ACCORD

A Consortium for COnvection-scale modelling Research and Development

Recent developments in dynamics

Ludovic Auger, 29 september 2021, 43rd EWGLAM and 28th SRNWP Meeting
With contributions from X. Yang, Th. Burgot, Ph. Marguinaud, F. Voitus, and many other colleagues

Generalities

Our NH dynamical core is still successful with its semi-implicit and semi-lagrangian approach, enabling longer timesteps (we do more communications but less often).

There are different "flavors" of ACCORD model, but all have quite similar dynamical cores.

Concerns on the long term :

- The suitability of the dynamical core to run on future massively parallel machines (with or without GPU).
- For very high resolutions we fear that the treatment of the steep slopes in the orography will become unstable or inaccurate.

We need to pursue 2 strategic goals in parallel :

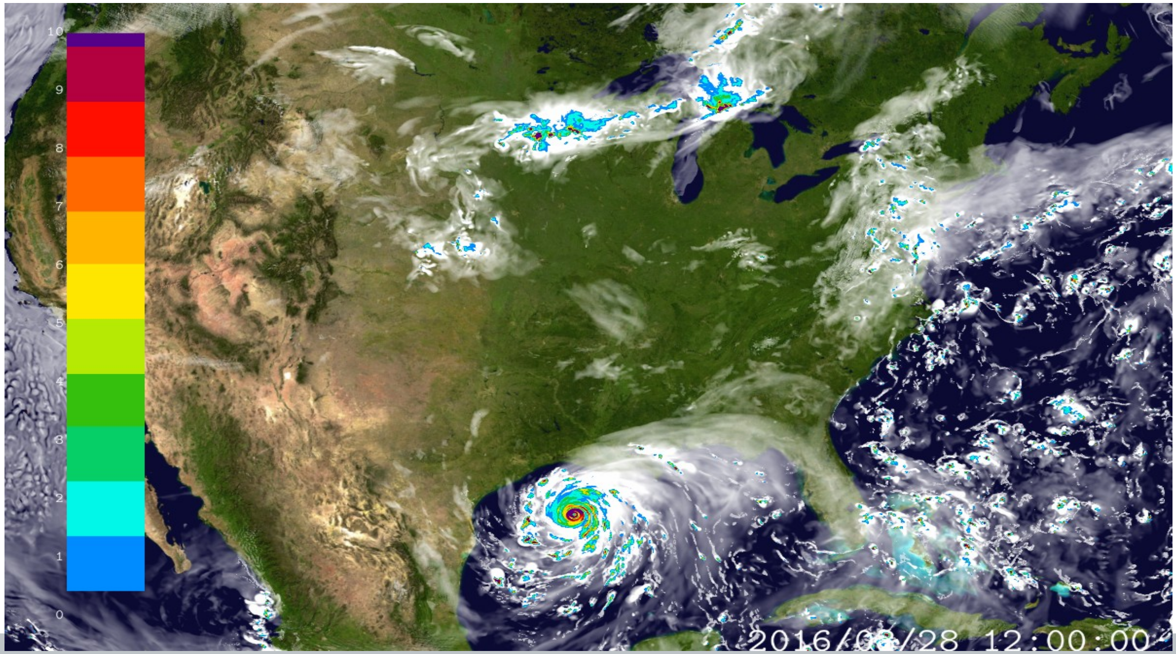
- Continue with our current core by improving its accuracy, stability, efficiency.
- Invest in the long-term (>10 yr) on non-spectral dynamics.

Outline

1) Scalability of spectral transforms
2) Stability improvement of spectral core
3) Developing a grid-point core
4) Improving stability : using a more complex implicit operator in grid-point space
5) Towards higher resolutions
6) Porting dynamics to GPU-accelerated HPC

Scalability of spectral transforms

- **Participation with ARPEGE (global dynamics close to ACCORD dynamics) to the DYAMOND project (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains), project of intercomparison of global models operating with a resolution allowing explicit convection.**
- **85 millions grid-points (truncation T8000, LAM equivalent 9500x9500 grid points)**



Global forecast T8000 (2.5km), zoom on the Gulf of Mexico

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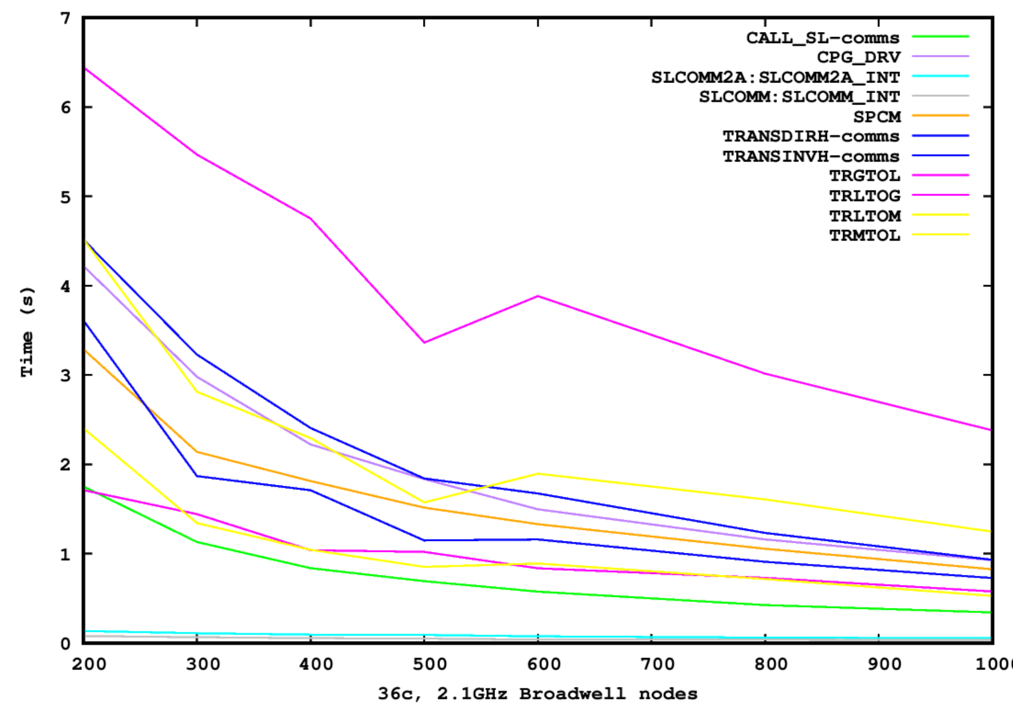
Scalability of spectral transforms

- On such a domain, the cost of spectral transforms communications becomes quite important (30% of time spent in spectral communication) but it is still affordable since we can maintain long time-step.
- Tests show scalability is still good.
- The dynamical core of ACCORD will probably still be efficient in this regard in operational use for many years.



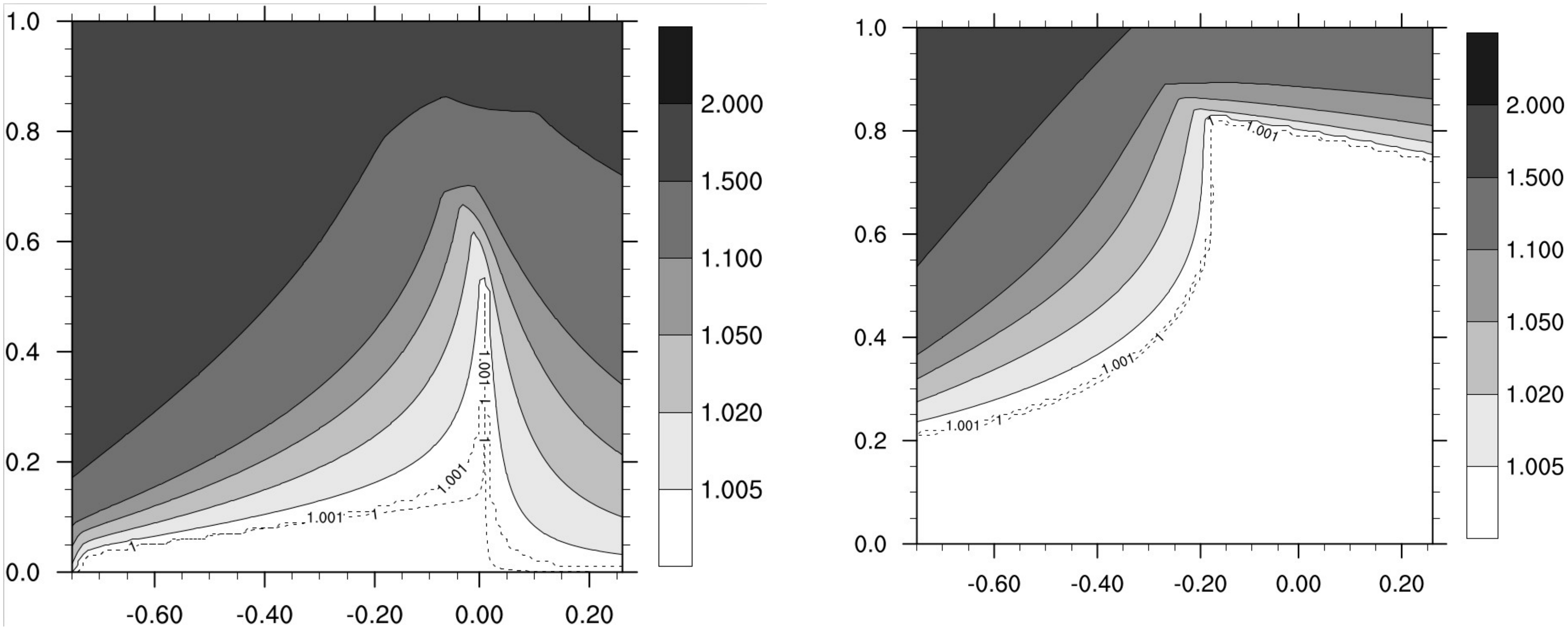
Elapsed time for various communication routines

Stability improvement of spectral core

- A new formulation of the full-compressible equations in mass coordinate has been developed. It is based on the use of a new prognostic variable for the vertical motion allowing to reduce the effects of the orography on the stability of the time integration scheme.

- This new variable is by construction subject to a homogeneous (null) lower boundary condition, which makes it less sensitive to horizontal variations of the orography. First tested in an academic context, then in a more operational context,this new formulation allows to reach a horizontal resolution of 375m while maintaining the same stability as at 500m.

Stability improvement of spectral core



- The figures represent the stability of the scheme (growth rate) as a function of the slope (ordinate) and the characteristic amplitude of the thermal non-linear residual (abscissa), in the case of using the current variable (left) and for the new variable (right).
- The enlargement of the stability region (white area) attests the improvement of the stability of the scheme brought by this new variable.

Stability improvement of spectral core

- A new upper absorbing Layer implicitly treated along the lines of the idea of Klemp et al. (2008). This UBC treatment improves the robustness of the model by minimizing reflection of badly resolved fast waves at the top of the model.
- An additional SI parameter for hydrostatic surface pressure stabilizing the model above high orography (e.g, Himalaya) where the amount of baric non-linear residuals is significant ($\pi_s << \pi_{s*}$).
- A more stable formulation for the discrete vertical Laplacian-like SI operator , taking in account somehow the extra coupling introduced by the orographic metric terms induced by the terrain-following transformation. (partially coded for finite difference in our most recent development cycle, to be extended to vertical finite elements).
- The possibility to build the linear model and (associated vertical parameters defined in a structure) "on the fly" (at each time-steps, even at each iterations). ⇒Refine the definition of SI parameters taking into account the actual value of some relevant variables (as π_s , T, $\nabla\pi_s$,....) in order to improve robustness and stability of the ICI scheme.
- Decentering : applied only at the predictor step and only for some specific variables ($\hat{q}$, T ,w).

Developing a grid-point core

- ACCORD dynamical core uses semi-implicit method, leading to an elliptic problem to invert :

$$\left[1-\frac{\Delta t^2}{4} C \circ \nabla_h^2\right] D^+ = D^\bullet$$

- Implicit operator is constant coefficient on the horizontal enabling projection onto vertical modes:

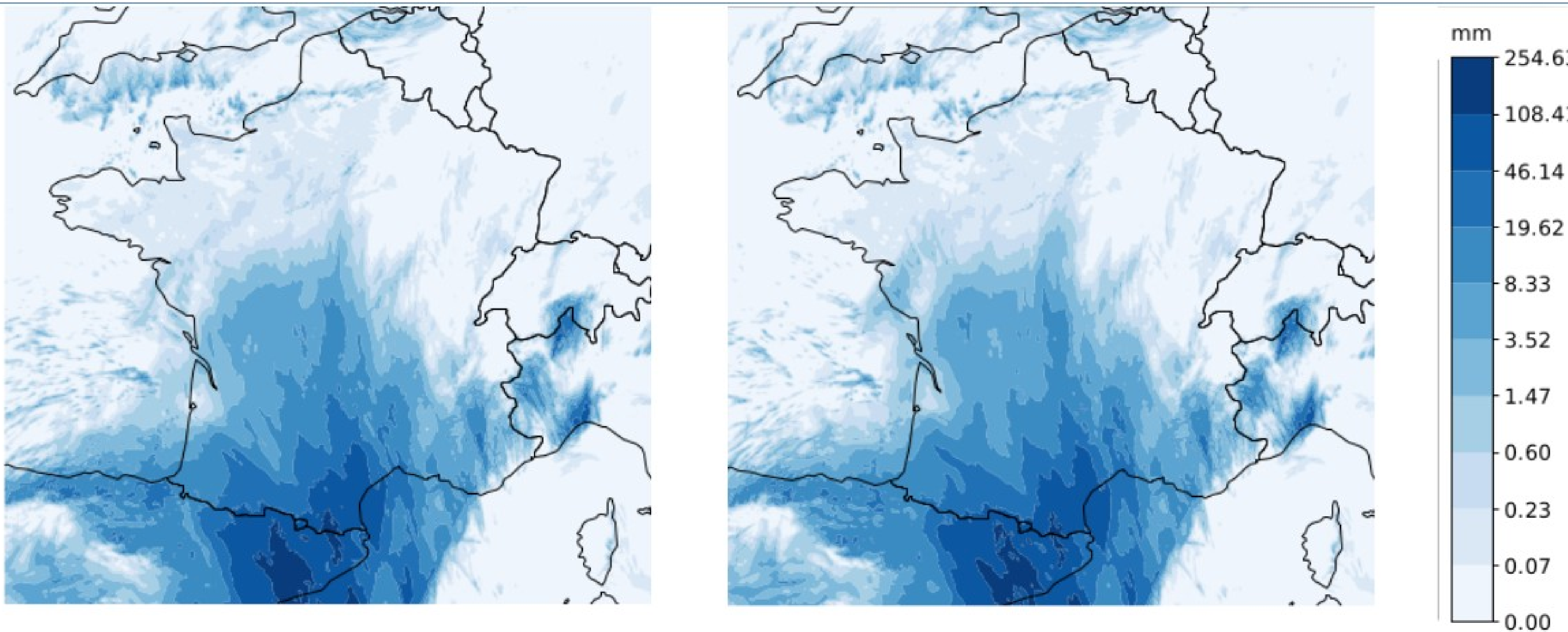
$$\left[1-\frac{\Delta t^2}{4} c_l^2 \nabla_h^2\right] \widetilde{D}^+ = \widetilde{D}^\bullet \qquad l=1..N_{lev}$$

- This part is very efficiently solved in spectral space
- Spectral space also allows to apply an implicit diffusion in a straightforward way.

Developing a grid-point core

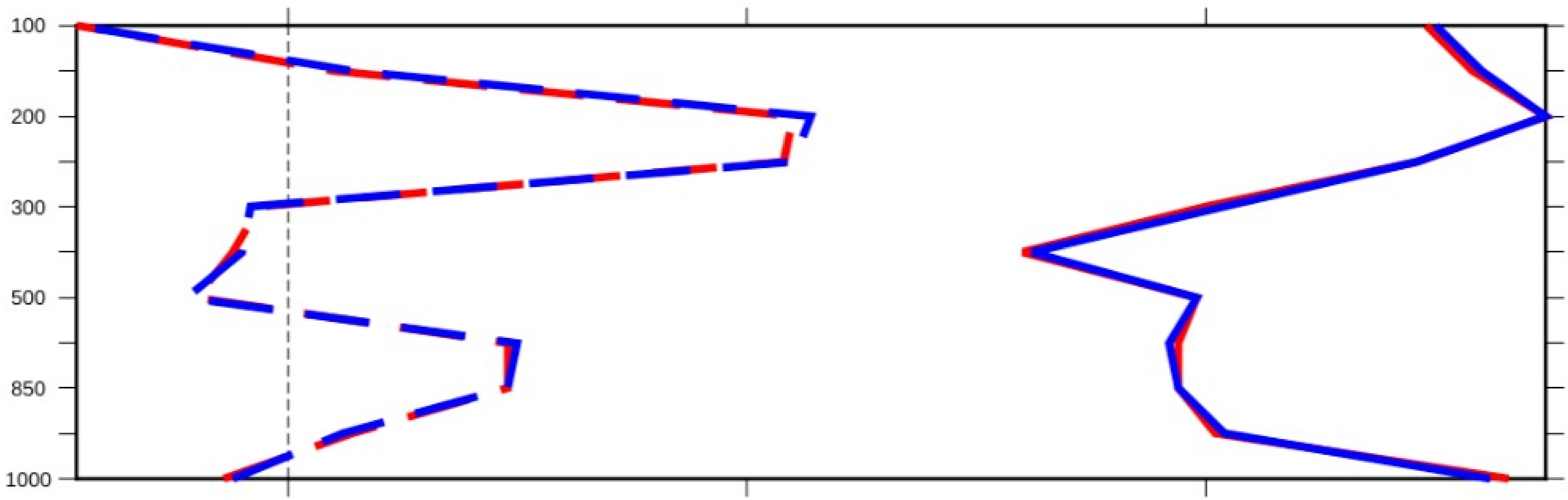
- We focused on inverting implicit problem with gridpoint methods.
- Condition number of implicit problem is ~ (CFL number)^2, this is well conditioned, consequently iterative methods such as Krylov space methods (GMRES, Conjugate gradient) are adapted.
- Most of the vertical modes are inverted in one iteration.
- On average, 6 iterations are required to invert efficiently the problem leading to a quality similar to spectral method.

Developing a grid-point core



- **22 october 2019, 24h rain cumulation.**
- **Spectral computation (left) is similar to gridpoint computation (right)**

Developing a grid-point core



One-month 24h forecast scores to temperature, bias and RMSE, gridpoint versus spectral core.

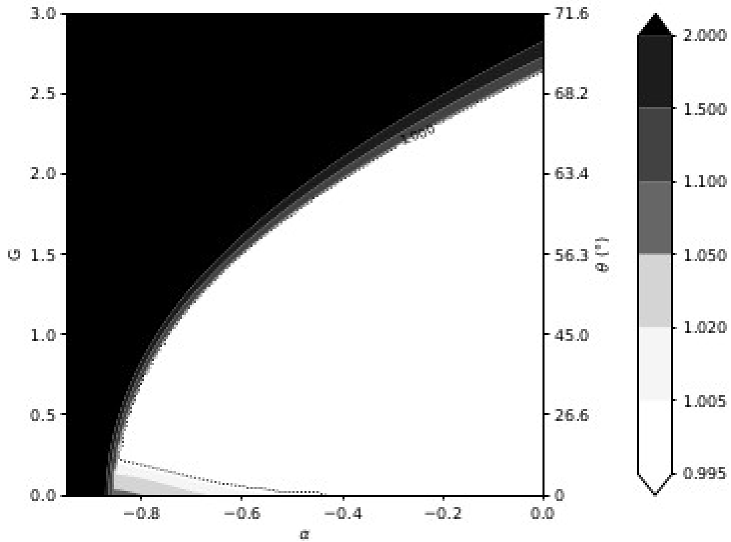
- **Quality is equivalent, but iterative methods approximate the solution and the result is in general depends of the number of nodes used.**

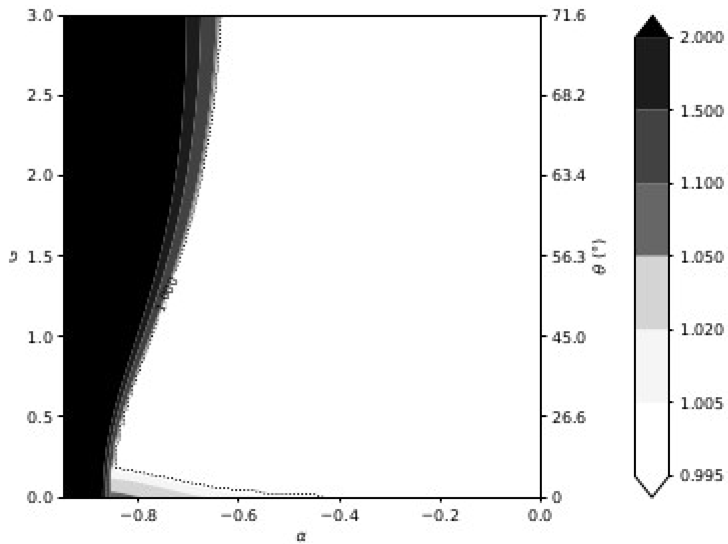
Improving stability : using a more complex implicit operator in grid-point space

- Here the strategy is to linearize the model around an isothermal basic state, at rest, but with an orography.
- With a more realistic basic state as regards orography, we should gain more stability and more accuracy.
- This system is not horizontally constant, consequently it can not be solved in spectral space.
- Now the implicit system is a 3D matrix that must be inverted at once.
- Significant stability gains: ' +70% on the maximum slope
- No strong degradation on the convergence speed of the Krylov solver.

Improving stability : using a more complex implicit operator in grid-point space

Von Neuman stability analysis :





Growth rate as a function of the non-linearity parameter α and the slope G for the predictor-corrector scheme with dt=12s, semi-implicit temperature=350K, cold semi-implicit temperature=100K, with (right) and without (left) topography in the operator.

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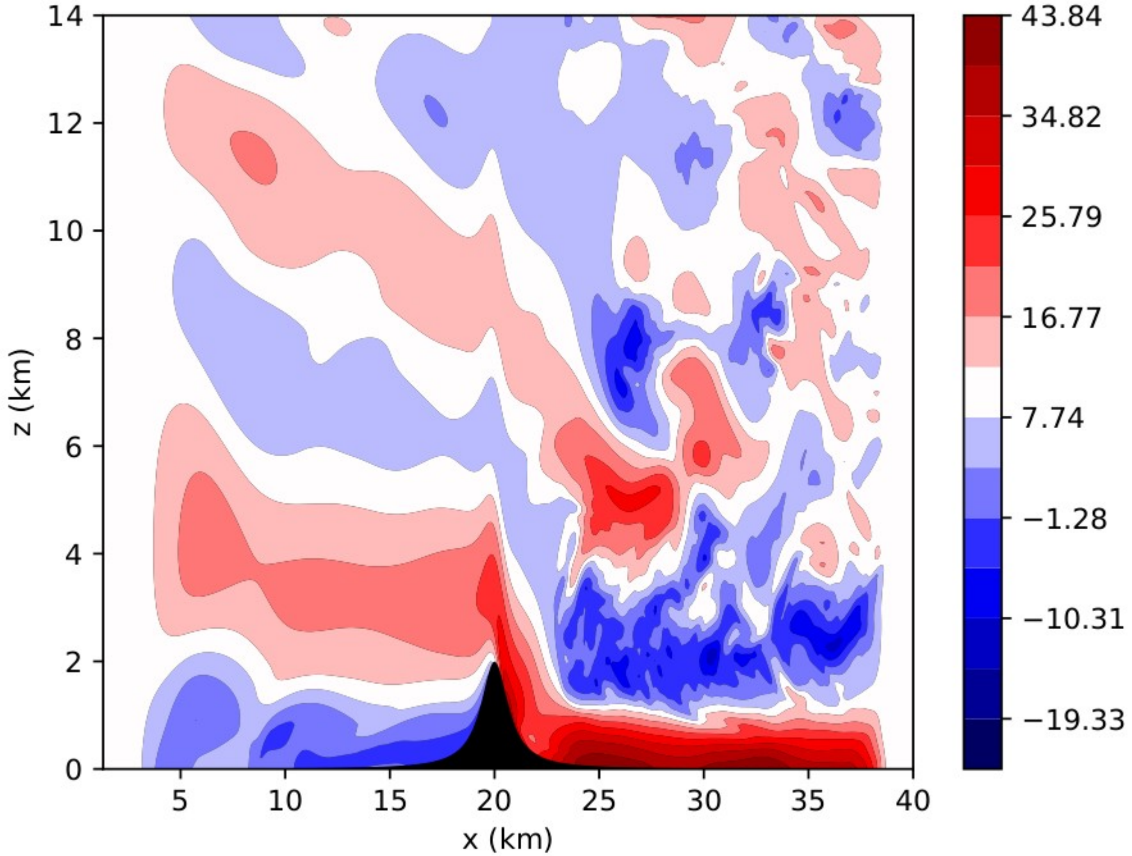
Improving stability : using a more complex implicit operator in grid-point space



Vertical plane simulation, horizontal wind after 1 hour. Maximum slope is 43°. That simulation crashes after a few timesteps when no orgraphy is used in implicit system.

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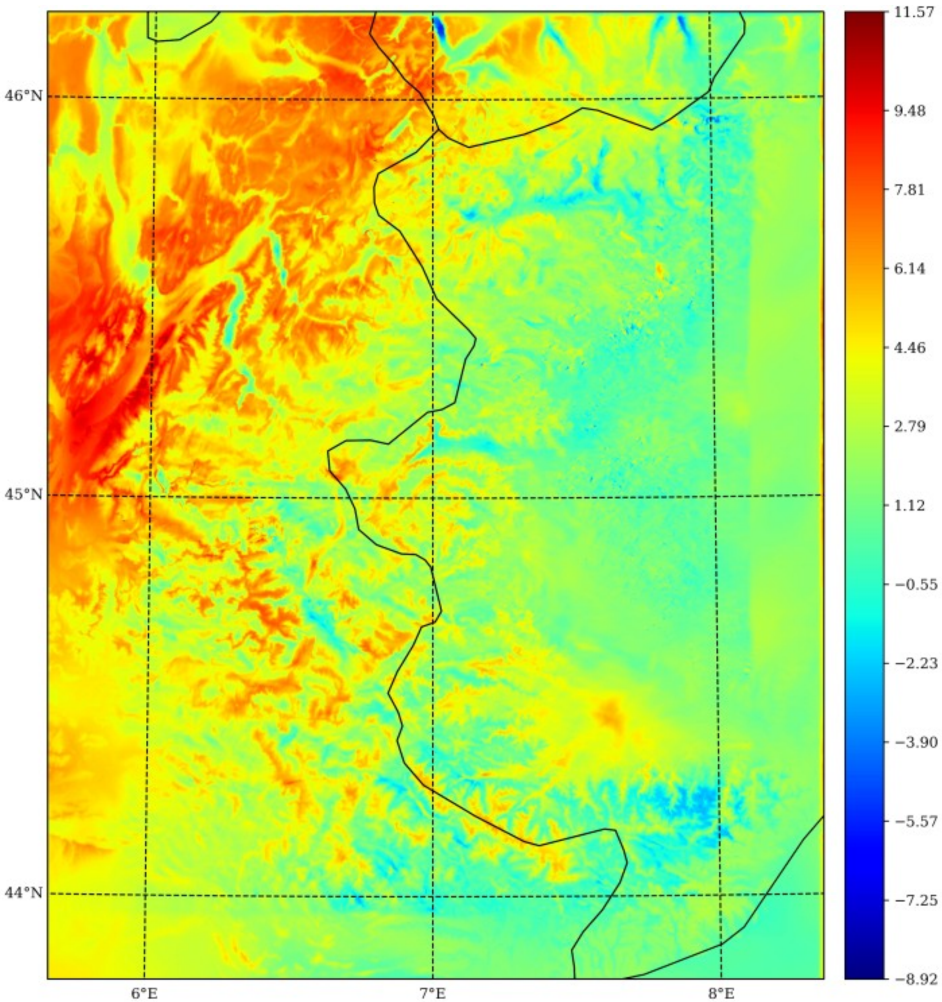
Towards higher resolutions



- **Research Domain on the Alps, maximum height is 4770m, maximum slope is 70°.**

  - 1440x1800 grid-point at 150m (216x280 km), linear truncation.

  - 156 vertical levels with vertical first level at 1m.

  - Very stable options are used here with a cold temperature of10K with an implicit pressure of 600 hPa, DT=10 s (quite large timestep for that resolution 150m) but 4 iterations of the predictor-corrector timescheme for the dynamics !

  - On such a small domain, validation is difficult, wind is automatically improved in the boundary layer.

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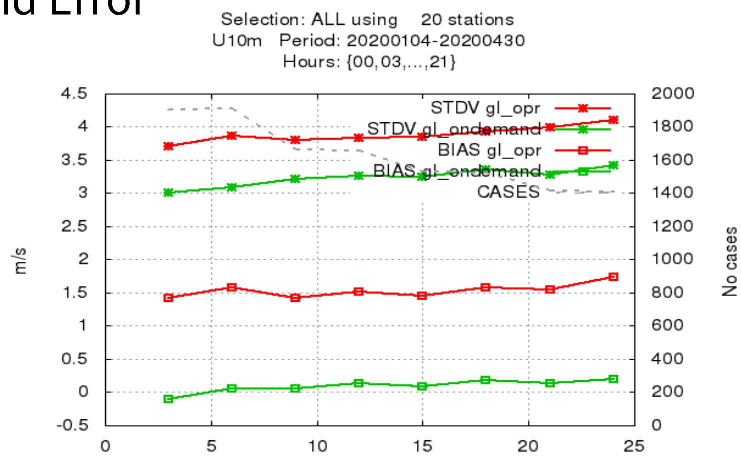
Sub-km, on-demand forecast with Harmonie-arome @ DMI

Four sub-km, on-demand setup have been introduced into the operational NWP in early 2021 to improve wind forecast for coastal regions of Greenland frequently hit by storms. For these area, the operational Harmonie-arome @2.5 km often over-predict winds due to poor representation of orographic effects.

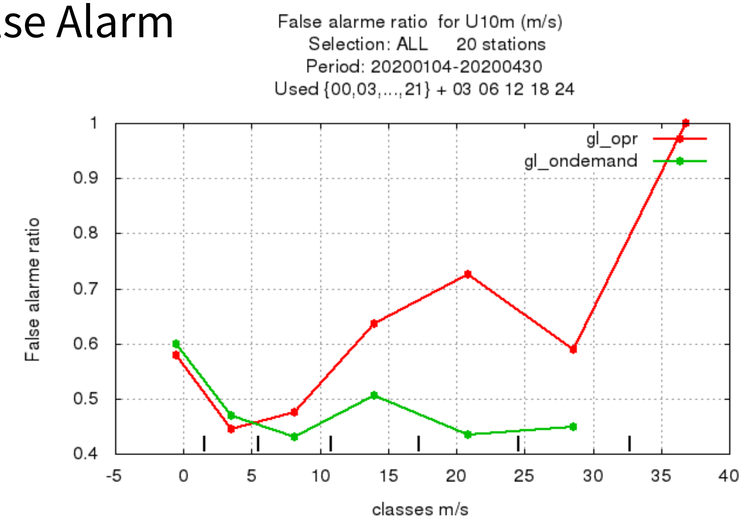
The on-demand suites are triggered by either forecast of high wind speed by Harmonie-2.5km, or

by observations. It can also be launched by duty forecasters. They are coupled to IFS HRES.

Wind Error

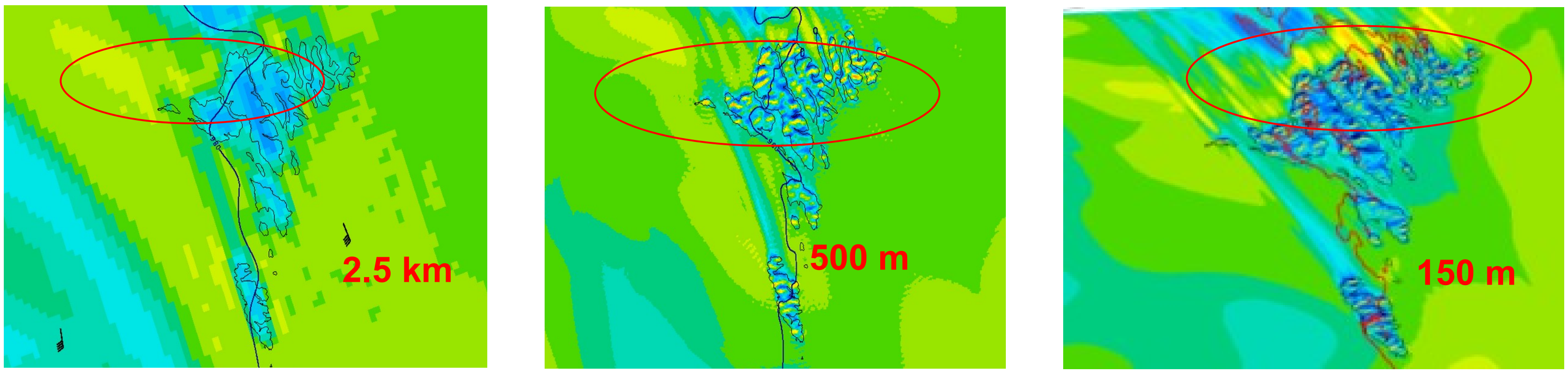


False Alarm



Verification of wind speed forecasts during pre-operational phase (Jan-Apr 2020) for 4 high resolution, on-demand suites in comparison to the operational Harmonie-arome at 2.5 km. The sub-km forecasts are found to reduce over-prediction in wind speed and alleviate false alarm situation for high wind situations.

Hectometric-scale Harmonie-arome at 100-200m range



At 150-m grid resolution, Harmonie-arome is found to improve significantly prediction of a winter storm for Faroe Islands, North Atlantic, on March 10 2021, which experienced hurricane scale wind. The storm was largely missed by main forecasts at ECMWF (9 km), and DMI (2.5km and 500m). The 150-m Harmonie-arome clearly represented better the event. Similar finding is also valid for the hurricane on March 27 2021, indicating that hectometric scale model is needed to resolve extreme storm events reinforced by small scale orographic effects.

Feasibility experiments with 100 m-scale NWP for the EU DestinE project have been carried out, running Harmonie-arome at downscaling mode for Faroe Islands and for Denmark. In view of the promising results, experimental on-demand configuration have been set up to use high resolution downscaling to improve detection of extreme wind for Denmark and Faroe Islands.

Operational, pre-operational and experimental NWP domains at DMI

Operational

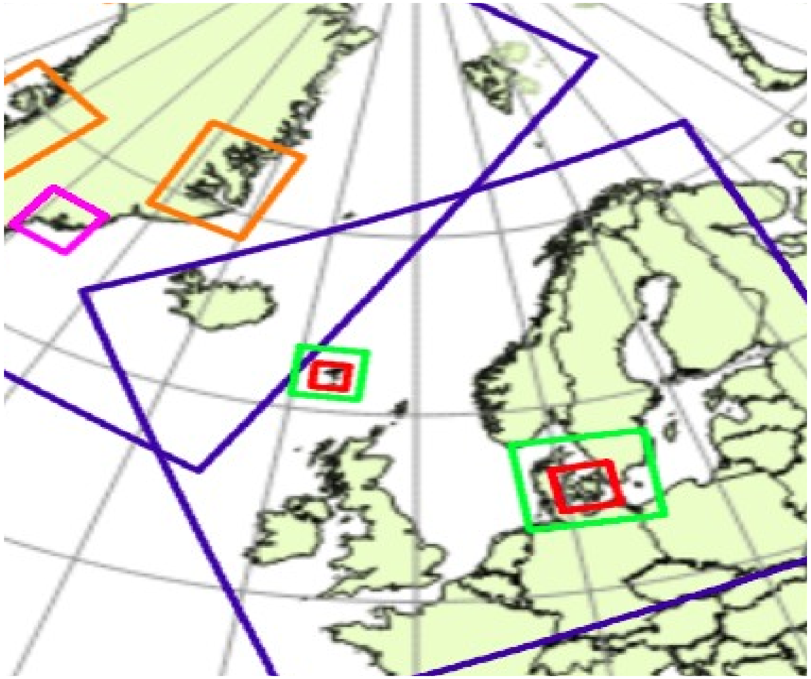
- Main suites: 2.5 km

  - COntinuous Mesoscale EPS, 19 member, hourly probabilistic forecast, 57h Iceland-Greenland model with 3h refresh, 66h

- Regular, Sub-km

  - TASillaq, 750m, 51h
  - South GreenLand, 750m, 51h

- On-demand
  - 750m: Nuuk, Qaanaq, 51h
  - 1 km: Scoresbysund, Diskobugt , 51h



Pre-operational

- **Nowcasting**

  - 750m, hourly refresh full data assimilation 9h

  - Regular HighRes 500m, Faroe Islands, downscaling, 24h

Experimental

- **on-demand**

  - 150m: Faroe Islands, downscaling, 24h

  - 200m, Sealand, downscaling, 24h

Porting dynamics to GPU-accelerated HPC

- **Dynamics is "a priori" easier to port on GPU than physics or data assimilation since there are less routines involved and some parts are well isolated.**
- **Spherical harmonics transforms have already been ported to GPU by ECMWF and NVIDIA.**
- **Code has been adapted to 2D Fourier transforms.**
- **Test on HPC at IDRIS (HPE SGI 8600,nodes with 2 processors Intel Cascade Lake (20 cores at 2,5 GHz), 192 GiB memory, and 4 GPU Nvidia Tesla V100 32 GiB) show that beyond 4 nodes computation time is not optimal. This is due to the lack of fast hardware direct communications between GPU when more than 4 nodes are used.**

Thank you for your attention !