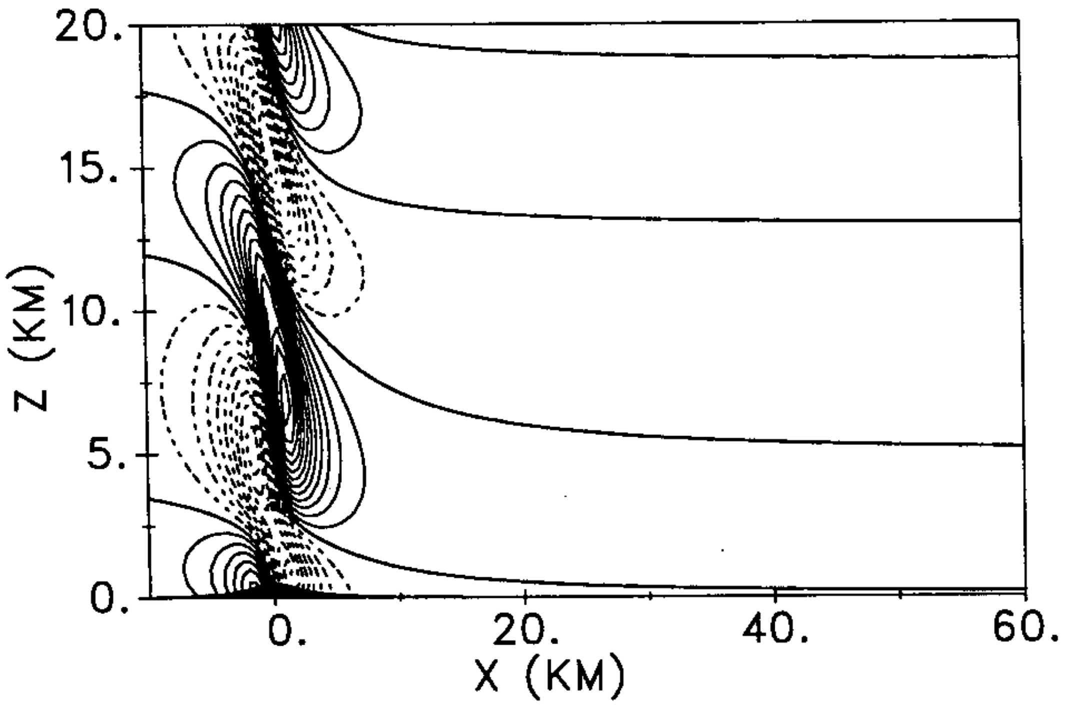
Maximum vertical velocity



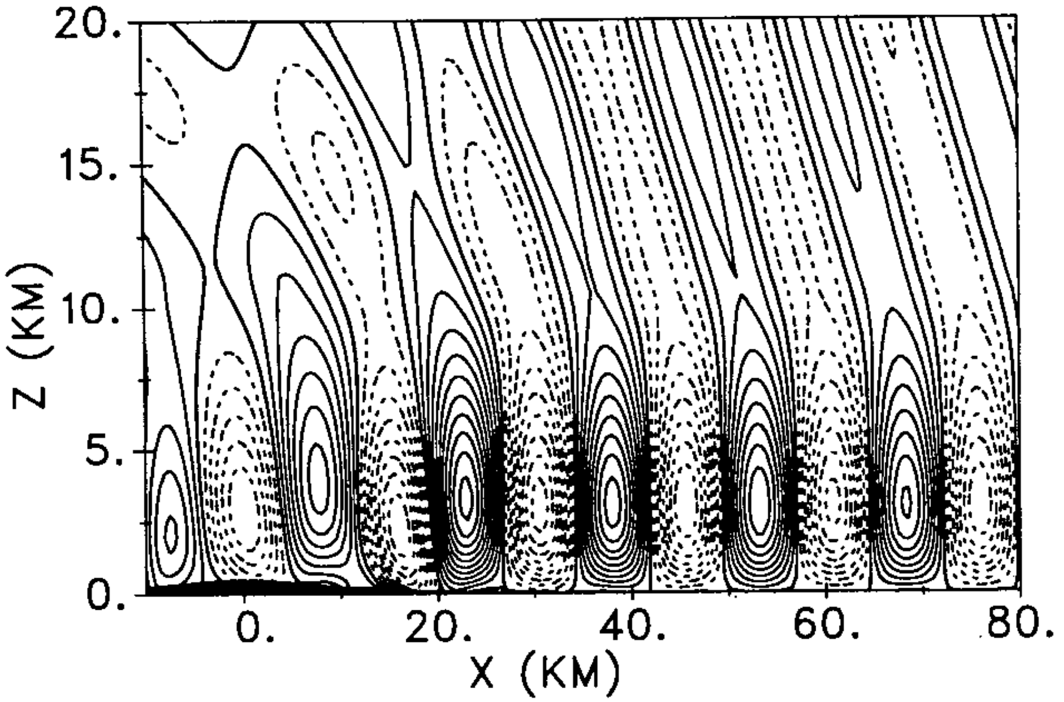
Validity of hydrostatic approximation: Example 3

Dispersion relation for hydrostatic and non-hydrostatic gravity waves is different.

In practice, non-hydrostatic effects only important at 1km horizontal resolution.



Hydrostatic



Non-hydrostatic

From: Keller (JAS, 1994)

Recap

Horizontal resolution in IFS is determined by both spectral truncation and the physical space grid used in semi-Lagrangian advection (+ other right hand side terms).

Current IFS horizontal resolution in HRES medium-range forecasts is TCo1279. This means spherical harmonic expansion up to total wavenumber 1279, and cubic octahedral grid with physical space resolution of ~9km.

Tests where small-scale convection is explicitly resolved show that non-hydrostatic dynamics only important for horizontal resolutions < 1km. Same applies for non-hydrostatic gravity waves. For resolutions > 1km there can be differences between H and NH results, but these can be as large as differences when tuning model dynamics or physics.

Large scale convection can, however, be sometimes resolved even at 9km horizontal resolution.