

SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	HIRLAM-C 4th phase (2023-2025) Special Project
Computer Project Account:	Spsehlam
Start Year - End Year :	2023 - 2025
Principal Investigator(s)	J. Onvlee
Affiliation/Address:	KNMI, Utrechtseweg 297, 3731 GA De Bilt, the Netherlands
Other Researchers (Name/Affiliation):	Magnus Lindskog (SMHI), Emily Gleeson (Met Eireann), Ekaterina Kurzeneva (FMI), Inger-Lise Frogner (Met Norway), Daniel Santos (DMI) plus ~80 researchers

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The main areas of attention have been:

- introduction and optimization of flow-dependent assimilation techniques (4D-Var, 3/4DEnVar)
- increasing the range, coverage and impact of high-resolution observations to be assimilated (esp. all-sky radiances, Mode-S, crowd-sourced data and surface observations)
- improvement of model behaviour for fog, convection initiation and stable boundary layer conditions
- a more sophisticated description of the radiation-cloud-microphysics-aerosol interaction and stable boundary layer conditions
- introduction of a more sophisticated surface modelling system.
- development of hectometric resolution and nowcasting (ensemble) setups.
- Computational efficiency and scalability

Summary of problems encountered

Running longer experiments for integration testing of new model components has been rather problematic, due to the transition to ATOS and the many changes in the research working environment. This unstable environment has resulted in frequent crashes and delays in many of our experiments and has caused users to switch to local facilities for longer experiments.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The procedures concerning application and progress reporting are clear and well-supported by templates.

Summary of results (from January 2023 to December 2025)

The HIRLAM-C research programme (January 2016 - December 2025) is a cooperation of the national meteorological institutes of Denmark, Estonia, Finland, Iceland, Ireland, Lithuania, Netherlands, Norway, Spain and Sweden. Research efforts are focused on the development and implementation of the mesoscale Harmonie-Arome NWP model, and its associated ensemble prediction system HarmonEPS. A Harmonie-Arome Reference system is maintained on the ECMWF HPC platform. Computational resources for the HIRLAM-C Special Project at ECMWF have primarily been used for long integration test runs and performance assessments for newly developed elements for this Reference System. Below, the main R&D and testing activities in the fields of data assimilation, atmospheric modelling, surface analysis and modelling, ensemble prediction and coding aspects during the special project period 2022-2025 are outlined.

A) Data assimilation

A1: Development, operationalization and optimization of flow-dependent data assimilation methods

In the years 2023-2025, the focus has been on achieving the following goals:

- Develop, assess and make ready for operational use flow-dependent data assimilation algorithms (4D-Var and 3/4D (hybrid) EnVar, capable of handling the full set of operationally available observations
- Ensure that these algorithms can be run in both the MasterODB and OOPS/JEDI coding frameworks, and start to explore the new functionalities which the new OOPS/JEDI framework can bring.
- Explore coupled atmospheric-surface data assimilation, initially weak forms and then progressively stronger forms of coupling.
- Explore the use of machine learning (ML) within data assimilation, e.g. through developing ML-based obs operators and quality control, emulating VarBC or generating ensemble members for computational efficiency, and gain first experience with fully observations-driven initialization through ML.

In the beginning of this phase, the Harmonie-4D-Var system in the MasterODB framework was extended with the full set of observations which can also be handled operationally by 3D-Var. Meteorological tests of 4D-Var showed the advantages of flow-dependency for many individual meteorologically significant cases, but against standard operational verification scores did not yet show sufficient added value to warrant the greater computational costs. A variety of studies have been done aiming to reduce the additional computational cost of 4D-Var as compared to 3D-Var. Work is still ongoing on the evaluation of a wider use of single precision in 4D-Var, e.g. for the trajectory computations, and on the use of alternative simplified physics formulations, to improve both computational and meteorological performance. A 4D-Var implementation has been made in OOPS in Cy49T2h and validated, again for the full set of observations, and Cy50T1h. A main target for this OOPSified 4D-Var is to better exploit e.g. all-sky assimilation of radiances (see below) than 3D-Var.

In Cy49T2h, also an OOPS version of 3D-EnVar became available, the performance of which has been assessed versus 3D-Var for a variety of EnVar configurations. With this 3D-EnVar system experience has been gained with the greater ease and flexibility which the new OOPS/JEDI frameworks offer for e.g. the formulation and inclusion of new cost functions (Menetrier et al. 2026). It is being studied how to optimize the ensemble configuration towards best impact on both the analysis and the EPS system, including aspects like optimal ensemble size, localization lengths, use of full or hybrid EnVar, and spinup issues. An incremental perturbation scheme and a spatial-scale dependent localization are aspects to be investigated to further improve the capability of the ensemble to represent error growth adequately for very short-range forecasts. Also the potential of adding new control variables is being assessed, particularly for hydrometeors. Work is still ongoing to also bring two available flavours of a hybrid Harmonie EnVar from the MasterODB to into the OOPS framework. A generic C++ framework has been made without forecasting capabilities that may be used to run file-based experiments comparing 3D-Var, 3D(En)Var, and later also 4D(En)Var experiments in OOPS.

Until recently, various ways have been explored for introducing weak atmosphere-surface coupling in Harmonie 4D-Var (see fig.1 below for an example). OOPS/JEDI may be paving the way towards fully coupled data assimilation, at least over the ocean. A start has been made to explore this for LAM's; see also section C2.

Exploiting weakly coupled upper-air/surface DA through 4D-Var trajectory runs

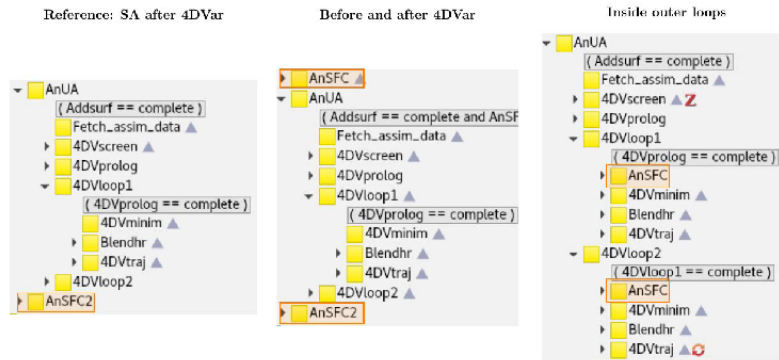


Figure 2. Experiment configuration with surface assimilation at different stages of upper-air 4DVAR assimilation. Middle and right configuration represent a two-way (weak) coupling between surface and upper-air assimilation.

A2: Optimal use of (high-density) atmospheric observations

At present, the operational Harmonie 3D-Var- and 4D-Var assimilation systems are capable of assimilating conventional data, cloud-free IR and microwave radiances from e.g. AMSU-A, AMSU-B, MHS, CRiS and IASI, radar radial reflectivity and wind volume data, GNSS ZTD, GPS-RO, SEVIRI water vapour observations, Mode-S data, AMV's, and scatterometer winds. In the past three years, the main target has been to enhance the utilization of observations from existing and new satellites. This has involved both the preparation for new instruments and platforms (MTG, EPS-SG, AWS and a wider range of radiance observations (esp. microwave) and scatterometers), and efforts to enhance the quality control, handling and impact of many observation types. The amount and spatiotemporal coverage of scatterometer winds and of microwave radiance data has increased significantly, and their handling in terms of e.g. quality control, the use of a footprint operator and bias correction has been improved, particularly for lower-peaking, surface-affected channels. All-sky radiances can now be assimilated both in 3- and 4D-Var (in MASTERODB). For ground-based observations, Mode-S has increasingly become the dominant sources of fine-scale information. An improved handling of temperatures and thinning procedures have further enhanced the impact of these airborne data. For radar winds and reflectivities, the assimilation system has been successfully adapted to employ OPERA NIMBUS 5-minute volume data. Radar Doppler winds quality control and bias corrections have become sufficiently mature to permit their operational assimilation. Additionally, work has continued on improving the handling and thinning of Mode-S data, the usage of GNSS STD observations and the quality control observations from private weather stations and smart phones. In order to rebalance the assimilation system with respect to the large increase in available observations, the Harmonie Cy46h1 assimilation setups have been retuned to optimize their observation usage: revisiting and optimizing background and observation error characteristics, thinning distances and rejection limits for quality control (Sanchez et al. 2025).

In 2026, a top priority topic will be the transfer of the setup for the assimilation of cloudy radiances to the OOPS framework for further validation and pre-operational assessment. HIRLAM members have been involved in the first assessment of EarthCare lidar- and cloud radar-based L1 and L2 products. These have great potential for the validation and optimization of Harmonie microphysics, radiation and cloud schemes behaviour (see below B2), and that will be a second key topic for observations usage and model improvement activities in the coming years.

A3. Optimization of data assimilation setups for the nowcasting range

For assimilation in sub-km (500m-750m) resolution model setups, the goal has been to move towards sub-hourly (O(5-15m)) cycling, assimilating data sources with sufficiently short latency (5-20min): SYNOP, Mode-S, radar, MTG/EPS-SG, NetAtmo/WOW stations and various sources of polar satellite data. Technically, sub-hourly cycling has been enabled, and extensive experimentation has started to assess the challenges for assimilation on these scales in space and time, particularly the issue of model spinup. A penalty-free J_k cost function, which prescribes greater weight to small-scale errors to allow a less costly computation of assimilation increments, has been introduced to obtain a more realistic horizontal spread of information, including from crowd-sourced data. Hydrometeor initialization from polarimetric radar data (generating profiles of rain, graupel and ice which would also be very good to have for microphysics validation, see section B2 below) looks promising. For nowcasting, an improved cloud ingest system (taking into account more cloud depth information) has been tested successfully and made operational.

B) Atmospheric forecast model

B1. Turbulence, convection and cloud organization:

A weakness of the Harmonie model has been its poor representation of the initial stages of cloud organization: open cell convection cloud structures, and the light precipitation associated with them. A scale-aware convection parametrization, designed to handle the grey zone where shallow convection is only partially resolved has been introduced. This scheme has improved the description of open cell convection and has also shown to work quite well in multi-scale evaluation of DestinE-Extremes setups down to 100m resolution. Use of the scale-aware shallow convection parametrization plus some pragmatic modifications was demonstrated to significantly reduce the issue of missing precipitation from shallow cold clouds, delivering showers that were previously missing in the model. Tests of this are being continued over more domains. It is intended to also make the cloud and turbulence schemes scale-aware in the near future.

A second long-standing forecasting problem has been the prediction of fog under stable boundary conditions: fog generally building up too quickly, having a too large extent (especially over sea), too much cloud water, and starting a too quick and too strong cooling over sea. This model behaviour has been shown to be critically dependent on the crude assumptions made in the ICE3 microphysics scheme on the density of cloud condensation nuclei. A temporary pragmatic solution for this was the adoption of a condensation nuclei density concentration (CNDC) vertical profile in the ICE3 microphysics, rather than assume a constant CNDC value over sea, rural and urban areas. The CNDC profile assumption generally does result in improved humidity and cloud base characteristics, but optimal values for the profile function differ between geographical domains. Single column model studies have shown that modelled fog development may be as sensitive to the assumed shape parameters of the cloud droplet size Gamma distribution (a rarely studied part of the microphysics parametrization) as it is to the underlying aerosol or cloud droplet number concentration (Contreras et al. 2022). These sensitivities have been explored further in the context of SPP perturbations for HarmonEPS (Tsiringakis et al. 2025). In parallel, much scientific development and assessment work has been done in the past years on the provision of a more realistic CNDC initialization for the various cloud particles by means of mass mixing ratios for aerosol types derived from near-real-time CAMS data (see also B2). This will hopefully be introduced soon, Many case studies for situations with significant aerosol loads have confirmed the significant impact of taking their impact on the microphysics explicitly into account. The next step in the coming years will be to also let mass mixing ratios develop during the forecast run, by means of a second moment microphysics scheme. First experiments are being held to validate and assess the impact of the second-moment scheme LIMA, which has recently been introduced in the model.

A third item of research has been the treatment of the (very) stable boundary layer ((V)SBL). In the VSBL, the assumption of surface horizontal homogeneity underlying the turbulence scheme is no longer valid, and surface fluxes are known to be strongly affected by the details of actual surface heterogeneity. This problem is especially crucial for the model representation of highly heterogeneous urban areas at sub-km scales, and tackling it has required new modelling approaches for handling the roughness sublayer (see section C2). A combination of high-resolution LES studies together with high-quality boundary layer observations are being carried out to better understand processes like the horizontal and temporal variability of wind and temperature and energy balances and profiles close to the surface, both in reality and within the model.

B2. Improved description of the cloud- aerosol - radiation – microphysics (CAR) interaction:

A refactored dataflow has been developed for introducing a consistent use of near-real-time or climatological aerosol information from global and/or regional CAMS data throughout the model physics: the ingest of CAMS fields and computation of mass mixing ratios, the handling of cloud droplets in the microphysics processes of auto-conversion, sedimentation and collision, and the handling of effective radius and extinction in the radiation and cloud schemes. Presently, 13 types of aerosol can be retrieved. Many case studies over a range of model resolutions from 2.5km down to 100m have shown that near-real-time aerosol information may have significant (beneficial) impact on e.g. model snowfall amounts, dust attenuation of SW radiation, fog life cycle and precipitation in situations with relatively high aerosol loads. Longer-term impact studies for both near-real-time and climatological CAMS aerosol information have been carried out for several domains. Measurements of droplet size distributions show that shallow fog has larger droplets than deeper well-developed fog, cooled from the top by turbulence. Because of this, it is being considered to make the activation of aerosols TKE and vertical velocity dependent. Research is ongoing on a parametrization describing the fraction of aerosols which are active in condensation. The added computational cost of using NRT aerosols is ~12-24% of the present forecast model cost.

In 2023-2024, aerosol impact assessment experiments were done using the 1-moment ICE3 microphysics and the old Harmonie IFS radiation scheme. In 2025, intensive testing and validation of the ECRAD scheme was started. In addition, much progress was made to create a setup able to run ECRAD on a coarser grid than the remainder of the physics. On the one hand, such a model configuration may supply the required computational resources to permit running Harmonie operationally at present resolutions with NRT aerosol. On the other, it could be used to estimate 3D cloud shading effects on radiation for sub-km resolution models in a computationally affordable way, using the SPARTACUS solver in ECRAD in combination with machine learning.

In 2026 and further, the next steps will be to 1) introduce the improved initialization of cloud condensation nuclei densities with near-real-time CAMS data, and 2) to use L1 and L2 data from the combined instruments of the EarthCare satellite (and its predecessors) to validate and optimize the ECRAD radiation scheme and the microphysics parameters in both the first (ICE3) and second moment (LIMA) microphysics schemes. The assimilation of relevant EarthCare products for improving the initial states for the radiation and microphysics should also be considered.

B3. Sub-km resolution modelling

Most HIRLAM services are routinely running real-time sub-km (150-750m) horizontal resolution model setups. Some of these setups have operational status, others are used in research mode to discover the limitations which the present dynamics and physics parametrizations may have on those scales. Many avenues in the field of hectometric modelling are being explored, ranging from the creation of appropriately fine-scale physiography (see section C3), sensitivity and grey-zone or (quasi)3D physics studies, to developing a prototype common data-centric workflow for on-demand triggering of hectometric-scale LAM runs and pursuing machine learning options for enhancing their computational efficiency (DestinE/Extremes).

Configuration studies indicate the added value of vertical resolution increase for the representation of low clouds and fog, but also clearly confirm the importance of large domain size and a great sensitivity of the model to the handling of lateral boundaries for hydrometeors. Noise issues in setups with resolution <500m have been determined and alleviated by careful validation and optimization of dynamics settings throughout the atmosphere. In daily running nested model setups down to 100m resolution, the transition has been studied from parametrized to fully explicit shallow convection and turbulence in the model (as compared to LES) when moving from present operational to 100m resolutions. To handle this transition, the development of scale-aware physics parametrizations has been initiated (see section B1). In sub-km resolution Harmonie runs, boundary layer cloud streets are often represented too strongly and smoothly. The introduction of stochastic elements in the physics parametrizations may help to disrupt this too smooth model behavior and locally trigger deep convection. Several options have been identified for introducing sub-grid scale stochastic physics, and work has started on an intrinsically stochastic turbulence scheme. Machine learning approaches have been selected with which to pursue this further.

C) Surface analysis and modelling

C1: Improving the sophistication of surface model components

In the past two years, many tests have been done with the new multi-layer diffusion soil, extended snow and snow-over-vegetation schemes (DIFF,ES, MEB) and the new SEKF assimilation scheme for soil and snow. A remaining blocking point for operational introduction is the “drying issue” seen in ISBA-DIF, on both NWP and regional climate model HCLIM timescales: far too much evaporation and too high latent heat fluxes over low vegetation and bare soil. The possible causes for this have been investigated with a combination of approaches: validation of the surface energy balance and fluxes versus mast data and ICOS stations, analysis of small-scale variations of soil moisture, and experiments with three patches (bare soil, rocks and permanent snow; forest; low vegetation) and several relevant DIF options, such as the dry soil layer (DSL) and mulch options. No satisfactory solution has been found yet.

Studies have continued on a more realistic treatment of the canopy layer (both vegetation and urban). For this purpose, the vegetation roughness sublayer (RSL) scheme of Harman and Finnegan (2007; doi: 10.1007/s10546-006-9145-6) has been introduced, which accounts for the effects of canopy-induced turbulent mixing. This parametrization includes the concept of displacement height, and a more advanced computation of roughness length z_{0m} as a function of leaf area index (vegetation sparseness) and atmospheric stability. Validation against ICOS forest sites (fig.2) has shown that the RSL scheme improves flux-gradient relationships over the forest, with the largest effects on friction velocity and wind above the canopy.

At present, in Harmonie there is a strict interface between the atmosphere and the surface at the lowest atmospheric model level, where state variables and fluxes are interchanged. However, for the urban TEB

scheme a new approach has been tested (Schoetter et al 2020; doi:10.5194/gmd-13-5609-2020) in which urban (high) buildings may interact with the lowest model levels, depending on their height (fig.3 below). In several urban studies, this approach appears to be more realistic for the treatment of very heterogeneous urban landscapes in hectometric scale models.

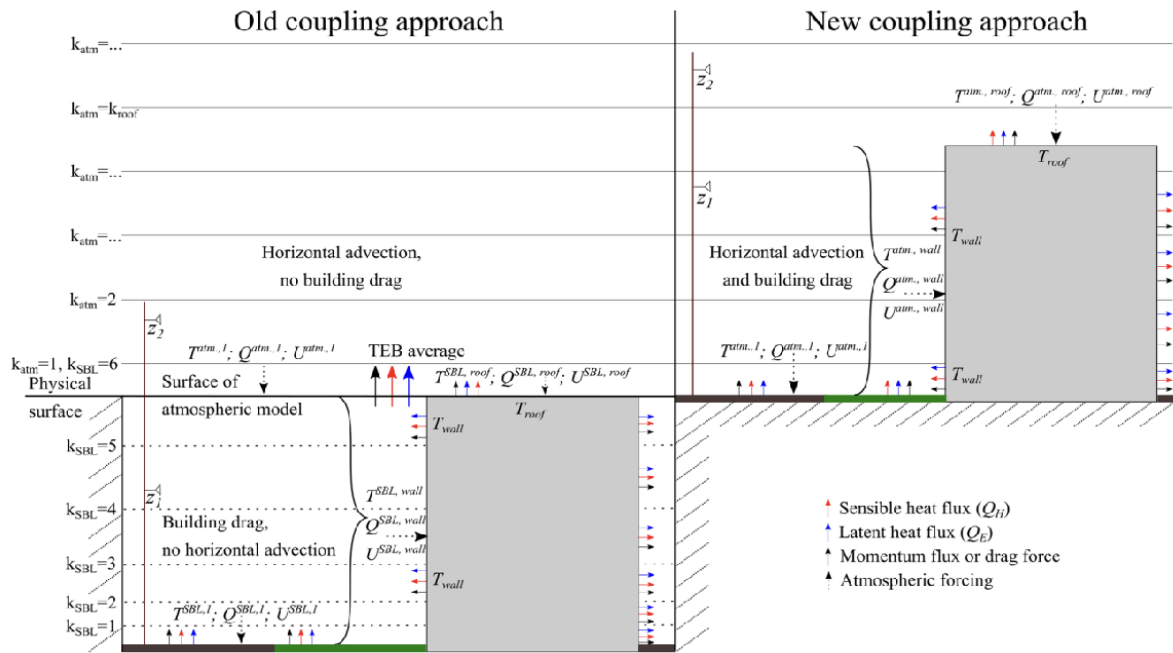


Fig.2: The old (left) and new (Schoetter et al., right) approach for atmosphere-surface coupling in the urban model TEB via several lower atmospheric model levels rather than the lowest model level above building height only.

A new parametrization for surface fluxes over the ocean, ECUME-6, has been tested. ECUME-6 in general was seen to have verification scores comparable to its predecessor ECUME, but to lead to stronger fluxes of heat and moisture than its predecessor, and a lower bias in mean sea level pressure.

A windfarm parametrization according to Fitch et al. (2012) has been successfully tested and introduced in Cy46h1, together with input metadata on wind farm and turbine locations and characteristics.

Progress has been made in testing the performance of coupled atmosphere-ocean-wave model setups over Arctic and Irish domains, with neutral to slightly positive results. The 1D ocean model GOTM has been implemented in Surfex, to facilitate coupled atmosphere-wave-ocean-sea ice studies in the Arome-Arctic domain. Work is ongoing to couple the 3D ROMS ocean model to the already developed coupled Harmonie-WaveWatch3 wave model, and to create and assess the coupling of Harmonie with two hydrological models.

C2. Enhanced use of satellite surface observations in combination with more advanced surface assimilation

The new SEKF assimilation scheme enables increased use of satellite surface products. The first thing which has been tested in this context, is the assimilation of satellite snow extent, which is important in the cold season in areas where SYNOP snow cover stations are sparse or missing. To avoid errors in the screening/thinning and interpolation of raw satellite data, the so-called “snow barrel” method has been developed by FMI for the assimilation of satellite snow extent data. The data flow in the Harmonie assimilation system has been adjusted to permit satellite snow extent assimilation with the barrel approach.

Regular production of “snow barrel” data has started at FMI. Other satellite data which have been studied for future progressive inclusion in the surface assimilation after the SEKF introduction, are soil moisture from Sentinel-1 C-band SAR and Metop ASCAT, OSI-SAF and MODIS sea ice concentration and sea ice surface temperatures, snow depth from Sentinel-1, and retrievals from various satellites in lake data assimilation.

For the sea ice assimilation, a so-called bias-aware EKF was developed, aiming to take into account the SICE model temperature bias under certain situations. Normally, in an EKF, a bias correction is done at analysis time; but in SICE, it was seen that for “fast” variables like air temperature, a bias was very quickly regained during the forecast. In the bias-aware EKF, the bias correction is applied incrementally during the first three hours of model forecasts, as a flux term in the surface energy balance. The general performance of the new sea ice data assimilation scheme is being tested against independent MODIS observations.

In several studies, it has been explored how to move towards (strongly) coupled atmosphere-surface assimilation. One idea which is being pursued is to add an additional layer of “screen level values” to the 3/4D-Var control vector in the OOPS framework. Also, a technical solution has been explored to make the results of land surface DA available to the atmospheric assimilation; however, some issues remain to be solved when applying that method to the new many-layer surface physics. After the introduction of the SEKF soil and snow assimilation, it is intended to move stepwise towards a more advanced ensemble Kalman filter (EnKF) setup which can serve as basis for a strongly coupled atmosphere-surface assimilation system capable of using satellite surface radiances. An initial EnKF setup has been prepared. A restructuring of the surface assimilation is planned with the aim to permit the use of various assimilation algorithms (SEKF, EKF, EnKF) independently from specific tiles and/or patches (which is presently not the case).

C3. Enhancing physiographic information

A critical aspect for surface modelling is the quality of the surface characterization (orography and physiography). Especially in the light of the ambitions to move to hectometric-scale models, there is a clear need to improve over the existing ECOCLIMAP-Second Generation global 300m resolution database by means of local high-resolution databases and/or satellite data in a consistent manner. Work has begun to create a workflow by which a physiography sufficiently detailed for use in hectometric NWP models on European domains can be created from regularly updated satellite-based maps. The idea is to use as a starting point a set of existing land cover databases and thematic maps of O(10m) resolution for the European area, which are regularly updated in e.g. Copernicus context. Machine learning is then used to “translate” this aggregation of map to an improved 60m resolution physiography database for Europe, with the same labelling (set of land cover types, water bodies and urban local climate zones) as ECOCLIMAP-SG and ESA-CCI. This work is being pursued among others in the context of the DestinE/Extremes programme.

D) Probabilistic forecasting

In the EPS area, the focus of developments in 2023-2025 has been on the development and assessment of model perturbations using SPP, gradually shifting attention from atmospheric to surface parameter perturbations. End 2025 a large upgrade of the HarmonEPS SPP system has been introduced, extending the set of perturbations from 5 parameters to 21, in such a manner that the bias properties of the ensemble versus the control were not affected. The newly added parameters include e.g. several new mass-flux related parameters which affect the intensity of dry and moist updrafts, new microphysics perturbations in the shape of particle size distributions and fall speeds, and two new surface parameters, vegetation heat capacity and minimum surface resistance. The resulting new SPP system was demonstrated to lead to larger spread and improved to neutral skill for different seasons and regions (Tsiringakis et al. 2025). Full operational testing of the new HarmonEPS setup will be done by the UWC groupings in 2026.

In Destination-Earth/Extremes context, high-resolution HarmonEPS systems (500-750m) based on SPP have been developed and assessed. Fig.4 shows an example of the benefits that such high-resolution EPS systems may have for the accuracy of probabilistic predictions for (intensity and location of) an extreme precipitation event.

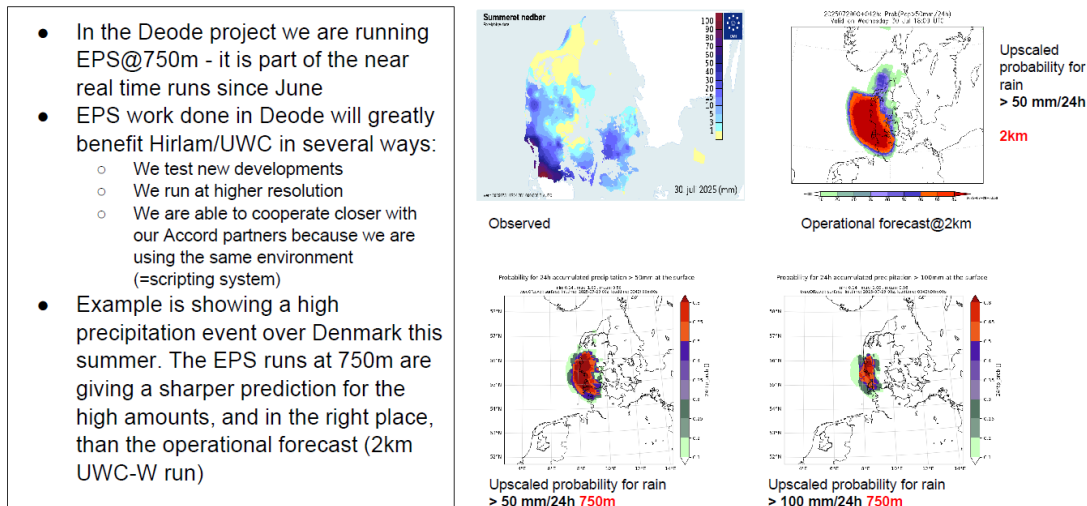


Fig.3: DEODE HarmonEPS run at 750m resolution, showing probabilities of strong precipitation for a severe precipitation event over Denmark on 30 July 2025. The 750m resolution runs shows a more precise location and more accurate peak precipitation values than the 2km resolution UWC-West run.

E) Computational efficiency, portability and system aspects

Various tests have been carried out for the deterministic Harmonie-Arome model in single vs double and mixed precision (SP/DP/MP), for the forecast model and for the 3- and 4D-Var data assimilation systems, see section A above. For 4D-Var, some problems remain with using SP in minimization. When going from DP to MP, typically run time reductions of ~35-40% are found, mainly because data volumes get smaller (memory cache can hold larger arrays, data involved in MPI passing is halved). In addition, experiments have been done to study the impact of computing perturbed ensemble forecasts in single precision (SP), while keeping the control run in double precision (DP). SP ensemble member forecasts were ~30-40% faster than DP runs. Meteorological differences between SP and DP forecasts for any single member appeared to be quite small compared to differences between individual perturbed members, and SP and DP runs generally performed equally well in terms of meteorological scores.

In collaboration with ECMWF, staff at DMI have been working on improving the computational efficiency of a part of the ECRAD radiation scheme by ~40%, using machine learning (ML). In the coming years the speedup achieved in ECRAD may be used to explore a quasi-3D radiation approach in the future (see B2). In addition, the potential of ML for optimizing parameters will be further explored. Other applications of ML in which activities have started up or have become more refined, are in the quality control of crowd-sourced observations, ensemble calibration, the derivation of observation operators, and the construction of improved physiographic data.

Given the increasing heterogeneity of HPC architectures, it is essential to establish model performance on a wide range of different architectures. A “containerized” version of the model has enabled porting and assessing the computational efficiency of Harmonie on a wide range of platforms for benchmarking purposes (involving CPU, GPU, AMD, ARM and mixed architectures). Kernels for smaller parts of the model are being created and maintained to facilitate faster detection and localization of computational performance problems and easier porting of code components, e.g. to university partners.

In 2022-2024 a refactoring and code cleaning of the forecast model code has taken place, which was required for near-automated code adaptation tools to optimize its use on GPU and other (mixed) architectures. By these efforts, a vastly improved modularity and interoperability between the Arome-France, Harmonie and ALARO forecast models has been achieved, at the level of individual parametrizations schemes. Largely automated tools have been introduced to perform the adaptation of the refactored code for use on other HPC architectures, e.g. on a variety of EuroHPC platforms. This has been achieved in different ways for different parts of the code: by hardware-optimized external libraries, API's, and semi-automatic code transformation tools. (LOKI, fxtrans) to generate hardware-specific code through e.g. loop re-ordering, memory layout etc. A similar refactoring of the data assimilation code has been achieved with the inclusion of the Harmonie data assimilation algorithms into the OOPS system.

List of publications/reports from the project with complete references

- Bessardon, G., et al., 2024: “High-resolution Land use cover dataset for meteorological modelling – Part 1: ECOCLIMAP-SG+”, Land, <https://doi.org/10.3390/land13111811>
- van den Brekel, S., 2023; “Validating the surface flux ECUME and ECUME6 parametrizations used in the Harmonie model”, MSc thesis TUDelft, <https://doi.org/10.5281/zenodo.8276789>
- de Bruijn, E.I.F., et al., 2023: “Wind observations from hot-air Balloons and their application in an NWP model”, Met. Appl., <https://doi.org/10.1002/met.2128>
- Calvo-Sancho, C., et al., 2023: “Assessing the performance of the HARMONIE-AROME and WRF-ARW numerical models in North Atlantic Tropical Transitions”, Atm.Res. 291, p.10680
- Eresmaa R., et al., 2025: “Estimating the Potential Impact of the EPS-Sterna Satellite Constellation in Regional NWP”, subm. to QJRMS.
- Gleeson, E., et al, 2024: “The Cycle 46 configuration of the Harmonie-Arome forecast model”, Meteorology, vol.3 pp.354-390, <https://doi.org/10.3390/meteorology3040018>
- de Haan, S., de Jong, P.M.A, Koutek, M., 2025: “EMADDC: high-volume, high-quality, and timely wind and temperature observations from aircraft surveillance data (Mode-S EHS).” Atm. Meas. Techn. 18(14):3341-3359, <https://doi.org/10.5194/amt-18-3341-2025>
- Kähnert, M., Sodemann, H., Remes, T.M. et al., 2023: “Spatial Variability of Nocturnal Stability Regimes in an Operational Weather Prediction Model”. Boundary-Layer Meteorol 186, 373–397. <https://doi.org/10.1007/s10546-022-00762-1>

- Kähnert, M., H. Sodemann, T. M. Remes, and M. Homleid, 2025: “Impact of Adjustments in Surface–Atmosphere Coupling for Model Forecasts in Stable Conditions.” *Wea. Forecasting*, **40**, 1371–1381, <https://doi.org/10.1175/WAF-D-24-0163.1>.
- Lean, H.W., et al. , 2024: “The hectometric modelling challenge: Gaps in the current state of the art and ways forward towards the implementation of 100-m scale weather and climate models”, QJRMS Vol.150, pp.1–38. <https://doi.org/10.1002/qj.4858>
- Lindskog, M., et al., 2023: “Impact of Mode-S Enhanced Surveillance Weather Observations on Weather Forecasts over the MetCoOp Northern European Model Domain”, JAMC, <https://doi.org/10.1175/JAMC-D-23-0009.1>
- Maalampi, P., 2024: “ Studying the effect of a new aerosol option on HARMONIE-AROME sea fog forecasts “, Helsinki Univ. M.Sc thesis, <http://urn.fi/URN:NBN:fi:hulib-202403111471>
- Marseille, G.J., et al., 2023: “Aeolus Raileigh-channel winds in cloudy conditions”, QJRMS, <https://doi.org/10.1002/qj.4555>
- Marseille, G.-J., et al., 2025: "Exploiting Aeolus Winds in Regional NWP", subm. to QJRMS.
- Martín Pérez, D., et al., 2024: “Use of CAMS Near-Real-Time Aerosols in the HARMONIE-AROME NWP Model.” *Meteorology*, <https://doi.org/10.3390/meteorology3020008>
- Mile, M., Guedj, S., Randriamampianina, R., 2023: “Exploring the footprint representation of microwave radiance observations in an Arctic limited-area data assimilation system”, *Geophys. Model Dev.*, <https://gmd.copernicus.org/preprints/gmd-2023-195/>
- Morales, G., et al, 2024: “Evaluation of Harmonie-Arome Cy46h1 at AEMET”, ACCORD Newsletter 5, p.41-48, accord-nl5.pdf (accord-nwp.org)
- Oskarsson, J., Landelius, J, Lindsten, F., 2023: “Graph-based Neural Weather Prediction for Limited Area Modeling”, <https://arxiv.org/pdf/2309.17370>
- Ridal M., J. Sanchez, M. Dahlbom,2023: “Optimal use of radar radial winds in the HARMONIE numerical weather prediction system”, JAMC, <https://doi.org/10.1175/JAMC-D-23-0013.1>
- Ridal M. et al. 2024: “CERRA, the Copernicus European Regional Reanalysis system”, QJRMS Vol.150, pp.3385-3411, <https://doi.org/10.1002/qj.4764>.
- Rieutord, T., Bessardon, G., Gleeson, E., 2024: “ECOCLIMAP-SG-ML: ensemble land cover maps for numerical weather prediction”, *Land*, <https://doi.org/10.3390/land13111875>
- De Rooij, W.C., 2023: “Lateral mixing in shallow cumulus convection”, Ph.D. Thesis TU Delft.
- Savazzi, A.C.M., et al., 2023: “Momentum Transport in Organized Shallow Cumulus Convection.”, *J.Atm.Sc.* 81 p.279-296, <https://doi.org/10.1175/JAS-D-23-0098.1>
- Savazzi, A.C.M., et al., 2025: “The influence of parametrized shallow convection on trade-wind clouds and circulations in the Harmonie-Arome mesoscale model”, JAMES, <https://doi.org/10.1029/2024MS004538>
- Steinslid, M., Sodemann, H., Kähnert M., 2025: “Biases in the representation of fall velocity revealed by investigating precipitation characteristics at high time resolution”, subm. QJRMS
- Theeuwes, N., et al., 2025: “ Improving numerical weather prediction at urban to neighbourhood scales”, <https://doi.org/10.5194/icuc12-616>
- Tsiringakis, A., et al., 2024: “An Update to the Stochastically Perturbed Parametrizations Scheme of HarmonEPS”, *Monthly Wea. Rev.*, <https://doi.org/10.1175/MWR-D-23-0212.1>

Future plans

In December 2025, the HIRLAM-C programme has been closed down. R&D activities on developing and evaluating the Harmonie-Arome model will be taken over by the new United Weather Centers programme, a cooperation between the NMS’s of Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Netherlands, Norway, Spain and Sweden. This will not involve a dedicated Special Project at ECMWF any longer, although UWC will continue to make use of the Harmonie-Arome working environment which has been set up within the HIRLAM programme.