Execution of Rolling ACCORD Work Plan 2025

A Consortium for COnvection-scale modelling Research and Development

ACCORD Management Group and Support Team

1. Introduction

The scientific reporting has been prepared by the ACCORD Management Group, as a companion document to the Rolling Work Plan for 2025 available here:

http://www.accord-nwp.org/IMG/pdf/rwp2025_adopted.pdf

2. Summary of ACCORD activities in 2025 on Management

2.1. Scientific Management and organization of the MG

2.1.1. Adaptation of the working procedure for the preparation of the Detailed Action Plans.

An alignment of the DAP planning period with the main milestones of the RWP preparation was organized in 2024 (see the Scientific Reporting from last year presented at the autumn 2024 STAC). In addition, an electronic form was proposed, open to all teams, in order to collect in a wide effort the proposals for scientific visits, WW/WDs or simply mention topics of interest for DAP actions. This new calendar of DAP planning has been reconducted in 2025 (there was no particular objection noted at any level in the consortium).

2.1.2. All Staff Workshop topical sessions.

For the ASW2025, the AMG devoted specific attention and efforts on defining and organizing topic-oriented and Area-transversal sessions, beside the Area-wise scientific sessions. The aim behind this initiative was to organize more focussed and purpose-oriented discussions, also going more directly toward preparing coordinated activity in the rest of the year (WW/WDs for instance). The AMG also considered that this specific re-orientation of part of the ASW agenda would increase the interest of the staff in attending the meeting and actively participating (ideally, trigger active participation on site, or at least motivate proactive remote participation). The list of topical and transversal sessions at the ASW2025 reads:

- Documentation, a cross-cutting topic
- DA-EPS cross-cutting topics
- MQA infrastructure
- Urban forecasting and observations
- Code refactoring, code evolution including coding norms and their documentation
- Developer system environment
- NWP and Machine Learning. Where are we going ?

Another novelty in the ASW2025 was the organization of a newcomer presentation session where newly arrived staff in ACCORD teams could present themselves in-person or remotely. For in-person participants, there was then the additional possibility to approach experienced scientists on site.

Feedback collected after the ASW indicates that these adaptations in the ASW agenda have been welcomed and there will be an effort with the old and the next AMG (phase 1, phase 2) to reconduct similar sessions in 2026.

Figure 2.1.1: All Staff Workshop group photo 2025. During the walking tour in the surroundings of Zalakaros.

2.1.3. Next phase ACCORD strategy. Common scripting roadmap.

The A/A on 9 December approved forming a Task Force (TF) to work out a roadmap for the common scripting system (this topic has been recognized as very sensitive during the preparation of the scientific strategy). The TF has been active from December 2024 until mid-June 2025. STAC reviewed the roadmap proposal at its meeting on 27 June 2025.

Scripting roadmap: main goals

- The common scripting will facilitate R&D collaboration across ACCORD teams.
- It will ease local installation of complex configurations such as EPS or DA, and increase the level of meteorological quality assurance by enabling teams to use and/or compare similar workflows.
- It can be considered by the teams for local use although this will not be mandatory, neither for research nor for operations.
- The roadmap includes:

- Manpower and expertise estimates per tasks;
- A trajectory about dedicated staffing for the scripts, i/o to build a small team. The scope of competence-building of this team should go beyond the scripting code alone, including HPC environments and existing tools that can accelerate the development;
- Milestones.

Each milestone includes a list of tasks that span in time from the autumn 2025 to the first part of 2027. It would be desirable for ACCORD to be able to build a small team of but a few people who will develop and maintain these scripts. These people will become experts of the scripting codes as such (ie the functions and the code for implementing them), but they also will have to build an expertise on the existing tools and on HPC environments. The profile of this small "scripting experts team" could be seen as fairly similar to the profile of the "DAVAÏ contributors' team" which has been formed during phase 1 (ie a size of eventually about 4-5 persons, with some variety of competence around a core tool).

In order to facilitate the collaboration on various NWP configurations and workflows, and in order to make the connection to the existing scripts, it is very important that many teams are involved.

The scripting roadmap has been officially approved by the A/A at its meeting of 7 July, making it a kind of an ACCORD-official companion document to the Scientific Strategy.

2.2. Information and communication

2.2.1. Documentation and Documentation Officer.

Hereafter are the headlines of the topics addressed by the Doc Officer this year.

- Start a general inventory of existing documentation (most of the work so far in connexion with Hirlam-based documentation, however other important existing archives of documentation will be taken into account in the next months)
- The elaboration of a scientific documentation of the codes has begun:
  - organized per Area and per large code component
  - shared online editing (using the Overleaf tool)
  - long-term archiving under GITHUB (for versioning)
- A first version of the Welcome pack is ready
  - including info where to find tutorials and webinars such as for GITHUB and the ACCORD source code forge
- The appropriate way of building a "Namelist repository" with documented namelist files is being discussed. This item might require more good discussions with the teams, to be able to define a largely accepted format
- Support was provided to other Project staff for organizing information and documentation in ACCORD-related GITHUB projects
- Reminder: the Documentation Officer is Jana Sanchez (AEMET)

2.2.2. Visits to member institutes.

HungaroMet

The AMG met the Hungarian NWP team besides the ACCORD All Staff Workshop, to discuss suggested matters of interest (or concern) raised by their team. The team at

HungaroMet had prepared some material to present themselves, and they introduced the two teams in which NWP activities are mostly located (from the same department):
- the core NWP team (with AROME-based DA, EPS, operational environment) - led by Gabriella Szépszó (LTM),
- the section for verification + postprocessing + some kind of nowcasting - led by Boglarka Toth.

The general structure of the institute also was presented in order to explain how these sections were organized within HungaroMet activities. Regarding the questions to AMG:

1. The (early!) experience of the AMG regarding the user representative (UR) activity was addressed, and the AMG outlined their plans for further organizing the UR work in ACCORD in the near future. In Hungary a similar kind of exchange between forecasters and developers exists. Although it requires considerable effort from both sides, it is found very useful.

2. The plans regarding the development of the ACCORD common scripting system have been addressed. The Hungarian team pointed out that they would be interested in following the progress, since they currently also have their operational and research systems based on ***ecflow***.

3. Porting plans on GPU platforms have been shortly addressed.

4. The Hungarian team noted that hosting the ASW was an opportunity for them to be introduced to new elements of the consortium (document officer, changes in the DAP working methods etc). This more global insight was felt very beneficial for the young team members, who otherwise just saw a piece from ACCORD.

The ACCORD MG expressed its high satisfaction about the quality of the organization of the ASW in Zalakaros (outside the Capital City).

SMHI.

The AMG met representatives of the SMHI management besides the EWGLAM conference in September. The topics addressed during this meeting encompassed: how does the AMG see the main priorities for phase 2 of ACCORD, taking into account the experience and lessons learnt during phase 1; how does SMHI presently see the balance of resources in their institute between traditional NWP and AI-based (staffing, HPC).

The AMG stressed the importance of keeping momentum in the implementation of a common development environment (tools for information, communication, documentation, system aspects like scripting) besides maintaining efforts on flagship scientific achievements (SURFEX developments, data assimilation based on EnVar, VHR modelling etc.). The start of the development of an MQA-infrastructure also was pointed out, since it is felt like a potential strong trigger for an increased scientific co-development and validation in the consortium. The User Representative feedback and how the AMG intends to organize it also was discussed. Such efforts still are very new at the scale of ACCORD.

SMHI explained that currently they develop their AI R&D program mostly with additional resources, however in some near-to-mid term future they consider rebalancing resources. This would in particular hold for the HPC resources, where AI modelling would receive a larger

share of dedicated compute power on the next HPC. In terms of activity, human resource investment into nowcasting and post-processing programs would be diminished while investment into AI+OBS programs was expected to increase.

2.3. On the edges of the consortium, link with other organizations at a scientific and technical level

2.3.1. ECMWF.

Two IFS/Arpege coordination meetings have taken place in 2025 (and at the time of writing this report), the one remotely and the other in Reading (and hybrid). The ACCORD PM, the Integration Leader and the Area Leaders for System and for Code Adaptation attend these meetings. The 2025 meeting's agendas included discussions on the status of code adaptation and content and timing of the next IFS/Arpege joint cycles (CY51). Considerations about some more coordinated CI/CD approach in the creation of new code versions, spanning over the whole code community (ECMWF, MF, ACCORD), have started and remain for now at an early stage. It is however expected that the design, including prototyping, of some CI/CD methodology will take place in the coming months.

Another theme that has recently gained an increased attention is code modernization. While the code refactoring and adaptation for GPUs is continuing, with several important milestones reached, ECMWF and MF/ACCORD have been exchanging in 2025 on the need to extend the code refactoring efforts beyond the mere requirements for GPU adaptation, with an aim to reorganize much of the high level control routines of IFS/Arpege. The goal of this extended refactoring is to continue modernising the codes, enable young generations of scientists and engineers to work with it, and ease the maintenance of the IFS/Arpege/LAM (IAL) codes for the next decade or so. This theme falls under the ECMWF “IFS software strategy” and will be presented to ECMWF Member States this autumn (SAC and Council).

In the next months and years, ACCORD should aim at being proactive on these code-related topics by leveraging on the knowledge and the staffing achieved during phase 1 for GPU adaptation, as well as for the modernization of the working practices. The benefits for the ACCORD members are manifold: enable young scientists to work with the codes, keep up momentum in the preparation of the codes for Exascale computing, and ease code maintenance within our collaborative development framework. To keep up expertise and staffing on the physics-based NWP codes, their programming paradigms and the needs for efficient porting to HPC, should therefore remain a clearly recognized and prioritized goal in the consortium.

2.3.2. Destination Earth.

At technical level, a version of the DEODE scripts has been uploaded as a new GIT project within the ACCORD source code forge, making them visible to the teams in the consortium.

At management level, as in the previous years, LTMs are invited to flag during registration their DEODE-funded manpower working on topics which fall in the scope of ACCORD R&D activities. The main areas where DEODE resources enter the scope of ACCORD work are Code Refactoring and Adaptation (see the section CRA), the evaluation of hectometric-scale

model configurations (for the three CSCs), EPS and probabilistic measures of skill and model validation.

At the level of code policy, the discussion between MF and ECMWF about assigning back subsisting IPRs in the DE-funded improvements to the ACCORD codes has continued in 2025. Assigning back these IPRs is considered important to ensure the full integrity of the ACCORD codes. It is also a formal, legal-type request which is foreseen in the DE Agreements. The current expectation is that the official request would be handed over to ECMWF before the end of phase 2 of DEODE. ECMWF would then have to discuss the request with the EU Commission.

2.3.3. Cooperation with LEGMC (Latvia).

The status of the 2025 activity and collaboration between LEGMC and ACCORD has been discussed during September 2025. The headlines of the NWP-oriented activity at LEGMC are listed below (they mostly encompass MQA, DA and Surface-related topics).

Status of work in 2025:

- Remote and on-site participation in the ACCORD All Staff Workshop (1 on-site and 6 remote participants).
- Presentation "Integrating harp verification into Python based visualization tools" (https://www.accord-nwp.org/IMG/pdf/1_gatis_prieditis_accord_asw.pdf) at the ACCORD All Staff Workshop with successful tests on integrating various 'harp' datasets and modular design of the visualisation front-end interface.
- Gained introductory knowledge on the DA-related verification from preparing visualisation front-end interface for 'obsmon' specific results.
- Development of a visualization front-end interface for 'harp' and 'obsmon' in Python code, within the collaboration in DEODE and with the 'harp' lead developers..
- Coordination with the MetCoop group regarding the surface descriptions in the SURFEX databases and SYNOP data flow due to the introduction of SAPP. Check whether the descriptions for Latvia are up-to-date (work in progress).

It is noted that the LEGMC staff has a good expertise on Python programming and very little with R-programming. This technical background will shape the collaboration and a focus will be on Python-based tools.

Planned tasks in 2026:

- Further development of the visualization front-end for 'harp' and 'obsmon' results; coordination with Met.no and AEMET within the collaboration in DEODE to expand the set of results that are included.
- Pending on staffing, further increase the involvement of LEGMC in DA in the MetCoop context and consider to gain knowledge on DA diagnostic tools. ACCORD could facilitate the transfer of knowledge of specific diagnostic tools toward LEGMC.
- Participation in ACCORD workshops and working weeks, usually remotely. If resources are available, an in-person participation to the All Staff Workshop and/or to a thematic WW will be considered.
- RWP2026: MQA1.3 and MQA2.4 for potential contributions.

An outcome of the ACCORD/LEGMC collaboration discussions this year is the high interest of ACCORD teams to have a wider sharing of the customizable visualisation code developed

at LEGMC. A discussion inside ACCORD about the conditions under which this code could be widely shared and co-developed in the framework of the cooperation with LEGMC should be organized in 2026.

3. Activity report per Area

3.1. Code Refactoring and Adaptation (CRA)

3.1.1. overview of the activity in the area

In the first half of 2025, 32 person-months have been registered in the CRA work package, which is slightly below half of the committed amount for 2025 (83.5 person months).

CRA1/CRA2: GPU porting

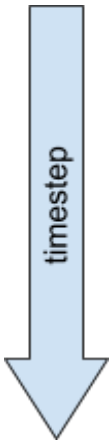
Before porting the ACCORD model to GPUs, a refactoring is necessary to increase the flexibility of the code and to make it suitable for the application of source-to-source translation scripts. In 2025, this refactoring effort was continued, addressing the semi-implicit spectral computations, the treatment of the lateral boundary conditions, the AROME and HARMONIE-AROME physics parameterizations, and the IO interface. The refactoring of these parts was consolidated by introducing it in CY50T1.

A key part of the refactoring consists of wrapping the meteorological fields with FieldAPI structures. FieldAPI is a library that provides smart hardware-aware data structures. This library was developed further in 2025, both in terms of functionality and performance.

The limited-area spectral transforms were already ported to NVIDIA GPUs before. In 2025, an effort was made to integrate these LAM spectral transforms along with the global spectral transforms in the main ectrans repository, in order to improve the maintainability. The development of a FieldAPI-based interface, which will streamline the integration of the GPU-ported spectral transforms in the rest of the model, has also started.

The porting of the dynamical core and the physics parameterizations happens with source-to-source translation scripts where possible. In 2025, these scripts were adapted and applied for the porting of the lateral boundary conditions and the semi-implicit spectral computations.

The following table gives an overview of the current status of the refactoring and GPU-porting of various parts of the ACCORD model. The highlighted cells indicate progress with respect to 2024.



	Refactoring	Porting to NVIDIA	Porting to AMD
IO	Started	Not yet started	Not yet started
Inverse spectral transforms	(not necessary)	Done	Done
Diagnostic computations	Not yet started	Not yet started	Not yet started
Gridpoint dynamics	Done	Done	To be tested
Semi-Lagrangian	Done	Done	To be tested
Physics	Done for ALARO, AROME and HARMONIE-AROME	Done for ALARO	Partially tested for ALARO
Lateral boundary conditions	Done	Done	To be tested
Direct spectral transforms	(not necessary)	Done	Done
Helmholz solver	Done	Done	To be tested

Table 3.1.1: Status of GPU porting of components of the ACCORD model. Highlighted cells were addressed in 2025.

CRA3: DSL exploration

As an alternative to porting the existing code through refactoring and application of source-to-source translation scripts, the application of a domain-specific language (DSL) can be considered. Concretely, the gt4py (GridTools for python) DSL provides the functionality to develop stencil-based algorithms in python, after which the gt4py toolchain converts this code into a hardware-specific backend. In 2025, the ICE3 microphysics parameterization was converted to a gt4py-based implementation. This exercise proves the feasibility of such a conversion, as well as some of the benefits brought by the DSL-based approach in terms of portability and performance.

CRA5: testing and integration

With the amount of GPU-ported parts of the ACCORD model increasing, building and testing on various platforms becomes more and more important. In 2025, the development of a CMake-based compilation system for the ACCORD model (see also COM2.1, section 3.9.2) provided an opportunity to improve the portability also of GPU-ported parts. Also the integration of source-to-source translation scripts into the CMake-based compilation system is being explored.

3.1.2. highlights from 2025

A highlight in 2025 regarding the refactoring and adaptation of the ACCORD model to accelerators, is the milestone of having an ALARO timestep running fully on GPUs. The figure below shows the profile of one ALARO timestep running on NVIDIA GPUs on the Leonardo HPC.

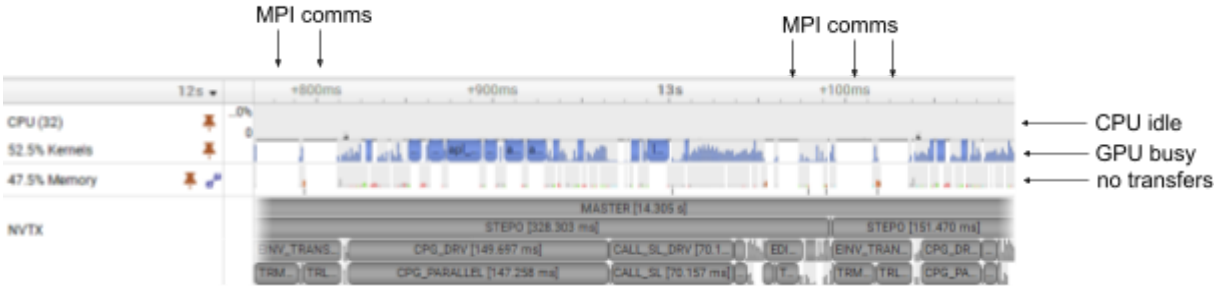


Figure 3.1.1: Profile of an ALARO timestep running entirely on NVIDIA GPUs.

This figure shows that (a) the CPU is idle during the timestep, meaning no computations remain on the CPU; (b) the GPU device is busy during most of the timestep, except during the MPI communications of the spectral transforms, and (c) no substantial data transfers are done between the CPU and the GPU device. This last point is especially important, as such CPU-GPU transfers are known to be a common bottleneck when porting scientific codes to GPU. With all of the computations during the ALARO timestep now happening on the GPU device, these transfers could be eliminated.

3.1.3. perspectives and priorities for 2026

Following developments are considered to be the priorities for next year:

- Now the refactoring of the AROME and HARMONIE-AROME physics parameterizations is finished, the actual GPU-porting of these can be addressed. This work will already start in 2025. This will make it possible to run the 3 ACCORD CSCs on GPU.
- The refactoring (and possibly, porting) of diagnostic parts of the ACCORD model, such as post-processing (FullPos) or vertical profile extraction (DDH).
- Further integration of GPU-porting into the common build and testing platforms.

A concern regarding the Code Refactoring and Adaptation work package is that the involved workforce is distributed very sparsely along the consortium members. In fact, only 3 member states were involved in this work package in 2025. An effort should be made to involve people from more member states in this work.

3.2. Towards modelling at (sub-)km resolution (HR)

3.2.1. Overview of the activity in the area

Some of the activity targeting VHR modelling is supported by external projects which are listed in the Annexe.

3.2.2. highlights from 2025

The ACCORD R&D activity on VHR modelling is now transferred to the topical sections (dynamics, physics, surface, DA, EPS and MQA). In this specific subsection, the focus only is on a few aspects of VHR modelling and local aspects of forecasting, as reported and communicated inside ACCORD. At this year's All Staff Workshop, several talks explicitly dealt with very high resolution configurations and use cases:

- Validation of 500 m AROME runs in the Framework of DEODE (Geosphere)
- Overview presentation on how TEB is used in our operational systems (FMI)
- The UrbanAir project (KNMI)

Besides those, a number of other contributions addressed studies that could be considered as largely overlapping from km-to-hm scale modelling (very high resolution satellite data, turbulence, radiation, microphysics, new options in the dynamics etc.).

The ACCORD teams regularly provide Newsletter contributions containing references to VHR or hectometric model configurations, as well as to local aspects of forecasting. For instance, in NL7 published 28 July 2025:
(https://www.accord-nwp.org/IMG/pdf/accord_nl7.pdf)

- Evaluation of the use of LCZ from ECO-SG in AROME and its impact on urban simulation over Algiers (ONM-Algeria)
- Implementation of AROME/HU cy46t1 model version with modified town fraction (HungaroMet)
- Improving maximum wind speed forecast from AROME_Tunisia Model Using Machine Learning (INM-Tunisia)

3.2.3. perspectives and priorities for 2026

The aim is that VHR R&D and exchange of information on specific VHR configurations will more and more be dealt with inside the thematic Areas of ACCORD.

3.3. Dynamics (DY1 to DY3)

3.3.1. overview of the activity in the area

The ACCORD consortium has the long term goal of improving the existing dynamics kernel, developing the new FVM model (Finite Volume Module), and converting spectral computations into gridpoint form.
New dynamics options have been implemented and tested to enhance model stability. Previously implemented options have also been ported to recent software cycles, which required additional effort due to code refactoring for GPU compatibility.

Because of limited manpower, progress has been slower on certain topics—particularly the gridpoint kernel. Nevertheless, we have continued our research and development within the traditional spectral model to maintain our 500 m resolution configurations. Over the next few

years, we do not anticipate exploring operational resolutions beyond 500 m, except in specific applications such as urban meteorology. In these cases, where the terrain is generally quite flat, stability can be achieved without the need for overly aggressive stabilization options.

3.3.2. highlights from 2024

Dynamics tasks are distributed among the improvement of the current dynamics kernel (DY1), the work related to the new FVM model (DY2), and the porting of spectral computations to gridpoint (DY3).
Below are the most notable activities for this year.

DY1.1 Testing of New Dynamics Options in Recent Cycles

New dynamics options were implemented in the DEODE_330 workflow in CY48T3 and CY49T2:

- Elimination of the linear system up to horizontal divergence (LSI_NHEE=T)
- New vertical divergence variable (NVDVAR=5)
- Consistent moisture inclusion in the definition of vertical motion (L_RDRY_VD=T, L_RDRY_NHX=T)
- Improved bottom boundary condition for the vertical velocity variable (LBIGW=T)
- Diagnostic treatment of the orographic part of the vertical divergence variable (the *X-term*)
- Suppression of the transformation of the X-term to model spectra and back (LSPNHX=F)

These new options were tested and ported to new cycles. No degradation in scores or stability issues has been observed.

The conversion between the vertical wind speed in the non-linear computation and the vertical divergence in the linear part involves the so-called X-term. The X-term is a model variable saved across timesteps. A new method was introduced to remove this model variable and recompute the X-term at each timestep. This code modification was originally proposed for CY46T1 and has since been phased into CY48T3, CY49T2, CY50T1, and the corresponding DEODE_330 code.

DY1.6 Coupling Procedure

Several promising tests have been conducted with increased coupling frequency. Regarding file compression, we observed that standard compression tools can significantly reduce the size of LBC files, especially when these contain mostly constant values. However, this compression step is currently performed externally, as we lack the manpower to implement it directly within the code.

One limitation is that compression must be applied separately to each domain, which adds complexity given the large number of domains involved. Nevertheless, this remains an open topic with strong potential for improvement.

DY1.7 Numerical Methods on the Kilometric and Hectometric Scale

In this task, we aim to study the limitations of the spectral approach and, possibly, of the semi-Lagrangian scheme. Experiments conducted in urban conditions (i.e., with relatively flat terrain) at 200 m or 100 m resolution with dt = 3 s have shown good stability.

A current configuration including the Himalayan range is used to test how the dynamics behaves over high plateaus and steep slopes. The presence of a significant portion of the domain at very high altitudes restricts the stability range and requires the use of vertical levels based more on the sigma coordinate.
Domains covering parts of Greenland with steep slopes appear to be much less challenging.

DY1.8 The Semi-Lagrangian Scheme

The semi-Lagrangian advection scheme used in the ACCORD model, combined with its implicit time-stepping scheme, allows for long timesteps and therefore a highly computationally efficient system. The main drawback of semi-Lagrangian advection is its lack of conservativity, although several mitigation strategies have been implemented.

Work is ongoing to evolve the COMAD scheme, with the goal of improving surface conservation. An improved new 1D linear version of COMAD (both horizontal and vertical) has been developed and tested on idealized cases (bubbles) in mountainous and lowland areas in ARPEGE, showing visible improvements.

We also plan to test the impact of conserving dry air mass rather than total mass (as is currently the case). One possible solution is to use the dm=1 option[1], which is currently being updated. Another option is to rewrite the conservation equation explicitly for dry air mass.

- The following developments are currently being implemented in the IFS/Arpege/LAM common software:
  Saving the origin point from the previous timestep, as well as from the previous iteration (LELAM=T).
- Preconditioning via the Jacobian of the flow at the origin point (in both global and LAM contexts), aimed at accelerating the convergence of the search algorithm - particularly for high Lipschitz numbers, where the usual algorithm tends to diverge.

DY2 : FVM-like Solution as an Alternative to the SISL Dynamical Core

The European Centre for Medium-Range Weather Forecasts (ECMWF) is currently developing a new dynamical core called the Finite-Volume Module (FVM). This project aims to eventually replace the current IFS dynamical core to improve the performance and resolution of global forecasts.

We are contributing to this effort by helping to develop the limited-area version of FVM. Our main goal this year was to continue the porting of AROME physics using FVM's DSL GT4Py. The DACE backend is used for parts of the code where GT4Py has limitations. Approximately 70% of the code has been rewritten using GT4Py.

[1] the dm=1 option precisely aims at ensuring the consistency of dry air mass conservation in the codes

The ice_adjust routine has been completely rewritten, but algorithmic issues remain unresolved in routines such as rains_ice. Reproducibility tests have also been performed. At present, the use of LOKI to port SURFEX is not feasible.

3.3.3. perspectives and priorities for 2026

Very high resolution settings: The work will continue, in the context of the DE_330 project and with the objective of many Meteorological Services to explore the possibility of using the hectometric range for their operational model forecasts. This year research and development at 500m resolution showed that more improvements still need to be done at that resolution to clearly have benefits compared to kilometric models before exploring even higher resolution.

Time scheme on demand and recent model features:

Numerous recent model options require comprehensive testing, with a particular focus on assessing their stability. Over complex terrain, such as alpine domains, these options should allow simulations to achieve finer resolutions under otherwise identical conditions.

Future Dynamical Core:

The most recent version of the FVM core must be tested on the provided forecast domain (The Faroe Islands) and the required timestep and forecast accuracy must be assessed. Other test domains should be set up.

Semi-Lagrangian Scheme:

Many new options like improving the conservation of the scheme with cubic interpolations and quasi monotonous options are available and will be tested in real situations.

Regarding resources, ACCORD would need more manpower in the area of Dynamics in order to test some of the options developed over the past few years (e.g. VFE) as well as for strengthening the testing of the FVM model. A key question is to see to what extent FVM could meet our very high resolution needs.

3.4. Data Assimilation (DA1 to DA9)

3.4.1. Overview of the activity in the area

During the first two quarters of 2025, a total of 224 person-months (around 50 different contributors) was dedicated to data assimilation (DA) work. Research and development activities continued in nine research and development (RD) Teams, each corresponding to a DA working package in the Rolling Work Plan (RWP). These teams held periodical meetings, complemented by three DA Working weeks, which proved valuable in fostering collaboration and knowledge exchange within the consortium. Participation in DAWWs remained strong across a majority of ACCORD institutes. Members maintained a common reporting practice using a shared working document. In addition, while bi-monthly meetings with the DAsKIT group provided a platform for monitoring and supporting their implementation progress.

Following the operational implementation of 3DEnVar in OOPS at Météo-France in 2024, algorithmic development efforts focused on expanding its capacity: enlarging the control vector to include additional variables (e.g. enabling direct feedback from radar reflectivity to

hydrometeor fields), introducing scale-dependent localization and extending the temporal dimension towards 4DEnVar. These developments were with consortium members, triggering aligned work in several ACCORD institutes, with the first 3DEnVar configurations now running daily. Progress was also reported on porting HIRLAM's limited-area 4DVar system into the OOPS environment, in line with the long-term objective of running all DA algorithms within OOPS. Efforts to modernize baseline algorithms took place at MET Norway on the revised calibration and application of static B-matrices.

Significant progress was also made on the use of observations. Several observation types benefit directly from hydrometeor feedback (e.g. radar reflectivity, cloudy and precipitation-affected microwave radiances, lightning data). Work continued towards more unified assimilation of radiances under all-sky and all-surface conditions, including improved reflection models over ice and snow and dynamic emissivity treatments. Better representation of observation error statistics and their covariances was also investigated, with benefits for current instruments, those under testing (e.g. AWS, FCI), and those becoming available in the near future (e.g. IRS). A special thinning algorithm (adaptive weighting) was developed to more efficiently handle dense Mode-S observations. Assimilation of STD and ZTD gradients (with a newly developed operator) was evaluated. Migration from Bator to Obsconvert for more efficient BUFR handling has emerged as a consortium-wide action, and the validation of various national datasets was addressed during two DAWWs.

In parallel to that, significant efforts were devoted to the use of new observations. Numerous observation types were shown to directly benefit from feedback to hydrometeor fields (radar, cloudy and precipitation microwave radiances, lightning data). Actions towards more unified assimilation of radiance data in all-sky (microwave and infrared) and all-surface conditions (e.g. different reflection models over ice and snow, dynamic emissivity), improved representation of observation error and its covariances can improve the currently used sensors, those in the testing phase (e.g. AWS, FCI) and future instruments (e.g. IRS). A thinning algorithm has been developed to better handle large amounts of observations coming through Mode-S. Several studies evaluated STD and ZTD gradients (new operator developed) in comparison with widely used ZTD. For the preprocessing the need to migrate to Obsconvert instead of Bator for better handling of BUFR data is seen as a common consortium action and has been a subject of working weeks.

Finally, work continued on establishing shared software infrastructure, notably a repository of commonly used preprocessing tools (AccordPreprocTools), complementing the existing suite of diagnostic utilities (AccordDATools).

3.4.2. Highlights from 2025

Highlights from 2025

- ➢ Implementation of 4DEnVar with improved localization in OOPS: Building on the operational introduction of 3DEnVar at Météo-France in 2024, the recent e-suite (Brousseau, Vogt, Martet, Arbogast, Berre et al.) extended the system to 4DEnVar, enabling assimilation cycles with 15-minute frequency. This increases the data amounts and impact of radar, ground-based GNSS zenith total delays, SEVIRI radiances and surface stations. The EnVar algorithm relies on localization to suppress sampling noise in ensemble covariances; the introduction of scale-dependent localization in three spectral bands reduces sensitivity to the choice of (vertically varying) localization length scale. Together with improved use of observations (e.g. direct assimilation of reflectivity,

Mode-S data, AMVs), these changes resulted in systematic performance improvements, as demonstrated in both forecast scores and case studies.

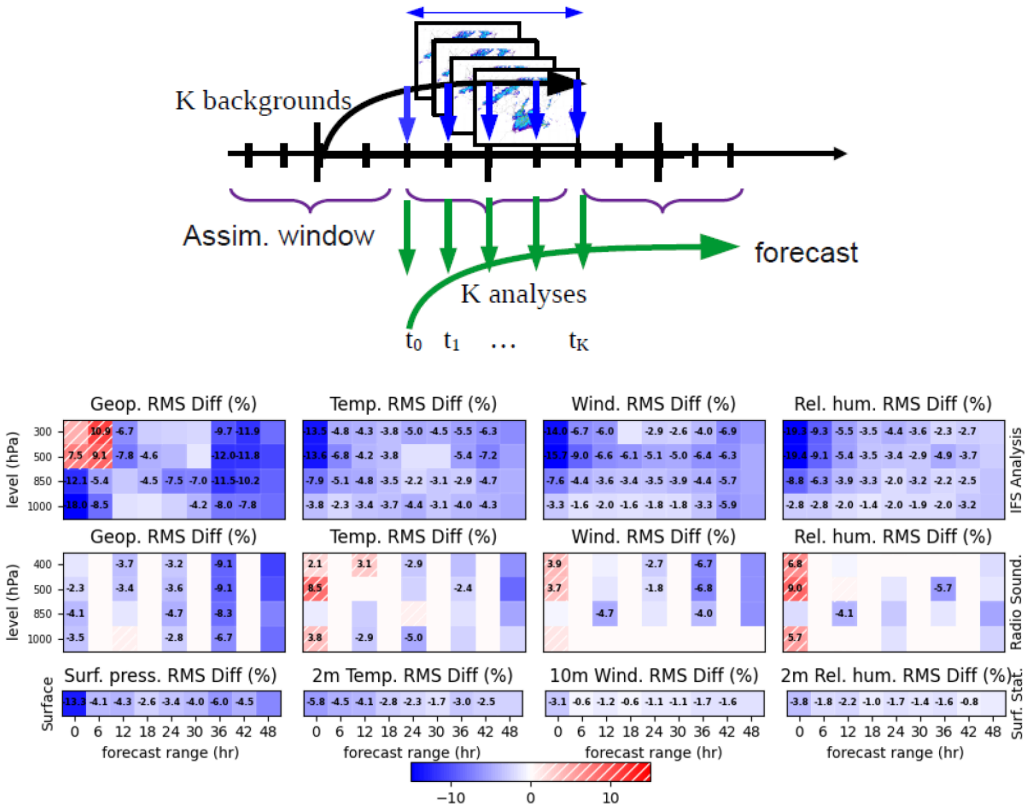


Figure 3.4.1: Top: schematic illustration of 4DEnVar. Bottom: relative RMSE differences between the e-suite and operational suite against different references (IFS analysis, radiosonde and surface station measurements) across parameters and forecast ranges. Blue boxes indicate a better performance of e-suite with respect to operational suite, numeric values are shown where they are statistically significant.

➢ Enhancing radar data assimilation: Most notably, the EnVar algorithm allows for inclusion of hydrometeors into the control vector for minimization and allows for directly assimilating radar reflectivity observations. Direct and tangent-linear/adjoint versions of the observation operator have been developed, tested, and documented (M. Martet) and are now part of the Météo-France e-suite. In parallel, several ACCORD members, in close collaboration with OPERA, contributed to the consolidation of centralized 3D radar data processing (NIMBUS) to serve consortium needs. Work in this area also included optimizing preprocessing methods for radial wind assimilation and improving estimation of radar sensitivity parameters, leading to new operational implementations.

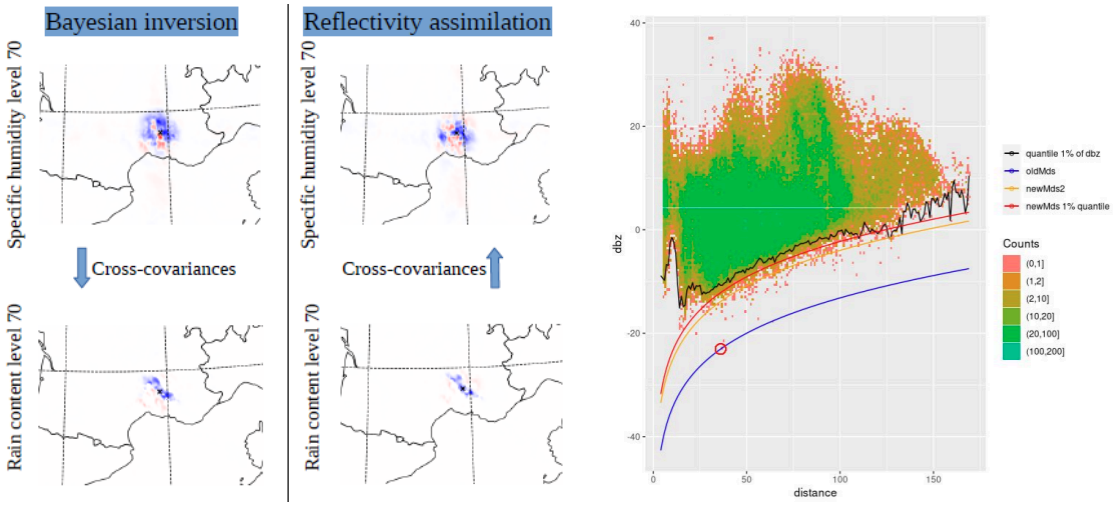


Figure 3.4.2: (left) Demonstration of coherence between increments in rain and specific humidity with Bayesian inversion (humidity assimilated) and direct reflectivity assimilation (M. Martet, MF). Feedback is enabled through cross-covariances in EnVar. (right) Refinement of a method to detect minimum detection threshold in the implementation of Bayesian inversion at the Czech Hydrometeorological Institute.

Perspectives and Priorities for 2026

- Consolidation and further testing of 3DEnVar/4DEnVar in OOPS, including scale-dependent localization, with test and operational configurations across members (DA5/DA6),
- Finalization of the migration of LAM 4D-Var into OOPS, ensuring consistency across DA systems (DA5),
- Advancements in radar data assimilation: operationalization of direct reflectivity assimilation in EnVar systems, optimization of preprocessing with NIMBUS, and improved quality control of radial winds (DA2),
- Enhanced exploitation of satellite data: use of MTG instruments (IRS, FCI), extended all-sky radiance assimilation (microwave/infrared), and improved bias correction and error modelling (DA3),
- Exploration of AI/ML applications in DA (QC, emulators, observation operators), with links to European initiatives (DA9),
- Implementation of the common scripting system for DA R&D inline with the scripting Roadmap (also with a focus on supporting DAsKIT members).

3.5. Physics parameterizations (PH1 to PH8)

3.5.1. Overview of the activity in the area

The majority of the activities in ACCORD Physics working groups in late 2024 and so far in 2025 were focusing on the technical and scientific adaptation of the models for simulation over a variety of scales and meteorological conditions, with the objective to improve the impact weather forecast. Therefore the development and validation of scale-aware physics parameterization schemes were dominant activities. This work included: the development and validation of the 3D-turbulence parameterizations (PH1 and PH8), scale- and organization-aware convection (PH1), and integration and testing the ecRAD-radiation

scheme (PH2) in combination with the use of CAMS climatology (PH6). A substantial work during 2025 was put on the surface-atmosphere coupling (PH7), and the further development and testing of double-moment microphysics schemes (PH3) in ACCORS NWPs. The work on the preparation of a common single column model (MUSC) idealised tests in DAVAI is an ongoing activity with a clear objective for conclusion by the end of 2025. A brief summary for each of these activities is highlighted in what follows.

3.5.2. Highlights for 2025

Subgrid-scale mixing

- ***Towards 3D-turbulent mixing.*** In the previous report I have stated that this group has defined a clear strategy to account for the behavior of our turbulence and shallow convection schemes and their interaction with the dynamics solvers and the horizontal diffusion in very high resolution NWP systems. These, among other objectives, include a combination of observational campaigns and model setups with a common domain, outputs, and formats for validation. As part of the UrbanAIR project we have now possibility not only to further explore the applicability of the recently developed pseudo-3d turbulence scheme (Rogel et al. 2024, ACCORD 6th Newsletter) in AROME, but also validate and further improve its capability by validating over specifically designed observational datasets and LES. Moreover, the development of the new TKE-based turbulent length scale in TOUCANS turbulence scheme, as well as the latest improvements in the physics-dynamics and atmosphere-surface interfaces in ALARO across-the scales are already providing positive results in various weather conditions (Fig. 3.5.1, more details on this page). The existence of these two approaches within the DE_330 framework opens a path for increased transversal collaboration and knowledge exchange across the consortium to further improve the schemes and thus enhance the confidence in the impact-oriented weather forecasting.

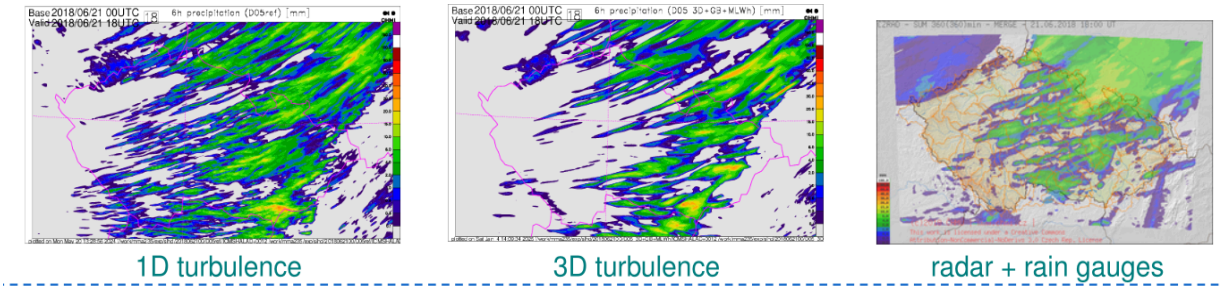


Figure 3.5.1: The impact of 3D turbulence in ALARO at Δx = 0.5 km (by Mario Hrastinski and Petra Smoliková)

- ***Scale-and organization aware shallow convection.*** The testing and the validation of the latest modifications in the shallow-convection dual mass-flux scheme in HARMONIE-AROME have shown great potential not only to appropriately adjust the non-local convective mixing in increased grid resolution setups, but also to improve the small-scale showers in shallow-to-deep organized convection (e.g. open-cell convection and the consequent precipitation) on coarser resolution (e.g. 2.5 km). The latter was a long-standing problem in HARMONIE-AROME based on the history of forecaster feedback (see user feedback for a reference). The main modifications include: scale-aware decrease of dry and moist mass-flux contribution to TKE, using

the resolved vertical velocity (w) as indication of organisation, but also the subgrid evaporation and melting.

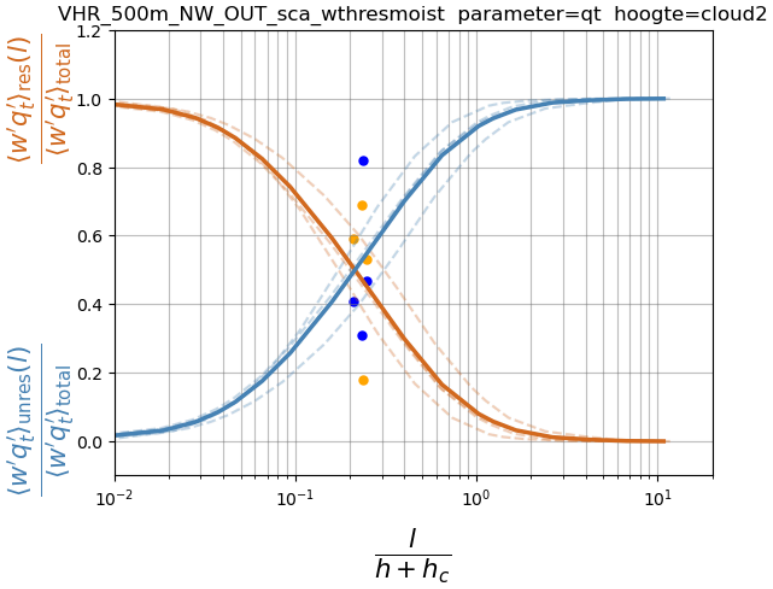


Fig. 3.5.2: Quantitative analysis: Compare the partitioning of total turbulent moisture transport in LES (coarse-grained) and Harmonie-Arome (dots) in Honnert plot (by Wim de Rooy).

Interaction of radiation with aerosols and clouds

A substantial work has been done across the consortium in interfacing the radiation schemes of (the old IFS radiation scheme, ecRAD, and ACRANEB2) with CAMS aerosols (instead of TEGEN). Most of the work on the aerosol climatology entered CY50T1 (committed PR) and is available for further testing and usage. Thus the reading of the CAMS aerosol fields (climatological and near-real-time (NRT)) has been introduced in a user-optional way; the user can decide to use 2D CAMS climatological aerosols (maximum number of species 11), 3D near-real-time aerosols CAMS aerosols (maximum number of species 42), or combination of 2D CAMS climatological aerosols and 3D NRT-CAMS aerosols (maximum number of species 42) (see technical documentation).

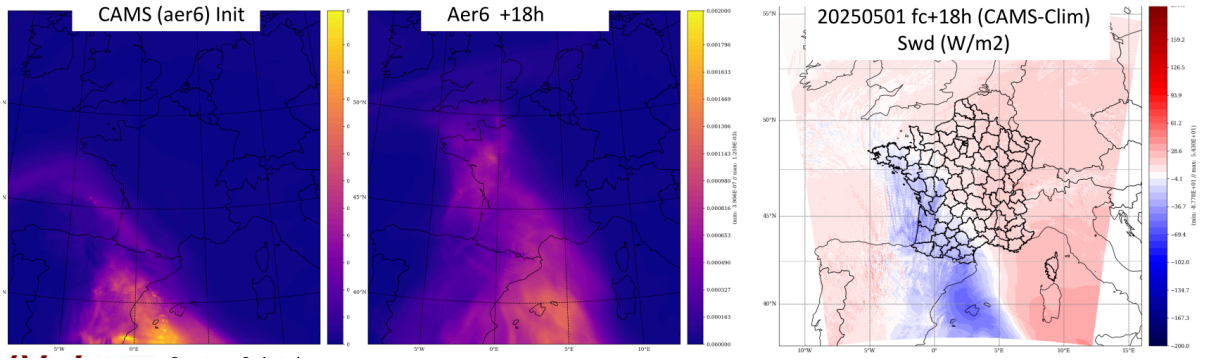


Fig. 3.5.3: NRT-CAMS in EcRad in AROME (also in ARPEGE) (by Salomé Antoine).

Moreover, the conversion of CAMS MMRs to aerosol optical properties, the vertical distribution (gamma) of 2D CAMS climatological aerosols and the externalization of the

effective radius from the ACRANEB2 scheme have also been provided. In similar context, the evaluation of AROME daily runs with NRT-CAMS and ecRAD is an ongoing activity (e.g Fig. 3.5.3).

On the surface-atmosphere coupling

A tremendous amount of work was put into fully coupling the ALARO atmospheric model to SURFEX. A working week with training was organized. This work is done for the CY49T2, but many developments have to be backphased to the CY48T3 or even CY46T1 before they can be implemented operationally.

A work has been done to evaluate the building height effect "explicitly" in AROME, which allows more physical comparison with the multi-layer coupling (available soon in the cy49T2_Deode) with a focus on TKE and wind field over Antwerp, Barcelona and Paris (as part of the UrbanAIR project).

By adding increased physical details in the classical similarity coupling scheme over a vegetated surface, the roughness-sublayer parameterization improves the surface-atmosphere coupling in HARMONIE-AROME (nocturnal sensible flux, near surface wind and temperature overall, as well as introduces dynamical vegetation roughness (roughness length and displacement height). The study reveals a few important questions about the differences between the offline and online coupling due to counter-gradient flow (we can ignore this process but it seems relevant), and the effects of inaccurate physiography data (e.g. vegetation height and LAI). ACCORD has presented this work on the ECMWF's 50th anniversary celebrations - workshop on surface process coupling and its interactions with the atmosphere. The summary of the workshop has been submitted within the BAMS "Meeting Summaries" and will be available after acceptance.

3.5.3. perspectives and priorities for 2026

- ➢ Convection and Turbulence in hectometric simulations (PH1, PH7, PH8):
  - Pseudo 3D (Horizontal Shear Production), impact of the slope on the surface fluxes; implementation of the pseudo-3D turbulence code in HARMONIE
- ➢ Radiation:
  - ecRAD in HARMONIE
  - Towards 3D radiative effects in hectometric simulations
- ➢ Microphysics:
  - Daily run with LIMA with several options for preliminary evaluation with maps on website and not only with "classical skill-score"
  - Development of ice phase in ALARO double-moment microphysics scheme; several open questions: (i) separation between the cloud ice and snow, (ii) the shape of snow particles, (iii) size distributions, (iv) phase split (MPACE tests with CAMS aerosols vs. f (T))
- ➢ CAR (PH6):
  - evaluation of NRT-CAMS (options) in ICE3 (AROME), ICE-T (HARMONIE) and ALARO double-moment microphysics scheme with ecRAD and ACRANEB2
- ➢ Surface-atmosphere interaction (PH7):
  - ECO-SG with diffusion scheme (14 layers), ES+MEB , 2 or 3 patches (ACCORD/DE_330)

➢ process-oriented validation framework is under development in collaboration with other groups within ACCORD (MQA, SFX, PH, SYS)

3.6. Surface analysis and modelling (SU1 to SU6)

3.6.1. Overview of the activity

We have continued with the agreement among surface leaders to arrange one surface working week per semester at ACCORD level, the spring one in-person and the autumn one online only. Last November the online version gathered some 20 participants attending six different sessions (link to wiki). This year, in May, the in-person one was hosted by Samuel Viana at AEMET, Madrid, where 10 people participated at site and some 10 by remote connection (link to wiki). Also, we had a visit by representatives from Complutense University of Madrid (UCM) and CIEMAT where they described their work with the Multiurban project. The next online working week will happen November 24-28 2024 and the next in-person working week will be hosted by CHMI, Prague, in May 2026.

In addition to the ACCORD overall working weeks a specialised WW was arranged on multi-layer surface physics hosted by Jan de Pue at RMI in Brussels last December (link to wiki). Also, our ALARO community arranged a dedicated ALARO-SURFEX coupling working week hosted by CHMI, Prague, last June (link to wiki) which gathered 14 participants. And the online monthly meetings have continued during the year (link to wiki).

With respect to the SURFEX code and its development, the efforts to bring our NWP developments into SURFEXv9 has continued during the last year. It has now reached a stage where all contributions are finalised and the ongoing process now is to test them through the SURFEX testing tool STRATO. When final corrections are made these tests are fulfilled a new release of SURFEXv9 will be launched by the SURFEX team including all ACCORD contributions. During this v9 merging period the ACCORD MG decided to freeze our SURFEX NWP version corresponding to CY49T2. Thus, no SURFEX development has entered the cycle developments since then. This freeze period is not optimal from a development and collaboration perspective but has been motivated from a work load perspective for those colleagues involved in the merging process.

3.6.2. Highlights from 2025

The ACCORD strategy for 2021-2025 divides the surface activities in three main topics: surface model, physiography and data assimilation. In this section we present some specific progress in these topics during the last year.

Surface model: For our ALARO community it has been a year with intense testing and development connected to the goal to replace ISBA with SURFEX. It has been concluded that the activation of a couple of more advanced SURFEX options are beneficial for the results. These include e.g. the orographic radiation processes (ORORAD) and the urban/TEB garden option where the garden vegetation is kept inside the urban area. Also the Building Energy Model (BEM) and settings for anthropogenic sources of heat and moisture from traffic and industry have been evaluated. Some positive impact has also been reached by tuning of the D95 snow model. A quite important aspect is related to the initialization of surface prognostic

variables. Figure 3.6.1 shows how different initialization strategies have considerable impact on bias and standard deviation statistics for near surface air temperature and humidity.

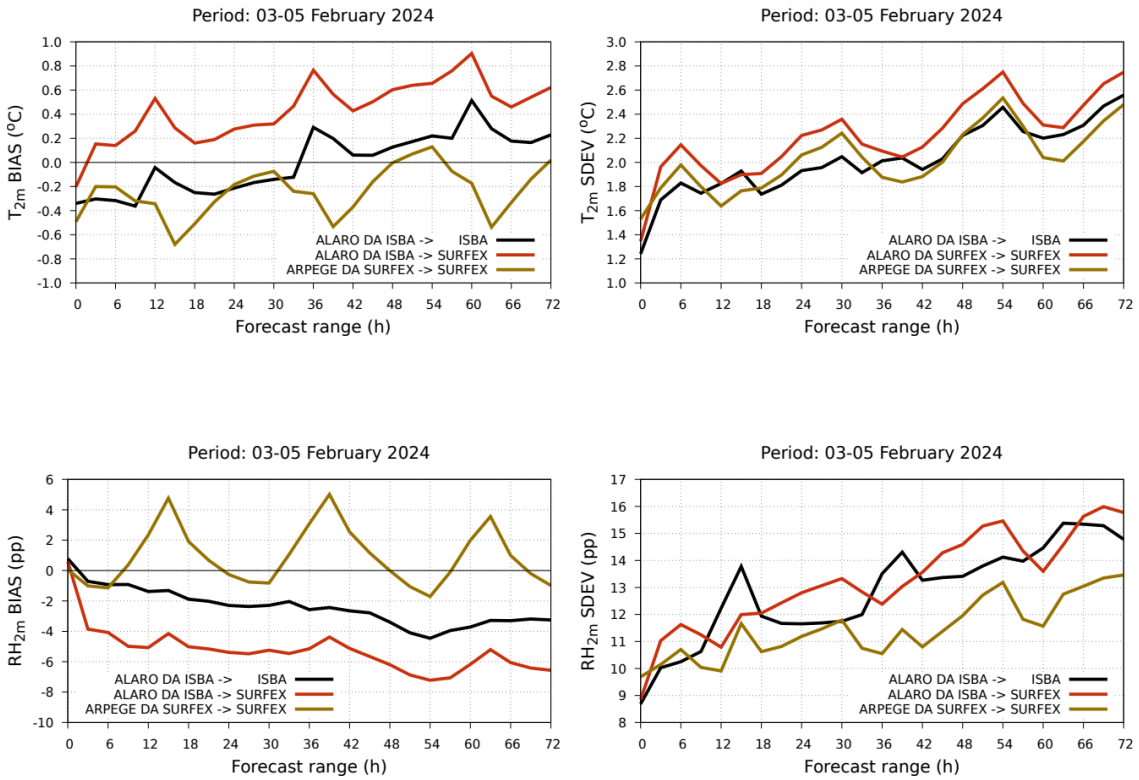


Figure 3.6.1: Comparison of ALARO + SURFEX simulations initialised from ALARO + ISBA DA or ARPEGE + SURFEX DA against the ALARO + ISBA reference: 2-m temperature (top left) and 2-m relative humidity biases (bottom left) and respective standard deviations (top right and bottom right).

The last years have included activities to test and further develop the multi-layer surface physics components in SURFEX for NWP purposes. These components include the 14 layers diffusion soil scheme, the 12 layers explicit snow scheme and the explicit canopy parameterised by the multi-energy balance (MEB). Besides being used in the ongoing CARRA2 reanalysis project we have recently seen an important step forward where the multi-layer surface physics is now for the first being used in an operational NWP setup, namely the AROME-Arctic system by MetNorway. At the same time the combination of these components are being further developed in our research activities. During the last year a step was taken to expand the number of patches to three by separating the open land part into low vegetation and bare soil, and activate MEB not only for forest but also for low vegetation. During some time it has been understood that we need additional approaches to tackle some identified issues related to e.g. energy fluxes over open land areas and biases in soil prognostic variables. Recent modifications related to top soil characteristics have given promising results with respect to these issues.

The multi-layer surface physics is chosen as target configuration for the next ARPEGE setup by Météo-France, although the MEB component might not be included. Currently, an offline global configuration is running in near real time and 102h coupled forecasts are being produced. Evaluation is still going on with promising initial results. A full 4dvar experiment must also be designed and launched to properly assess the impact of this new physics. In

parallel, the CMO (oceanic mixing layer) parameterization has been activated in the ARPEGE configurations of the operational cy49 system.

Included in ACCORD's strive for increased focus on process validation an initiative to develop the Offline Surfex Validation System (OSVAS) was taken during the year. Here different observations (flux observations, observations within the soil) from ICOS observation sites are being used to validate offline SURFEX simulations. Samuel Viana (AEMET) is the main developer. A team around him will meet at the MQA WW in Helsinki in December to continue the development.

Physiography: Operationally in ACCORD, depending on setup, the land-cover is based on ECOCLIMAP 1st generation (ECOFG at 1 km), including ECOCLIMAP I and II, or 2nd generation (ECOSG at 300 m based on ESA-CCI land cover). Also other physiographic databases vary in use, e.g. with respect to soil texture and orography.

A long standing problem with ECOSG has been its long processing time in the PGD step of SURFEX. This problem has been accepted for a while but through the Deode activities, where an on-demand domain is expected to be launched quickly, this problem became more critical. An initiative was taken to make the processing more efficient and Tryge Aspelien (MetNorway) provided a NetCDF-based solution which considerably reduces the processing time.

ECOSG has been used operationally by HARMONIE-AROME NWP setups for several years. More recently Météo-France now plans to activate ECOSG, in combination with the Soilgrids soil-organic carbon database. EGOSG has also been tested out in the ALARO-SURFEX context, where it has been concluded that there are no issues with urban fractions, as were identified for ECOCLIMAP II.

Work on alternative land-cover databases is ongoing for a couple of reasons: To overcome earlier reported issues with ESA-CCI land cover (ECOSG) and the need for higher resolution O(50-100 m). The ML-based physiography product at 60 m resolution has been released and published. Since then, and during the last year, a team at FMI has been working on corresponding parameter databases represented by LAI, albedo and tree height.

Data assimilation: For operations the combination of 2D-analysis of SYNOP observations with CANARI and vertical OI assimilation in the SODA/ASSIM part of SURFEX of soil temperature and soil moisture is still dominating. However, two exceptions exist, at the Hungarian Met service and MetNorway, both based on SEKF for the vertical assimilation. It should also be mentioned that a few Met services are not yet applying any surface data assimilation but development is ongoing.

Thus, from an operations perspective the surface data assimilation looks very homogeneous in ACCORD. However, for research and development, to reach next generations of operational setups, we have quite a wide spread in both algorithms and use of observations. One reason for this is that some major activities are supported by external projects.

At Météo-France the 2DEnVar data assimilation system for screen level analysis, replacing Canari, has been further developed and the assimilation of land surface temperature from SEVIRI instrument has been added to this system in AROME model, with encouraging

results on short range forecasts. The vertical soil part of the surface data assimilation of ARPEGE model has been adjusted to the new physics setup (multi-layer for soil and snow, multi-patches).

Another alternative to Canari, the Pysurfex package developed at MetNorway, is currently being used in the CARRA2 pan-Arctic reanalysis system and in the new AROME-Arctic operational setup by MetNorway. It is also used in all development of multi-layer surface physics experiments performed in the HARMONIE-AROME framework.

For the vertical assimilation part, beyond OI and SEKF, the activities based on different flavours of EnKF have continued during the last year. This research is mainly done within the CERISE project. Much of the CERISE development is done in a python framework. However, we also now have an LETKF implementation available within the OOPS framework.

As has been reported earlier, within the Deode framework a development based on Pysurfex is ongoing where SURFEX offline continuous simulations, forced by as good forcing as possible, are used to create initial values for the surface part of coupled systems. Recently an initiative was taken to utilize this development to create an offline database for ACCORD 3D setups with multi-layer surface physics. The purpose is to take the long term memory of the soil into account for initial conditions.

Within LACE, testing and development of SYNOP-based snow analysis for ALARO CSC, with the ISBA scheme, have continued during the last year. At CHMI master student Jáchym Ševčík, supervised by Alena Trojáková, has implemented an algorithm which better accounts for differences in characteristics with altitude. The goal was to define a single configuration suitable for both lowlands and highlands. To achieve that, the RMSE based cost function was used and minimized by the downhill simplex method. The snow reservoir field produced by analysis with optimized settings appears more realistic than the reference, as it better captures both topography and continental gradients. See Figure 3.6.2 for an example on the developed snow analysis. Please refer to this manuscript for further details.

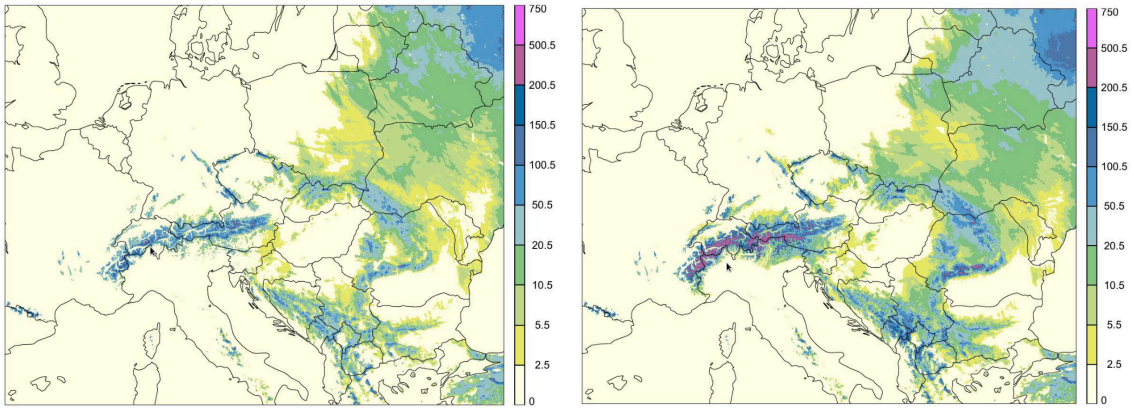


Figure 3.6.2: The snow reservoir of first guess (on left) and analysis (on right) on 25th January 2022. The analysis is using the downhill simplex settings.

3.6.3. Perspectives for 2026

Perspectives with respect to the three main topics surface model, physiography and data assimilation:

Surface model: The activities to test and further develop the multi-layer surface physics will continue in all CSCs. At Météo-France the priority for 2026 is to successfully run a full ARPEGE-4DVar system using this multi-layers surface physics setup. Corresponding Arome-France experiments will be performed, initialized from the Arpege system. Work with development of the Offline Surfex Validation System (OSVAS) will continue.

Work on initialisation aspects and tests of different physics options will continue in LACE. These options include e.g. use of urban patches, traffic/industry sources, BEM, ORORAD and FLAKE. For C-LAEF Alpe Adria, based on AROME, testing ISBA-DIF, ES snow scheme, and 2/3 patches is foreseen for the next model update.

Physiography: Steps toward updated physiography will be taken in all CSCs. For ALARO an increase in horizontal resolution ($\Delta x \sim 1.2$ km) will be combined with the use of SUREX and ECOCLIMAP-II physiography. At Météo-France the evaluation of ECOSG includes also an evaluation of the KAL data sets for LAI and aledo, with respect to the SAT data sets (see more info here) and for ALARO issues with the combination of ECOSG and LGARDEN will be looked into.

On the HARMONIE-AROME side the efforts to make use of the 60m resolution ML physiography will continue. Activities include validation and technical work connected to parameter values of LAI, albedo and tree height. The next step will be to assess the impact on forecasts.

Data assimilation: On the ALARO side, activities to get surface data assimilation to work for the combination of ALARO and SURFEX, including CANARI and OI_MAIN, has high priority for 2026. Also, activities connected to assimilation of satellite-derived moisture information within the SEKF framework in AROME/SURFEX will continue, supported by further impact experiments. Further tuning of snow analysis in CANARI is ongoing across several member states.

In the HARMONIE-AROME framework Ekaterina Kurzenea has carefully investigated and developed the interaction between use of physiography and its impact on data assimilation. These efforts will continue.

At Météo-France, experiments will be pursued with the AROME 2DEnVar system including the assimilation of snow depth. Also, the 4DVar assimilation of ARPEGE model will be adapted to the new surface physics setup in the trajectories.

Overall in ACCORD, during the coming year we will have some initiatives that hopefully can bring us forward together on the data assimilation side with respect to surface. These initiatives include trying out a pathway where we combine the ECMWF's Object-Oriented Prediction System (OOPS), the Local Ensemble Transform Kalman Filter (LETKF) implemented in OOPS by Benjamin Ménétrier (MET-Norway) and the 2DEnVar system developed by Météo-France (Sophie Marimbordes et al.).

3.7. Ensemble forecasting and predictability (E6 to E12)

3.7.1. overview of the activity in the area

The total person.month commitment for the ensemble work packages is practically the same for 2025 as it was for 2024, while there has been a slight increase (~10%) in realized person months for the first half of 2025 compared to the first half of 2024. This is mostly due to an increase in model perturbations (E9), particularly in development and implementation of stochastically perturbed parametrizations (SPP).

Perturbations. The work on SPP includes several aspects, e.g. training of newcomers, development and tuning of additional parameter perturbations, including both surface parameters and flow-dependent SPP, and implementation and testing in e-suites. Other model perturbations include random parameter perturbations (the parameters are perturbed only at the forecast start) and multi-physics.

Migration and preparation of ensemble systems. The Météo-France AROME-EPS e-suite, based on cy49t1, has been finalized and includes several major upgrades. It benefits from improvements of AROME deterministic and ensemble data assimilation schemes, in particular the transition from 3DEnVar to 4DEnVar. The main modification to the ensemble setup is the introduction of random perturbations for 19 parameters of the different physical schemes, that complements the SPPT approach for model error representation. This new configuration has significantly improved performances for most variables and lead times.

C-LAEF AlpeAdria (formerly known as C-LAEF 1k) is running in a pre-operational version on the ECMWF Atos. It is developed and run in cooperation between Austria, Croatia, Slovenia. C-LAEF AlpeAdria is based on cy46t1, running as a continuous lagged ensemble with 8 runs per day and a total of 16+1 members. The horizontal resolution is 1km and the forecast length is 60h. EnVar assimilation is tested, and operationalization is planned for the beginning of 2026.

The Alaro-based A-LAEF e-suite based on cy46t1 with new multi-physics and SPPT for ISBA surface prognostic fields was started in summer 2025, but operationalization has been postponed due to the departure of the main contributor from SHMU.

Both MetCoOp and UWC-West have prepared cy46h1 HarmonEPS e-suite versions where the number of SPP perturbations has been extended from 5 to 19 parameters, and where the new parameters include a dynamics perturbation: wind in the semi-lagrangian advection scheme (SLWIND), two radiation perturbations, two surface perturbations and an extended set of cloud and microphysics perturbations. The aim is to maximize probabilistic skill without introducing member biases compared to the unperturbed control forecast.

Post-processing. Development has continued of statistical and ML-based post-processing targeted at the renewable energy sector. Also, enrichment of NWP ensembles has continued using generative ML models, although with a shift from generative adversarial networks to diffusion models.

A new method, the cascading ensemble method has been tested by IMGW where ensemble members are perturbed during the forecast and new members added, leading to increased ensemble spread. The method is applicable to both ML and NWP models, and tests with the former shows a significant improvement of CRPS skill (see highlights below).

All-staff workshop. The EPS session included an SPP overview presentation, a presentation with details on perturbation of precipitation fall velocity, a presentation on flow-dependent SPP, and a presentation on the use of the URANIE platform to optimize SPP perturbations, illustrated by optimization of the SLWIND perturbation; see the presentations here. In addition there was a topical session on "Advanced data assimilation algorithms and DA-EPS cross-cutting topics" that included a couple of presentations on ensemble variational data assimilation methods.

Working weeks. Since the last report a working week was held at FMI in Helsinki in December 2024 with 13 in-situ participants and some joining online, mostly for the presentations. The working week focused mostly on SPP developments; more information is available in the wiki and in a report in the 7th ACCORD Newsletter.

In 2025 a working week is planned to take place at GeoSphere in Vienna in late October with more information in the wiki.

Scientific visits. Two scientific visits were planned, both of them dealing with the URANIE platform. It turned out that they could be merged, so that two experts and two newcomers could all meet for a week in Dublin and work on (1) using URANIE to run a MUSC sensitivity analysis (python script developed for this), and (2) testing SPP optimization in HARMONIE-AROME; see notes from the week in the wiki and more about (2) below.

3.7.2. highlights from 2025

As mentioned above the main modification to the ensemble setup in the Météo-France AROME-EPS e-suite is the introduction of 19 new random parameter perturbations. The improvement for several surface variables is illustrated in the scorecard in Fig. 3.7.1 for verification of forecasts during August 2025.

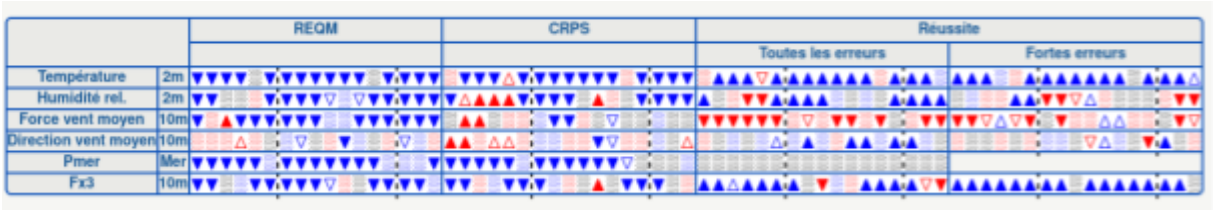


Figure 3.7.1. *Scorecard for AROME-EPS e-suite vs the operational suite for August 2025. Blue triangles indicate improvements and red triangles degradations. Courtesy of Laure Raynaud.*

The addition of more SPP perturbations in HarmonEPS has also improved probabilistic skill. As an example Fig. 3.7.2 shows the increase in ensemble spread and reduction in RMSE for total cloud cover for a two-week period in July 2022.

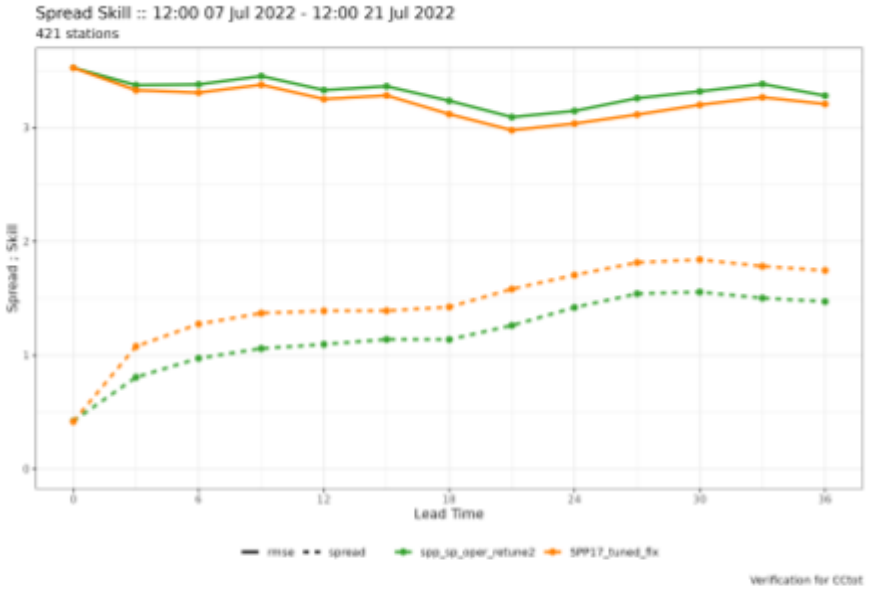


Figure 3.7.2. *Spread (dashed) and RMSE (solid) for total cloud cover before (green) and after (orange) addition of 14 new SPP perturbations in HarmonEPS. Courtesy of Inger-Lise Frogner.*

Tuning the SPP perturbations to maximize probabilistic skill while at the same time making sure member biases are not introduced compared to the unperturbed control members is quite tedious, and so attempts have been made to use the URANIE platform to assist in this task. During the above-mentioned scientific visits several SPP optimization experiments were carried out, focusing on simultaneous optimization of SPP configurations of the original five-parameter SPP setup in HarmonEPS. The cost function used in the optimization was intended to strike a balance between CRPS improvement and systematic member bias relative to the unperturbed control forecast. However, it turned out to be quite hard to get, e.g., the perturbation magnitude to not converge to either the maximum or minimum of the allowed range as illustrated in Fig. 3.7.3. The optimization test is carried out for a domain around Ireland for a two-week period in January 2025, and only the perturbation magnitude for the length scale for stable conditions (parameter CMPERT_RZC_H) converges to a non-trivial value. There are more details about the experimental setup in the ECMWF special project report Utilising the URANIE platform for sensitivity analysis and optimisation of ensemble perturbation methods in the HARMONIEAROME model

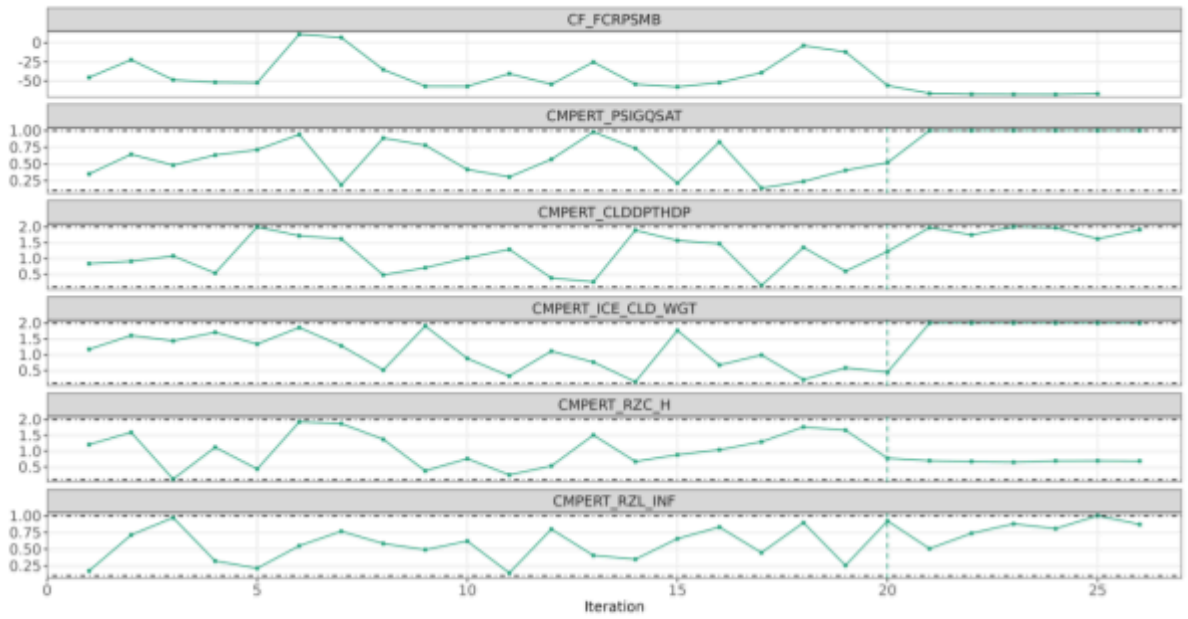


Fig. 3.7.3. *Cost function (top) and convergence of perturbation magnitude (CMPERT) for 5 SPP perturbations for a two-week period in January 2025. Courtesy of James Fannon.*

Work on flow-dependent SPP has continued and has now been tested in both the 2.5km C-LAEF and the 1km C-LAEF AlpeAdria, and a paper has been submitted to QJRMS.

In the cascading ensemble method, perturbations are not all applied at the beginning of the forecast. Instead some perturbations, and hence new ensemble members, are “saved” for later during the computation of the forecasts, reducing the computational costs and increasing the ensemble spread. The method has been tested on the FourCastNet data-driven global weather model where a 256-member ensemble was compared to a cascading ensemble that doubled in size every 6h of the forecast reaching 256 members 48h into the forecast. The two ensemble forecasts were verified against synop observations for January 2023 in a band between 7.5°W and 7.5°E, and the results for 2m-temperature are shown in Fig. 3.7.4. Note the big difference for CRPS where the cascading ensemble scores much better than the 256-member ensemble (smaller is better).

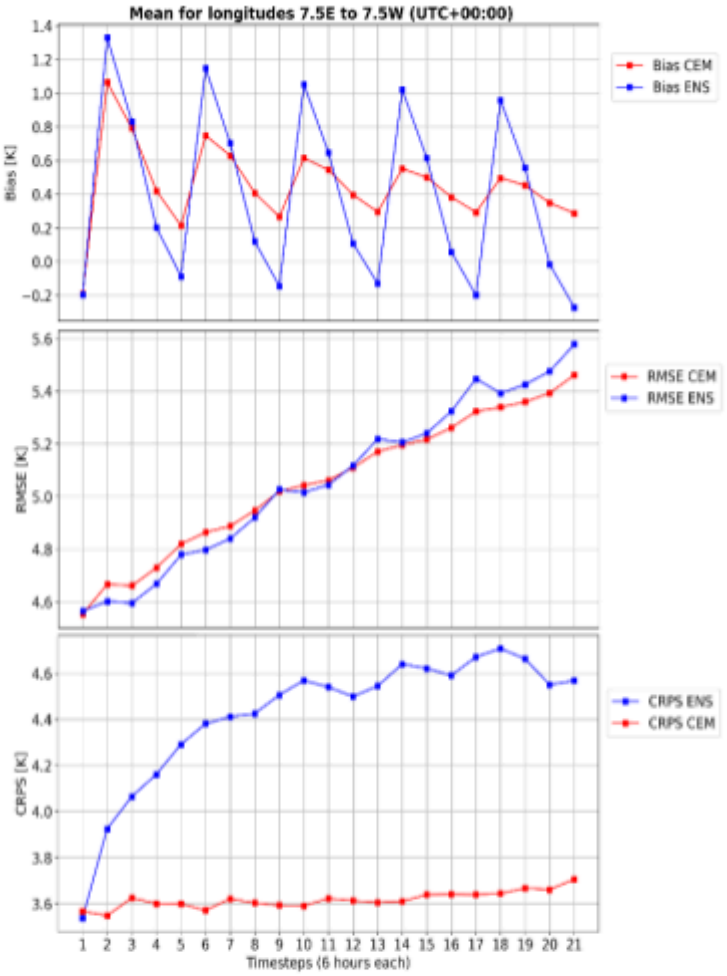


Figure 3.7.4. *2m-temperature mean bias (top), RMSE (middle) and CRPS (bottom) for 256-member ensemble (blue) and cascading ensemble (red). Courtesy of Jadwiga Rog.*

In the context of the DE_371 project, progress has been obtained on the production of EPS members with generative ML. After demonstrating the capabilities of GAN-based algorithms (Brochet et al., 2025), recent works focused on diffusion models and explored different ways of conditioning the generation. It is demonstrated that ML-enriched ensembles, conditioned on a small number of Météo-France Arome-EPS members, can offer a promising alternative to very large ensembles. As indicated by Fig. 3.7.5, it reduces the under-dispersion of a small Arome-EPS, and provides an estimate of distribution tails which is in very good agreement with a large physics-based ensemble.

3.7.3. perspectives and priorities for 2026

The development of a common workflow, including scripting, for research (see Section 2.1.3) is expected to significantly benefit EPS development across the different CSCs. Some EPS functionality is already included in the DEODE workflow, and it is a priority for 2026 to develop it further to the benefit of both DEODE and ACCORD.

The planned upgrade of the Alaro-based A-LAEF has unfortunately been postponed due to the departure of the main contributor. As A-LAEF is used by several teams, somebody else

must take over maintenance. Fortunately, it looks like a team from IMGW may take over A-LAEF monitoring, upgrading, etc. from 2026.

3.8. Meteorological quality assurance and verification (MQA1 to MQA5)

3.8.1. overview of the activity in the area

The 2025 rolling work plan for meteorological quality assurance aims on the one hand at **developing** methods and software for validation and verification, and on the other hand at **applying** such methods and software in validating innovations, evaluating new forecasting systems, monitoring operational forecasts and interacting with users. A new work package for 2025 deals with preparing a common infrastructure for meteorological quality assurance. As in previous years, operational forecast verification and evaluation of e-suites receives the bulk of the labour reported under MQA. The common verification and diagnostics software Harp has continued to gain in popularity as the main engine for verification.

Quality assurance is strongly interconnected with other areas. Thus validation and evaluation of innovations typically applies MQA methods and software, and takes place in a border zone between MQA and areas where the innovations are introduced. Moreover, with the emergence of a common infrastructure for MQA, connections to the System area are rising to a new level of importance.

A joint working week where staff contributing to the areas of MQA, System, Physics, and Surface will meet to set up a common MQA infrastructure is to be held in December 2025 in Helsinki. Scope and planning for the infrastructure is described in Section Highlights. In addition, two scientific visits have taken place in 2025, both related to Harp. During a stay in Prague, Martin Petras (SK), in collaboration with Alena Trojakova (CZ), worked on validating and improving HarpIO using OBSOUL TEMP data. Several issues were identified and corrections were uploaded to the HarpIO GitHub repository (harpIO PR#124). During a three-week stay at GeoSphere in Vienna, Carlos Peralta (DMI), in collaboration with Polly Schmederer (GeoSphere) and Phillip Scheffknecht (GeoSphere) implementation and validated spatial verification methods for high-impact forecast assessment, particularly for extreme weather events. See MQA progress report 2025 for further details.

3.8.2. highlights from 2025

Common MQA Infrastructure:
In order to facilitate the validation and evaluation of ACCORD forecasting systems a new work package MQA5 was introduced in the 2025 work plan, preparing for a common infrastructure for MQA. The goal is to organize and make available data under commonly agreed formats, along with tools and methodologies, suitable for model development (R&D) and enabling ACCORD to assess the added value of its HR models. In order to evaluate technical and administrative choices with concrete examples and bring together scientists to participate in common MQA, the goal in 2025 was set at prototyping a common MQA infrastructure providing a limited selection of services. At the 2025 ASW a whole session was devoted to scoping this prototype, which is to be implemented on the facilities of the ECMWF during a working week yet to take place in December this year. Capabilities of the prototype include the following:

- Support for DDH and MUSC
- process-oriented validation cases for different parameterization schemes (Turbulence and Convection, Microphysics, Radiation, CAR, surface-atmosphere continuum) making use of Cloudnet data and products
- evaluation of soil variables and processes using The Offline Surfex Validation System (OSVAS) and ICOS data
- the Panelification tool for comparison of forecasts wrt spatial scores
- Lagrangian verification and diagnosis of moist processes based on pattern recognition verification using observations and observation operators that can be used for data assimilation

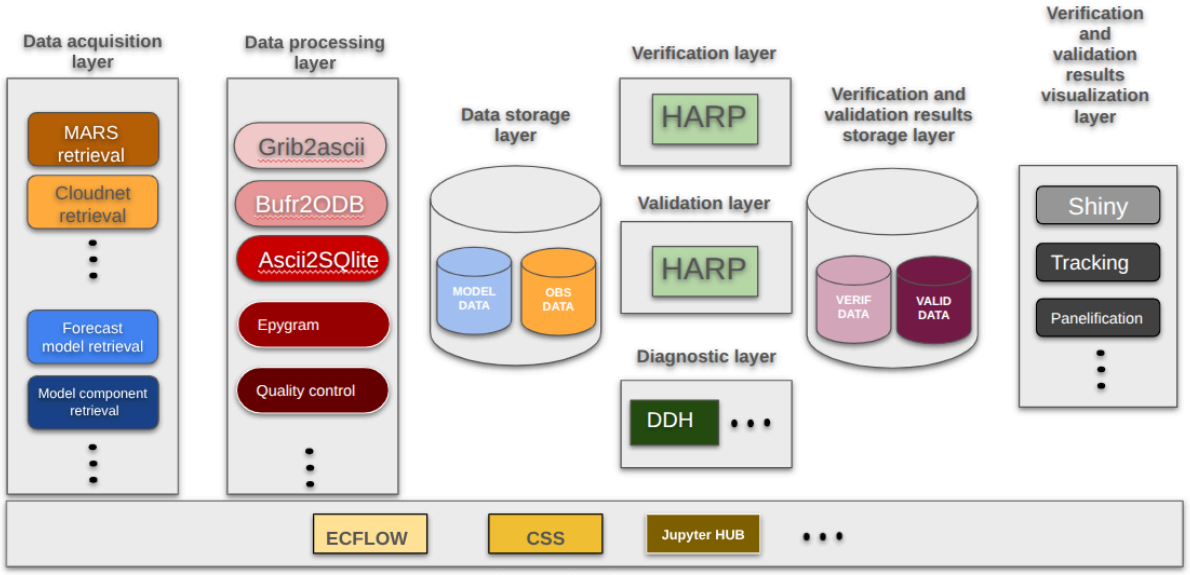


Figure 3.8.1: General workflow of the intended infrastructure, outlining from left to right its different layers for handling the acquisition, processing, and storage of input data, applications in verification/validation/ diagnostics, storage and display of results, all controlled by an orchestration layer (bottom) (figure by Daniel Santos).

Interaction with users:

To date, 20 ACCORD members have nominated a *user representative,* tasked with collecting and transmitting user feedback and response between their respective home institutes and ACCORD, the Management Team acting as entry point to the programme. The representatives are asked to make use of an electronic form, providing meteorological information about the issue at hand, and detailed technical information about the forecasting system in question. The representatives are expected to devote approximately 10% of their annual working time to this activity. On the side of ACCORD, a working group consisting of the AL MQA, PM, and the three CSC-leaders have been responsible for organising response to the feedback. Currently the response is organised in three levels consisting of:

- A simple acknowledgement that a report was received
- A quick answer composed by experts proposed for each report by the working group
- For a few reports, the working group initiates further studies and actions aimed at understanding and dealing with the reported problem within the frame of the rolling Work Plan.

An on-line meeting with the user representatives was held on February 13, with the PM and AL MQA explaining the aims and organisation of the feedback loop. Since the start of the activity in 2024, a total of 8 User Feedback Reports have been delivered using the electronic form. Out of these, three cases have triggered further investigations. These are:

- a case of overestimated convective precipitation in the alpine region of Tyrol reported by the Austrian UR
- a case of missed spring time snow fall in Ireland, reported by the Irish UR
- a case of missed convective rainfall in south west Finland reported by the Finnish UR

The reports are collected on a wiki-page set up for the purpose, together with the response from ACCORD. The user representatives will be kept notified when new material is added to the wiki by means of a mailing list set up for this purpose.

New harp version:
Harp version 0.3 will soon be tagged. It collects innovations from more than a year of work by the developer team. The new version offers many improvements to the user friendliness, capabilities, and efficiency of Harp. Some of these are presented below, and more are described in a presentation by Andrew Singleton.

A new function *run_point_verif()* handles the entire chain from data ingestion to calculation of metrics according to configuration files allowing a high degree of control over the process. The new function makes it easier to set up and maintain verification jobs, as the passing of arguments through multiple function calls in a user-defined verifications script is reduced to a minimum.

Related to IO, accessing FA files has been made consistent with other file formats and several issues hindering the use of OBSOUL data have been dealt with. Support for Parquet data sets is available for point data, but sqlite is still the default file format.

Point verification scores can now be computed separately over specified intervals of controlling parameters selected by the user, by making use of a comparator argument in the relevant function calls. The limits of threshold scores can now be given as quantiles as well as absolute values, and over intervals as well as for single valued thresholds. A threshold weighted CRPS has been added to the probabilistic scores, making it possible to focus the verification on intervals of particular interest such as extreme events.

In pursuit of a thorough assessment of their forecasts, users of Harp have developed increasingly sophisticated patterns of verification, grouping and filtering their data in different ways in order to obtain scores specific to different regions, surface types, weather regimes, and more. As a result, computational efficiency, particularly memory usage, has become a growing concern. In response, the new release of Harp has undergone a substantial refactoring, including a complete overhaul of its data handling processes. Beyond the enhanced efficiency, the new framework also makes it easier to add new scores into Harp.

3.8.3. Perspectives and priorities for 2026

In response to the rapid emergence of data-driven forecasting systems and forecasts, the ACCORD Phase 2 strategy calls for a substantial increase in ambition regarding meteorological quality assurance compared with Phase 1. The goal is to achieve more meaningful forecast veriification—particularly for high-impact events—and to ensure a more

efficient use of resources in model development. Two key milestones toward these objectives are the significant **expansion of the observational basis for verification** and the preparation of shared guidelines and **workflows for verification and model validation**. Achieving these milestones without substantially increasing the workload of the MQA area requires a more efficient allocation of resources by focusing on high-priority topics and minimizing redundant efforts.

At the end of Phase 1, the MQA area still lacked a unifying framework to integrate the contributions of individual scientists—similar to the CSCs and common scripting that help plan and coordinate the development of ACCORD forecasting systems. Solutions for forecast verification and model validation are often developed locally or within small groups, and the results are not always promptly communicated, let alone made widely available. Consequently, similar problems are sometimes solved multiple times in different ways, leading to diverging development paths.

In 2025, initial steps toward establishing a common framework were taken with the creation of a prototype for a shared MQA infrastructure. This infrastructure provides workflows for process-based verification and model validation and enables the use of all observation types from data assimilation also for verification purposes. Beyond coordinating efforts within the MQA area, the new infrastructure is expected to enhance collaboration with related areas of Physics, Surface, Dynamics, and EPS.

A key priority for 2026 should therefore be to **firmly establish this infrastructure as an integral part of the common ACCORD resources** and to further develop it based on lessons learned from the prototype. Achieving this will require strong support from System experts in particular, as well as from ACCORD governance to address potential administrative challenges. In addition, AI/ML experts should be involved to ensure that meaningful comparisons between data-driven and physics-based forecasts become a core capability of the infrastructure.

3.9. Technical code and system development (SY1 to SY4)

3.9.1. overview of the activity in the area

This section presents the progress made in five key work packages. The first two are **SY1**, which focuses on code optimization, and **SY2**, which deals with the maintenance and development of the Harmonie reference system.

As one of the main objectives of ACCORD is to strengthen collaboration between partners, this goal is further addressed through three additional work packages: **COM2.1**, which covers code generation and maintenance, including regular upkeep, updates, and official releases; **COM2.T**, which focuses on transitioning to new work practices and computing environments; and **SY4**, which aims to develop a more common working environment by exploring practical solutions, prototyping, and scripting.

3.9.2. highlights from 2025

Code Optimization (SY1) focuses on identifying and addressing computational performance bottlenecks through profiling and benchmarking techniques. Recent trends in

high-performance computing (HPC) favor hybrid, coprocessor-based architectures for enhanced economic and energy efficiency. In this context, significant efforts have been made to evaluate the performance of refactored code on vector-accelerated HPC systems. One example is the use of simplified benchmarks for parallel systems, like RAPS, tested across different architectures.

The Arome and Harmonie-Arome systems now support compilation and execution in single precision (SP), double precision (DP), and dual precision modes, enabling mixed-precision simulations. Preliminary tests in operational environments suggest that SP computations can improve execution speed by 30–40%. To systematically evaluate the impact of SP on model accuracy and overall performance, the URANIE platform is being used.

In parallel, efforts are underway to develop a single precision version of the ALARO configuration, aiming to extend the advantages of mixed-precision computing to a broader range of model components. The ALARO physics package, including ACRANEB2 radiation, TOUCANS turbulence, and the 3MT deep convection scheme with Lopez microphysics, has been successfully adapted to single precision. Comparisons with double precision runs show meteorologically insignificant differences, smaller than the impact of a ~10% reduction in time-step length (Figure 3.9.1). The necessary single precision modifications have been phased into cycle cy50t1. However, the coupling of ALARO with SURFEX in single precision remains unsupported at this stage.

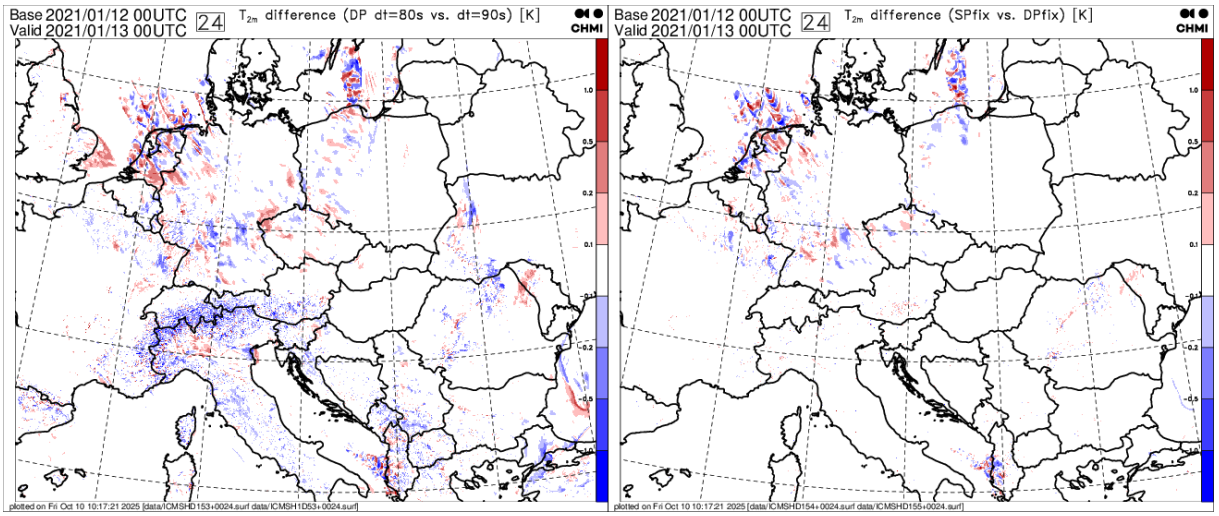


Figure 3.9.1: 2-meter temperature sensitivity in 24-hour ALARO+ISBA integrations over the CHMI 2.3 km domain with 87 vertical levels. Left: Impact of reducing the time step from 90 s to 80 s (both in double precision), illustrating sensitivity due to temporal discretization, which remains meteorologically acceptable. Right: Impact of using single precision compared to double precision (with time step = 90 s); the effect is smaller than the time-step sensitivity, indicating it is meteorologically safe. (source Jan Masek and Olda Spaniel)

Work is also progressing on the implementation and evaluation of mixed precision in SURFEX, with the aim of ensuring consistency and performance gains across the surface scheme.

Thanks to cross-collaboration with the DestinE On-Demand Extremes Digital Twin (DT), under the joint coordination of DEODE/WP10.2 and ACCORD/SPTR-CRA GPU Porting,

recent efforts have focused on aligning GPU porting activities across ECMWF, ACCORD, the LUMI and Leonardo EuroHPC centres, and GPU hardware vendors. The aim is to ensure consistent and harmonised progress toward GPU-enabled model components within ACCORD systems.

Maintenance and Development (SY2) of the Harmonie Reference System focuses on creating new releases based on CY46T1, while maintaining integration with previous versions to ensure consistency. Meteorological validation of harmonie-46h1.1 has been completed, and a new technical release has been tagged harmonie-46h1.1.1 in September 2025. Concurrently, development has begun using CY49T2 as the base code and alpha version[1] has also been released.

The HIRLAM community has adopted a paid GitHub plan for source code management, improving collaboration and code quality. A new Git workflow has been established for CY49, centered on forking CY49T2 for source code management and separating scripting and

[1] Alpha version refers to a technically validated code of Harmonie-Arome that reproduces most of the functionality of the previous release and is ready for developers to start integrating new features

tools to develop the dev-CY49T2h version. This development branch allows for necessary code adaptations as a direct extension of CY49T2 within the IAL forge.

To support this effort, a Tiger Team of area experts has been formed to assist with integrating missing harmonie-46h1.x components and new functionalities. Training on Git and the new workflow is planned to promote best practices and maximize effective use of GitHub.

In parallel, a technical infrastructure has been established to support future UWC needs. This includes a data portal built on the Amazon Web Services (AWS) cloud platform, and a dedicated Confluence space to facilitate more efficient information sharing and collaboration.

Code generation and maintenance (COM2.1)

Cycles (Figure 3.9.2): CY50, common with ECMWF, has been released at the end of 2024. The first half of 2025 saw the reception of contributions and the integration of CY50T1, declared at the beginning of July 2025. *CY50T2 will have seen the externalisation of FA, PHYEX and SURFEX.*

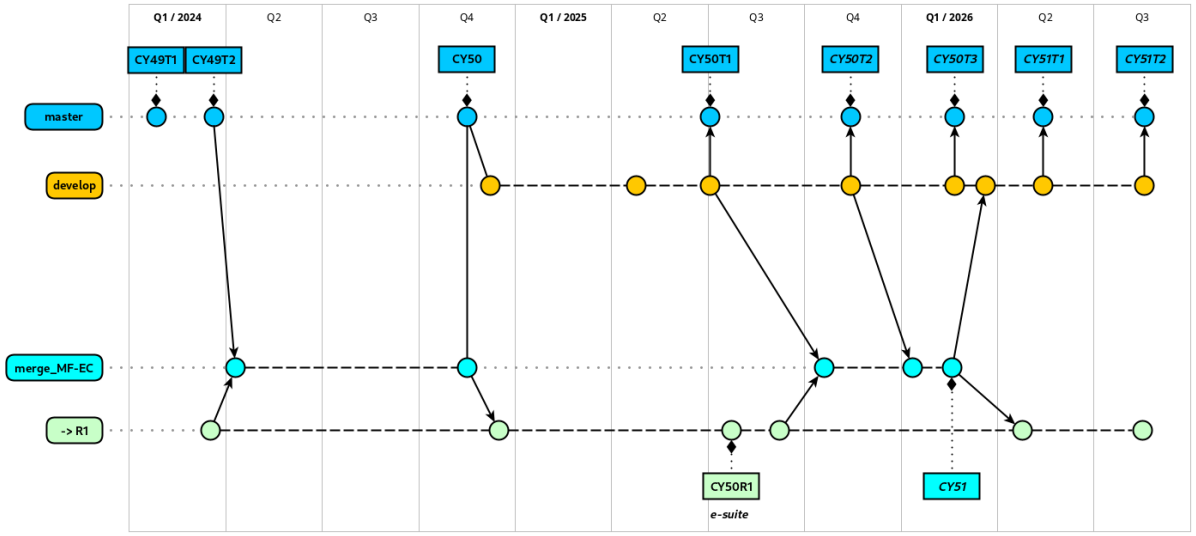


Figure 3.9.2: Timeline of the main R&D code versions (aka cycles) created or planned in the time span 2024-2026. (Alexandre Mary)

DAVAI: the validation system has been thoroughly worked on to bring structural (testing experiment as a python virtual env, rationalization of the DAVAI package, config files in Git, dashboard visualisation) and contents improvements (MUSC, combination of dynamics options from the Mitraillette tool, DDH, 3DVar and 3DEnVar).

FA: the FA, LFI and LFA file formats library has been externalised as a standalone project, including its python interface and a set of validation tests. CY50T2 will have seen its removal from the IAL repository, to rely on this standalone library.

CMake-build: A CMake-based compilation strategy has also been designed to enhance compilation efficiency and portability. Coordination among partners has begun to explore the possibility of adopting a unified CMake implementation across the community. A build system based on CMake/ecbuild has been set up (contributions to IAL and IAL-bundle); it enables the build of the MASTERODB binary in CY50T1. *Its integration in Davaï as an alternate build system will be one main objective by the end of 2025, using the opportunities of the CMake WD and the DAVAI WW.*

Transitioning to new work practices and environments (COM2.T)

Bundlisation: as stated above, packages FA/LFI/LFA and PHYEX (Arome and Harmonie-Arome physics) have been externalised, i.e. removed from IAL, managed as standalone repositories, and bundled for the build of IAL executables. This occurred in CY50T2.

(SY4) Towards a more common working environment

As described in section 3.1.2, and as part of the next phase of the ACCORD strategy, a dedicated effort has been initiated to develop a common scripting system aimed at enhancing collaboration, streamlining workflows, and supporting long-term development goals.

Several important preparatory actions have been undertaken to support this initiative. These include the implementation of the DEODE scripting system (which has recently adopted the name *Tactus*), and associated tools on the Leonardo supercomputer, with dedicated efforts toward enabling single-precision execution. Collaborative development between the

ACCORD and DEODE teams has continued, with focused R&D activities on the effective use and improvement of Tactus. Additional contributions include providing guidance on screen-based verification, further enhancing workflow integration. Significant progress has also been made in the co-design of a unified ACCORD/DEODE scripting system. In parallel, porting of Tactus to the Belenos platform has begun, reinforcing the aim of establishing a robust, portable, and interoperable scripting infrastructure.

3.9.3. perspectives and priorities for 2026

The goal is to achieve more continuous integration of the common code base and to advance the delivery of meteorologically quality-assured model versions through the implementation of several strategic priorities. These include consolidating methodologies for code generation and maintenance, ensuring the regular development of official model releases, and supporting the systematic transfer of knowledge. In this context, HIRLAM will continue to apply its multi-repository strategy to harmonise working practices and improve code visibility within the ACCORD forge. Strategically, there is a strong emphasis on developing a common scripting framework and a shared infrastructure for meteorological quality assurance, both essential for streamlining workflows and enabling collaborative development. Knowledge transfer across existing scripting systems will be promoted, and potential synergies explored, including the definition of procedures for the joint design and co-development of selected components.

Annex

To complement on the R&D activity in ACCORD, the table below lists projects with external funding & international collaboration (non-exhaustive list).

Name of project	Short description	Outcome useful for ACCORD teams	Link to the webpage of the project
DEODE	Developing an on-demand digital twin for extreme events. Contract-based project with ECMWF acting as stakeholder for the EU (DE_330).	Visibility (DEODE is using the ACCORD CSC models). Acceleration of GPU porting, of VHR model developments and their evaluation.	https://destination-earth.eu/ https://www.ecmwf.int/en/about/what-we-do/environmental-services-and-future-vision/destination-earth
UrbanAir	URBAN simulation for AIr quality and heat Resilience strategies. Using a cascade of models. EU-funded: HORIZON-INFRA-2024-TECH-01-03	Expected outcomes: - Improved representation of turbulent transport - Spin-up turbulence and convection at boundaries and improve nesting frequency - Improved representation of urban processes	https://www.urbanair-project.eu/ https://cordis.europa.eu/project/id/101188131/fr