Dynamics developments within the ALADIN NWP consortium

P. Termonia

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& work of many, many others

http://www.umr-cnrm.fr/aladin/

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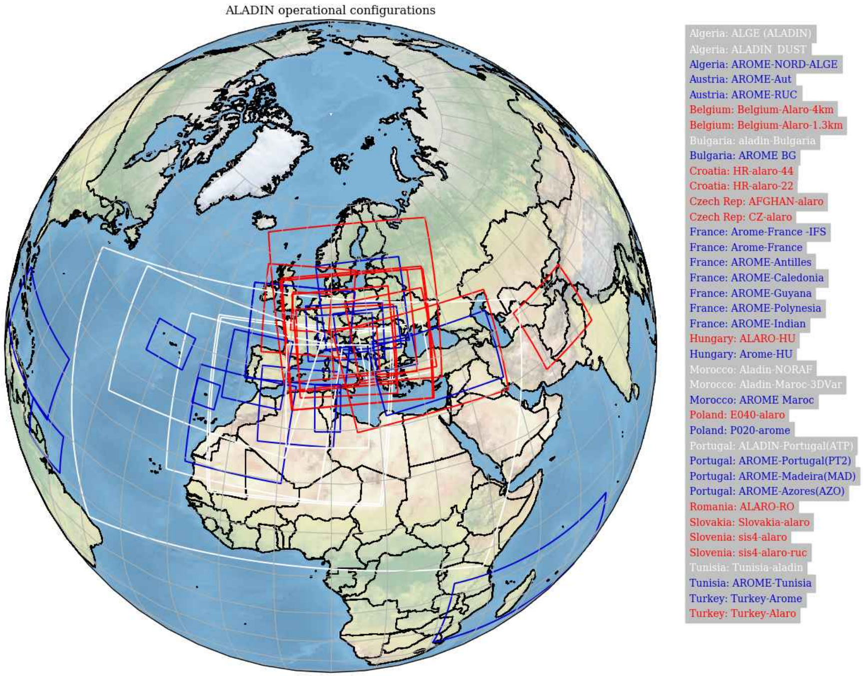
Outline

- The ALADIN-HIRLAM system
- Challenges for the spectral solver
- Scientific strategy
- Evolution of the dynamical core
- An iterative Helmholtz solver
- Conclusions

Context

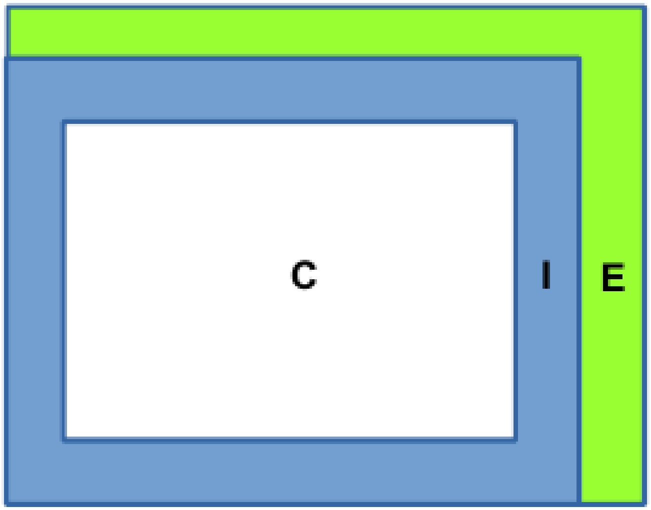
- ALADIN-LACE-HIRLAM collaboration
- Source code is shared with the IFS
- Historical search for cheap solutions, that can run on a wide range of HPC platform.
- Care for efficiency, so long time steps



Numerical approach

- The ALADIN-HIRLAM System uses a semi-Lagrangian, semi-implicit, spectral dynamical core
- Both a hydrostatic and a non-hydrostatic (ALADIN-NH, Bubnová et al. 1995) dynamical core are available and are used operationally.
- The vertical coordinate is a terrain-following mass-based coordinate
- The main reason for using a spectral dynamical core is to solve the Helmholtz problem arising in the semi-implicit timestepping
- The reference state for the semi-implicit scheme is constant in space and time

Spectral LAM



	Step	Options (LAM vs. global)
1.	Horizontal derivatives (vorticity, divergence and pressure–temperature gradients)	
2.	Inverse spectral transform: spectral to grid point	{ bi-FFT^{-1} / Legendre, FFT
3.	Computation of the physics contributions	{ AROME physics / ALADIN/ALARO physics
4.	Calculation of the tendencies of the prognostic variables of the model state	INTFLEX
5.	Computation of the explicit grid-point dynamics and adding it to the total tendencies of the prognostic variables	{ IFS–ARPEGE–ALADIN hydrostatic / ALADIN-NH
6.	Computation of the semi-Lagrangian departure points and Interpolation of the tendencies to these points	SLHD
7.	Addition of the interpolated tendencies to the model state	
8.	Lateral boundary coupling	bi-periodic LBC conditions
9.	direct spectral transforms	{ bi-FFT / Legendre, FFT
10.	solving the semiimplicit Helmholtz equation	{ IFS–ARPEGE–ALADIN hydrostatic / ALADIN NH

Davies relaxation zone (**I**)

- Here a relaxation is applied from the border of the C zone to the inner part of the E zone, were the large scale field from the (global) model is used.

Extension zone (**E**)

- is used to make the fields periodic using spline functions in both directions
- This allows to take FFTs in both directions.

Challenges for the current dynamics: scalability

- Spectral transforms require data-rich global communications (MPI_ALLTOALL)

- (These communications are not a bottleneck on current HPC's yet)

- On future massively parallel machines, the scalability of spectral transforms may become problematic.

Challenges for the current dynamics: steep slopes

- Going to higher resolutions, the resolved slopes become steeper
- The horizontally constant reference state of the semi-implicit scheme may deviate substantially from the actual atmospheric state
- The (explicitly treated) nonlinear residual term becomes more important, thus negatively affecting stability

Scientific strategy

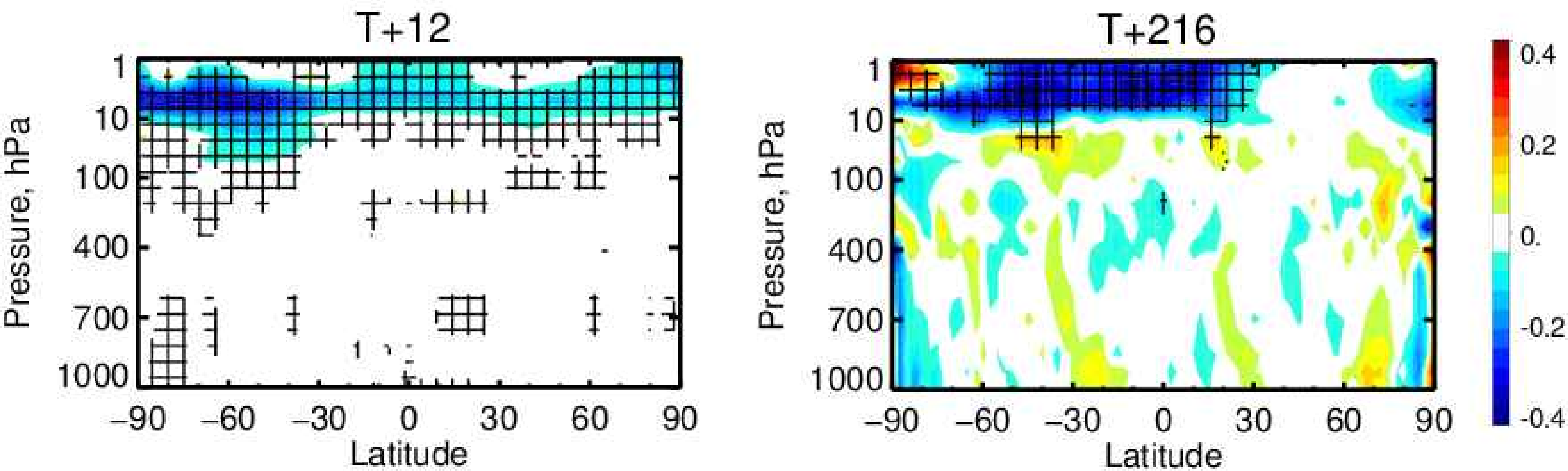
1) Continue with improvements of the present dynamical core towards the hectometric scale:

- Refinement of the LBC formulation
- More stable treatment of the orography
- ***Vertical finite elements***
- Transport: e.g. more conservative SL

1) The long-term dynamical core strategy for the LAMs is based on a twofold approach:

- Develop a LAM solution based on a finite-volume approach following the FVM developments of ECMWF (a.o. LAM Atlas).
- ***Finalize a gridpoint (finite difference) dynamics solver as a scientific testbed, as a backup solution and as an alternative to the spectral dynamics.***

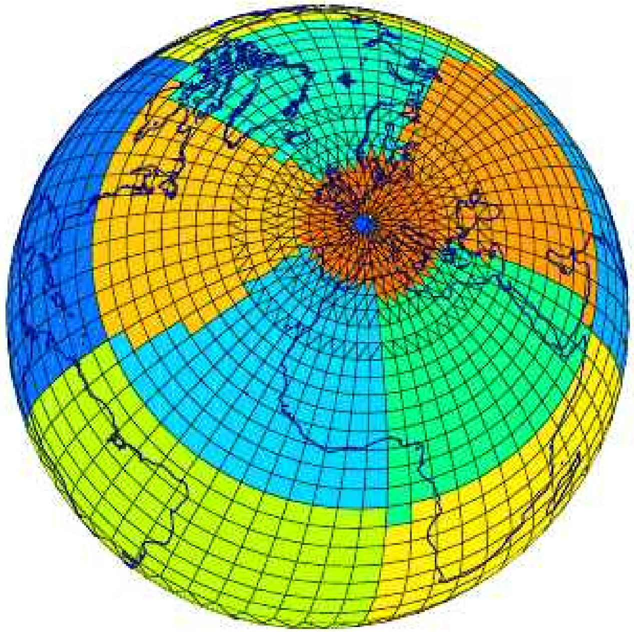
- NH dynamics as a departure from HPE [Jozef Vivoda]
- VFE new formulation for HPE [Jozef Vivoda]
  - VFE implemented in hydrostatic IFS in 2002 (Untch and Hortal)
  - extension of VFE to NH dynamics in 2013 (Vivoda and Smolíková) with new formulation of vertical integral and derivative operators with prescribed boundary conditions
  - in hydrostatic dynamics only vertical integral is needed
  - the new formulation of vertical integral together with a revised definition of explicit vertical coordinate may be beneficial for hydrostatic IFS, implemented in 2019

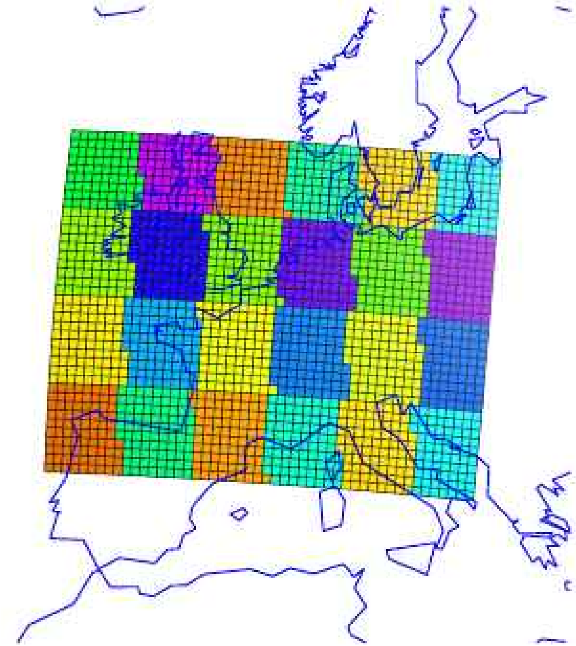


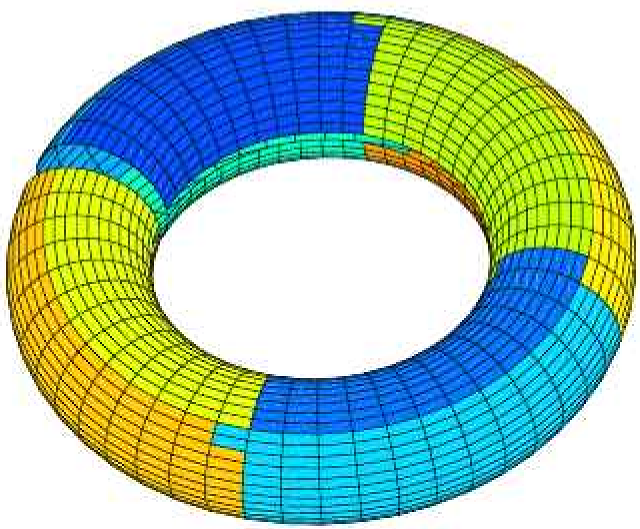
RMSE for T in IFS, Nov 2018 - Feb 2019, Tco1279: new VFE compared to the reference VFE. [improved, deteriorated, **++ statistically signif.]**

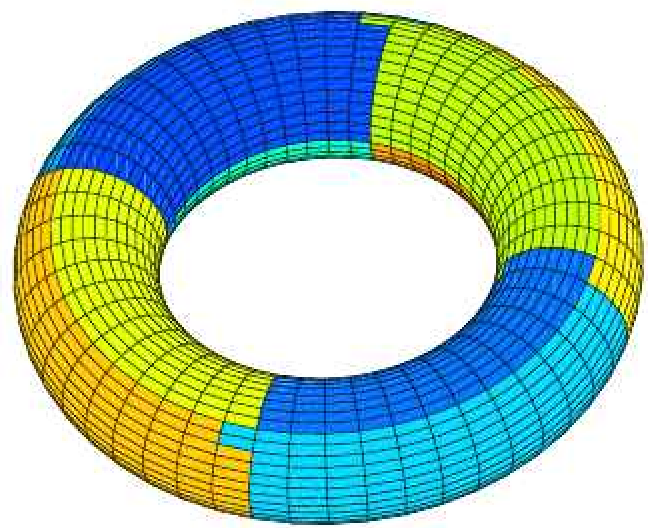
Atlas-based implementation

- Atlas is the library being developed at ECMWF for handling parallel data structures
- Developing an iterative Helmholtz solver based on Atlas to anticipate the appearance of Atlas in the IFS/ARPEGE/ALADIN/AROME code
- Several ingredients have already been developed:
  - (Biperiodic) limited area grids, meshes and functionspaces;
  - Limited-area versions of some ESCAPE dwarfs (GCR, SL);
  - Stencil operations for multigrid functionality;
  - Custom halo exchanges, e.g. for red-black Gauss-Seidel relaxation
- Hopefully, we can put these ingredients together in the next few months.





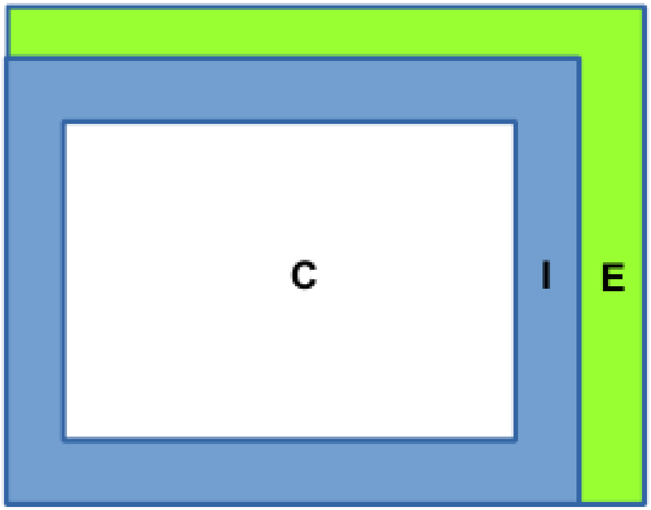




An Alternative gridpoint solver

Météo Algérie
الديوان الوطني للأرصاد الجوية
Office National de la Météorologie
ZAMG
IRM
DHMZ
METEO FRANCE
OMSZ
MAROC METEO
IPMA
Instituto Português do Mar e da Atmosfera
METEO ROMANIA
SHMU
ARSO METEO Slovenia
METEOROLOJİ

Spectral LAM



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- Consider the spectral part (blue boxes) as a Dwarf.
- The part only computes derivatives and solvers the Helmholtz equation
- The idea is to take it from the code and develop an alternative gridpoint solver.
- Test the scalability of this solver (cleanly) in comparison to the spectral solver.

Evolution of the dynamical core

- Keep as much as possible of the ALADIN-HIRLAM System intact, while addressing these two challenges:
  - keep semi-implicit timestepping
  - keep semi-Lagrangian advection
  - keep vertical coordinate system
  - keep physics
  - keep boundary condition formulation
  - …

- Only get rid of the spectral transforms
  - ⇒ develop a non-spectral solver for the Helmholtz problem

An iterative Helmholtz solver: formulation

- Thanks to the constant-coefficient semi-implicit formulation, the 3D Helmholtz problem can be split into a series of 2D Helmholtz problems:

$$(1 - c_\ell^2 \delta t^2 \nabla^2)\psi_\ell = RHS_\ell$$

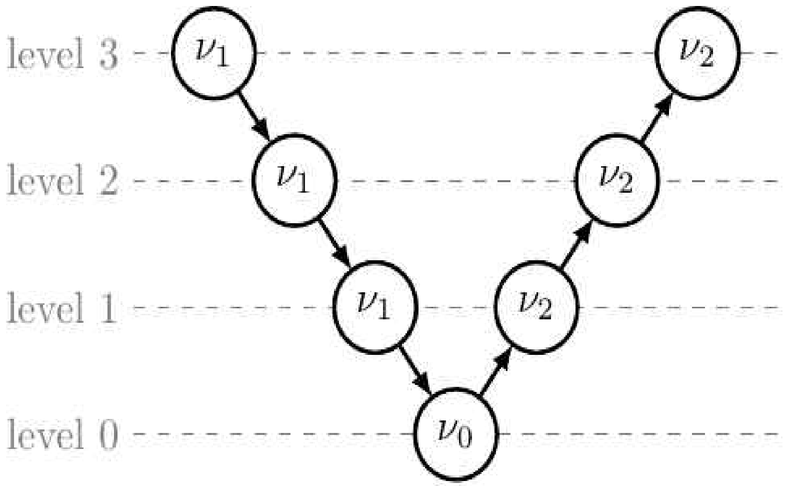
  - Each 2D HH problem has its own wave speed
  - The domain is rectangular
  - Boundary conditions are biperiodic (like for the spectral solver; physical boundary conditions are applied with Davies relaxation)

- Solving 2D Helmholtz problems is pretty common in computational physics; typically done with iterative solvers. But:

How to comply with tight operational constraints when using an iterative solver?

An iterative Helmholtz solver: multigrid preconditioner

- A multigrid preconditioner can be used to speed up convergence
- This preconditioner has 4 parameters:
  - the multigrid depth *d*
  - the number of pre-relaxations ν_1
  - the number of post-relaxations ν_2
  - the number of relaxations at the coarsest resolution ν_0
- The choice of these parameters will be discussed further
- Relaxation is done with a red-black Gauss-Seidel scheme



An iterative Helmholz solver: convergence speed

- Convergence of an iterative solver is determined by the spectrum, i.e. by the extreme eigenvalues of the system.
- Thanks to the specific formulation of the ALADIN-HIRLAM dynamics, i.e.
  - biperiodic rectangular domain;
  - constant-coefficient semi-implicit reference state;
  - vertical decoupling into 2D Helmholtz problems,

the eigenvalues of the (preconditioned) system can be determined analytically!

- The eigenvalues only depend on the wave Courant number, not on the domain size.

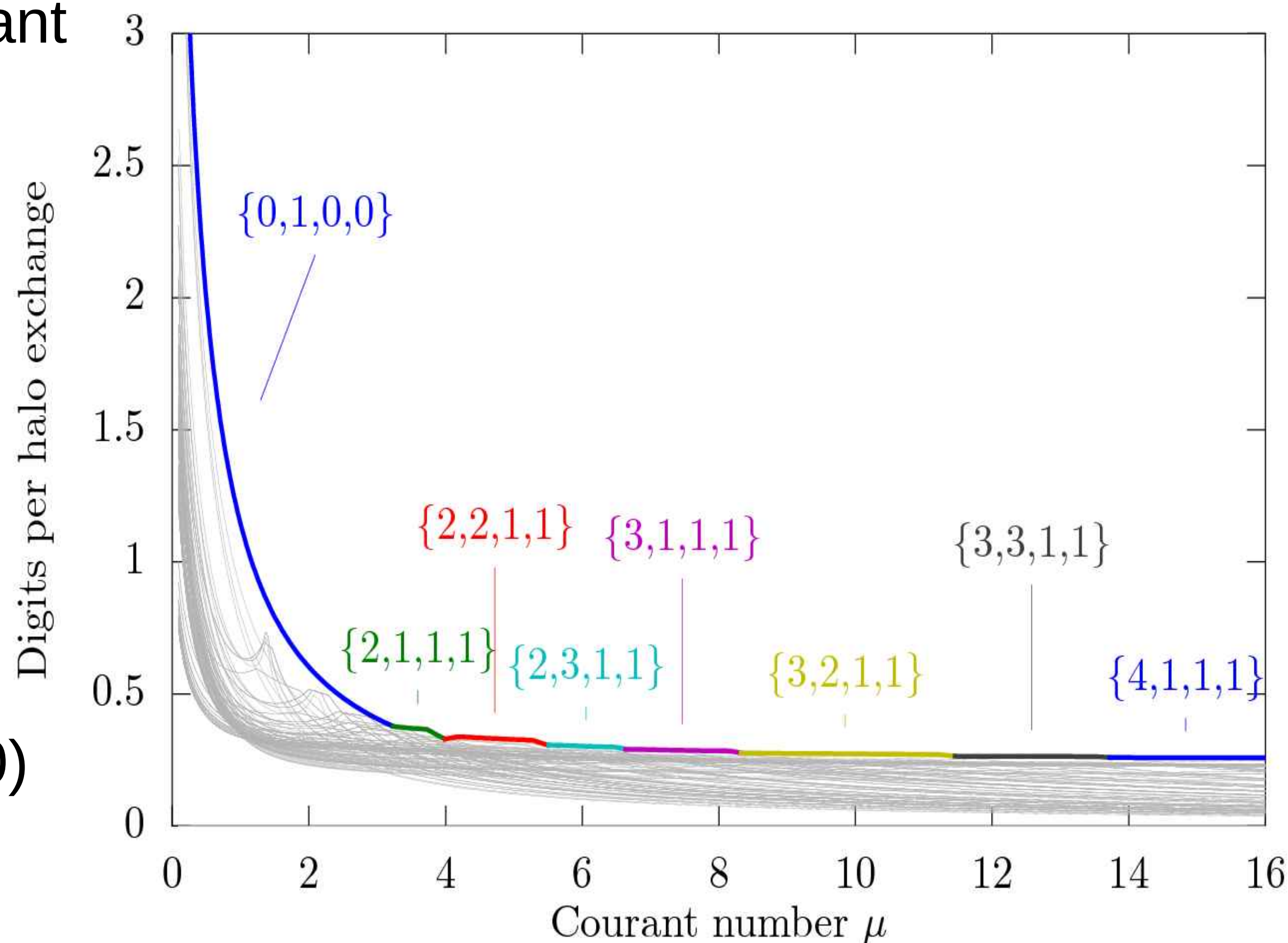
An iterative Helmholz solver: convergence speed

Knowledge of the extreme eigenvalues has important advantages:

1. The **convergence speed is guaranteed**: one knows – even before starting the forecast - how many iterations will be required.
   In an operational context, this is very valuable!
2. It becomes possible to compare different preconditioner settings, thus allowing to pick the optimal parameter values

An iterative Helmholtz solver: convergence speed

- Optimal preconditioner parameters *{ d,* ν_0*,* ν_1*,* ν_2 *}* for given wave Courant number of the 2D Helmholtz problems

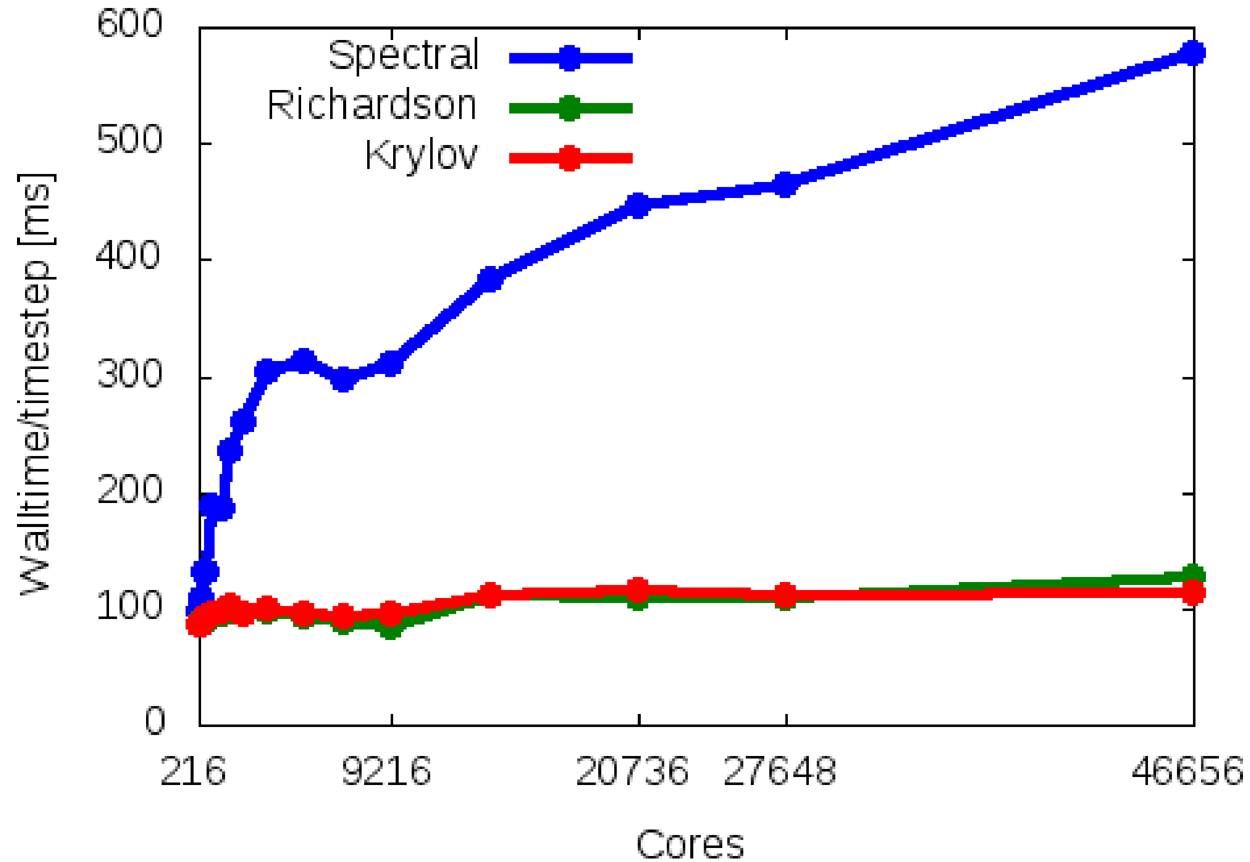


- No multigridding is necessary (*d*=0) for slow modes;
- Multigridding mainly pays off for fast modes

Scalability of the iterative solver

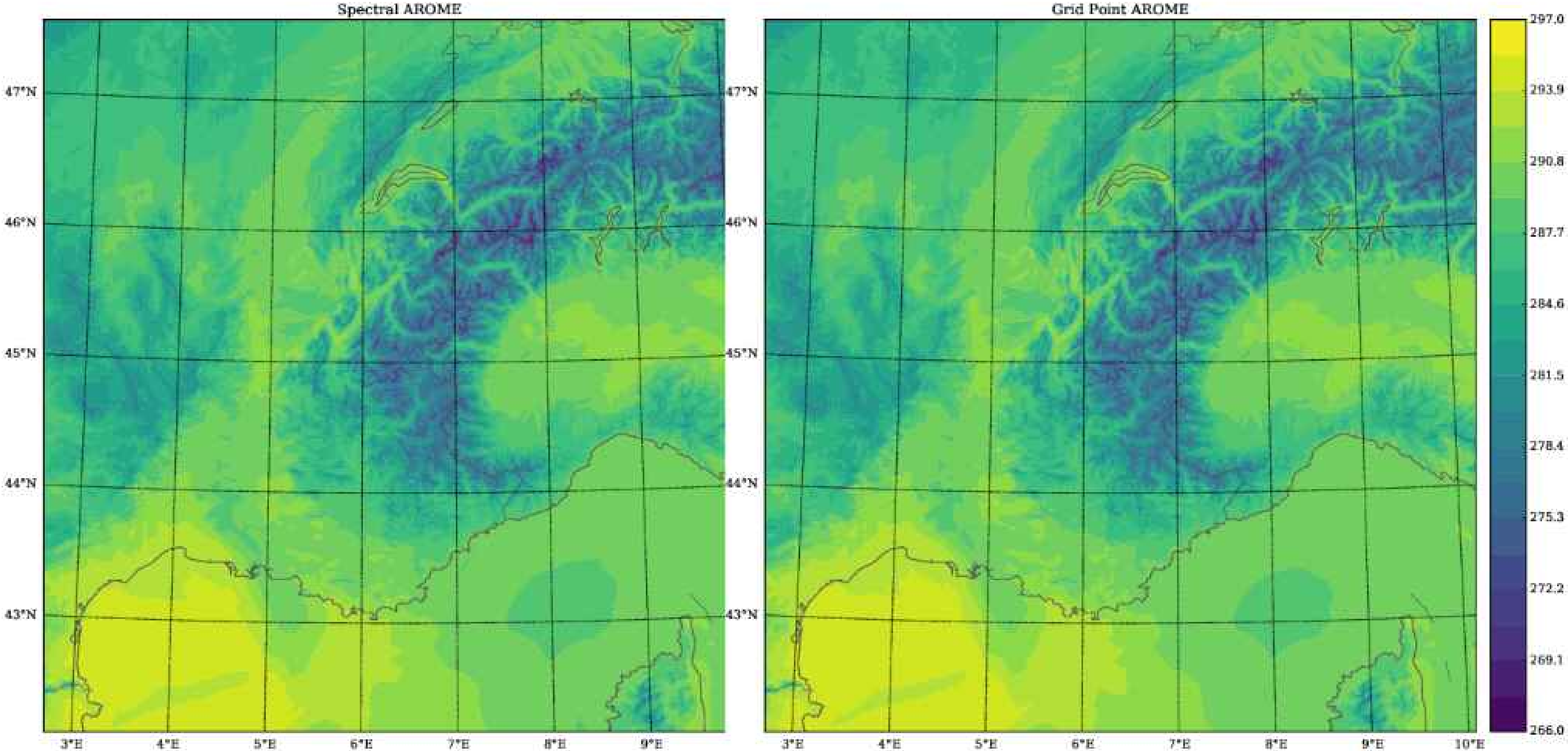
- Weak scalability test on ECMWF's cca

- Note: only scalability of Helmholtz solver, not of the entire atmospheric model



- The multigrid-preconditioned Richardson solver doesn't require any global communications or synchronization (not even to test convergence)!

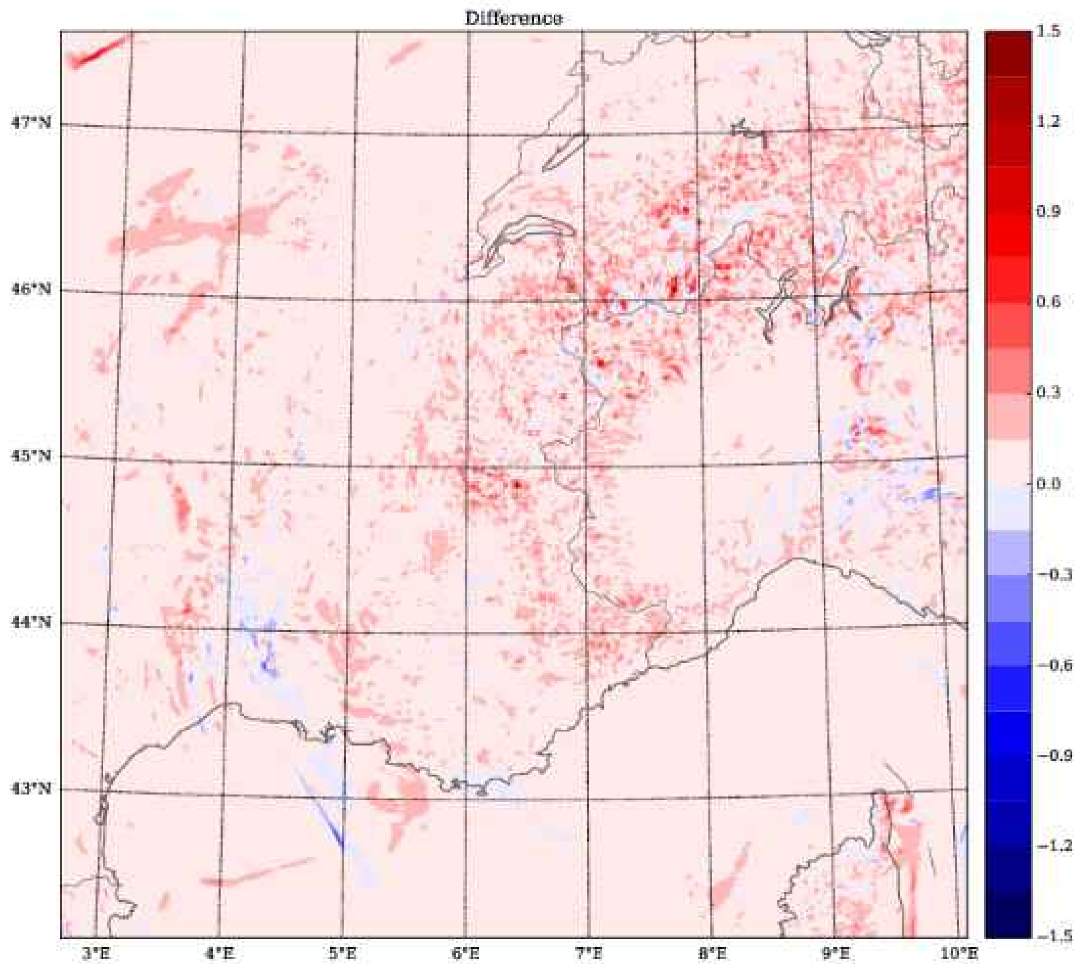
Impact on forecasts: T80



$$\text{T80},\ \delta t = 50\ s,\ T = 2\ h,\ \Delta x = 1.3\ km,\ N_{iter} \approx 13,\ 8^{th}\ \text{order}$$

Impact on forecasts: T80

Difference between spectral and finite difference:

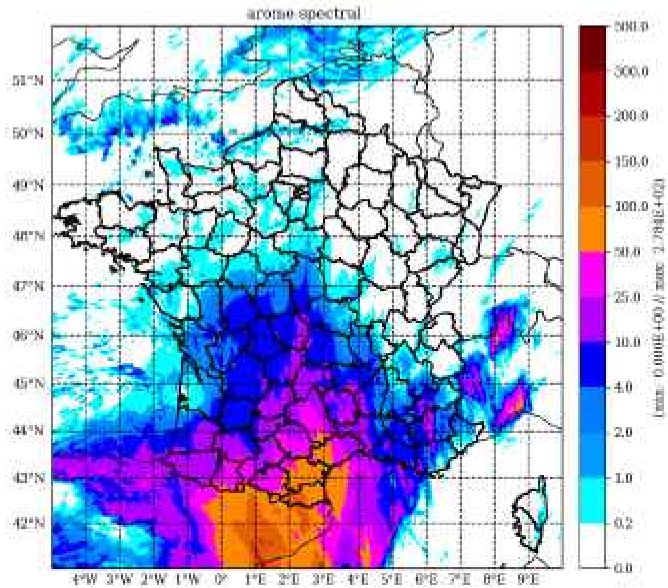


$$\delta(T80),\ \delta t = 50\ s,\ T = 2\ h,\ \Delta x = 1.3\ km,\ N_{iter} \approx 13,\ 8^{th}\ \text{order}$$

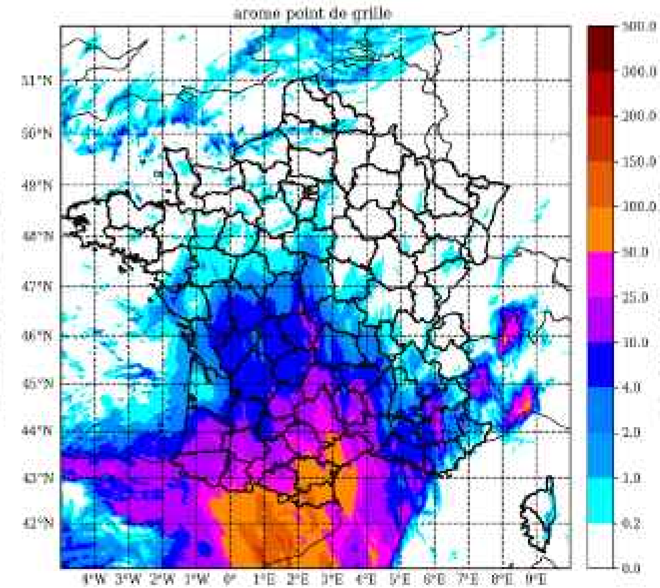
Impact on forecasts: convective precipitation

(22/10/2019 00:00 to 23/10/2019 00:00)

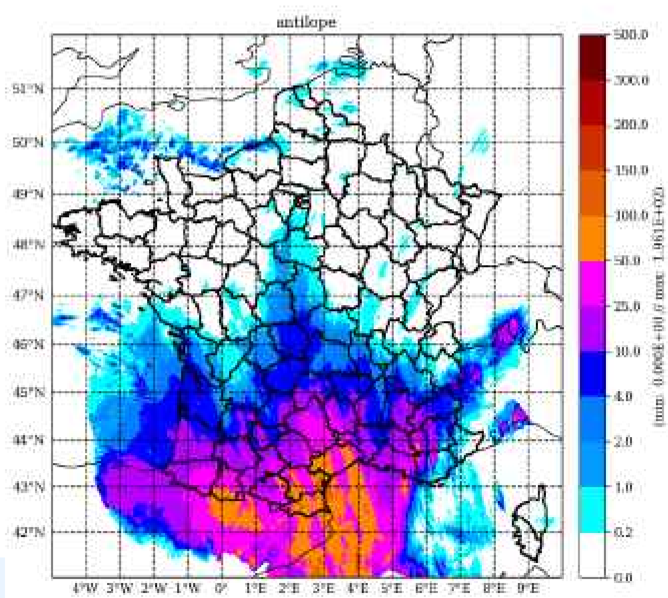
Spectral

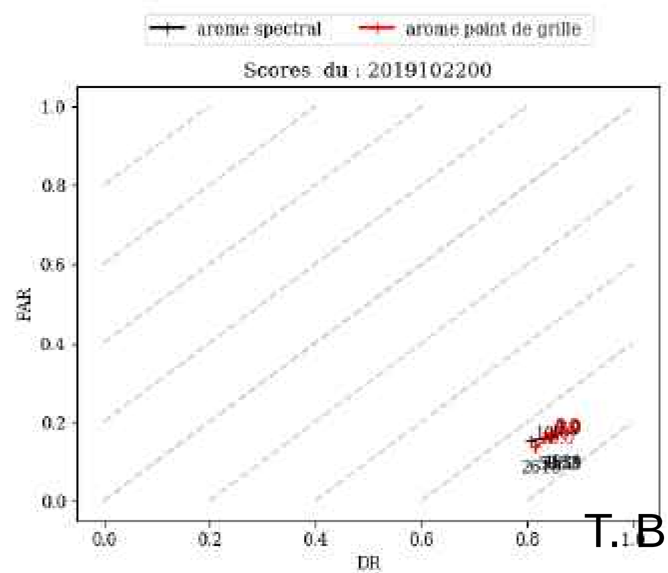


10th order FD



Radar





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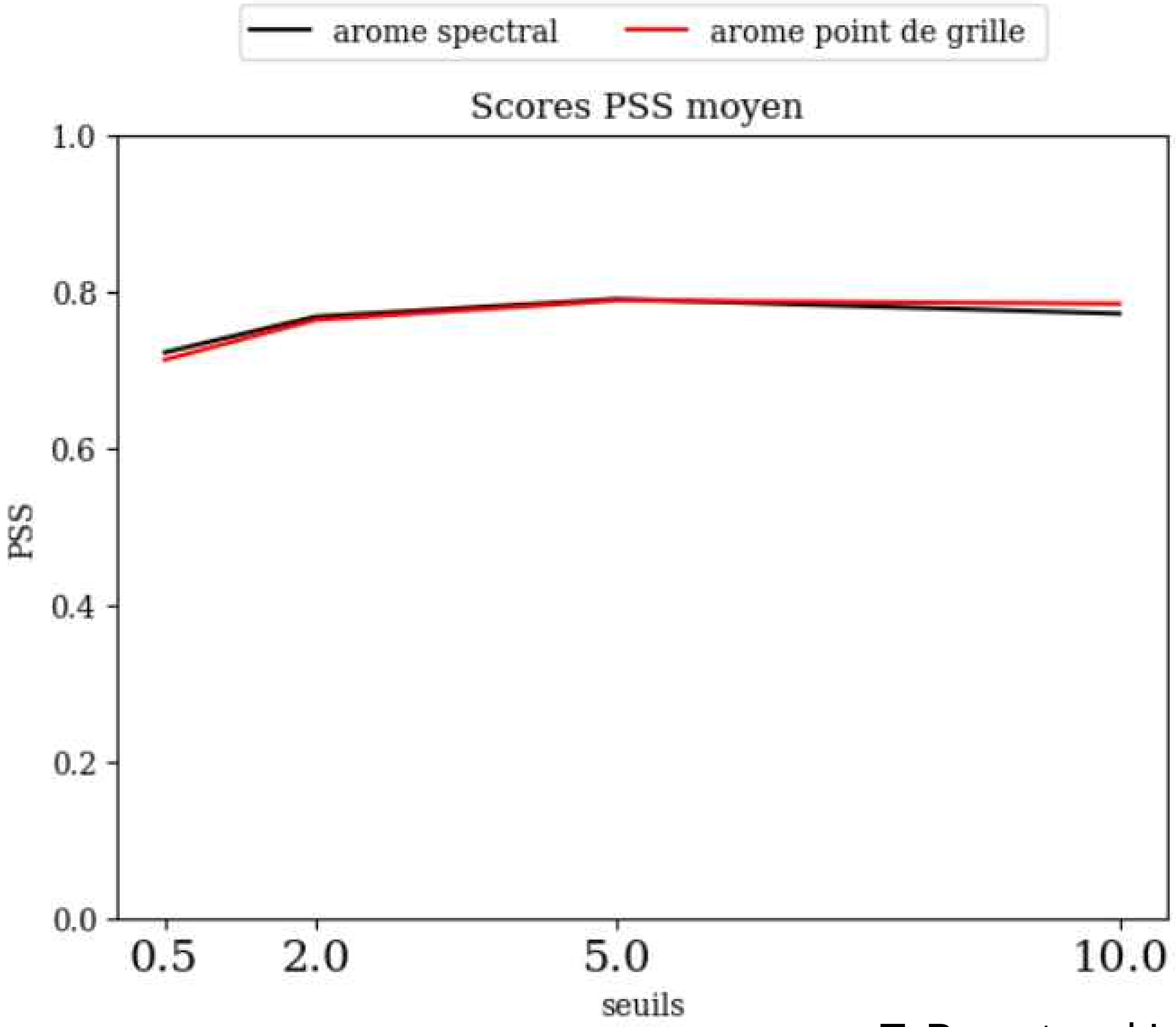
Impact on forecasts: precipitation skill score

Difference not significant



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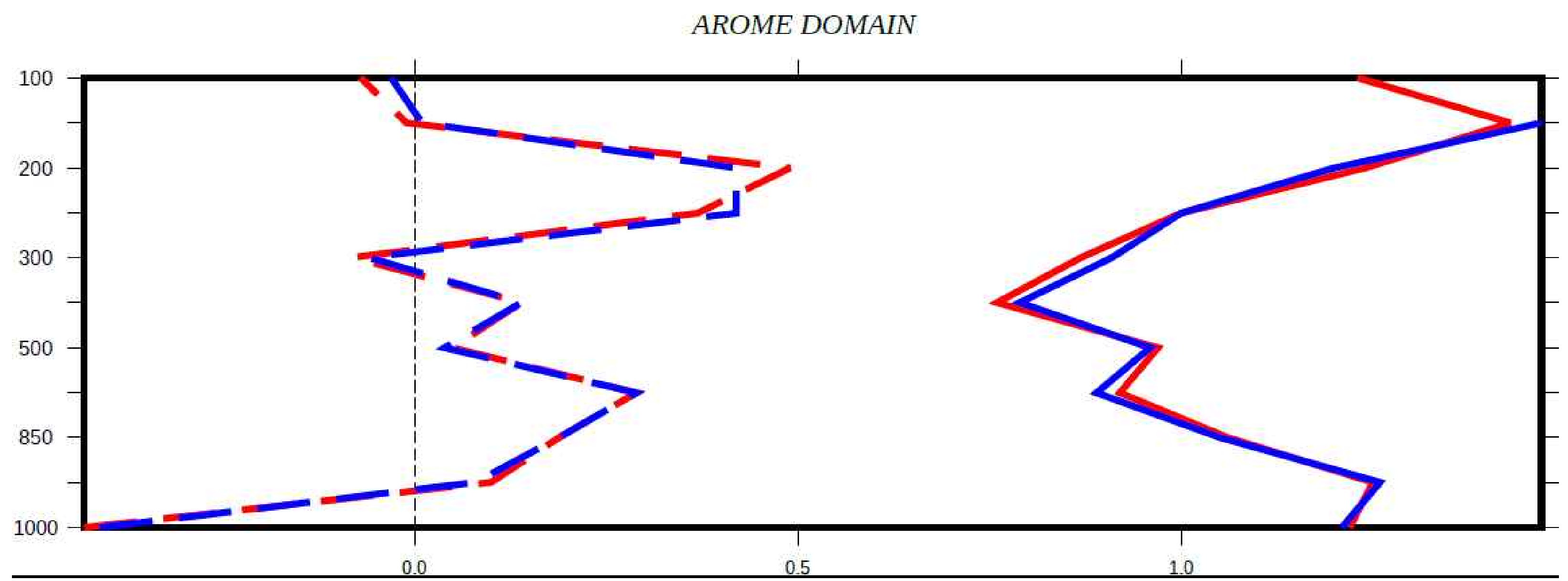
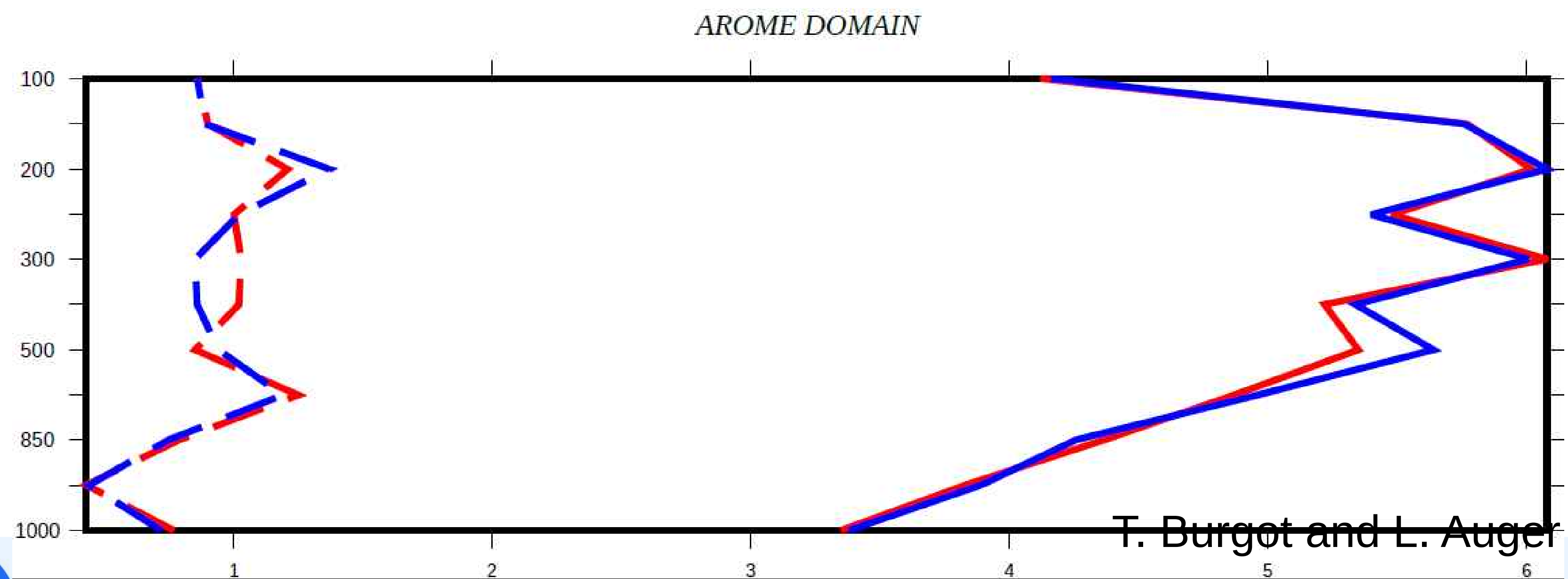
Impact on forecasts: radio soundings

Temperature



Wind



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Impact on forecasts: remarks

- Some computations are still done spectrally:
  - Conversion of vorticity/divergence to wind speeds
  - Some derivatives in the RHS of the Helmholtz equation
  - Numerical diffusion

- Verification only done on a limited period (6 days)

Conclusions GP dynamical core

- The current spectral dynamics of the ALADIN-HIRLAM model faces important challenges regarding scalability and steep slopes;
- Scalability does not seem to be a pressing issue at current resolutions on current machines;
- An alternative, non-spectral, iterative solver is being developed, while keeping as much as possible intact of the ALADIN-HIRLAM model.
  - Krylov solver with a multigrid preconditioner
  - Specific choices in the formulation of the semi-implicit scheme lead to predictable convergence speed, making the solver appropriate for use in an operational context
  - Scalability of iterative solver is superior to that of the spectral solver
  - Meteorological results are not affected when using high-order finite differences
- Ongoing development of an Atlas-based iterative Helmholtz solver

Thank you for your attention