Portable Model for multi-scale Atmospheric Prediction (PMAP)

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Thank you for support: Hannes Vogt, Enrique Gonzales-Paredes, Mauro Bianco, Peter Dueben, Nils Wedi, Ioan Hadade, Andreas Müller

ACCORD/DestinE collaboration: Tommaso Benacchio, Daan Degrauwe, Ole Lindberg, Fabrice Voitus

CSCS Centro Svizzero di Calcolo Scientifico Swiss National Supercomputing Centre

Platform for Advanced Scientific Computing

Funded by the European Union Destination Earth implemented by ECMWF esa EUMETSAT

The future of numerical models for weather and climate

Challenges with established operational models (specifically IFS and AROME, HARMONIE-AROME, ALARO):

- Fortran programming (limitations in compiler and library support, modern coding paradigms, narrow ecosystem)
- Resource-intensive to maintain, to develop, to use, and to adapt to **new hardware technologies**
- Lacks code interoperability and versatility particularly for new use cases such as **hybrid AI/ML**
- High barrier of entry for **next generation of scientists**, lower acceptance of legacy programming approaches among software engineers, smaller available talent pool
- Numerical limitations particularly for **high resolution**, e.g.:
  - Steep orography stability and representation
  - (Local) conservation
  - Flexibility of time stepping and physics coupling
  - Large-eddy simulation capabilities

Portable Model for multi-scale Atmospheric Prediction (PMAP)

Building on numerical principles of ECMWF's **semi-implicit finite-volume** dynamical core **FVM** in Fortran (Smolarkiewicz et al. 2014, 2017; Kühnlein et al. 2019) and selected ESM components of the IFS, key goals for the **PMAP** are:

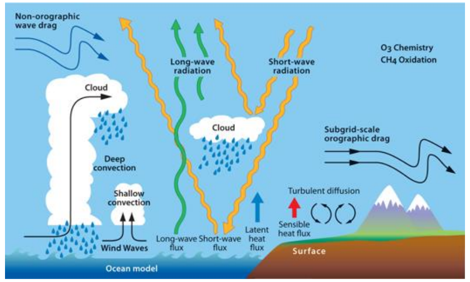
- **High-level programming** completely in Python
- **Performance-portability and computing hardware adaptation** by means GridTools for Python (GT4Py)
- Numerical methods suitability, physical fidelity, and high efficiency from **kilometer to meter scales**
- Support both **regional and global domains** using quadrilateral grids, and (one- and two-way) nesting functionalities
- Serve as **operational weather prediction** model and as **portable, flexible and user-friendly research tool**
- Deploy model across largest CPU/GPU supercomputers, cloud services and laptops
- Towards **auto-differentiation** of full model, for hybrid data-driven modelling, seamless ML, and data assimilation

High-level domain-specific programming with GridTools for Python

PMAP domain model

$$\frac{\partial \mathcal{G}\rho}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho) = 0 \,,$$
$$\frac{\partial \mathcal{G}\rho\mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho\mathbf{u}) = \mathcal{G}\rho \left[-c_p\theta_\rho \,\underline{\mathbf{G}}\nabla\pi + \mathbf{g} - \mathbf{f}\times\mathbf{u} + \boldsymbol{M}^{\mathbf{u}} + \boldsymbol{B}^{\mathbf{u}} + \boldsymbol{D}^{\mathbf{u}} + \boldsymbol{P}^{\mathbf{u}}\right]$$
$$\frac{\partial \mathcal{G}\rho\theta'}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho\,\theta') = \mathcal{G}\rho \left[-\underline{\mathbf{G}}^T\mathbf{u}\cdot\nabla\theta_a + B^\theta + D^\theta + P^\theta\right] \,,$$
$$\frac{\partial \mathcal{G}\rho\psi}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho\psi) = \mathcal{G}\rho \left[B^\psi + D^\psi + P^\psi\right] \,, \qquad \psi = r_v\,, r_l\,, r_r\,, r_i\,, r_s\,, r_g\,, \Lambda_f\,, \ldots$$
$$\pi = \left(\frac{R}{p_0}\rho\,\theta\,(1 + r_v/\varepsilon)\right)^{R/c_v} \,.$$

python™



Performance engineering → HPC execution

High-level domain-specific programming with GridTools for Python

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$$\frac{\partial \mathcal{G}\rho\theta'}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho\,\theta') = \mathcal{G}\rho\left[-\underline{\mathbf{G}}^T\mathbf{u}\cdot\nabla\theta_a + B^\theta + D^\theta + P^\theta\right] \,,$$

$$\frac{\partial \mathcal{G}\rho\psi}{\partial t} + \nabla \cdot (\mathbf{v}\mathcal{G}\rho\psi) = \mathcal{G}\rho\left[B^\psi + D^\psi + P^\psi\right] \,, \qquad \psi = r_v\,, r_l\,, r_r\,, r_i\,, r_s\,, r_g\,, \Lambda_f\,, \ldots$$

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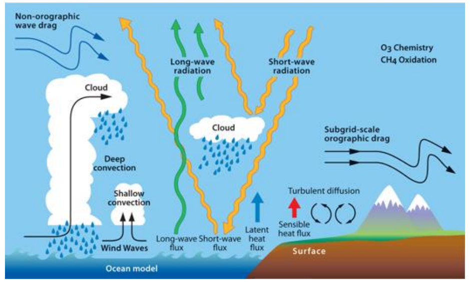
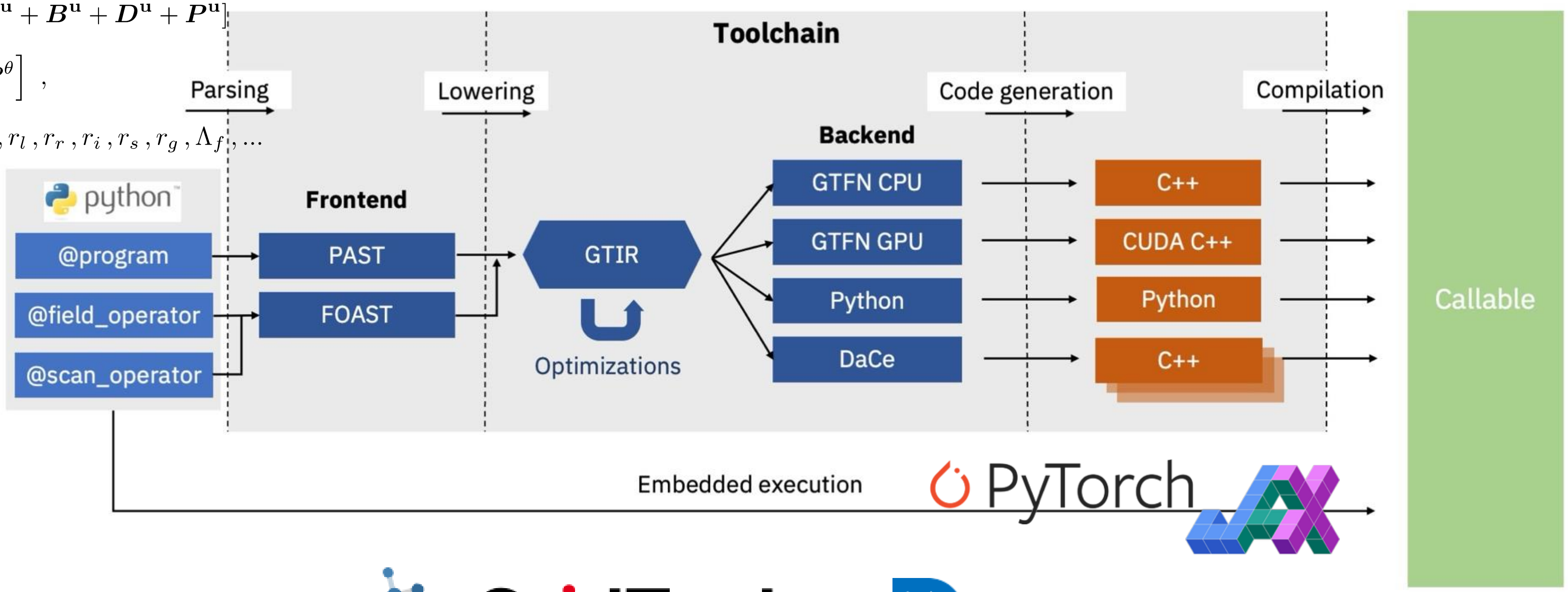
python™



Performance engineering → HPC execution



GridTools 4python

DaCe

https://github.com/GridTools/gt4py

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Domain-specific GT4Py framework in Python

- **GT4Py** is embedded in the **Python** eco-system
    - Versatile, portable, productive programming language
    - Broad selection of modules/libraries
    - Enables new user and developer workflows
    - Low barrier of entry for domain scientists and academia
    - Favourable choice with respect to ML/AI applications

GridTools/**atlas4py**

5 Contributors · 1 Issue · 1 Star · 3 Forks

spcl/**dace**

DaCe - Data Centric Parallel Programming

69 Contributors · 25 Used by · 15 Discussions · 497 Stars · 129 Forks

ecmwf/**pyflow**

A high level Python interface to ecFlow allowing the creation of ecFlow suites in a modular and "pythonic" way

9 Contributors · 3 Used by · 8 Stars · 7 Forks

pyFFTW/**pyFFTW**

A pythonic python wrapper around FFTW

28 Contributors · 938 Used by · 377 Stars · 108 Forks

GT4Py domain-specific library

GridTools 4python

- **Besides PMAP, two other atmospheric models are developed in Python with GT4Py**

  - **ICON4Py is** the GT4Py.next implementation of the ICON model in the EXCLAIM project at ETH Zurich

    https://github.com/C2SM/icon4py

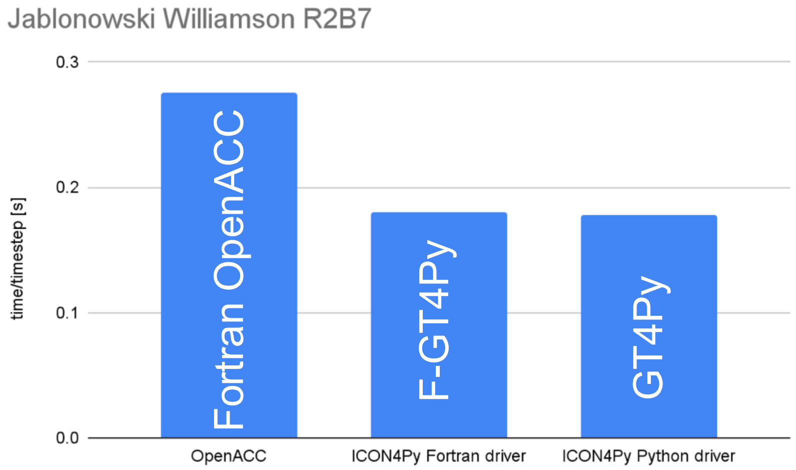
    EXCLAIM

    Schweizerische Eidgenossenschaft
    Confédération suisse
    Confederazione Svizzera
    Confederaziun svizra

    Swiss Confederation

    Federal Department of Home Affairs FDHA
    Federal Office of Meteorology and Climatology MeteoSwiss

    MeteoSwiss



Courtesy M. Bianco

  - **Pace** (Ben-Nun et al. 2022; Dahm et al. 2023) is the GT4Py.cartesian implementation of the FV3GFS/SHiELD model of GFDL and NOAA

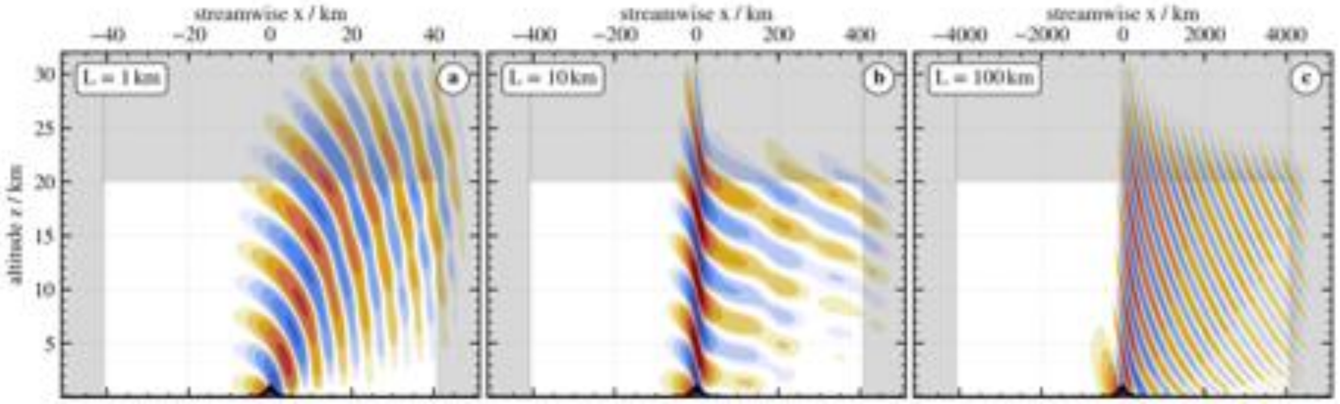
    https://github.com/NOAA-GFDL/pace

PMAP compressible semi-implicit finite-volume formulation

Overview of PMAP's formulation aspects (see upcoming PMAP paper for details):

- Fully compressible equations in strong conservation form (prognostic variables in Table →) in rotated spherical coordinates and generalized height-based terrain-following vertical coordinate
- Customized semi-implicit time integration with 3D implicit buoyancy, acoustic, Coriolis, metric terms
- Flux-form (locally conservative) semi-Lagrangian (FFSL) advective transport using PPM in 1D and various multi-dimensional splittings (Macho, Cosmic, Swift)
- Flux-corrected transport (FCT) or slope limiters to ensure monotonicity with advective transport schemes
- Variable-coefficient Helmholtz problem from implicit scheme: Preconditioned Krylov with options: GCR(k), BiCGStab, GMRES, IDR
- Diffusion: 3D flux-form, anisotropic, HEVI time stepping
- Turbulence: Prognostic TKE scale-aware across km-scale to LES resolutions (also using BL89, RMCP17, HMLN21)

Variable	Ψ	$\mathbf{V}$	G	a^{Ψ}	b^{Ψ}	Unit of Ψ	Equation
Dry density	ρ	$\mathbf{v}\mathcal{G}$	$\mathcal{G}$	-	-	$\mathrm{kg\,m^{-3}}$	(1a)
Zonal physical velocity	u^x	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{m\,s^{-1}}$	(1b)
Meridional physical velocity	u^y	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{m\,s^{-1}}$	(1b)
Vertical physical velocity	u^z	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{m\,s^{-1}}$	(1b)
Potential temperature perturbation	θ'	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	K	(1c)
Water vapour mixing ratio	r_v	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{kg\,kg^{-1}}$	(1d)
Liquid water mixing ratio	r_l	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{kg\,kg^{-1}}$	(1d)
Rain water mixing ratio	r_r	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{kg\,kg^{-1}}$	(1d)
Ice mixing ratio	r_i	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{kg\,kg^{-1}}$	(1d)
Snow mixing ratio	r_s	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{kg\,kg^{-1}}$	(1d)
Graupel mixing ratio	r_g	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{kg\,kg^{-1}}$	(1d)
Hail mixing ratio	r_h	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{kg\,kg^{-1}}$	(1d)
Cloud fraction	A_f	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	1	(1d)
Exner pressure perturbation	π'	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	$(1-\beta)$	β	1	(14)
Turbulence kinetic energy (TKE)	e	$\mathbf{v}\mathcal{G}\rho$	$\mathcal{G}\rho$	0.5	0.5	$\mathrm{m^2\,s^{-2}}$	(5)



Linear mountain wave spectrum with PMAP Binder et al. submitted

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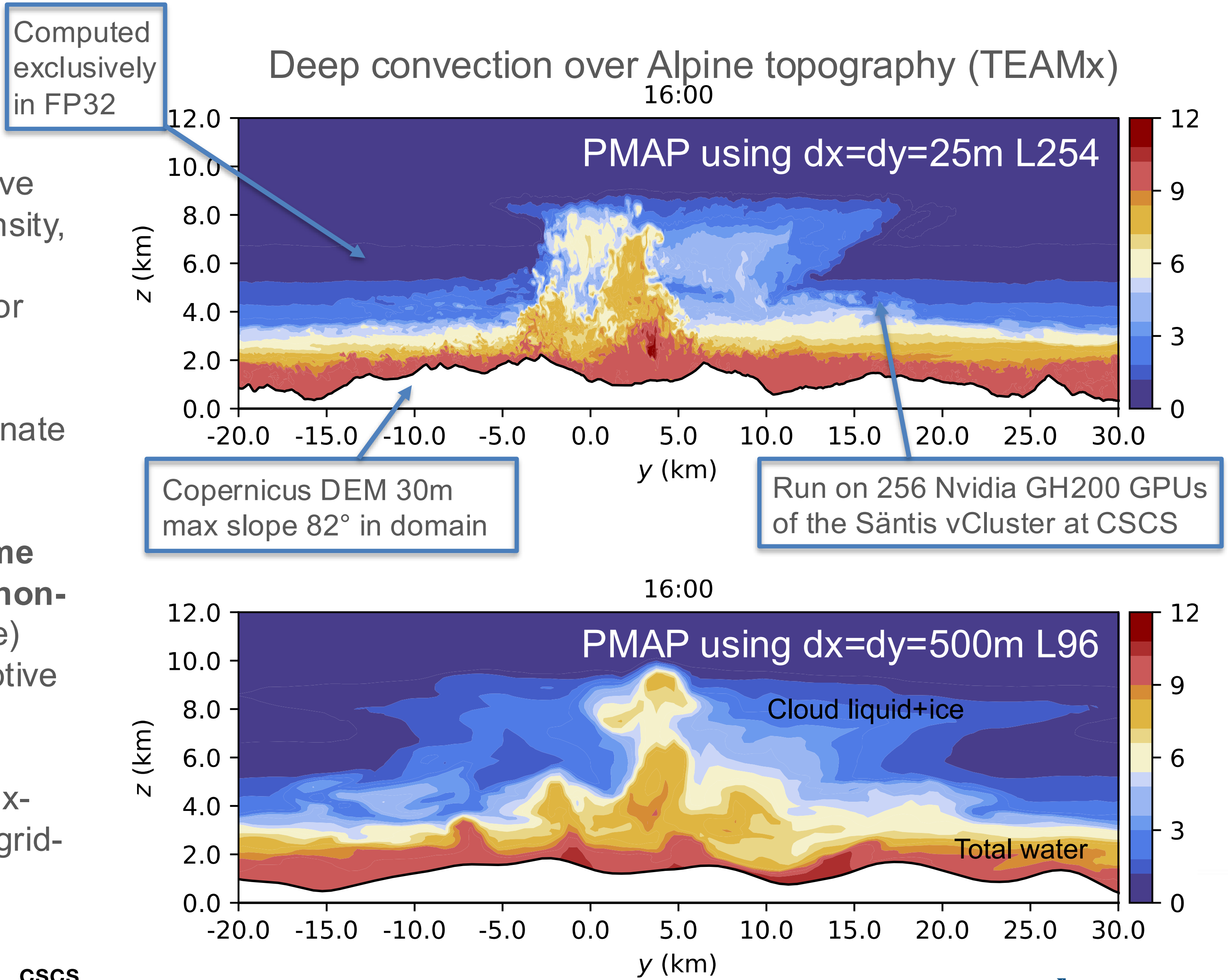
PMAP offers advanced high-resolution simulation capabilities

- Fully compressible equations in a strong conservation form accounting for comprehensive moist processes formulated in terms of dry density, dry entropy perturbation, Exner pressure perturbation, dry density and moist/hydrometeor mixing ratios

- Generalized terrain-following curvilinear coordinate based on height

- Numerical integration based on **3D implicit time integration** for core dynamics combined with **non-oscillatory flux-form** (i.e., locally conservative) semi-Lagrangian advective transport with adaptive time stepping

- Large-eddy simulation capabilities using 3D flux-form diffusion and scale-aware prognostic subgrid-scale turbulence kinetic energy (TKE) scheme



Setup from ongoing model intercomparison (Kirshbaum et al. in prep.)

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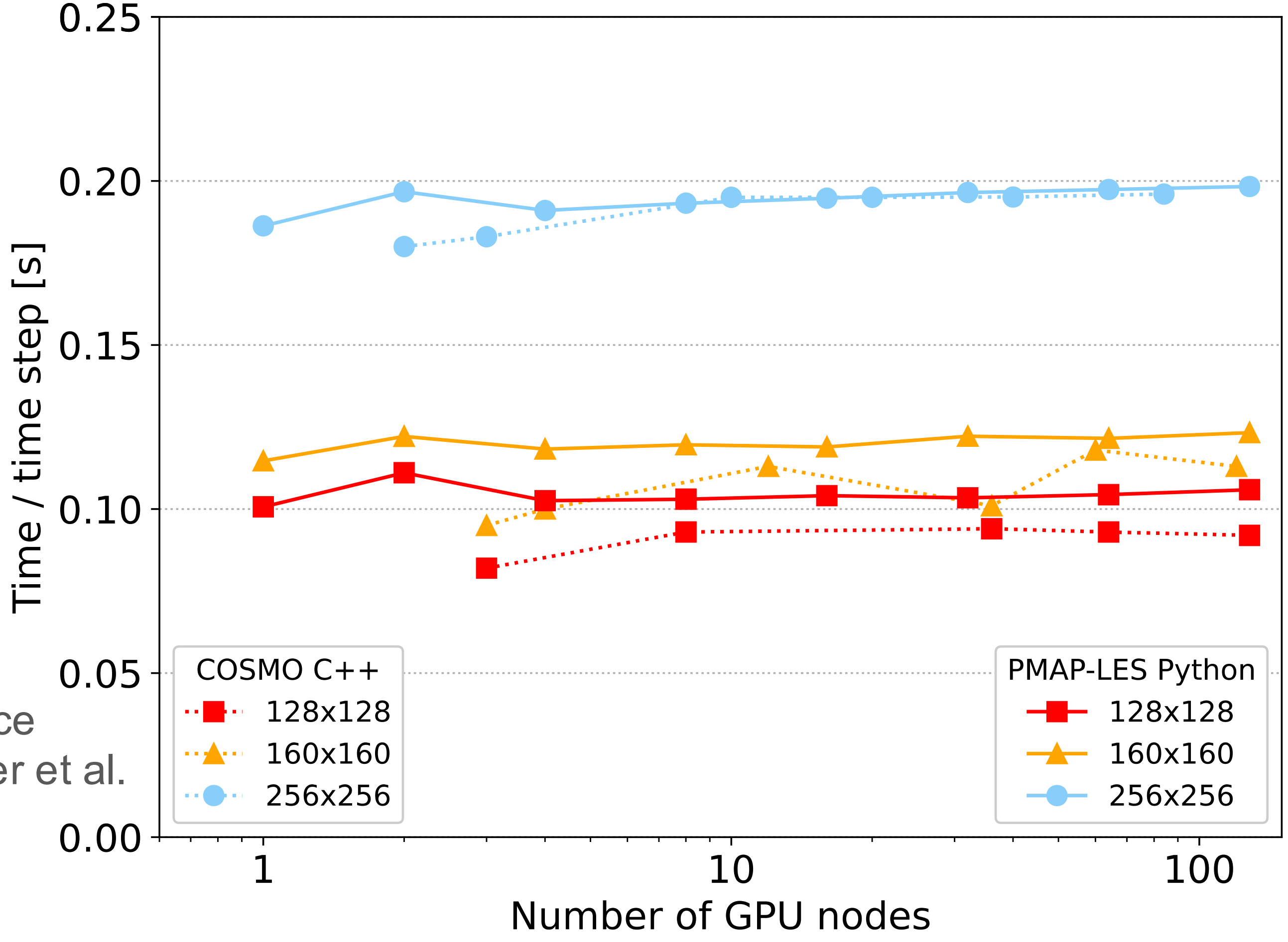
Is the PMAP Python approach viable in terms of computational performance? Yes.



COSMO performance numbers from Fuhrer et al. GMD 2018

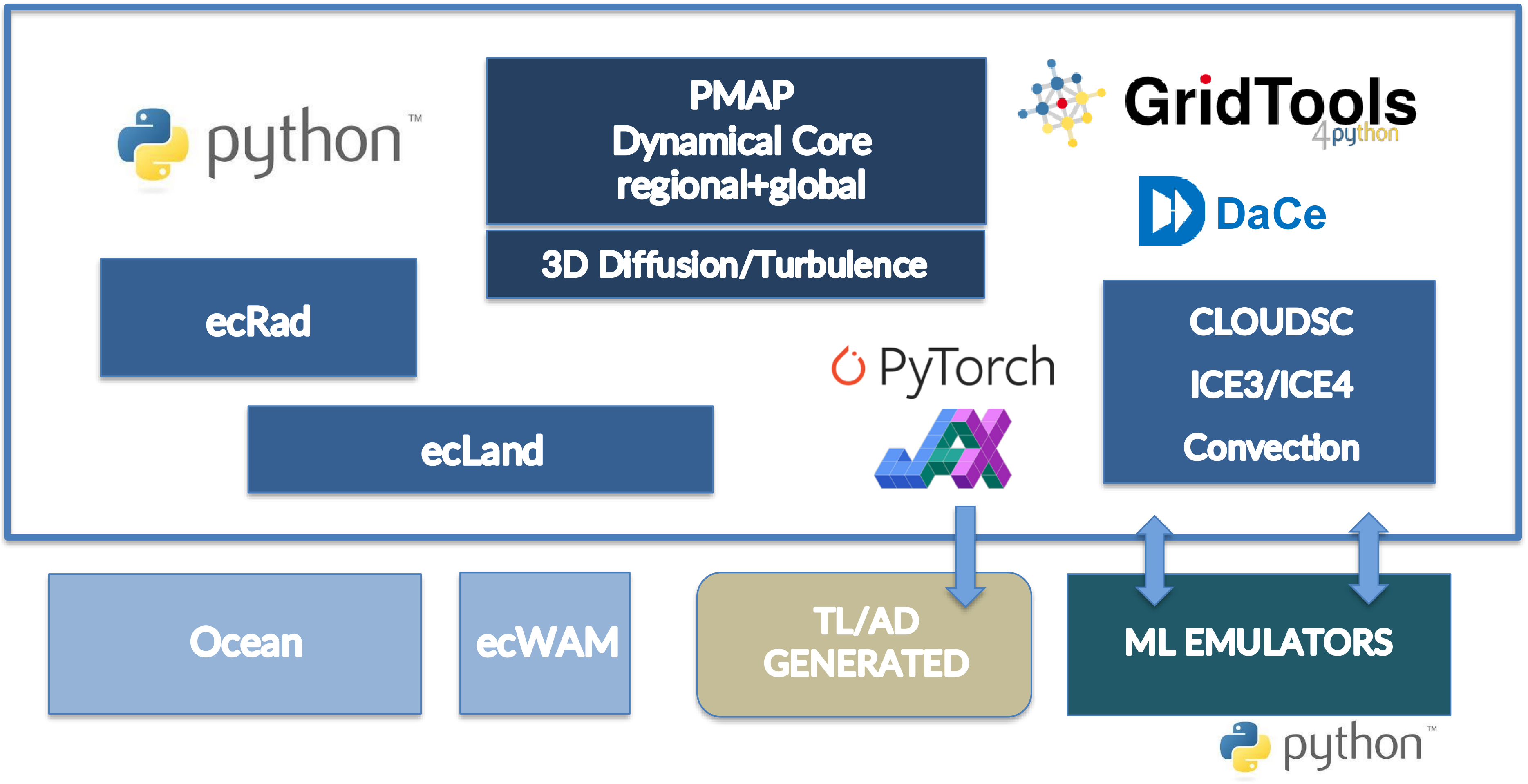
PMAP (Python DSL) vs COSMO (C++ DSL) showed same performance

Notes:
COSMO was
- operational (production-level),
- GPU-optimized for Piz Daint
- faster than its Fortran version

This comparison was done in 2024.

PMAP (solid lines) with the production-level COSMO model of MeteoSwiss based on the STELLA DSL in C++ (dashed lines), on the identical Nvidia GPU hardware of Piz Daint (CSCS). → Details discussed in upcoming PMAP paper in GMD

Envisaged PMAP forecast system with its components and codes



Complete Python-GT4Py version of the ecRad radiation scheme

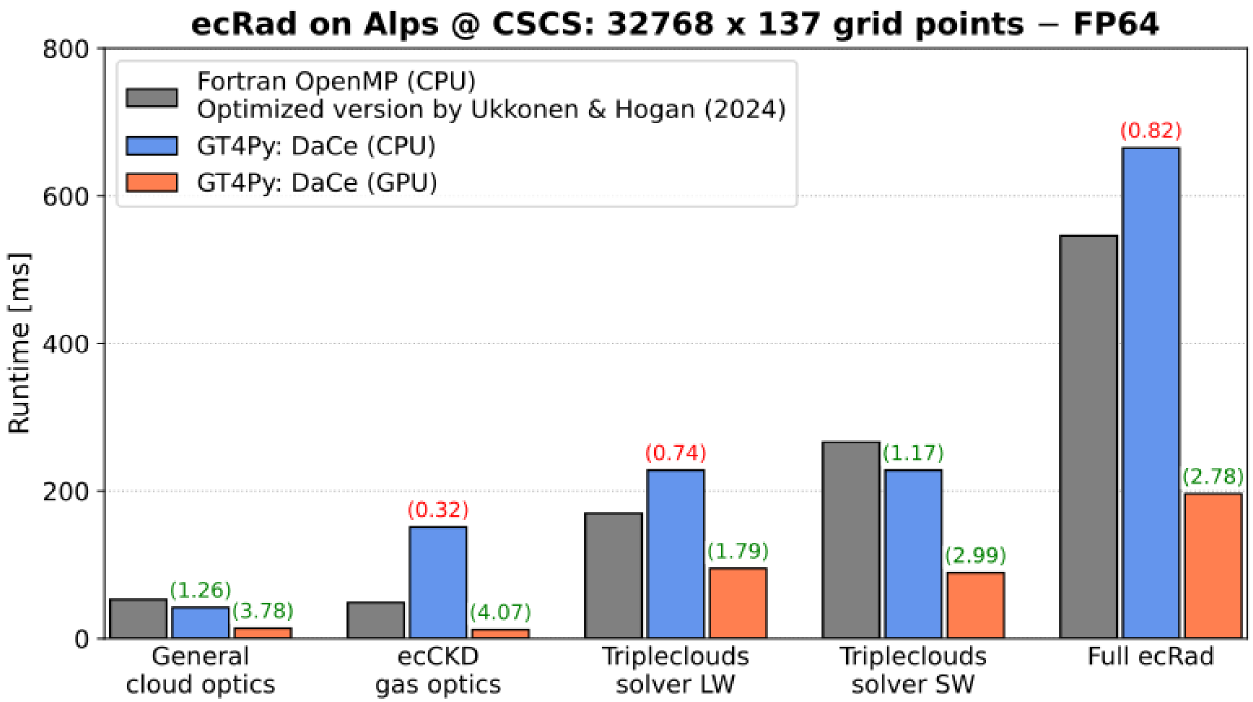
- **PMAP-TKE** 3D flux-form scale-aware prognostic turbulence kinetic energy scheme

- **CLOUDSC** various versions including CY49R1 and CY50R1 ported and coupled. NL, TL, AD of CLOUDSC2 in GT4Py.cartesian (Ubbiali et al. 2025) and recent GT4Py.next implementation by H. Vogt (CSCS) with embedded JAX execution to auto-generate TL, AD

- **ecRad** ported and coupling complete (G. Vollenweider, S. Ubbiali), coarse-grid option in preparation

- **ecLand** Python version to be completed in 2026 including coupling to PMAP

- **Physics-dynamics coupling in PMAP** will enable flexibility and various coupling strategies



ecRad in Python with GT4Py executes on Nvidia (CUDA C++) GPUs and AMD (HIP C++, not shown) as well as on CPUs (fig. S. Ubbiali)

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PMAP options for physical parametrizations and coupling: cloud schemes

PMAP will provide various schemes for cloud processes, there are two IFS and AROME relevant options for cloud microphysics:

❖ CLOUDSC from IFS

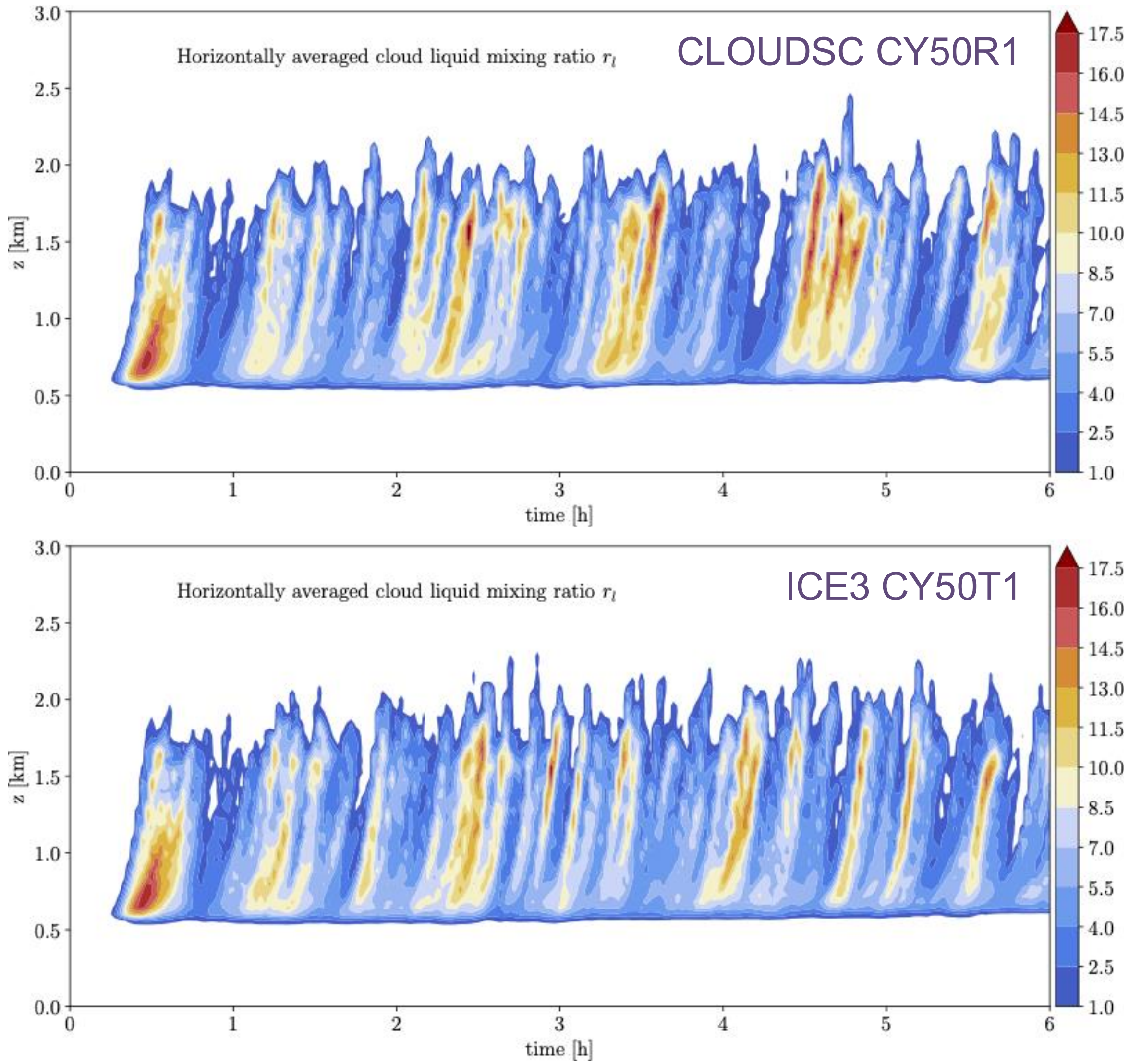
❖ ICE3/ICE4 from AROME/Meso-NH (as part of DestinE)

- Ported and validated from original Fortran to Python with GT4Py using an upgraded version of the Loki S2S translation tool done by Daan Degrauwe (RMI) and preparatory steps at Meteo-France (F. Voitus, L. Maurin)

- Loki-generated code adapted to PMAP [I, J, K] array layout, bottom-to-top vertical index, PMAP programming paradigms, formatting, and an extensive optimization effort using stencil fusing ~160 → ~35 (ECMWF)

- PMAP – ICE3/ICE4 coupling interface, refinement and testing (ECMWF)

BOMEX shallow convection LES benchmark with PMAP



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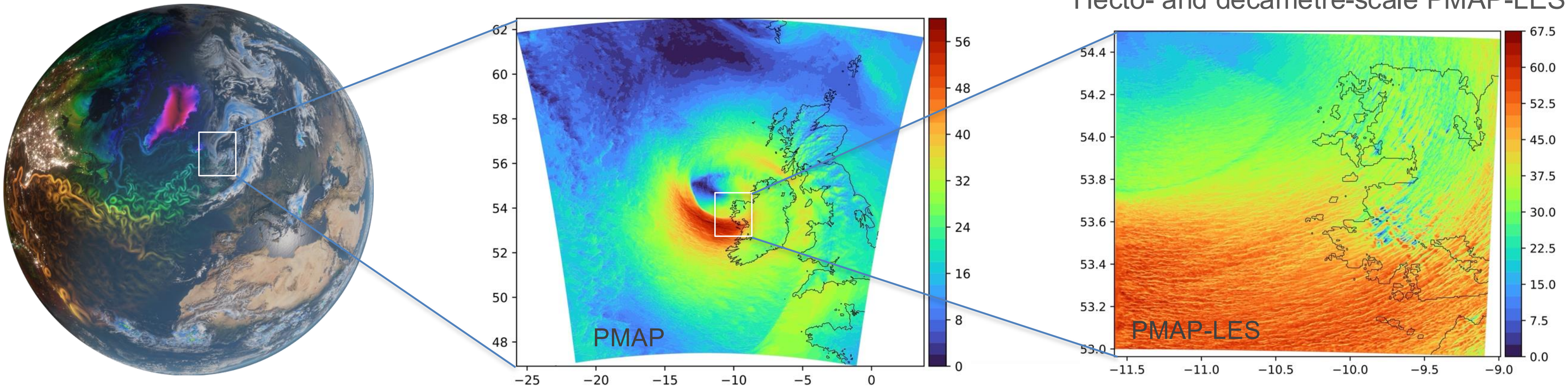
Weather and climate across scales: flexible configurations driven by Destination Earth Digital Twins

DestinE Digital Twins

Km- and Sub-km-scale PMAP driven by global DTs

Hecto- and decametre-scale PMAP-LES



Horizontal wind (m/s) in ABL

Setup and validation of **PMAP at kilometre, subkilometre and decametre resolutions** on EuroHPC GPU systems

Funded by the European Union
Destination Earth implemented by ECMWF esa EUMETSAT

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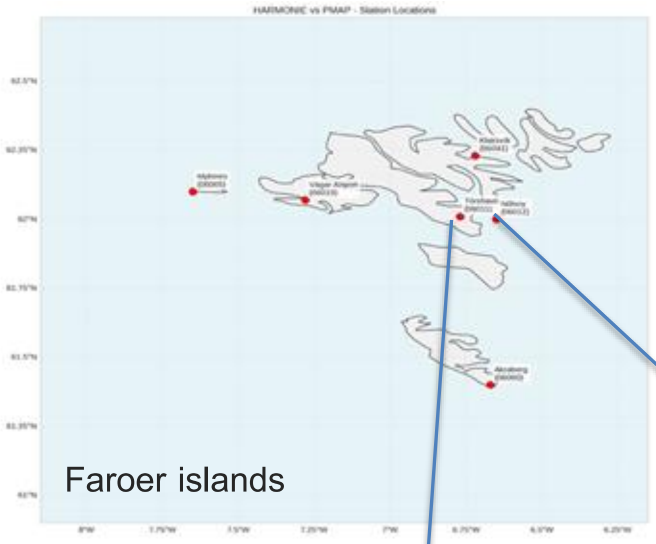
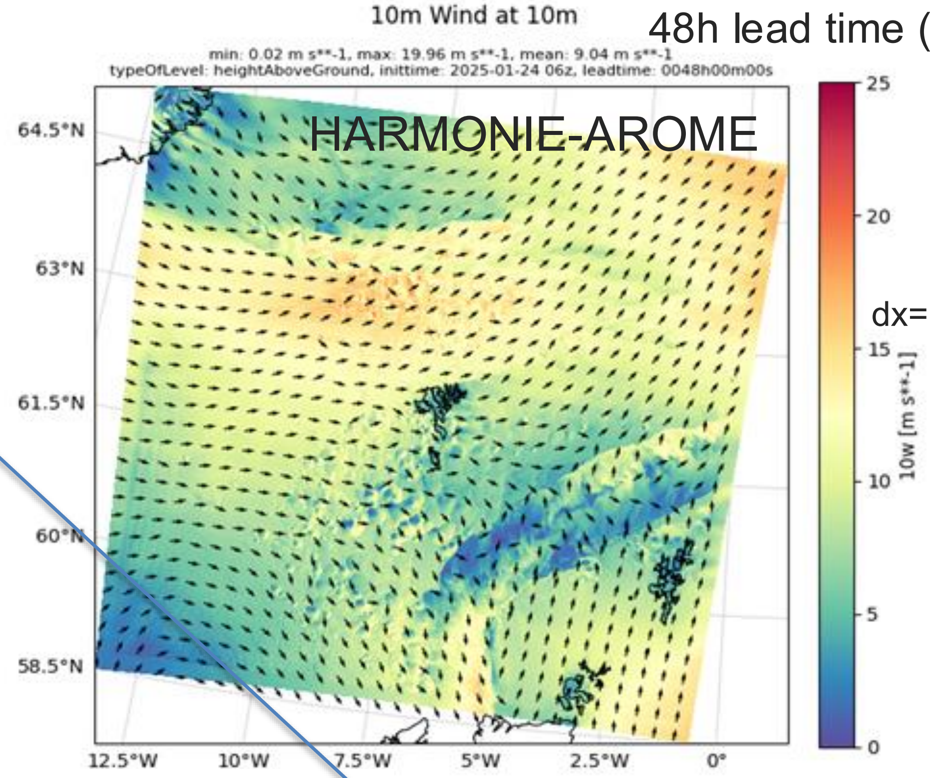
PMAP and HARMONIE-AROME comparison studies in Destination Earth

48h lead time (shown 10m wind)

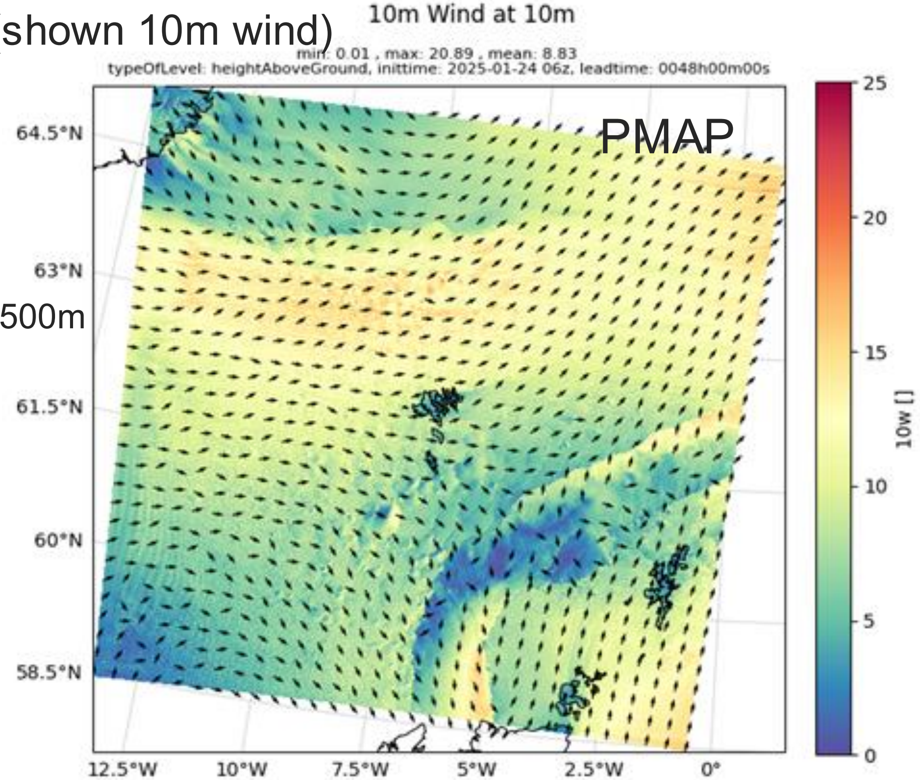


Faroer islands



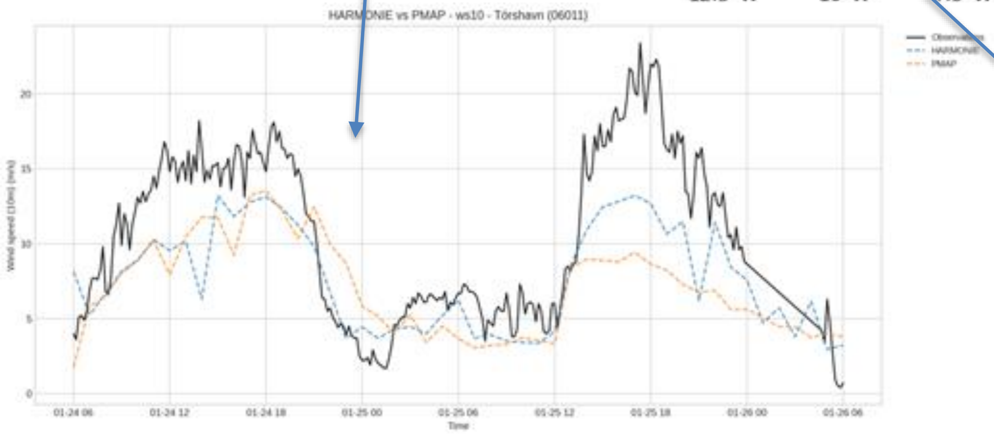
HARMONIE-AROME

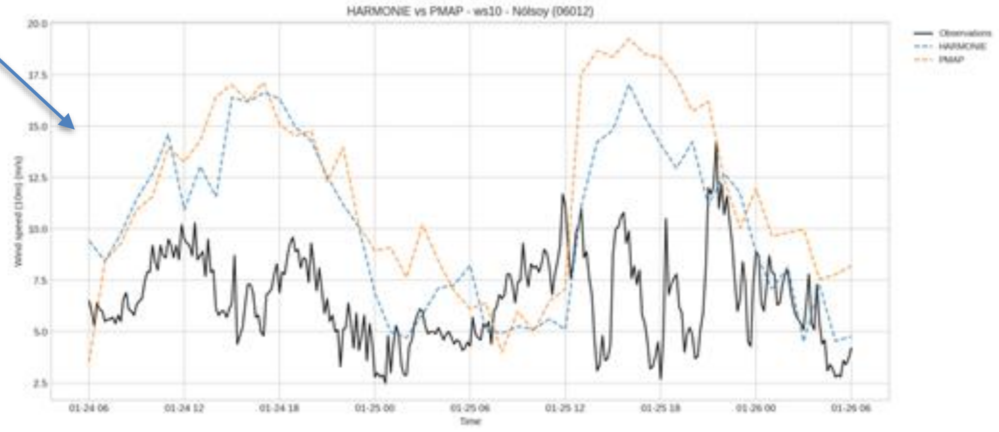
dx=500m



PMAP

Comparison to local obs





Note: PMAP (no radiation or interactive surface) in the shown experiment

Tommaso Benacchio
Ole Lindberg

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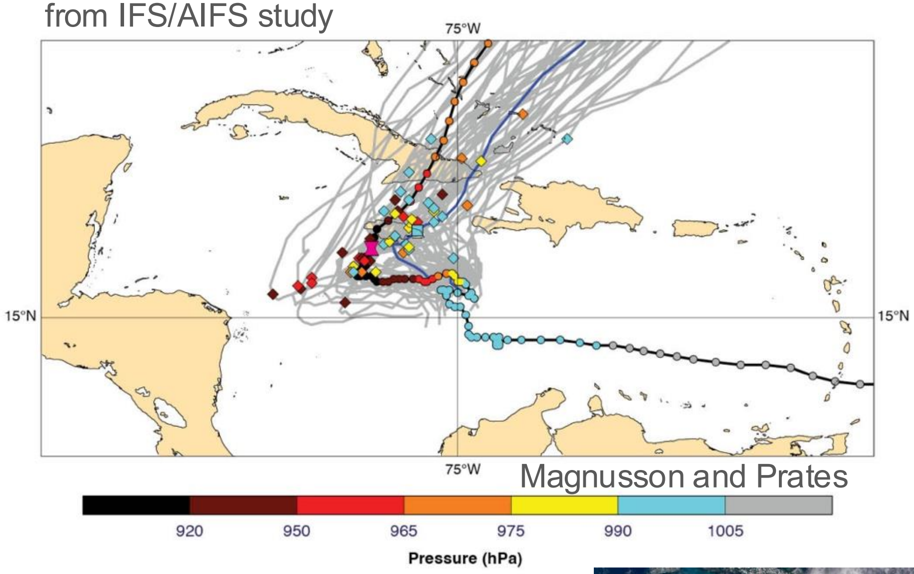
Developing PMAP real weather prediction capabilities across scales

Forecast uncertainty in track and intensity close to landfall, from IFS/AIFS study



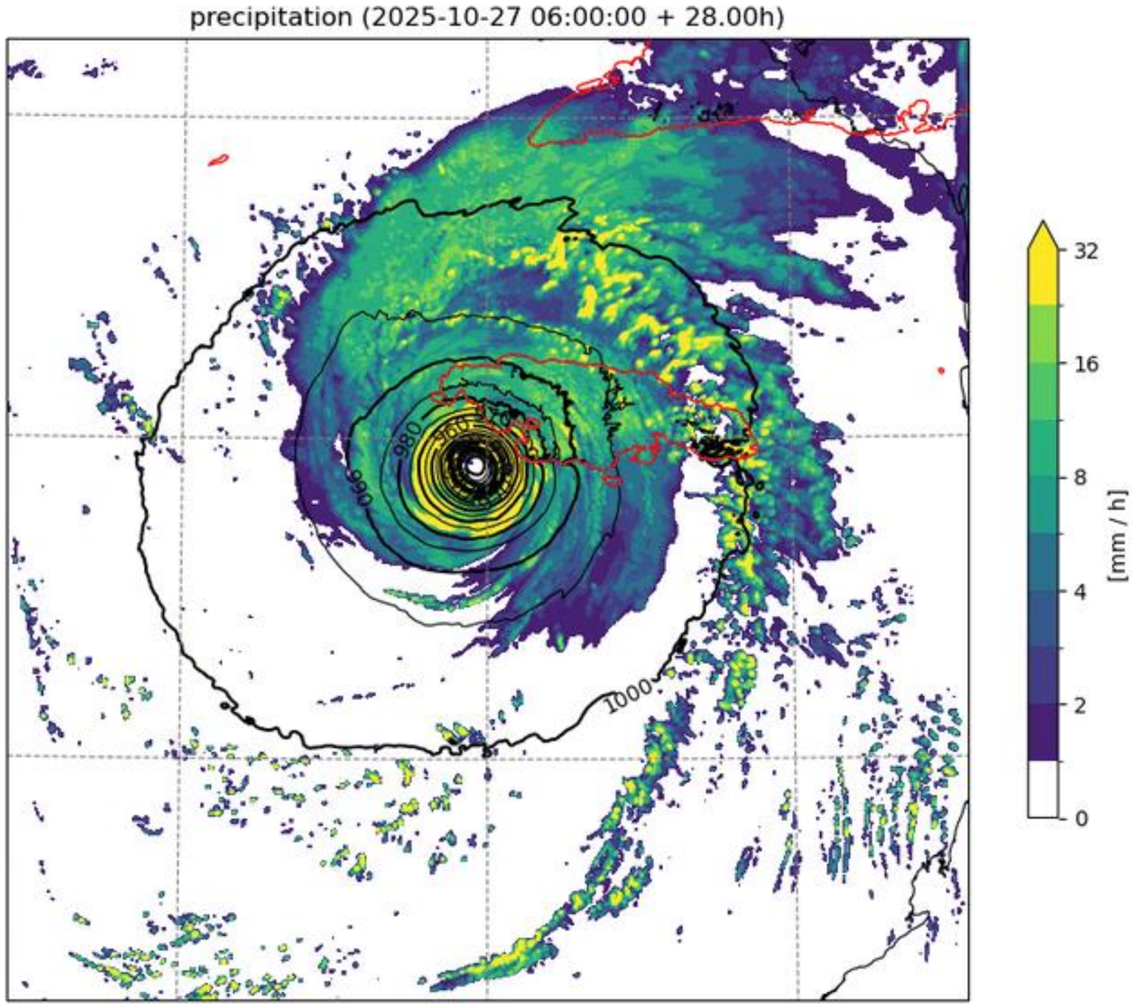
Magnusson and Prates

Hurricane Melissa

Category 5, October 2025

PMAP experiments at 500m grid spacing with comprehensive physical parametrizations

Validation and discussion in Papritz et al. EGU 2026



PMAP with full physics
(land-surface and ocean still non-interactive)

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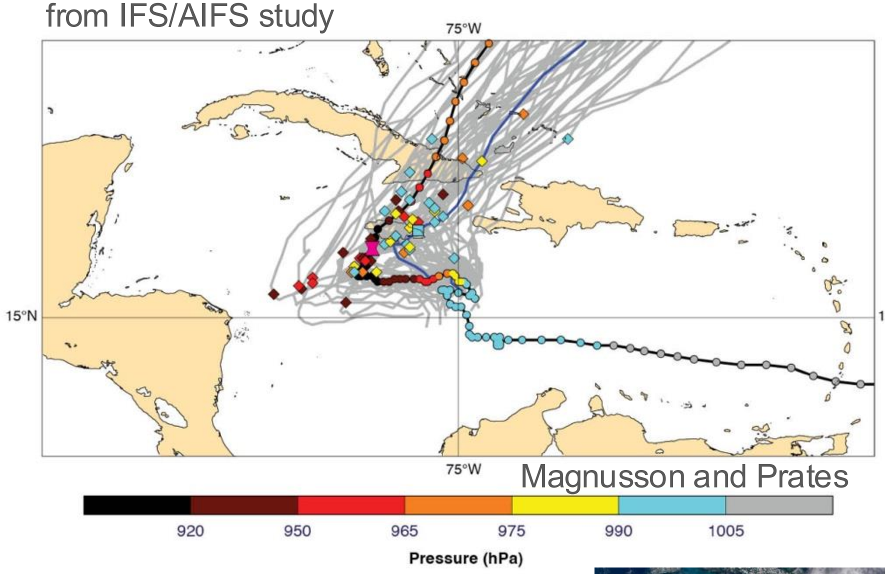

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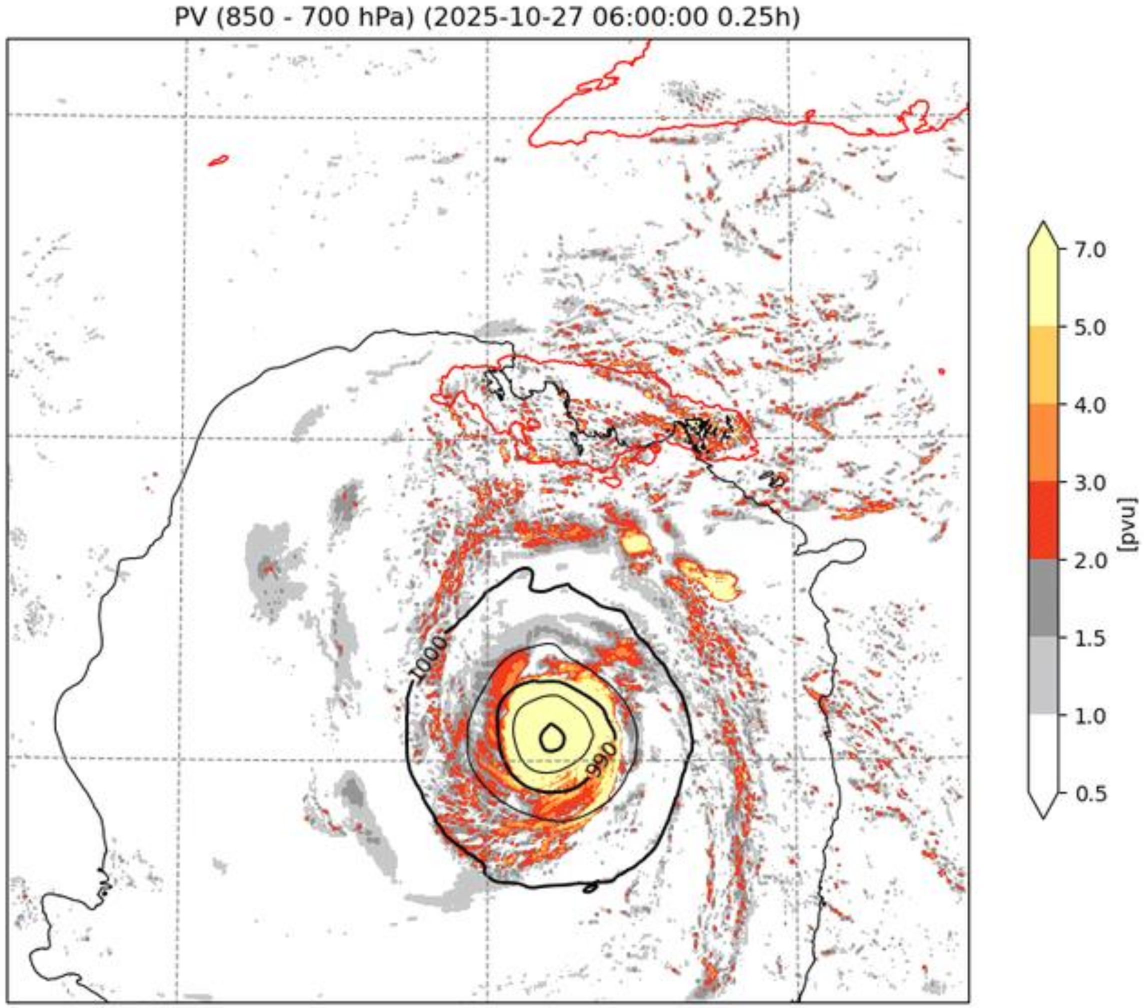

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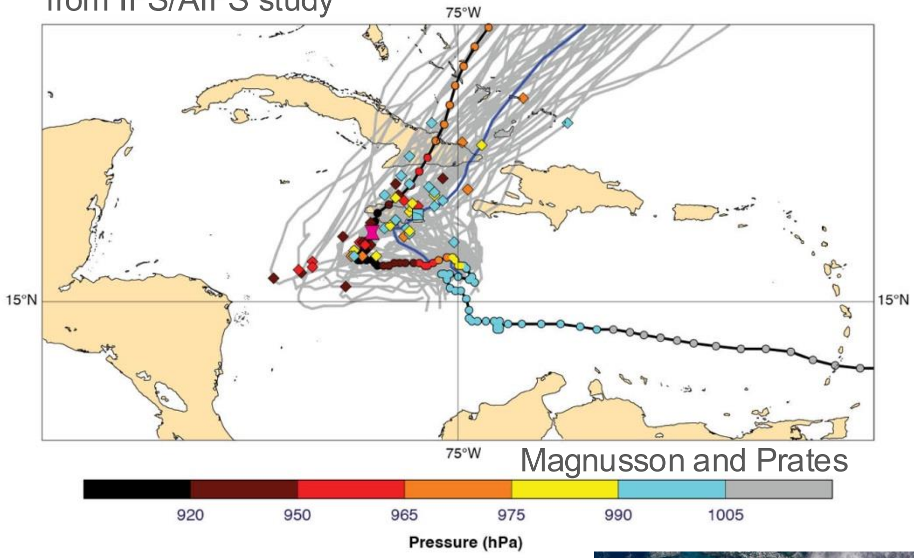

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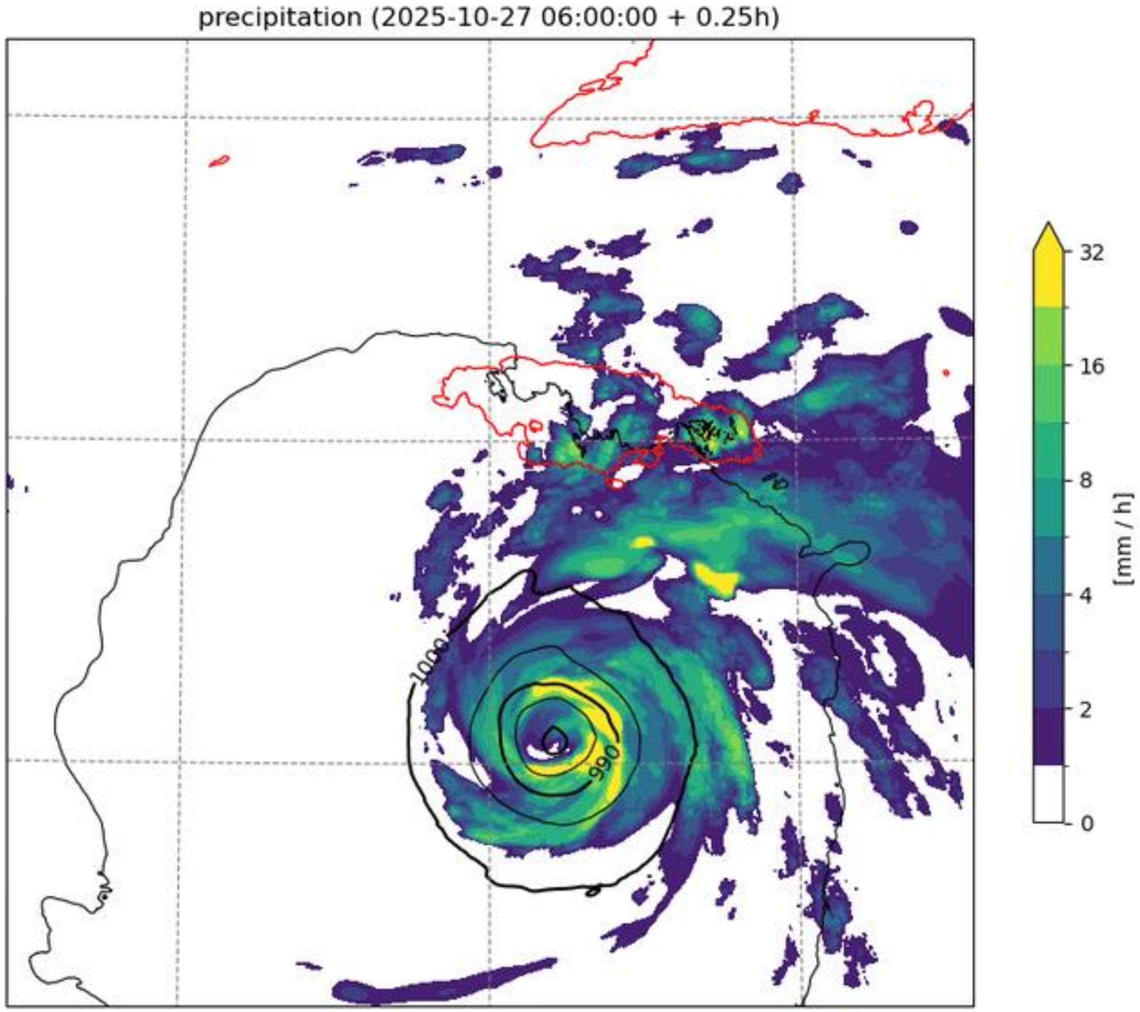
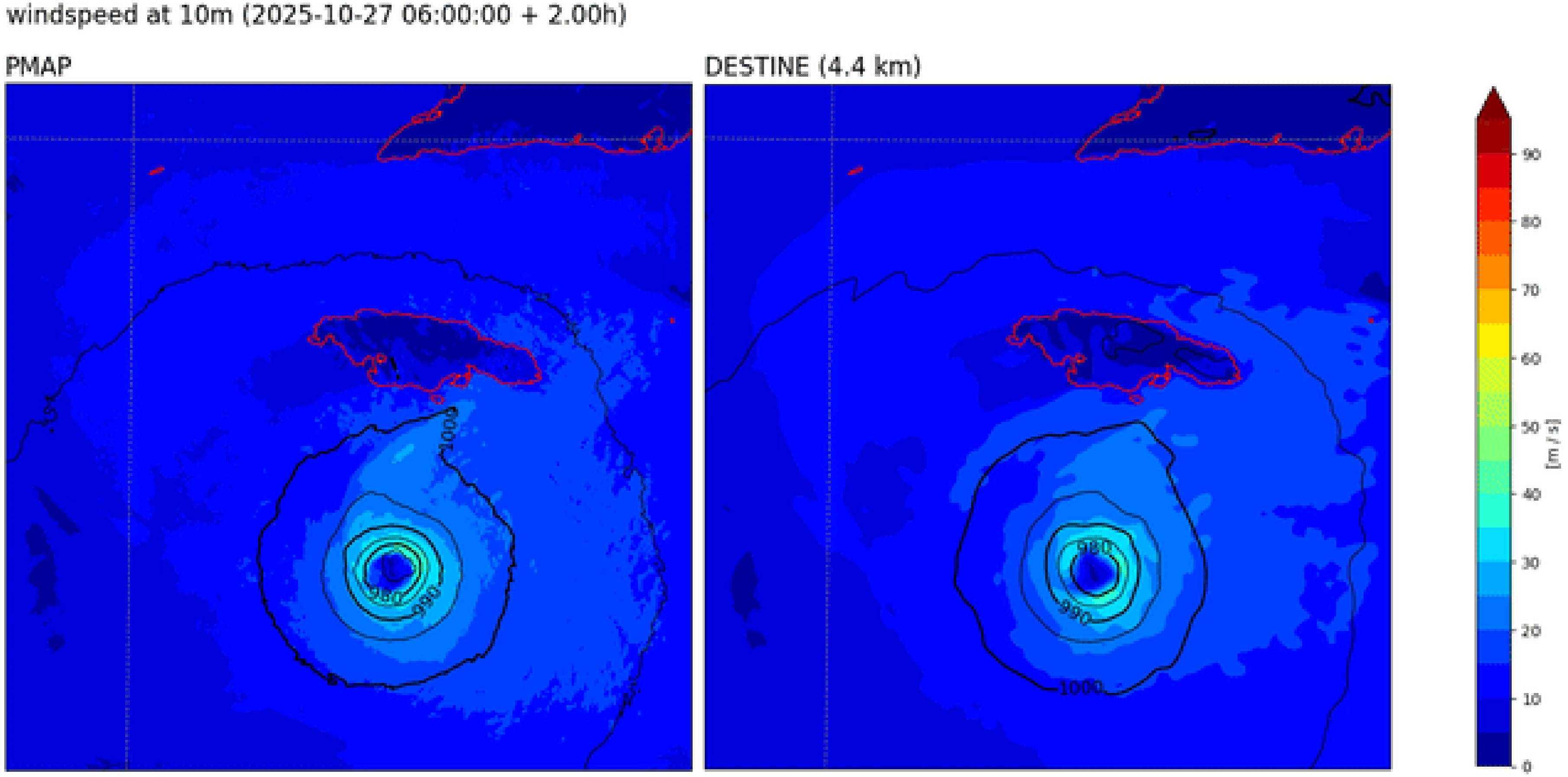


PMAP with full physics
(land-surface and ocean still non-interactive)

Developing PMAP real weather prediction capabilities across scales

PMAP with full physics (land-surface and ocean still non-interactive)



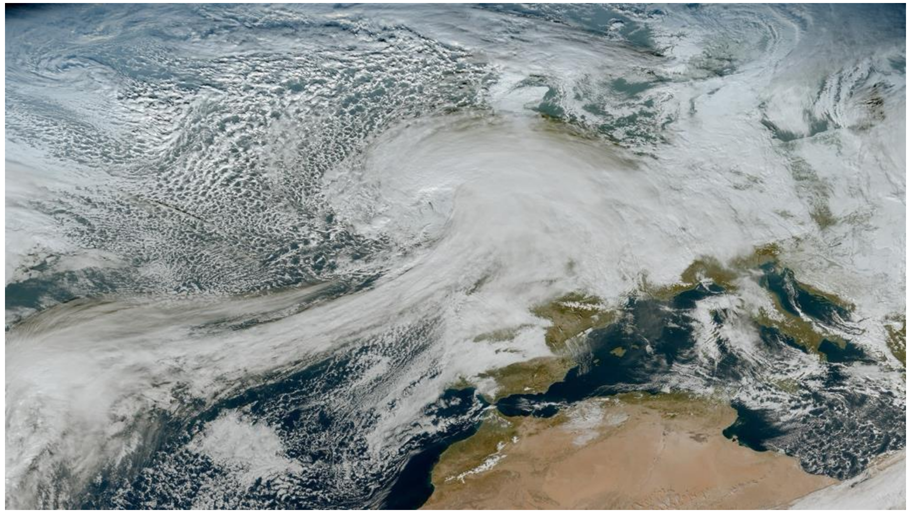
Hurricane Melissa

Category 5, October 2025

PMAP experiments at 500m grid spacing with comprehensive physical parametrizations

Validation and discussion in Papritz et al. EGU 2026

Developing PMAP real weather prediction capabilities across scales



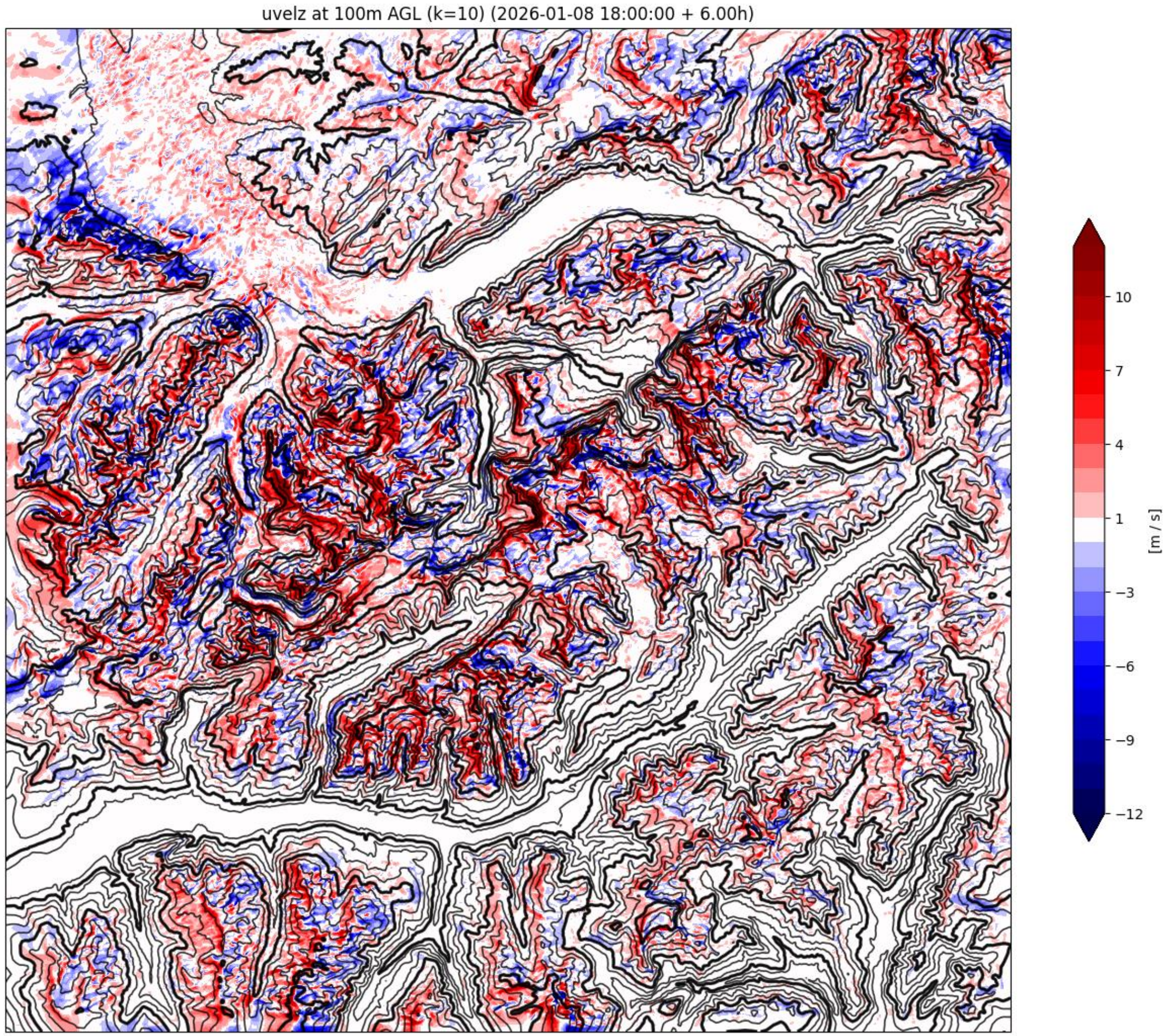
Storm Elli passing Swiss Alps

January 2026

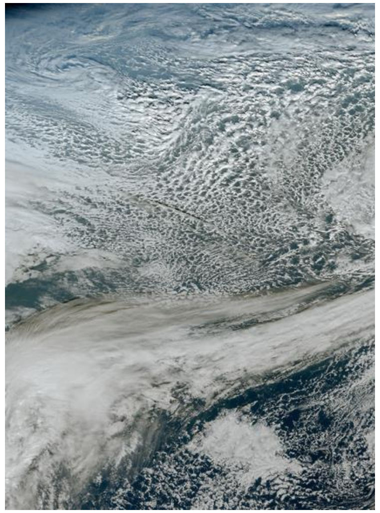
PMAP experiments at <=50m grid spacing with comprehensive physical parametrizations

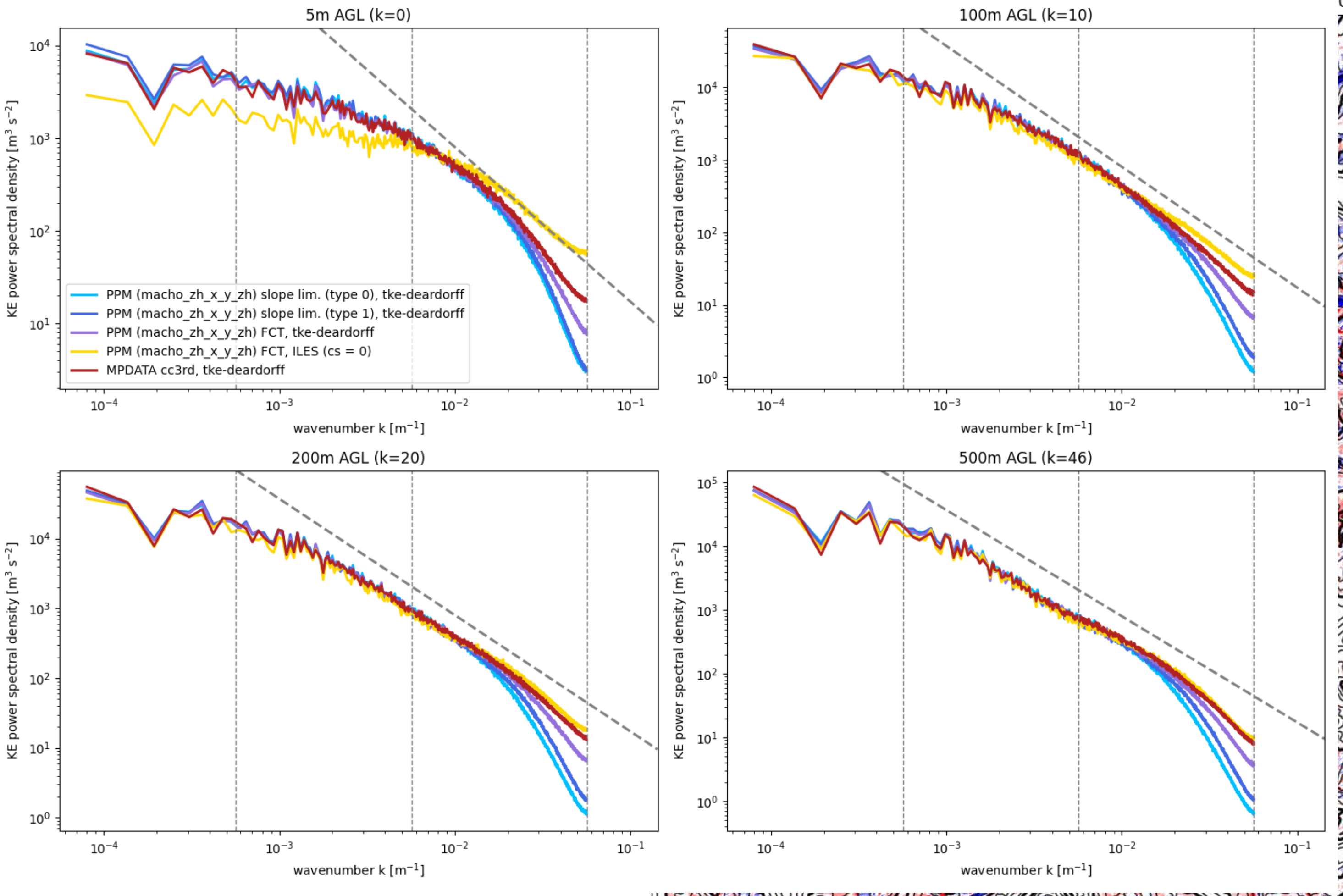
Max topography slope 82 deg

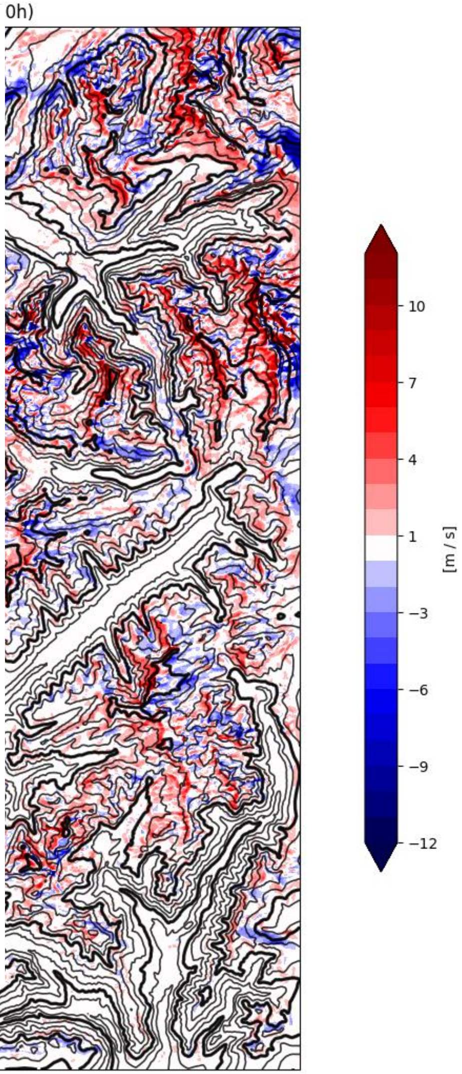
Validation and discussion in Papritz et al. EGU 2026



Developing PMAP real weather prediction capabilities across scales







Storm Elli passir

January 2026

PMAP experiments a
comprehensive phys

Max topography slop

Validation and discussion in Papritz et al. EGU 2026

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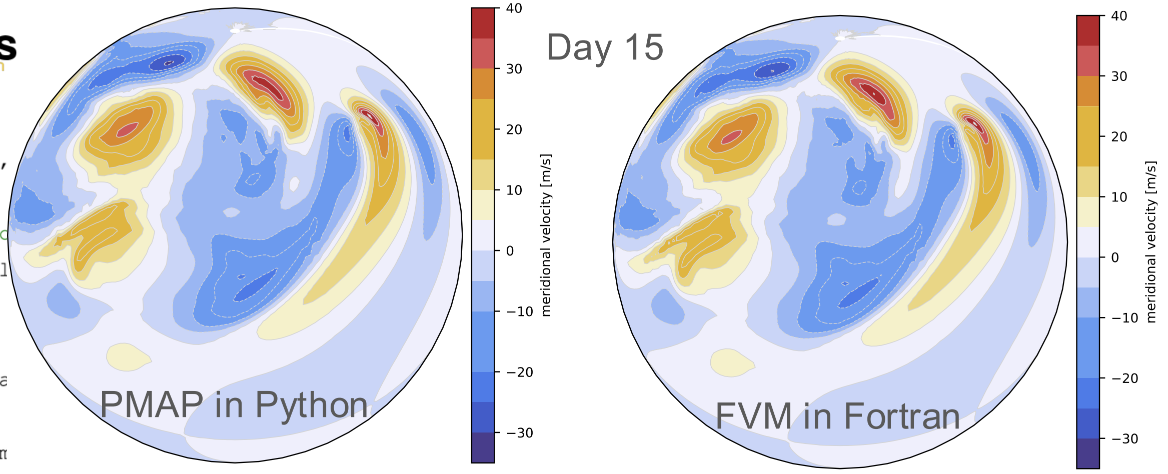
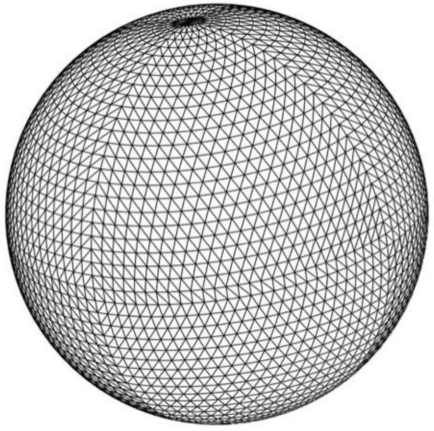
PMAP global dynamical core on the IFS octahedral grid

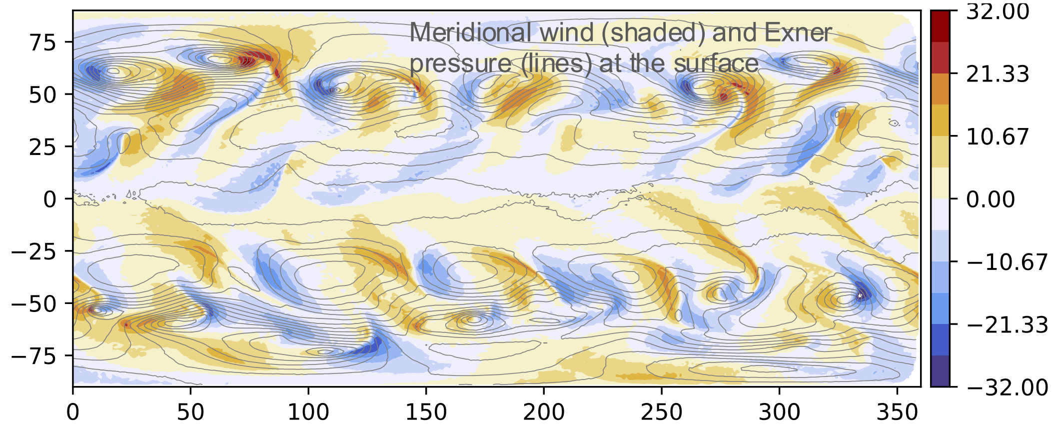
```python
@field_operator
def advection_scheme_upwind(
    rho: Field[[Vertex], float],
    dt: float,
    vel: tuple[Field[[Vertex], float], Field[[Vertex],
    vol: Field[[Vertex], float],
    dual_face_orientation: Field[[Vertex, V2EDim], flo
    dual_face_normal: tuple[Field[[Edge], float], Fiel
    dual_face_length: Field[[Edge], float]
) -> Field[[Vertex], float]:
    flux = upwind_flux(rho, vel, dual_face_normal, dua
    return rho - (dt / vol) * neighbor_sum(
        flux(V2E) * dual_face_orientation, axis=V2EDim
```

Baroclinic wave benchmark

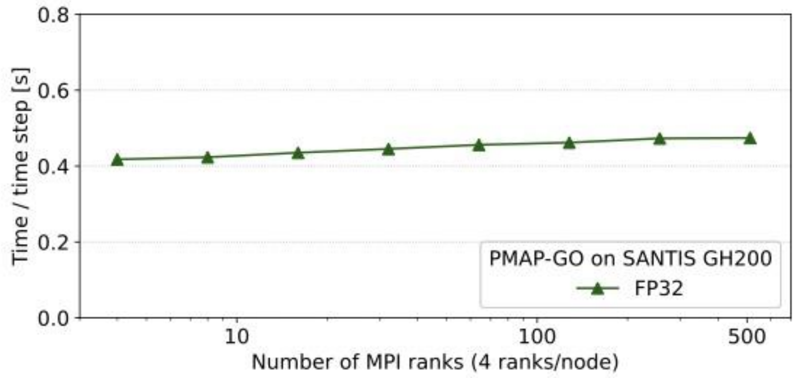




```python
from atlas4py import StructuredGrid
grid = StructuredGrid("O24")
mesh = AtlasMesh.generate(grid)
```



Held-Suarez climate benchmark with PMAP (O360/L91 in FP32 fits on a single Nvidia GH200 GPU)



Weak scaling on the CSCS Alps-Santis cluster (Grace Hopper GH200 GPUs). Computational grids: O640 (for 4 ranks) to O7240 (for 512 ranks)

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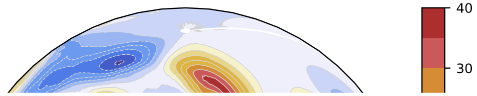
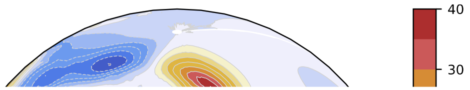
PMAP global dynamical core on the IFS octahedral grid

```
@field_operator
def advection_scheme_upwind(
    rho: Field[[Vertex], float],
    dt: float,
    vel: tuple[Field[[Vertex], float],
    vol: Field[[Vertex], float],
    dual_face_orientation: Field[[Verte
    dual_face_normal: tuple[Field[[Edge
    dual_face_length: Field[[Edge], flo
) -> Field[[Vertex], float]:
    flux = upwind_flux(rho, vel, dual_f
    return rho - (dt / vol) * neighbor_
        flux(V2E) * dual_face_orientati
```

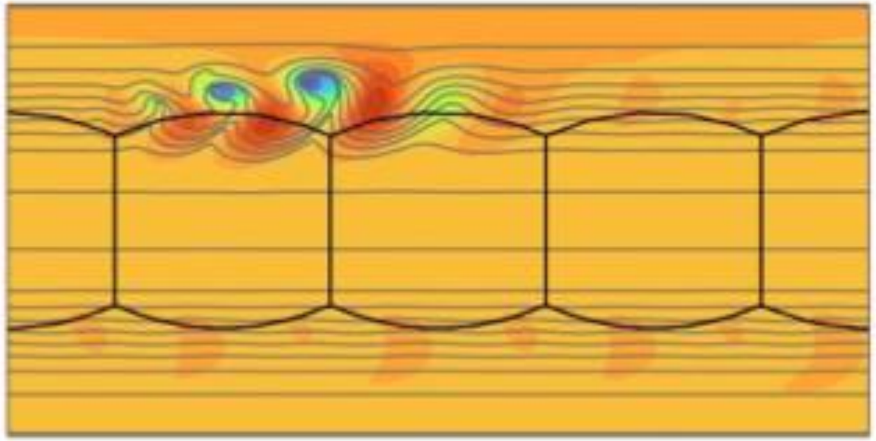
GridTools 4python

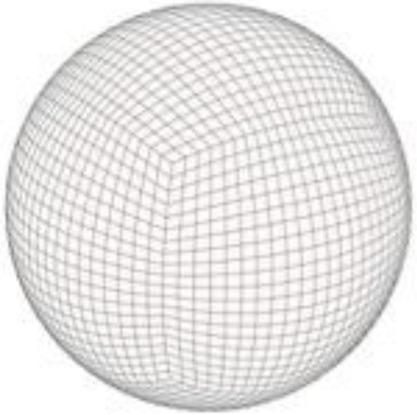
Baroclinic wave benchmark





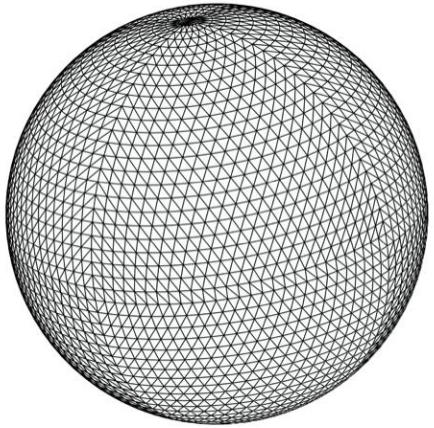
In preparation: Global PMAP on cubed-sphere





The cubed-sphere grid offers attractive properties and methods we can reuse directly from the regional PMAP

-> This is not a new model but a better grid option for local numerics!



```
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grid = StructuredGrid("O24")
mesh = AtlasMesh.generate(grid)
```
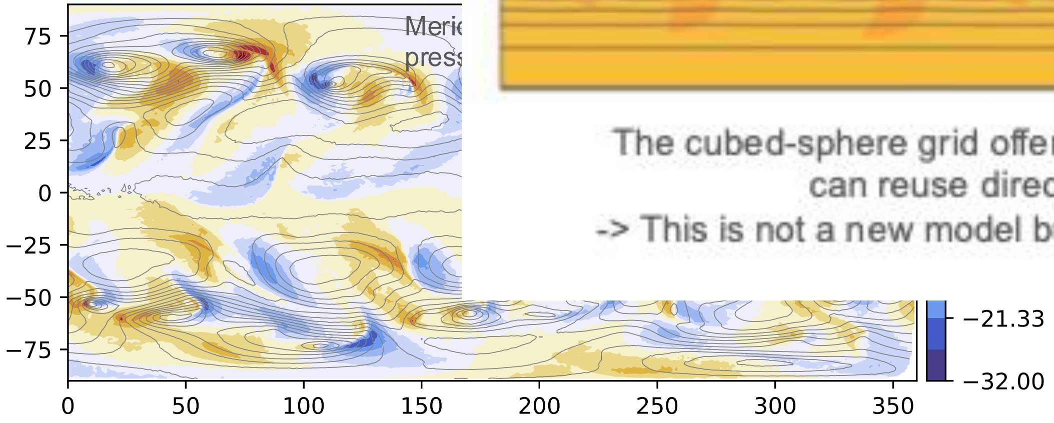
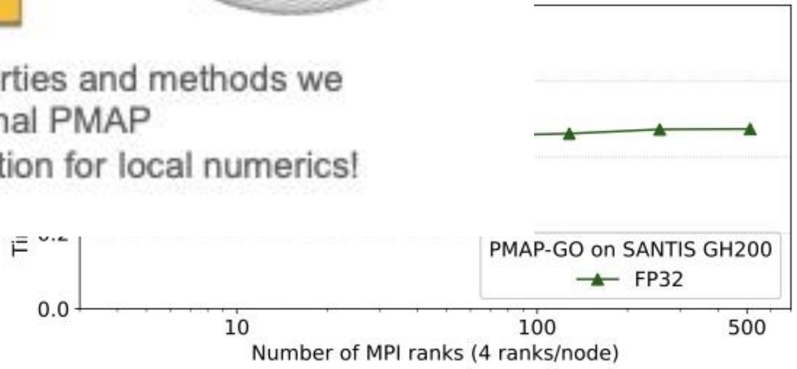



Held-Suarez climate benchmark with PMAP (O360/L91 in FP32 fits on a single Nvidia GH200 GPU)



Weak scaling on the CSCS Alps-Santis cluster (Grace Hopper GH200 GPUs). Computational grids: O640 (for 4 ranks) to O7240 (for 512 ranks)

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Final remarks and outlook

Next steps (main directions, no details):

- Complete GT4Py porting and coupling of land-surface model in 2026 focusing on ecLand (SURFEX relevant for ACCORD may be integrated on a longer time scale)

- Complete GT4Py porting and integration of (shallow) convection parametrization

- PMAP will be comprehensively tested and refined for a range of real weather applications/cases across km-scale to LES resolutions

- Automatize and optimize the initialization and boundary condition procedures (focus on ECMWF and MeteoSwiss data for the time being)

- Global PMAP on cubed-sphere/HEALPix targeted for 2027

- Work towards auto-differentiable PMAP for data assimilation and hybrid AI/ML (timeline depending on funding decisions)

Some relevant references

Binder M., A. Dörnbrack, N. Krieger, C. Kühnlein, L. Papritz, P. K. Smolarkiewicz, Linear Theories and Nonlinear Numerical Simulations Across the Orographic Gravity Wave Spectrum, to be submitted to JAS 2026.

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Krieger N., H. Wernli, M. Sprenger, C. Kühnlein, Revealing the dynamics of a local Alpine windstorm using large-eddy simulations, Weather and Climate Dynamics, 2025.

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Smolarkiewicz P. K., C. Kühnlein, N. P. Wedi, A consistent framework for discrete integrations of soundproof and compressible PDEs of atmospheric dynamics, J. Comput. Phys., 2014.

Ubbiali S., C. Kühnlein, C. Schär, L. Schlemmer, T. C. Schulthess, M. Staneker, H. Wernli, Exploring a high-level programming model for the NWP domain using ECMWF microphysics schemes, Geosci. Model. Dev., 2025.

PMAP overview paper and public code release upcoming:

Kühnlein C., T. Ehrengruber, S. Ubbiali, N. Krieger, L. Papritz, S. Faghih-Naini, G. Vollenweider, H. Wernli, et al.: Portable Model for multi-scale Atmospheric Prediction (PMAP). To be submitted to *GMD 2026.*

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The strength of a common goal