Progress in the Strategic Program on Dynamics (SPDY) package

Daan Degrauwe, Ludovic Auger, Fabrice Voitus,
Thomas Burgot, Pascal Marquet

ALADIN/HIRLAM Workshop 2020

Content

- Introduction
- SPDY1: Quasi-elastic equations
- SPDY2: Non-spectral semi-implicit solver
- SPDY3: Horizontally Explicit Vertically Implicit schemes
- SPDY4: Physics-Dynamics interface
- SPDY5: Development of the Atlas library
- Conclusions

Introduction

The strategic program on dynamics was initiated to address longer-term challenges for the existing dynamical core:

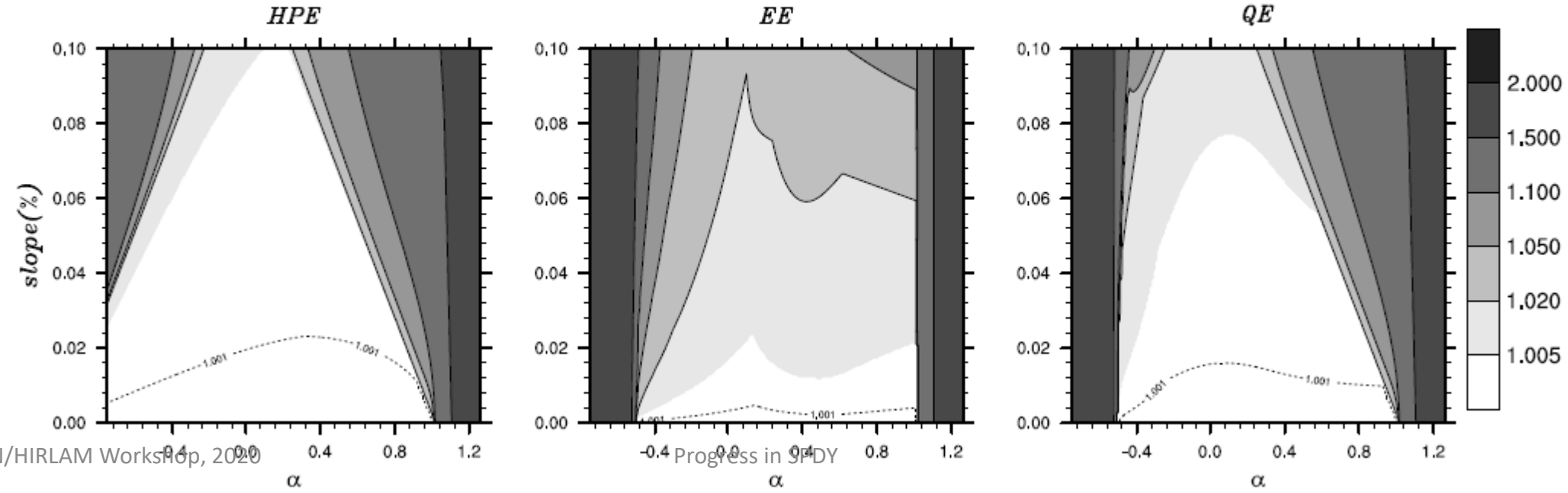
- Modify equations to maintain stability at higher-resolutions: Quasi-Elastic equations and "*W*" (SPDY1)
- Questionable scalability of communication-rich spectral transforms: development of a non-spectral semi-implicit dynamical core (SPDY2)
- Backup solution: treat horizontal coupling explicitly, and only use implicit in the vertical: HEVI (SPDY3)
- Strengthen the thermodynamic foundations of the way the physics are coupled to the dynamics (SPDY4, esp. important in view of the different CMC's)
- Follow the work on scalability at ECMWF, viz. the development of the Atlas library (SPDY5)

SPDY1: Quasi-Elastic Equations

Motivations :

- Design of a modern Sound-proof NH approximate set of equations less stiff than fully-compressible (EE) by exploiting Arakawa and Konor (2009) ⇒ Suppression of high-frequency vertically-propagating acoustic wave at their source ⇒ Potential benefit in term of stability.

• Time-discrete space-continuous linear stability analysis of 3-TL SI scheme with a uniform sloped orography (without advection). Settings: $\Delta x = 2000\,\mathrm{m}$, $\Delta t = 200\,\mathrm{s}$.



SPDY1: Quasi-Elastic Equations

Status and Perspectives

1. 2D Academic test-cases with prescribed orography (not shown) also confirmed the benefit of QE formulation with respect to fully-compressible.
2. A switch to Quasi-Elastic soundproof NH system is available since **cy46** under the **LNHQE**=true.
3. QE forecasts are qualitatively comparable to those of fully-compressible NH system
4. Unlike to the numerical analyses and 2D idealized test-cases, no significant positive impacts on the stability have been observed in QE real-case experiments.
5. This counter-intuitive result from need to be better understand to discard any coding issue ⇒ TO BE INVESTIGATED !!!

SPDY1: Equations with "$\mathbb{W}$"

Basic underlying idea

1. Impose homogeneous rigid BBC in explicit NL model through the definition of new vertical momentum prognostic variables :

$$\mathbb{W} = w - \overline{\mathbf{v}}^{w} \cdot \nabla \left[\mathrm{S}(\eta) z_s \right]$$

$$d_5 = -\frac{g\rho}{m} \frac{\partial \mathbb{W}}{\partial \eta} + \mathrm{X}_5$$

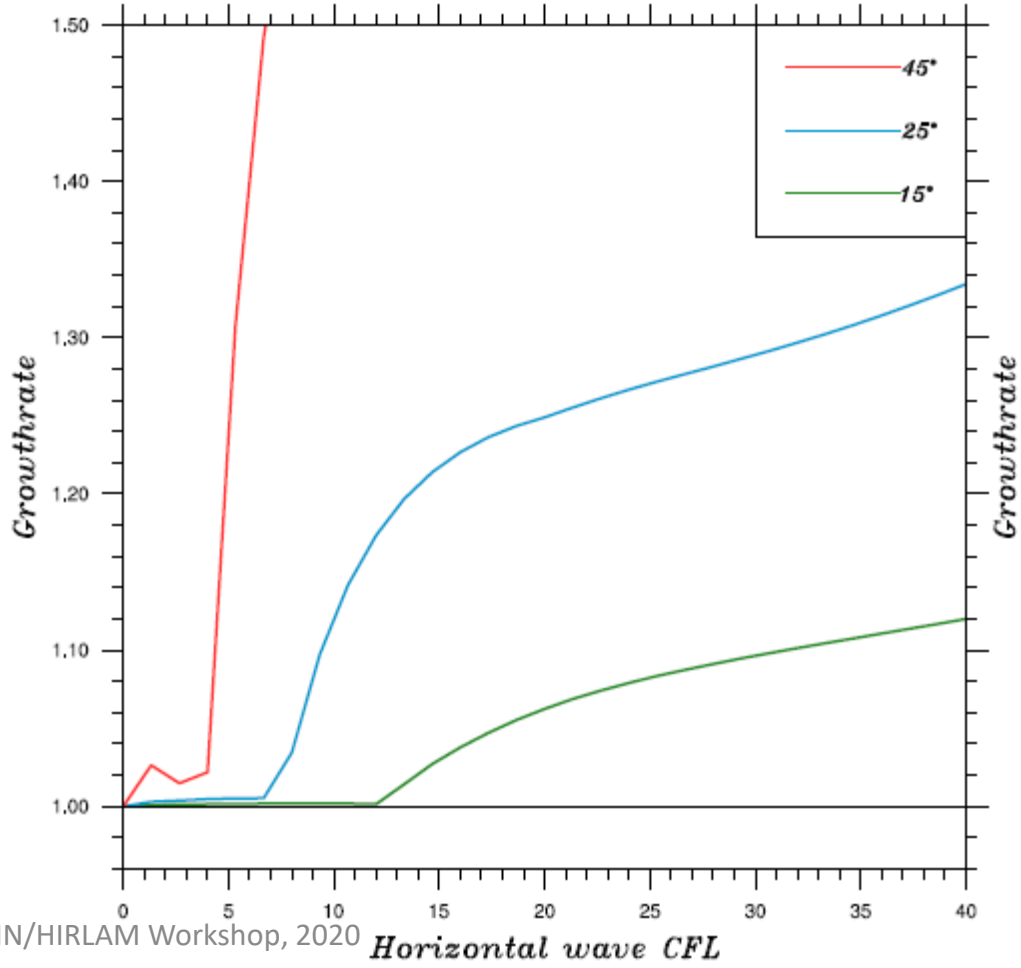
   S is a monotonic function only of η satisfying $\mathrm{S}(0) = 0$ and $\mathrm{S}(1) = 1 \Rightarrow \mathbb{W}$ behaves as w at top, and rigid BBC now becomes $\mathbb{W}_s = 0$ (homogeneous).

2. A refined definition for the SI linear vertical Laplacian operator

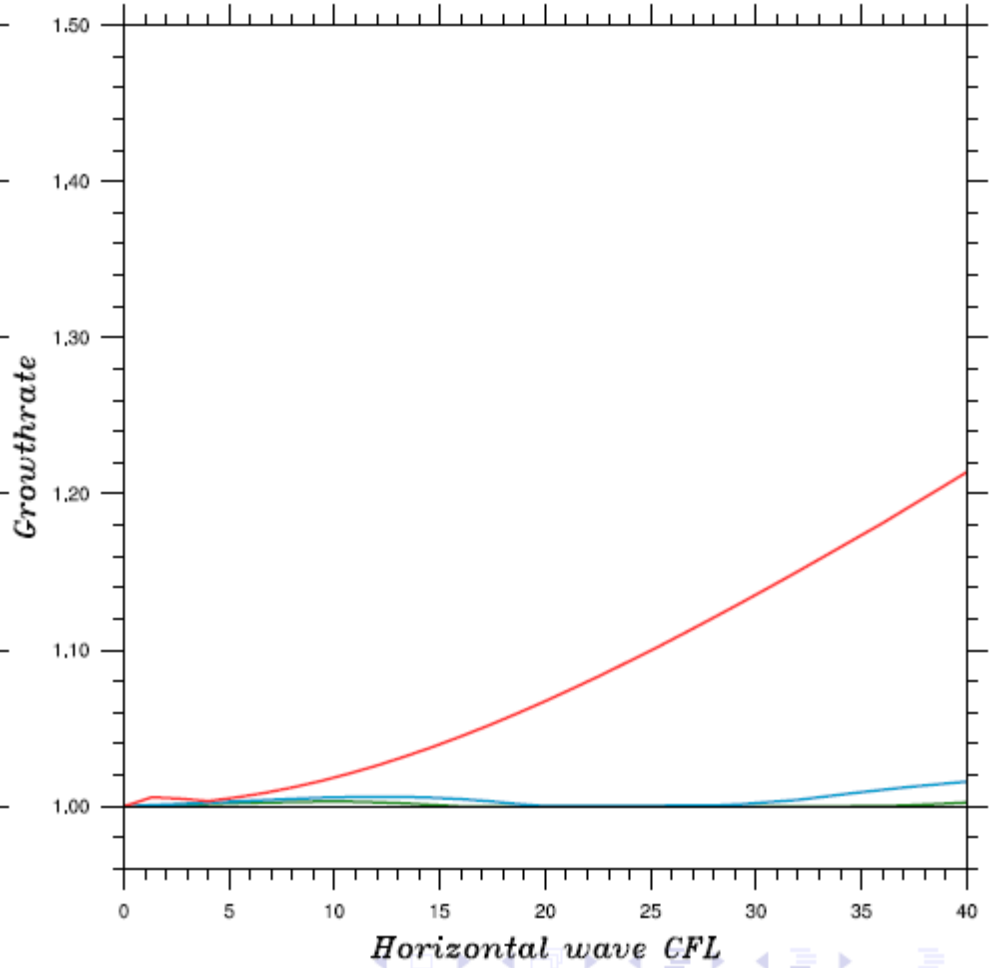
SPDY1: Equations with "$\mathbb{W}$"

- *Fully-discrete linear stability analysis of 2-TL ICI ($N_{siter} = 1$) with a prescribed sinusoidal orography (no advection). Amplification factor as function of horizontal wave Courant number for three different slopes : 15°, 30°, and 45°.*

(w, d_4)



$(\mathbb{W}, d_5)$



SPDY1: Equations with "$\mathbb{W}$"

Status and Perspectives

- This formulation takes advantage of the recent relaxation of the so-called **C1** discrete constraint in the elimination procedure of the implicit problem available since cy46t1 under **LSI_NHEE**=true.
- This new formulation leads to a gain of around 30% in the horizontal resolution limit; AROME may be run stably with mesh-sizes until 250 m above the Alps with only **NSITER**=1 and **LPC_FULL**=true.
- Some spurious osccilations occur with **LPC_CHEAP**=true.
- This new formulation should be available in the recently delivered cycle 48, under **NVDVAR**=5 and **LNHEE_REFINE_LAPL**=true. A cy46t1 version is also available on demands.
- Very promising results but it still requires more validations in operational context.

SPDY2: Non-spectral dynamical core

- For several decades, claims have been made that spectral methods would become unfeasible in the next 5 years…
- Is it possible to maintain as much as possible from our dynamics (esp. the long timesteps SI-SL allows), without relying on spectral transforms?
- Second motivation: implicit treatement of steep slope effects at high resolution should improve stability. This is not possible with the current spectral implicit solver.

An almost Grid Point version of AROME

- No MPI and Open-MP
- Fast convergence achieved : only 1.5 iterations required on average on the 90 vertical modes
- No significant differences between spectral and grid point versions after 8 sets of 24 hours forecast

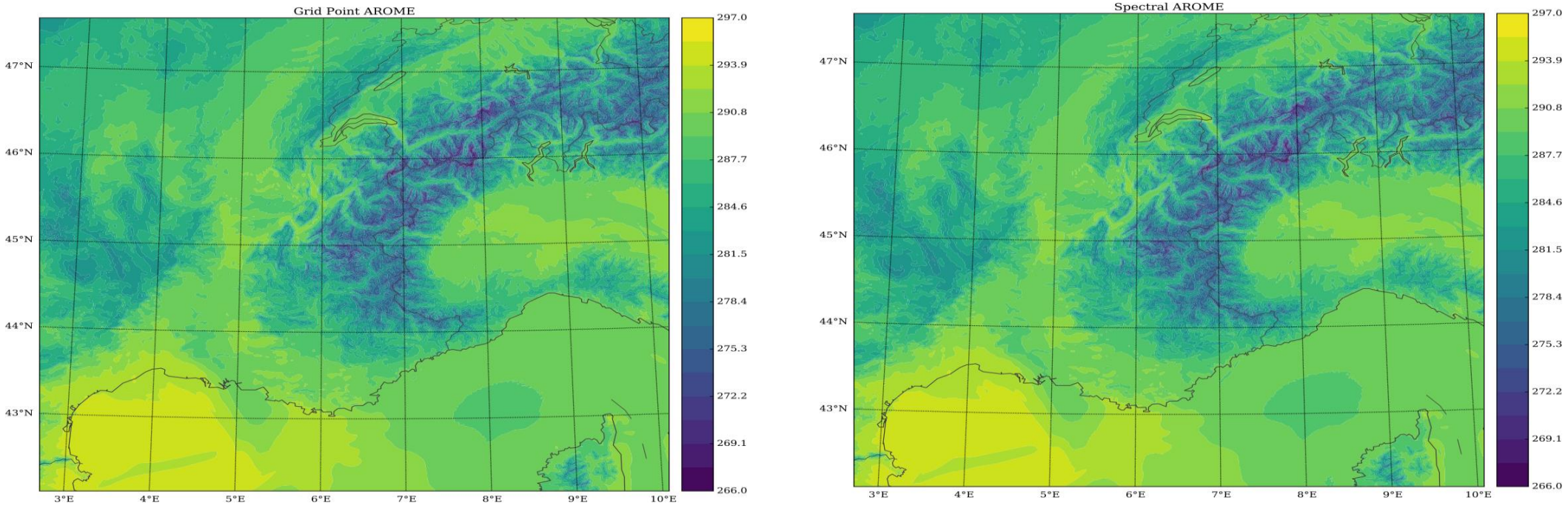


Figure : Temperature field at level 80 after 2 hours in the Grid Point (left) and Spectral (right) versions

Full implementation of gridpoint solution

- Currently the gridpoint code is implemented in espnheesi.F90 only.
- Work in progress consists in duplicating espcm.F90/espnheesi.F90, creating their gridpoint counterparts.
- Other task that has to be done : development of a gridpoint diffusion. Meanwhile tests can be performed without diffusion (model can run without diffusion for testing purposes, but it is less stable and quality is degraded). According to Pierre Bénard this should not be a problem.
- The feasibility to use semi-Lagrangian halo to implement MPI/openMP horizontal derivatives and Laplacian operators has been studied. For LAM, this should not be too complex, creating a derived type for the gridpoint horizontal computations. This is much more complex for a global geometry.

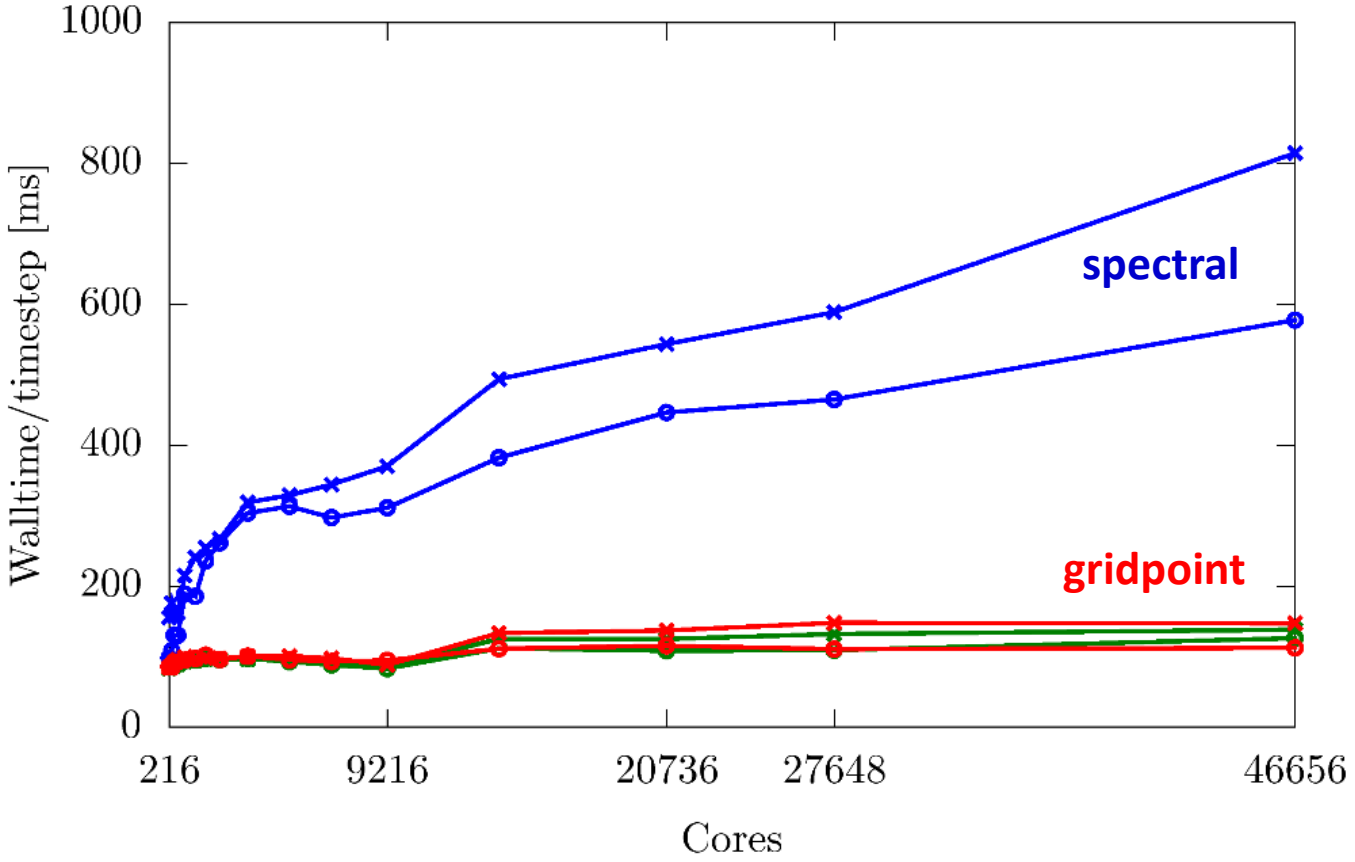
Steep slopes

- Derivation of the linear operator including orographic terms
- Coding it in a 2D clone of the AROME model in sigma coordinate
- Testing it with idealized orographic test cases
- Gain up to 10° on the maximum slope compared to the version without implicit treatment of orographic terms according to the first tests

Technical aspects

- Multigrid-based preconditioner delivering guaranteed fast convergence and excellent scalability for Helmholtz solver test program

- Novel developments in interconnect technology (Nvidia, Cray) may solve scalability challenge.



SPDY3: HEVI

Horizontally Explicit, Vertically Implicit schemes: avoid implicit system (expensive communications!) in the horizontal, while still treating the vertically propagating sound waves implicitly.

Status and Perspectives

- Two second-order accurate RK-IMEX HEVI schemes solutions have been designed to properly support the presence of advection processes without detrimental impact on their inherent stability. [Colavolpe *et al.* (2017)].
- For the time being HEVI-approach is considered as a **fallback alternative**, if gridpoint SI solvers fails to be efficient enough due to scalability issue ⇒ not entered in the code yet.

SPDY4: Physics-Dynamics interface

- The “de Groot and Mazur” formalism on which we have based our approaches is not applicable for our equations, because the turbulent flows are not on a molecular scale.

- This consideration of turbulent flows must also call into question the way in which turbulent kinetic energy is taken into account as a source in the thermodynamic equation.

- Implications of these findings for our equations for T or $c_p T$ and for the computations of moist-air turbulence fluxes will be further investigated.

SPDY5: Atlas development

- Atlas is a library under development at ECMWF for handling parallel data structures.
- Several “LAM features” were already introduced in Atlas some time ago: regional grids and meshes, geographic projections, C++ interface to etrans.
- The proof of the pudding …
  - New activities focus on using Atlas for problems on a LAM geometry, e.g.
    - Stencil operations for finite differences and multigrid tools for SPDY2
    - Semi-Lagrangian dwarf on a LAM domain
  - (These developments should still be merged into the main Atlas branch.)

Conclusions

- Expected stability gain by quasi-elastic equations not observed in experiments
- Introduction of a modified vertical velocity is promising
- Overall, things look brighter than a few years ago:
  - Non-spectral implicit solver is feasible: meteorological results are okay, technical performance is excellent
  - Scalability may not be such a pressing issue after all
- Backup solution of HEVI does not seem necessary
- After a few years of stand-still, progress is made on the theoretical foundations of the physics-dynamics interface.
- Progress on use of Atlas in problems with a LAM geometry

References

- Colavolpe C, Voitus F, Bénard P. 2017. RK-IMEX HEVI schemes for fully compressible atmospheric models with advection: analyses and numerical testing. *Q. J. R. Meteorol. Soc.* **143**: 1336–1350.
- Voitus F, Bénard P., Kuhnlein C., and Wedi N.P, 2019. Semi-implicit integration of the unified equations in a mass-based coordinate: model formulation and numerical testing. *Q. J. R. Meteorol. Soc.* **145**: 3387–3408.
- Voitus F, Karim Y., Vivoda J., and Smoliková P. 2020. A more stable formulation for the "constant-coefficient semi-implicit" Non-hydrostatic dynamical core of AROME/ALARO models. *in prep. for Mon Wea. rev.*.
- Marquet P 2019. Application of the second law to the atmosphere: impacts of the third-law definition for the moist-air entropy. *submitted to Entropy.*