Non-hydrostatic modeling with HARMONIE

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P.L. for dynamics of HIRLAM-A

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Outline

- Short description of HARMONIE
- Behaviour of AROME in HARMONIE
- Implementation of Finite Element discretization in the vertical

The HARMONIE model

- Collaboration HIRLAM ←→ ALADIN
- IFS dynamical core
  - Non-hydrostatic
  - Limited area version
  - Physical parameterizations
    - ALADIN
    - HIRLAM
    - ECMWF
    - ALARO
    - AROME

Brac-HR workshop

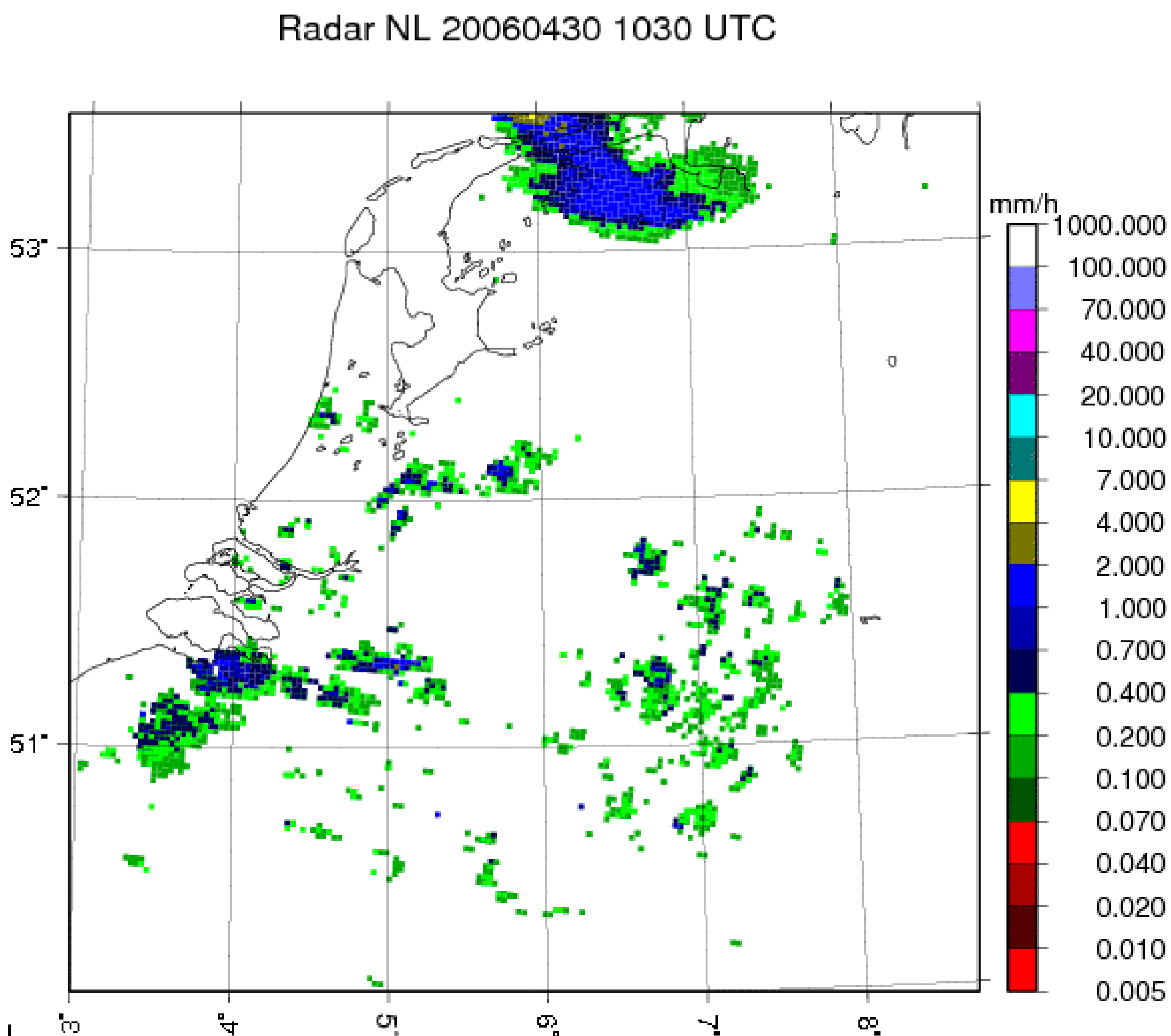
- BRain-storming on Advanced Concepts on High Resolution modeling
- Should the convection be parameterized (at least in part) at 2.5 km resolution?
- Implicit or explicit methods?

Convection in HARMONIE

- Deep convection and outflow
  - Impact resolution
  - Impact horizontal diffusion
  - Impact SLHD (Semi-Lagrangian Horizontal Diffusion)

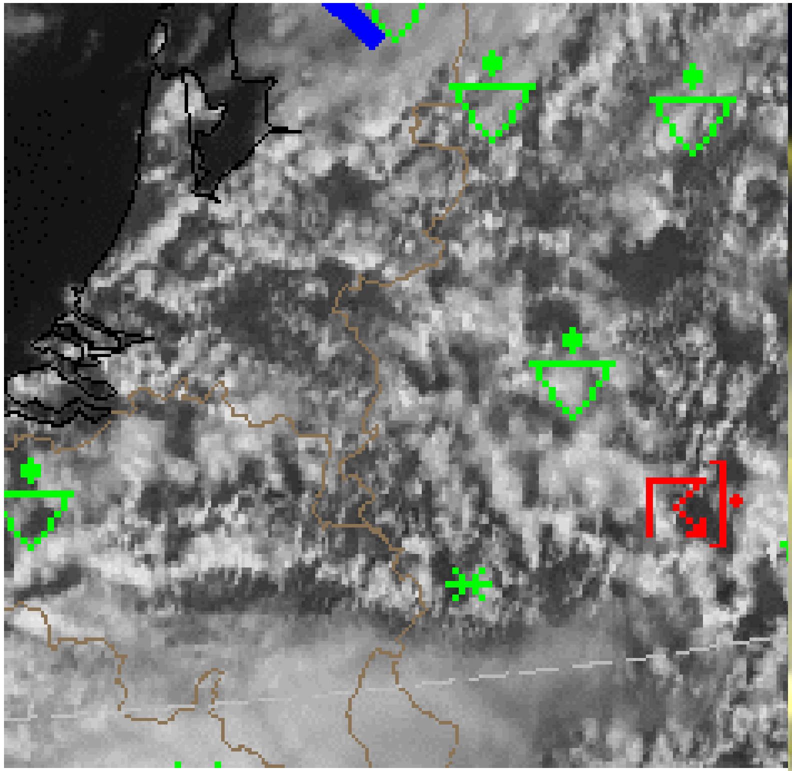
Impact resolution

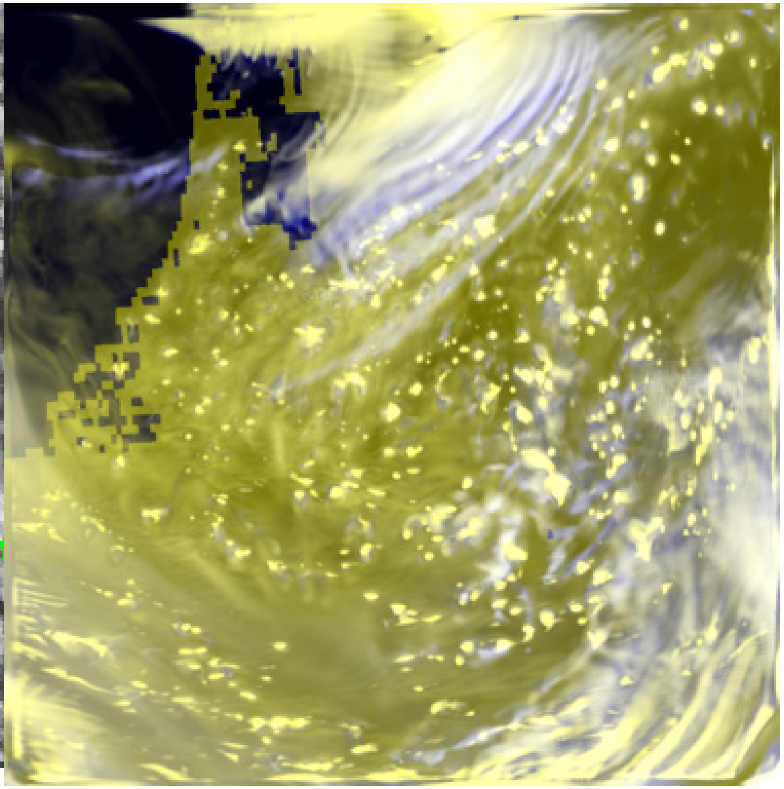
ALARO physics without deep convection ~AROME

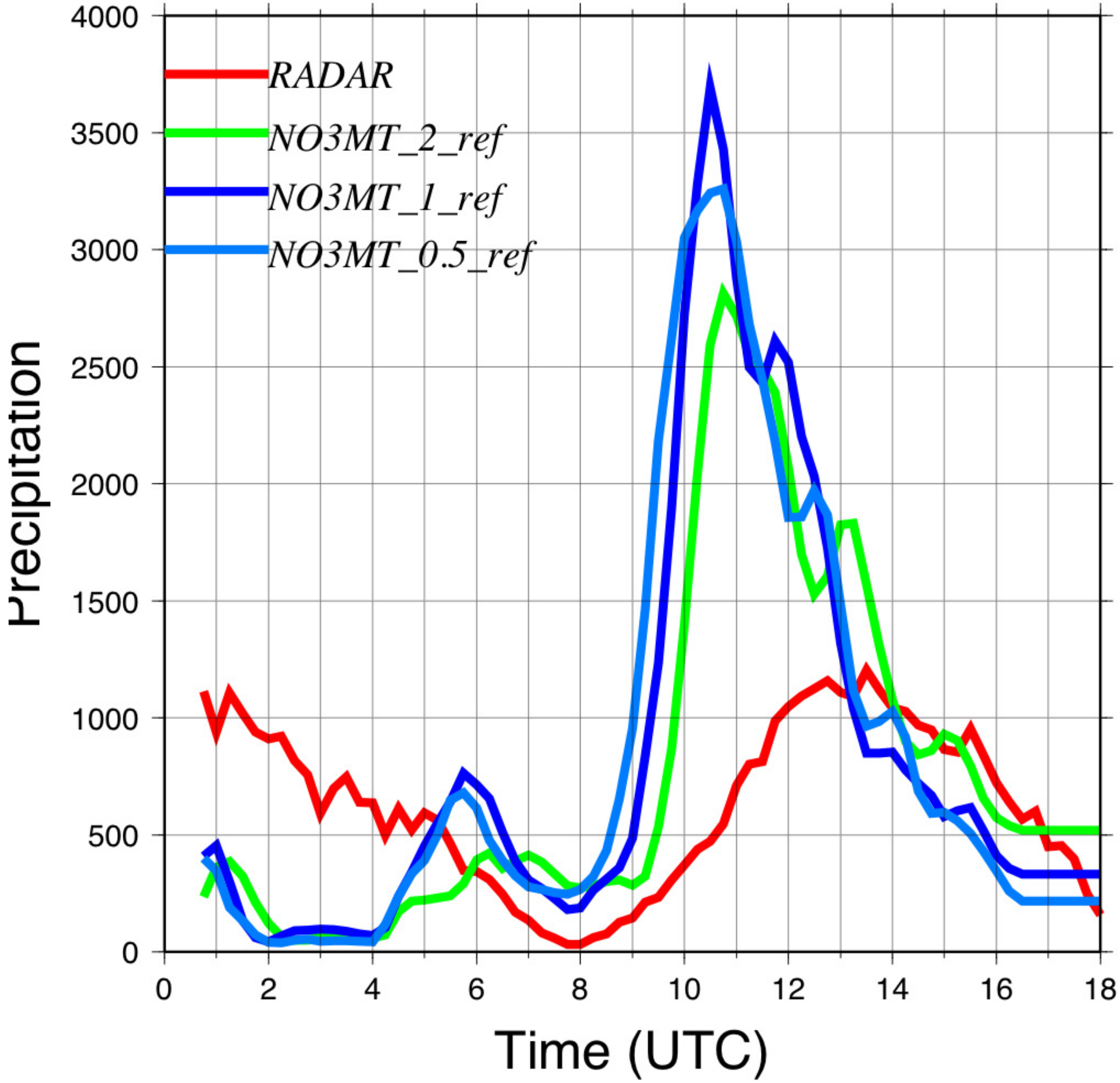


Comparison with satellite

- Satellite 2, 1, 0.5 km







4000
3500
3000
2500
2000
1500
1000
500
0
Precipitation
0
2
4
6
8
10
12
14
16
18
Time (UTC)
RADAR
NO3MT_2_ref
NO3MT_1_ref
NO3MT_0.5_ref

Impact of resolution

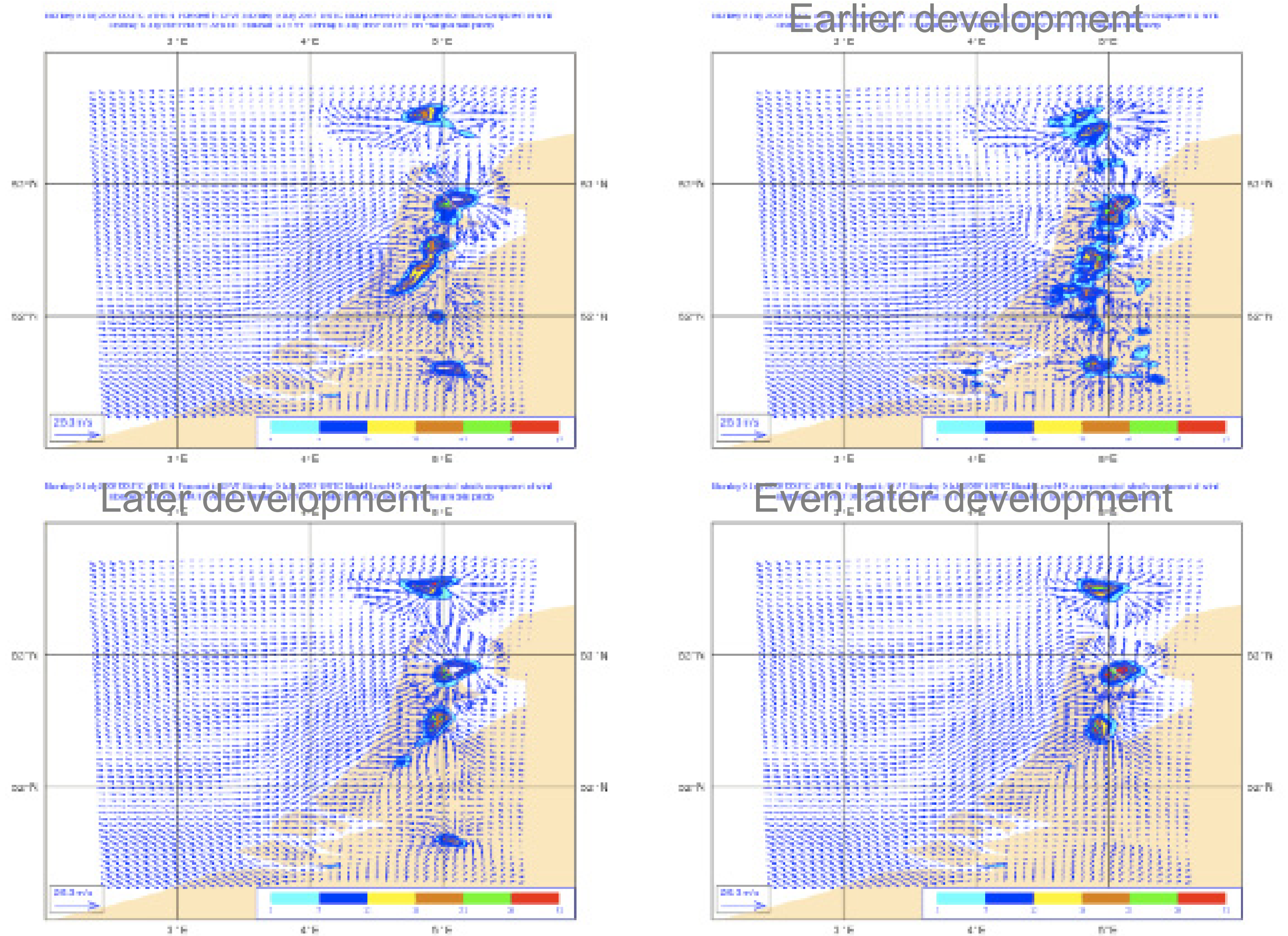
- Increasing resolution from 2 km to 1 km increases maximum precipitation, but it decreases from 1 -> 0.5 km. What happens at even higher resolution?
- Scales are not going to observed open cell scales
- Impact on onset of deep convection relatively small
- Scales become smaller with increasing resolution
- All resolutions show secondary maxima

Impact horizontal diffusion

- Linear spectral horizontal diffusion in HARMONIE
- Same horizontal diffusion coefficients for all parameters
- Initially too strong horizontal diffusion, and different strength for different parameters
- Caused later onset of convection, larger cells and stronger outflow (French fireworks case).

32h3

33h1



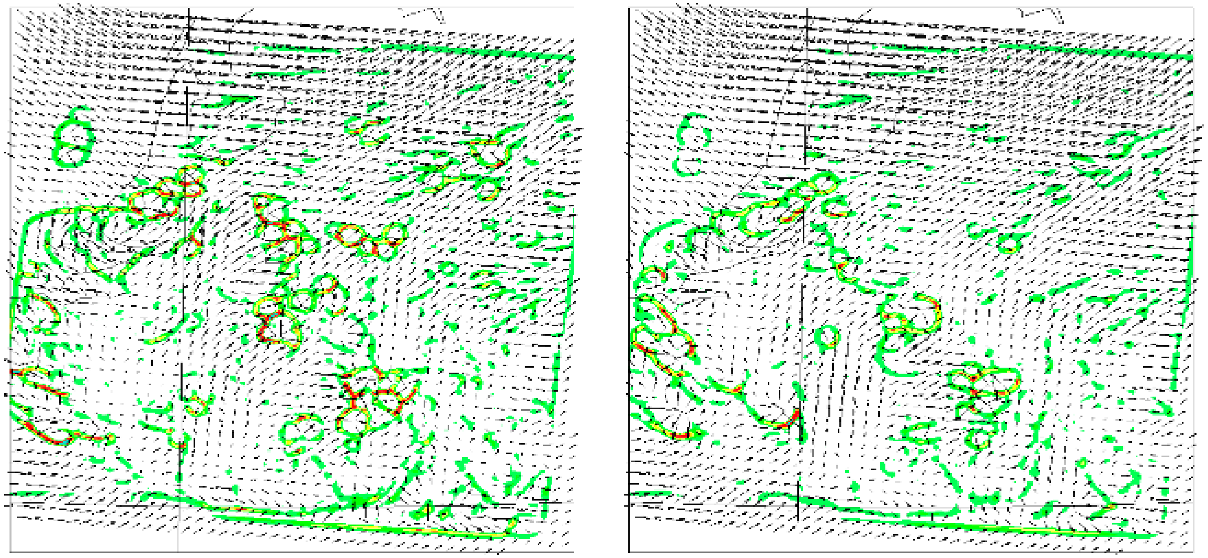
Outflow similar in all setups, case with strong outflow in reality

high1

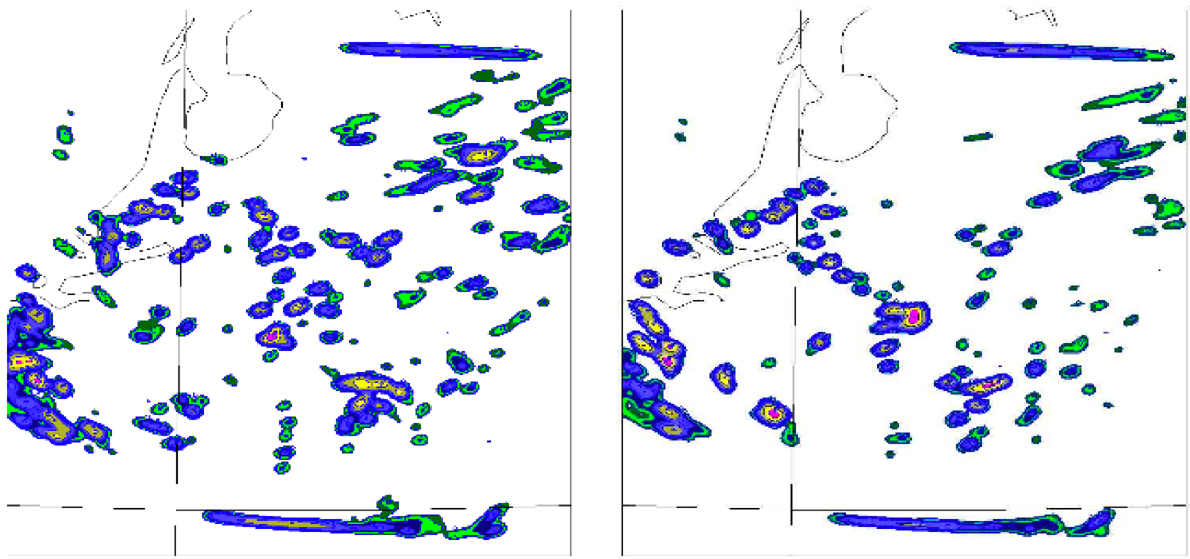
high2

Impact SLHD

- SLHD = semi lagrangian horizontal diffusion
- SL-scheme diffusive, strength of diffusion can be chosen, the semi-Lagrangian buffer is the only place in the model where 3-D fields are available and 3D effects can be implemented.
- SLHD applied to reduce the strength of spurious small scale lows in ALADIN



(a) *REF* experiment vertical divergence (b) *SL3* experiment vertical divergence



(c) *REF* experiment precipitation (d) *SL3* experiment precipitation

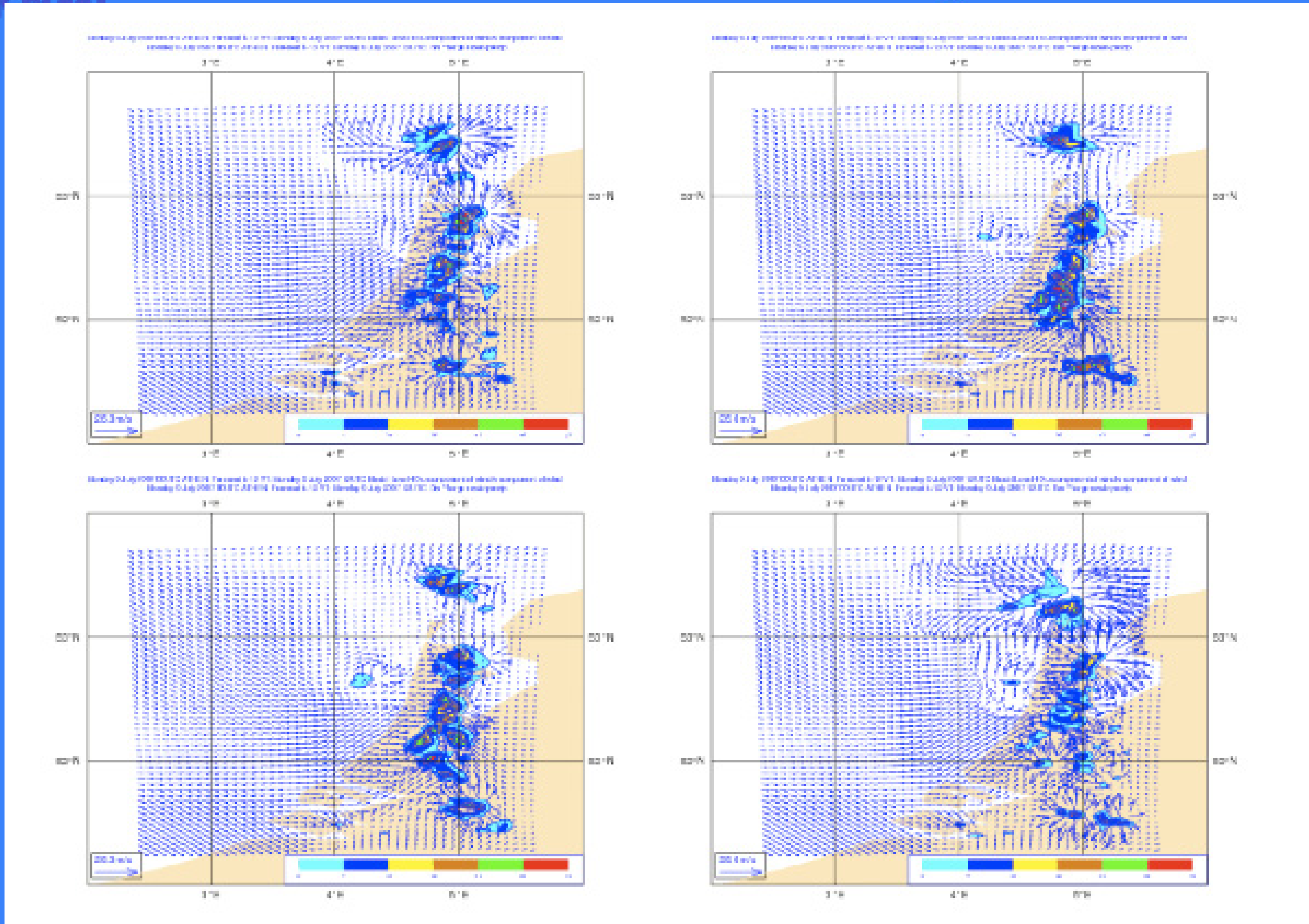
Impact microphysics

- Evaporation
- Removal of hydrometeor species
- Fall speed

Impact evaporation

- Hydrometeors often present in only a part of grid cell, especially at boundary of convective clouds
- Model does not know how large part of grid cell is occupied by hydrometeors
- Fraction of evaporation to take hydrometeor distribution into account?

33h1 evap/10



evap=0 evap*10

Koninklijk Nederlands Meteorologisch Instituut

Evaporation

- Reduction of evaporation increases the temperature of unsaturated air with hydrometeors
- Cold pools warmer, weaker outflow
- Study against observations: reduction to 50-30% of original values gives best distributions of temperature and wind direction

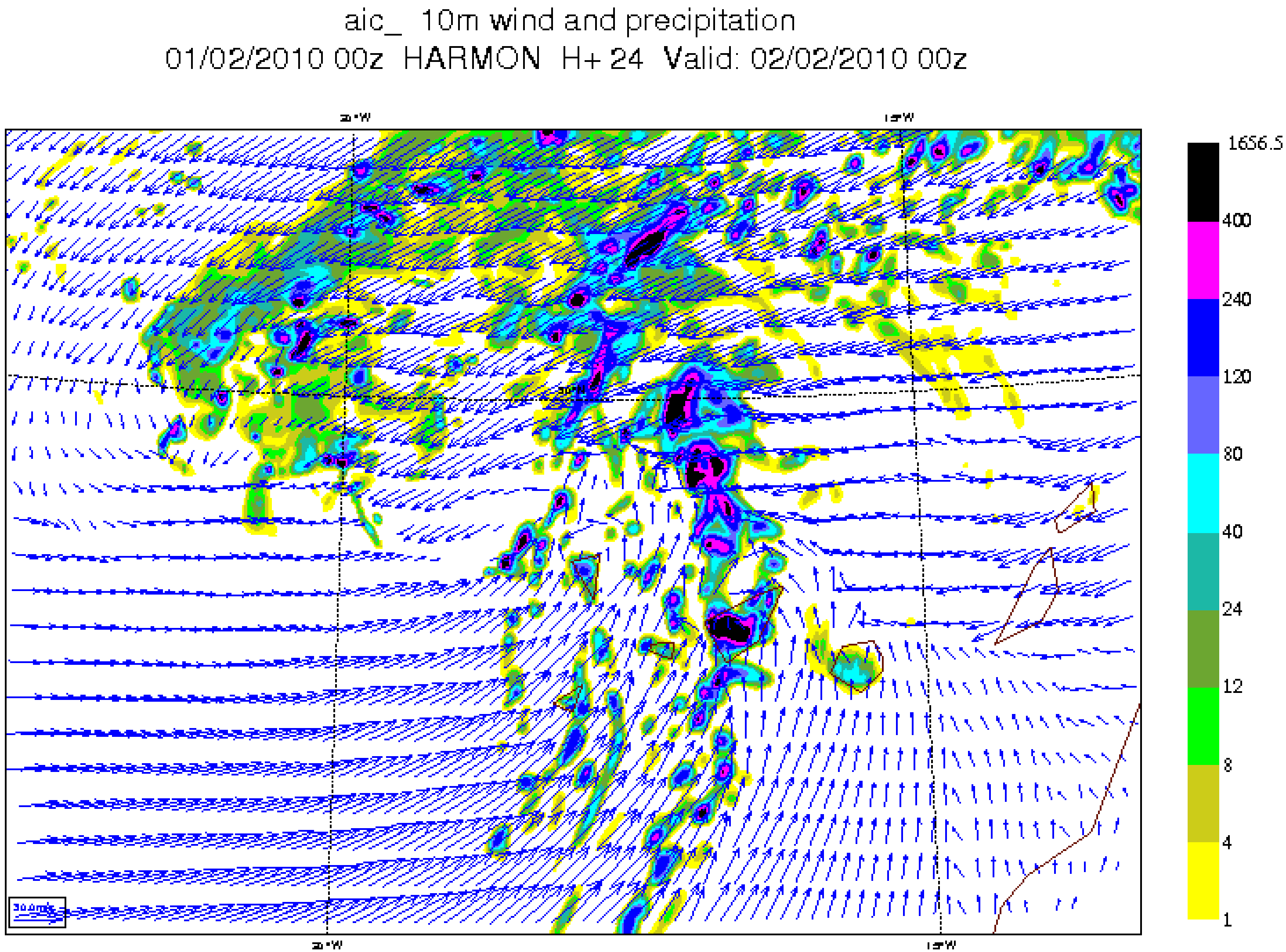
Removal of graupel

- Strong convection only when graupel (quick parameter) present
- Removal of graupel leads to larger convective cells, lower maximum precipitation intensity
- Probably due to snow becoming more important, lower fall speed, higher water loading effect (reduction updraft speed).

Operational setup for CY36H1.1

- SLHD applied to hydrometeors
- SLHD NOT applied to humidity
- Same (small) spectral horizontal diffusion to all spectral upper-air fields

Forecasts of strong rain event in Canary Islands



Implementation of the Vertical Finite Element discretization on the non-hydrostatic version

NH DYNAMICAL CORE

- Prognostic variables
  - Horizontal velocity, **V**
  - Vertical divergence, d
  - Temperature, T
  - non-hydrostatic pressure departure, q
- Stability in presence of orography needs a new divergence variable

$$dl \equiv d + X = \frac{p}{mRT}\left(-g\frac{\partial w}{\partial \eta} + \nabla \varphi \cdot \frac{\partial V}{\partial \eta} \right)$$

NH DYNAMICAL CORE (cont)

- Vertical coordinate
  - Mass based, hybrid terrain following coordinate
  - Time dependent
- Time stepping: semi-implicit
  - Constant and horizontally uniform coefficients
  - Linear system using additional elastic reference temperature for acoustic wave terms
  - Iterative centered implicit (ICI) implemented

NH DYNAMICAL CORE (cont)

- Spatial discretization
  - Spectral in the horizontal
  - Finite differences in the vertical
- Vertical operators must verify constraints

$$\mathrm{C1}: G^* + S^* - G^* S^* - N^* = 0$$

$$\mathrm{C2'}: L^* \left(S^* G^* - \frac{c_p}{c_v} \left(S^* + G^* \right) \right) \text{ must have real negative eigenvalues.}$$

- Not easy to implement with VFE

$$m^* \equiv \frac{d\pi^*}{d\eta}$$

$$\partial^* X = \frac{\pi^*}{m^*}\frac{\partial X}{\partial \eta}$$

$$G^* X = \int_\eta^1 \frac{m^*}{\pi^*} X d\eta$$

$$S^* X = \frac{1}{\pi^*}\int_0^\eta m^* X d\eta$$

$$N^* X = \frac{1}{\pi_s^*}\int_0^1 m^* X d\eta$$

$$L^* X = \partial^*\left(\partial^* + 1\right)X$$

Other prognostic variables?

- Test other prognostic variables
  - horizontal and vertical velocity, temperature, geopotential and logarithm of hydrostatic pressure at surface
- It is SHB stable
  - but instability appears when orography is present
- Constraints
  - Vertical differential and integral operators must satisfy constraints

Other prognostic variables?

- In sigma mass based vertical coordinate the prognostic equations are

$$\frac{dV}{dt} + \frac{RT}{p}\nabla p + e^{-q}\frac{\partial p}{\partial \sigma}\nabla \varphi = F$$

$$\frac{dw}{dt} + g\left(1 - e^{-q}\frac{\partial p}{\partial \sigma}\right) = F_z$$

$$\frac{dT}{dt} + \frac{RT}{c_v}D_3 = \frac{Q}{c_v}$$

$$\frac{d\varphi}{dt} - gw = 0$$

$$\frac{\partial q}{\partial t} + \int \nabla \cdot V d\sigma + (\nabla q)\cdot \int V d\sigma = 0$$

Other prognostic variables?

- This set of constraints must be satisfied

$$\mathrm{C1}: \quad \partial^* N^* = 0$$
$$\mathrm{C2}: \quad \left(1 + \partial^*\right) S^* = 1$$
$$\mathrm{C3}: \quad \left[\partial^* \partial^*\right] = \partial^* \cdot \partial^*$$

$$\partial^* = \sigma \frac{\partial}{\partial \sigma}$$

$$S^*\left[f(\sigma)\right] = \frac{1}{\sigma} \int f(\sigma')\, d\sigma'$$

$$N^*\left[f(\sigma)\right] = \int f(\sigma')\, d\sigma'$$

- The constraints can be fulfilled with VFE
- Strong instability when orography is present

Other vertical coordinate?

- Both mass and height based coordinates has been shown to be suitable for NH modeling.
- Why to introduce height based coordinate?
  - Is a time independent coordinate.
  - It has an easier mathematical treatment of covariant velocity than the mass based coordinate.
- Covariant derivative can be used in the discretization of differential operators.

Other vertical coordinate?

- Covariant variables and covariant derivative makes the expression of divergence operator simpler, without the non-linear term which is unstable in presence of orography.

$$\text{Covariant} \; : \operatorname{div} V = |g|^{-\frac{1}{2}} \sum \frac{\partial}{\partial X_i}\left(|g|^{\frac{1}{2}} V^i \right)$$

$$\text{Non Covariant, mass based} : \operatorname{div} V = \nabla_\pi \cdot V_H - \rho g \frac{\partial w}{\partial \pi} + \rho \nabla_\pi \varphi \cdot \frac{\partial V}{\partial \pi}$$

Covariant differential operators (gradient, divergence, curl and laplacian) are straightforwardly found, also in the 3D case.

2D (X,Z) model

- The set of prognostic variables used are
  - Covariant **V**, ln(T) and ln(p)
- SHB numerical linear stability analysis shows in the 3TL case:
  - amplification factors under 1.01 in most cases.
  - stability for residual term temperature T in the range 0.5 T*< T < 1.5 T*.
- Vertical discretization:
  - VFE has been implemented and it is more accurate than VFD with almost equal stability.
- Advection:
  - Covariant Eulerian and covariant semi-Lagrangian schemes has been applied successfully

2D (X,Z) model

- Covariant vertical velocity variable W is the prognostic variable used in the Helmholtz structure equation of the semi-implicit solver:

$$\text{Helmholtz} \quad \left(I - \beta^2 c_*^2 \left(\nabla^2 + L_Z\right) - \beta^4 c_*^2 N_*^2 \nabla^2\right) W_{n+1} = RHS$$

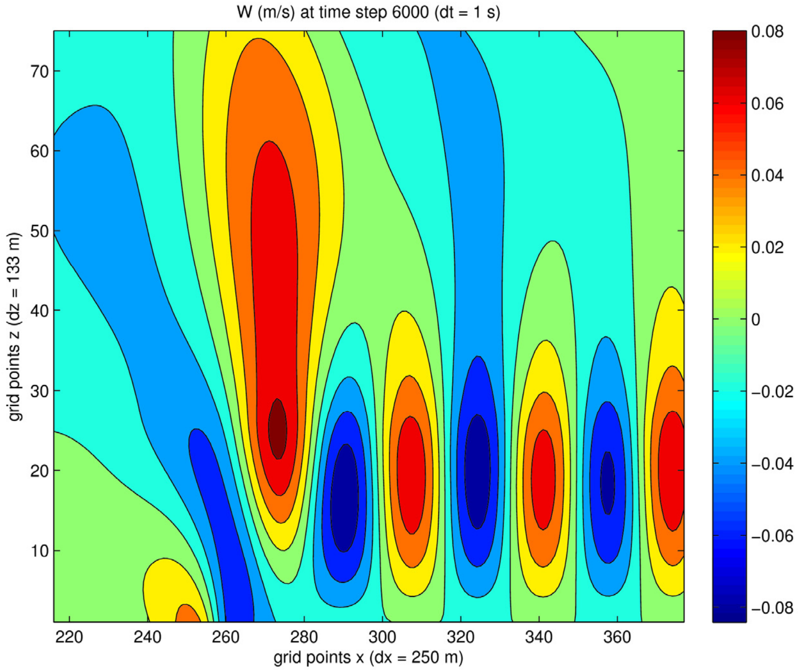
$$\text{where vertical Laplacian } L_Z = \frac{1}{H_*^2}\left(\frac{H_*}{H_T}\partial_Z \cdot \frac{H_*}{H_T}\hat{\partial}_Z + \frac{H_*}{H_T}\hat{\partial}_z\right)$$

$$c_*^2 \equiv R_d T^* \frac{C_{pd}}{C_{vd}}; \quad H_* = \frac{R_d T^*}{g}; \quad N_*^2 = \frac{g^2}{C_{pd} T^*}$$

- Robust boundary condition implementation
  - W=0 at boundaries is included in the semi-implicit solver.

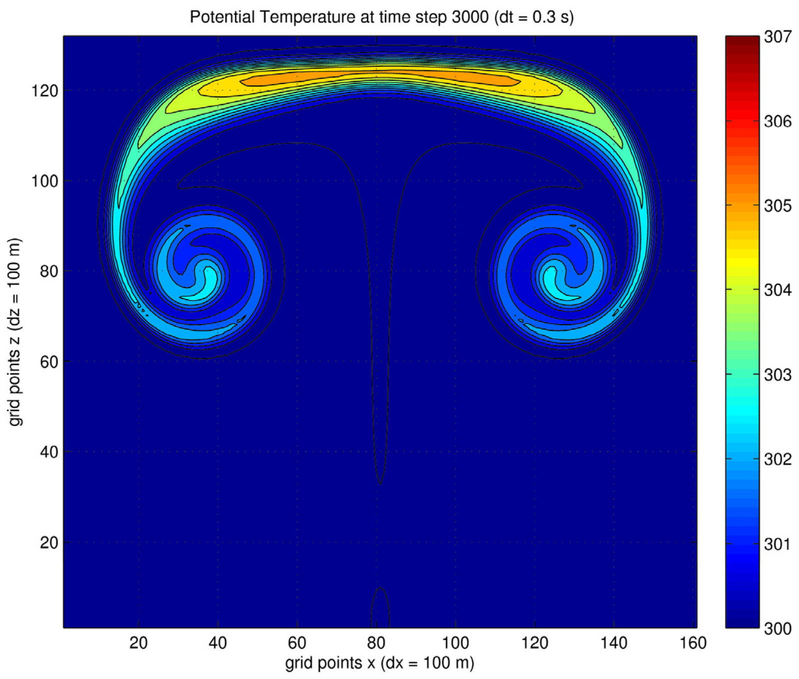
2D (X,Z) model tests

- Two layer atmosphere with two different stabilities
- Waves propagating downstream
- Good agreement with the linear analytical solution



2D (X,Z) model tests

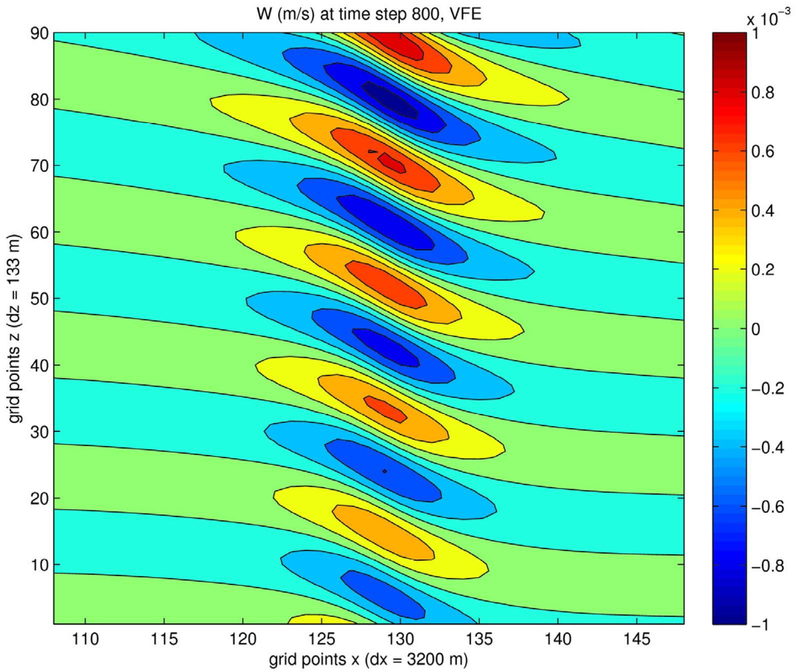
- Warm bubble.
- Good agreement with other published results.



Janjic Z. I., Gerrity Jr. J. P., Nickovic S., 2001: An Alternative Approach to Nonhydrostatic Modeling. Monthly Weather Review Volume 129, Issue 5 pp. 1164-1178

2D (X,Z) model tests

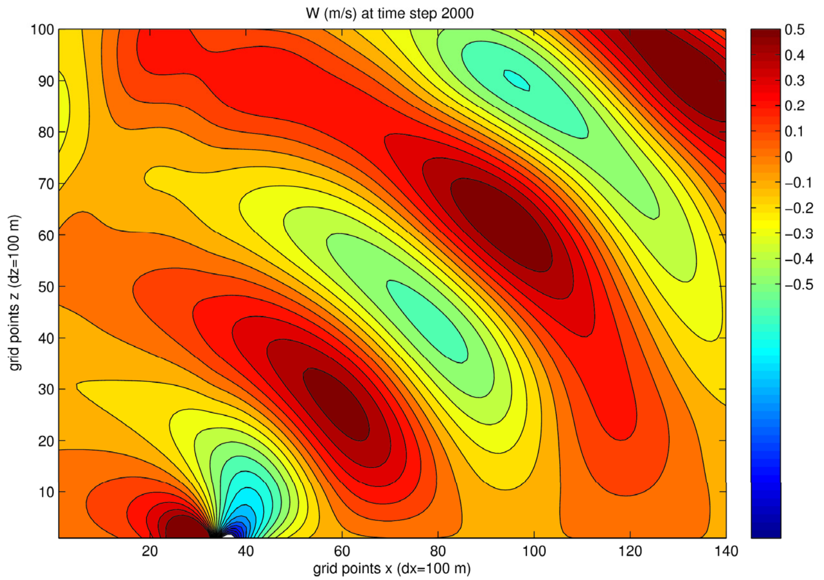
- Linear and non linear Hydrostatic waves.
- Good agreement with the analytical solutions and other results.



Bubnová R., Hello G., Bénard P., Geleyn J.F., 1995: Integration of the Fully Elastic Equations Cast in the Hydrostatic Pressure Terrain-Following Coordinate in the Framework of the ARPEGE/Aladin NWP System, Monthly Weather Review Volume 123, pp. 515-535

2D (X,Z) model tests

- Linear and non linear Non-Hydrostatic waves.
- Good agreement with the analytical solutions and other results.



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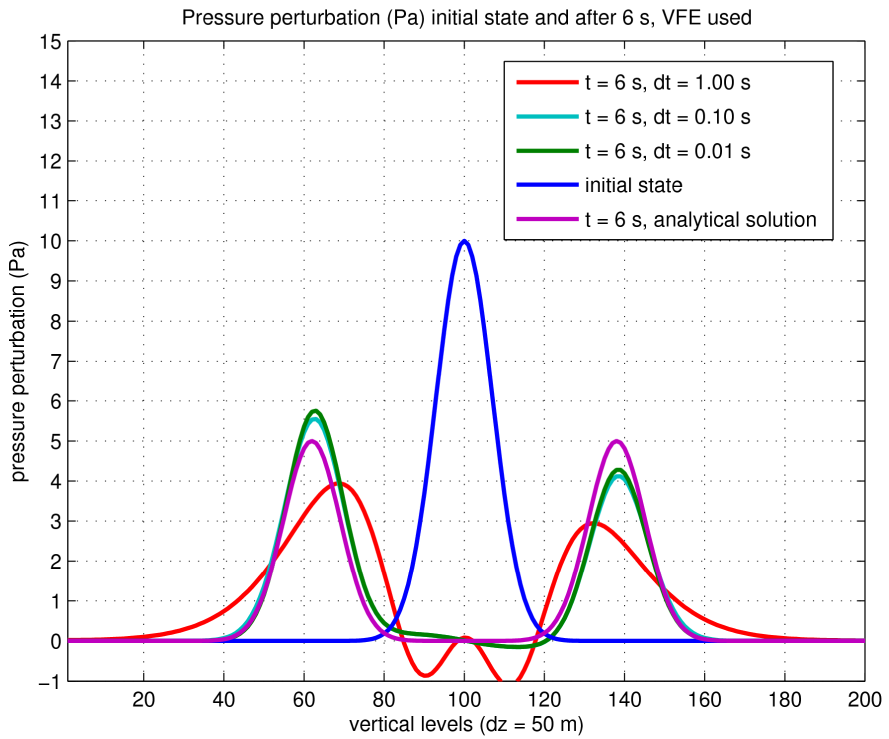
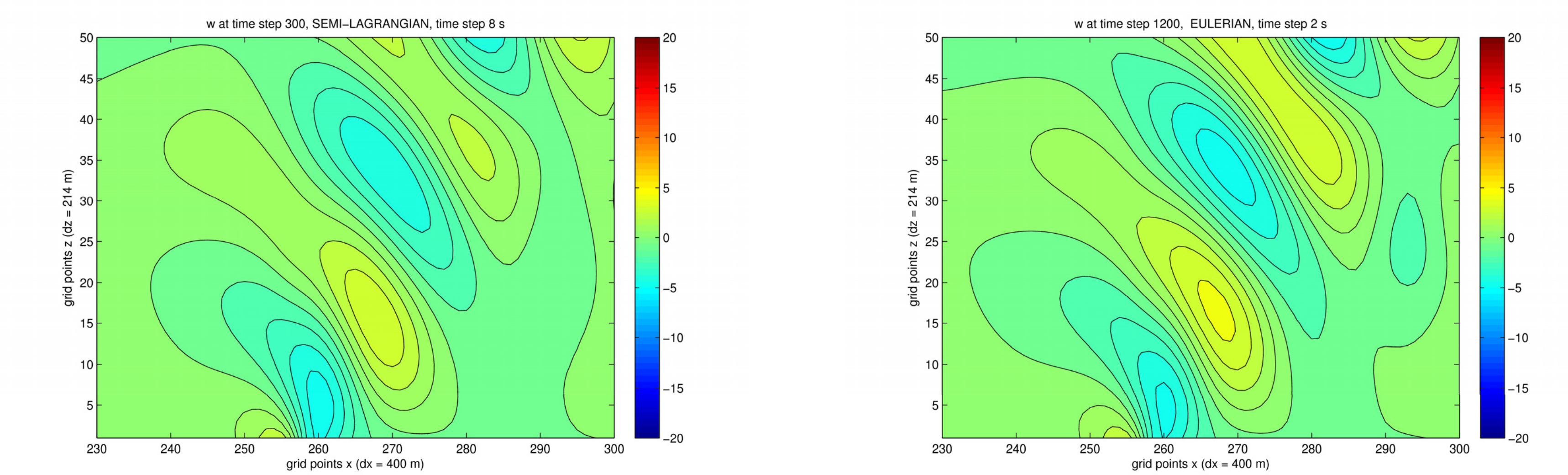
2D (X,Z) model tests

- Acoustic waves.
- It is a full elastic model and therefore can reproduce accurately acoustic waves.



Covariant SL scheme

- Euerian and semi-Lagrangian produce similar results although semi-Lagrangian is more dispersive (due in part to the low order bilinear interpolation)
- Semi-Lagrangian (left) allows bigger time steps than eulerian (right)



Thank you for your attention