SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	July 2024 – Jun 2025
Project Title:	HIRLAM-C 4th phase (2023-2025) Special Project
Computer Project Account:	Spsehlam
Principal Investigator(s):	J. Onvlee
Affiliation:	KNMI
Name of ECMWF scientist(s) collaborating to the project (if applicable)	……………………………………………………………… ………………………………………………………………
Start date of the project:	1 January 2023
Expected end date:	31 December 2025

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	40 MSBU	40MSBU + HIRLAM SBU pool resources	40 MSBU	< 1 MSBU (however, much use expected in second half of 2025, see report final page)
Data storage capacity	(Gbytes)	20.000		20.000	20.000

Summary of project objectives (10 lines max)

Special project resources are primarily used for pre-operational assessment and full integration testing. Main areas of attention in 2023-2025:

- Complete the refactoring and code adaptation of Harmonie-Arome for alternative HPC architectures
- Integrate all assimilation algorithms developed for Harmonie-Arome in the OOPS framework. Assess 3/4D EnVar and all-sky radiance assimilation, optimize assimilation for nowcasting, and work towards coupled atmospheric/surface data assimilation. Include new (esp. surface) remote sensing observations.
- Develop and assess hectometric scale and nowcasting (ensemble) setups, with focus on urban aspects
- Develop, and assess the impact of, more realistic descriptions of the microphysics, radiation, use of real-time aerosol, stochastic physics, new or improved surface model components and surface physiography.
- Build experience with machine learning applications, including emulation of the full Harmonie system.

Summary of problems encountered (10 lines max)

Running longer experiments for integration testing of new model components has been rather problematic for our researchers in the past year, due to instabilities in the research working environment, leading to crashes and delays in many of our longer experiments. This has increasingly been forcing users to switch to alternative facilities for longer model runs, which is one reason for the present underutilization of SP resources.

Summary of plans for the continuation of the project (10 lines max)

At the end of this project (Dec. 2025), the HIRLAM-C programme will be terminated. This special project will not be succeeded by a new Special Project for similar purposes.

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+: an agreement-based dataset”, Land 2024, Vol. 13(11) https://doi.org/10.3390/land13111811
- 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
- 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”, Q.J.R.M.S Vol.150, pp.1–38. https://doi.org/10.1002/qj.4858
- Maalampi, P., 2024: “ Studying the effect of a new aerosol option on HARMONIE-AROME sea fog forecasts “, Helsinki University M.Sc Thesis, http://urn.fi/URN:NBN:fi:hulib-202403111471
- Martín Pérez, D., et al., 2024: “Use of CAMS Near-Real-Time Aerosols in the HARMONIE-AROME NWP Model.” *Meteorology* 2024, *3*, pp.161-190. https://doi.org/10.3390/meteorology3020008
- 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, Vol.13(11), 1875 , https://doi.org/10.3390/land13111875
- Suomi, J., et al., 2024: “Evaluation of surface air temperature in the HARMONIE-AROME weather model during a heatwave in the coastal city of Turku, Finland”. Urban Climate, Volume 53, 101811, ISSN 2212-0955, https://doi.org/10.1016/j.uclim.2024.101811
- Saranko, O., et al., 2024: “Comparison of physically based and empirical modeling of night-time spatial temperature variability during a heatwave in and around a city.” JAMC Vol.63(10), pp.1053-1074, https://doi.org/10.1175/JAMC-D-23-0149.1
- 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
- Venstad, T., Batrak, Y. and Remes T. , 2024: “Impact of improved physiography data on hectometric weather forecasts in Svalbard”. MET Report 9/2024, ISSN 2387-4201, https://www.met.no/publikasjoner/met-report

Summary of results (from July 2024 to June 2025)

The HIRLAM-C research programme (January 2016 - December 2025) is a research cooperation of the national meteorological institutes of Denmark, Estonia, Finland, Iceland, Ireland, Lithuania, Netherlands, Norway, Spain and Sweden. Common research efforts are focused on the scientific development and implementation of the mesoscale analysis and forecast system Harmonie, and its associated ensemble prediction system HarmonEPS. Operational Harmonie model configurations are run locally in three subgroups of HIRLAM services: the MetCoOp collaboration (Norway, Sweden, Finland, Estonia, Lithuania and Latvia), the UWC-West collaboration (Denmark, Iceland, Ireland, and Netherlands), and AEMET (Spain). A Harmonie Reference system is being maintained on the ECMWF ATOS platform.

The computational resources for the HIRLAM-C Special Project at ECMWF are primarily used for pre-operational validation and verification of new model features and for meteorological performance assessment of new cycles of the Reference System, with a focus on the main domains of the three operational subgroups MetCoOp, UWC-West and AEMET. In addition to these special project resources, the HIRLAM services yearly create a common pool of SBU resources at ECMWF for scientific experimentation.

Below, the main R&D and testing activities in the fields of data assimilation, the atmospheric forecast model, surface analysis and modelling, ensemble forecasting, machine learning activities and code efficiency and system aspects during the past year are outlined.

A) Data assimilation

<u>A1: Development, operationalization and optimization of flow-dependent data assimilation methods</u>
Work on data assimilation algorithms in the July 2024 – June 2025 period has focussed on the integration of the 4D-Var system into the OOPS framework of Harmonie Cy49T2h, and on enabling it to run stably and efficiently with all available observations types. Extensive performance testing of 4D-Var vs 3D-Var in Harmonie Cy46h1 has been done pre-operationally in the three operational subgroups. Work is still ongoing on the evaluation of a wider use of single precision in 4D-Var, e.g. for the screening and trajectory computations, and on the use of alternative simplified physics formulations, to improve both computational and meteorological performance.

A second priority area has been the assessment of the performance of the 3D-EnVar systems in the OOPS framework. Aspects being studied are how to optimize the ensemble configuration towards best impact on both the analysis and the EPS system, and assessing the potential value of adding new control variables, particularly for hydrometeors. Until now various ways have been explored for weak atmosphere-surface coupling (see fig.1 below for an example on the use of different weak coupling configurations

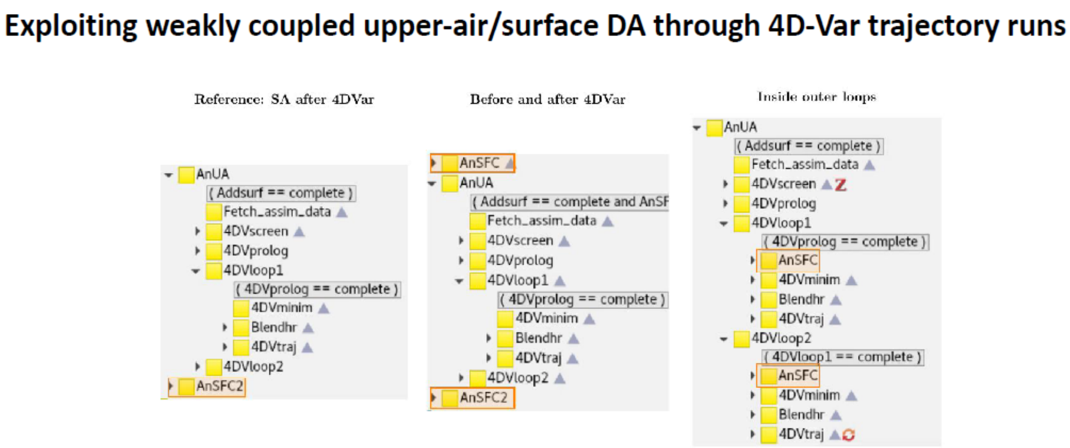

Figure2.Experiment configuration with surface assimilation at different stages of upper-air 4DVAR assimilation. Middle and right configuration represent a two-way (weak) coupling between surface and upper-air assimilation.

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through 4D-Var trajectory runs). OOPS/JEDI developments 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. For other progress on coupled atmosphere-surface assimilation, also see section C.2 (Surface).

Various activities are ongoing in developing the use of ML in DA: e.g. developing ML obs operators for the surface and over sea, emulating VarBC for computational efficiency, and several fully data driven approaches based on the BRIS and Neural-Lam machine learning models.

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

On the observations side, progress continues to be made in enhancing the utilization of observations from existing and new satellites. The highest priority in the past year has been given to the preparation for new instruments and satellites, in particular MTG, MetOp-SG and AWS. Work has continued in particular on a better handling of low-peaking radiance channels, in preparation for use of the Arctic Weather Satellite (AWS) and Meteosat Third Generation (MTG) imager and sounding instruments. In the past year, the use of all observations systems in the operational models (based on Cy46h1) has been re-tuned to optimize observations usage. The Harmonie DA team has become involved in a Eumetnet study on the impact of reducing the amount of E-AMDAR data. It is being considered how to move on from the various methods for Mode-S QC and thinning which presently are in use.

A3. Optimization of data assimilation setups at sub-km resolutions and for the nowcasting range

For assimilation in sub-km (500m-750m) resolution model setups, the goal is to move towards sub-hourly cycling, assimilating data sources with sufficiently short latency (10-20min): SYNOP, EMADDC Mode-S, radar (NIMBUS), NetAtmo/WOW stations and various sources of (geo and polar) satellite data. Technically, sub-hourly cycling has been enabled and a beginning has been made with extensive experimentation with sub-hourly setups to assess the challenges for assimilation on these scales in space and time, particularly the issue of model spinup. For nowcasting, an improved cloud ingest system (taking into account more information on the depth of clouds) has been tested successfully in the nowcasting range, and has been made operational in MetCoOp.

B) Atmospheric forecast model

The highest priority for model developments in the past year has been the completion of the code refactoring required to make the model GPU-enabled. A second key objective has been to start a comprehensive process-oriented validation and evaluation of the atmospheric and surface physics, and to make an overhaul of the observations and tools available for this (e.g. see fig.2 below). The full team of developers has been familiarized with how to routinely access and make use of satellite and ground-based remote sensing products suitable for process-oriented validation (Cloudsat, Calypso, MODIS, AMSR2, Sentinel missions, Earthcare and networks like Cloudnet and ICOS). On the one hand, such evaluation is needed for validating individual components of the refactored code, but it is also aimed to thoroughly assess the various model components and attribute several known weaknesses of the integrated forecast model to possible root causes.

B1. Turbulence and shallow convection:

A long-standing problem reported for operational Harmonie model setups across Europe has been missing precipitation from shallow convective clouds. A combination of different options in the pre-operational scale-aware shallow convection scheme has been shown to handle this type of weather situations structurally better (delivering showers that were previously missing and providing a better representation of the open cell cloud structures associated with it), without degrading model performance under other weather conditions. A next step in the coming year will be to make the cloud scheme scale-aware and test and tune it, like the turbulence scheme.

For (very) stable boundary layer conditions, a stochastic turbulence parametrization appear to be needed to create realistic boundary layer clouds. Both an intrinsically stochastic turbulence scheme and a data-driven approach to derive a stochastic stability correction to model turbulence are being used to study the transition of turbulence from weakly stable to very stable conditions, and its impact on energy balances and profiles close to the surface.

B2. Improved representation of the cloud-radiation – microphysics- aerosol interaction:
In the context of code refactoring, the Cloud-Aerosol-Radiation (CAR) team has been working hard on a unification of the CAR codes for the cloud scheme, microphysics and radiation parametrizations across ACCORD. This has very nearly been completed. As a second step, work is ongoing to finalize the refactored and unified codes for describing the interactions between aerosols and the radiation and microphysics schemes, both for climatological and near-real-time (NRT) aerosol.

Generally, the NRT aerosol setup (presently accounting for 14 aerosol species) provides forecasts at least as good as the present default setup with climatological aerosol. Validation of the Clear Sky Index (CSI) showed very good estimates over Iberia for summer 2023 when adding stratospheric aerosol (which had not yet been accounted for in the NRT scheme; see fig. 2). The added computational cost of including NRT aerosol for all available aerosols in Harmonie Cy46h1.2 on ATOS is ~+23%. A more realistic option which is therefore being considered for operations is to use NRT aerosols only for very few important aerosol types, like desert dust, and to use CAMS climatologies for others. The evaluation of clear-sky radiation for different aerosol options (climatological vs. near-real-time use of different aerosol species) is still ongoing.

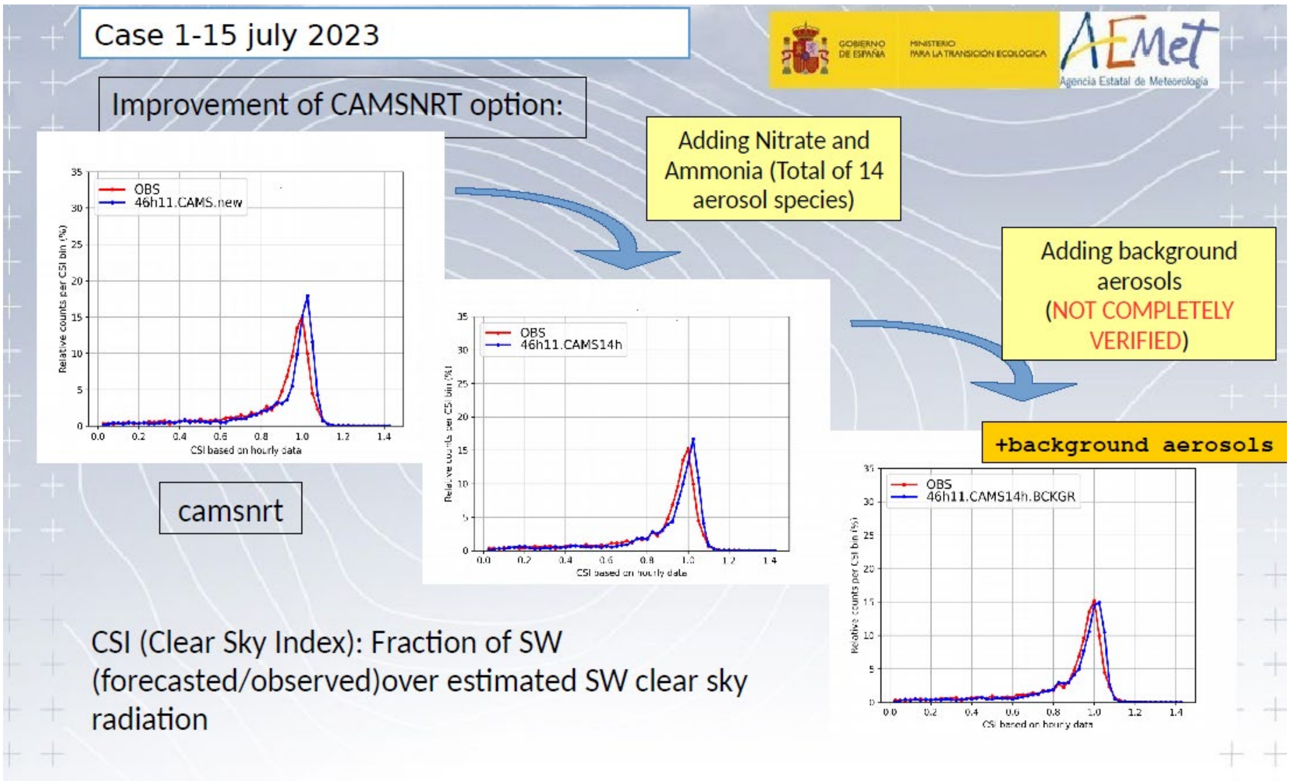

Fig. 2: Validation of Harmonie using NRT aerosol in the radiation scheme versus ground-based observations of Clear-sky index CSI, for a two-week period over Iberia in summer 2023. In the top left figure, Harmonie with 12 aerosol species overestimates the CSI compared to hourly CSI estimates from SW radiation observations. The fit to observations is improved by adding two more potentially relevant aerosol species, nitrate and ammonia (middle figure), and further still by adding background stratospheric aerosol, which had not yet been correctly included in the NRT aerosol codes (lower right figure).

In-depth validation of the new Ecrad radiation scheme in Cy49 versus the old IFS and ACRANEB radiation schemes has begun. First results have been obtained of testing Ecrad in Cy49 vs the old IFS radiation scheme with Tegen and CAMS aerosol climatologies. Work has started on enabling the option of computing radiation on a coarser grid than the remainder of the physics. Such an option is very attractive for making high-resolution models computationally more affordable. This will require externalization of the radiation scheme, and the use of the ATLAS library for regridding to and from the coarse grid.

B3. Sub-km resolution modelling
Meteorological assessment of several pre-operational sub-km models (500-750m horizontal resolution, ~90 levels in the vertical) is ongoing over many national domains. In scientific experimentation, attention is

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mostly focused on the development and validation of hectometric-scale (100-200m resolution) models in downscaling mode against supersites, Cloudnet data and LES runs. This move to hectometric models has given a strong impetus to the preparation and validation of high-resolution physiographic maps and a focus of attention on model performance over urban areas. New ML-enhanced physiographic datasets covering Europe at 60m resolution have been produced (Rieutord et al. 2024), and shown to be more realistic (fig.3). The codes for preparing and regularly updating this database have been parallelized for GPU, which makes its training an O(10) faster.

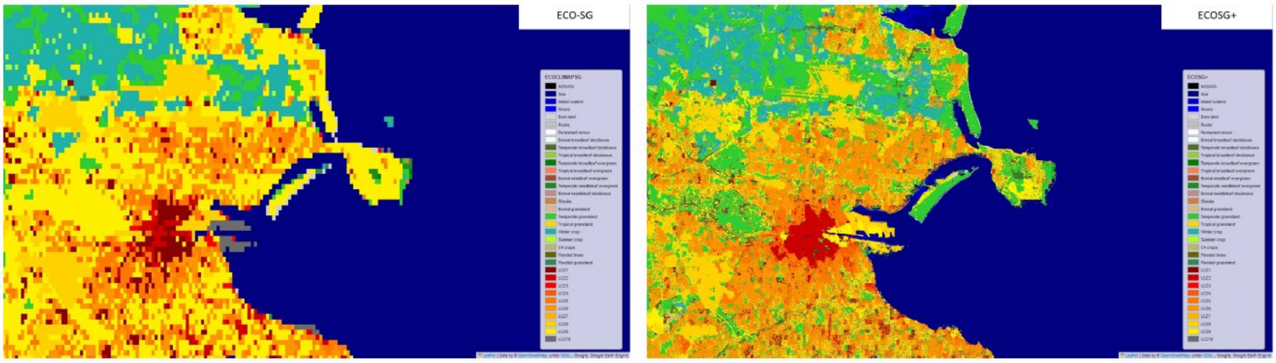

Fig. 3. An example of improvement of the ECOCLIMAP-SG land cover map in the Dublin region with AI: ECOCLIMAP-SG (left) and ECOCLIMAP-SG+ (right), based on a decision-tree method.

Assessment of the added value of both sub-km and hectometric-scale models as compared to operational mesoscale models is being performed in the context of use cases for the DE-330 project (Destination Earth-Extremes). One of the hectometric Harmonie model setups is being run daily over the Netherlands and validated against both LES runs and boundary layer profile data from the Cabauw supersite. Aspects that have been studied include the cloud representation as a function of resolution throughout the shallow convection grey zone in a variety of shallow convection formulations (in particular the new scale-aware shallow convection scheme, see B1), the impact of increasing the horizontal and vertical resolution on boundary layer dynamics and thermodynamics, the impact of nesting and coupling hydrometeors, and the development and assessment of quasi-3D turbulence and radiation schemes.

One big challenge for hectometric scale models is their representation of spatially highly variable urban areas. At present, in Harmonie there exists a strict interface between the atmosphere and surface at the lowest atmospheric model level, where state variables and fluxes are interchanged. A new approach which may be more realistic for the treatment of very heterogeneous urban landscapes is that by Schoetter et al. (2020), in which high buildings may interact with a number of the lowest model levels, depending on their height. Along those lines, a new coupling approach has been developed to couple the TEB urban scheme with several layers in the atmosphere. This multi-layer TEB scheme has been implemented and is being tested against a variety of urban areas for which dense observations are available, e.g. from the Paris 2024 Olympics observation campaign. So far, performance improvements of the new scheme against available observations have been seen in a fair number of cases, but not always; a very careful analysis and quality control of the local observations is needed still to have confidence in the outcomes of such studies. In a recently started European project, UrbanAir, intensive studies will be done over a larger set of European cities with dedicated urban observation networks. In this context, the performance will be studied of more advanced options in the TEB scheme and the optimal setting of sensitive parameters in it.

C) Surface analysis and modelling

C1: Improving the sophistication of surface model components

In the past years, many tests have been done with the new many-layer diffusion soil, extended snow and snow-over-vegetation schemes (DIF, ES, MEB) and the new SEKF assimilation scheme for soil and snow. In the operationalization of the new many-layer surface schemes, however, the remaining blocking point is the “drying issue” seen in ISBA-DIF: far too much evaporation over bare soil and low vegetation. Two possible solutions which have been extensively investigated in the past year are (a) the so-called “dry soil layer (DSL)” approach: adding such a hardened layer increases the surface resistance for evaporation from bare soil, and stores humidity in the soil throughout the year, which can then increase transpiration during summer, and (b) the addition of a mulch layer. These DSL and mulch approaches have both been comprehensively tested against observations from special sites and against dedicated surface flux campaigns, over several domains, but sofar have been unable to solve the drying issue. After these two failed attempts, it has been decided to organize an in-depth validation study of this problem, using a combination of approaches: validation of the surface energy balance and fluxes versus mast data and ICOS stations, an analytical solution for the heat diffusion equation, analysis of small-scale variations of soil moisture, and experiments with three patches (bare soil, rocks and permanent snow; forest; low vegetation) and (combinations of) several relevant soil scheme options, including the DSL and mulch options. Experimentation with this has started.

Online simulations with the roughness sublayer (RSL) scheme of Harman and Finnegan (2007) for canopy-induced turbulent mixing, have been done over Iberia and Sweden. This parametrization includes the concept of displacement height, and a more advanced computation of the roughness length z_{0m} as a function of leaf area index (vegetation sparseness) and atmospheric stability. Extensive offline validation experiments have shown improved performance when applying the RSL scheme. The present online RSL studies are focusing on the use of roughness length and blending height for the lowest model levels.

For the progress in urban modelling, see section B3 above.

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

The SEKF assimilation scheme which is being tested pre-operationally enables increased use of satellite surface products. Work is starting on the inclusion and testing of satellite retrieval data in the SEKF surface assimilation: snow depth from Sentinel-1, OSI-SAF and MODIS sea ice concentration and sea ice surface temperatures, soil moisture from Sentinel-1 C-band SAR and Metop ASCAT, and retrievals from various satellites in lake data assimilation. In the past year, the focus has been on snow assimilation involving satellite snow extent observations, which is important in the cold season in areas where SYNOP snow cover stations are sparse or missing. This so-called “snow barrel” method developed by FMI has been made operational in the MetCoOp operational collaboration.

Attention has been shifting towards the creation of a more advanced, strongly coupled atmospheric-surface data assimilation system, which is able to permit direct assimilation of e.g. satellite surface radiances. Presently, two roads to this are being pursued in parallel: an EnKF setup for Harmonie and a 2DEnVar framework for Arome-France. An intercomparison is being done between SEKF and EnKF in-soil profiles for Sodankyla. For the EnKF system, observed soil moisture profiles look more realistic after a fix of incorrect metadata at Sodankyla. SEKF shows less variability in the soil compared to EnKF, which seems realistic. The JEDI LETKF algorithm has been adapted for use in OOPS and is being explored for coupled DA. The strength of this method is that it permits rain gauge assimilation to improve the forcing, which is very beneficial. The downside is that it replaces the main model run by an offline run, which is considered suboptimal.

D) Probabilistic forecasting

For the HarmonEPS ensemble system, the focus of scientific development remains on model perturbations using SPP, gradually shifting attention from atmospheric to surface parameter perturbations. New atmospheric parameters for which perturbations have been introduced are the size distributions of solid water species and hydrometeor terminal fall velocities. The present operational SPP scheme, with perturbations of the five most influential physics parameters, has been re-tuned to remove bias issues. For this re-tuning, uncertainty quantification and optimization has been done using the URANIE platform, which was developed in the ESCAPE-2 project. Other available, less influential or more recently added parameters (such as the microphysics-related ones, and new surface perturbations for e.g stomatal resistance and inertia coefficients) have first been tested individually on top of this re-tuned, unbiased 5SPP system. Adding perturbations in e.g. the semi-Lagrangian scheme in this way has already been shown to give promising results in terms of spread-skill-bias behaviour. A few problematic parameters will be evaluated more deeply for cases specifically relevant to those parameters, rather than for test periods. The aim is to extend the HarmonEPS SPP system from 5 to 17 parameters in a pre-operational setup: 3 perturbations related to shallow convection, 8 to microphysics, 3 to turbulence, 2 to radiation and 1 to the semi-Lagrangian trajectories midpoint. This extension was originally intended to happen in the first half of

2025, but due to delays it will take place in the early autumn of 2025. The pre-op testing of this integrated SPP setup will likely require most, if not all, of the SBU special project resources of this year.

E) Machine learning (ML)

Activities in this field have been expanding rapidly in the past year. Examples of applications of ML within the context of the NWP model itself are e.g. the work on ML-derived observation operators and VarBC, the use of data-driven approaches to stochastic turbulence, the improvement of physiographic maps, and the detection and tuning of sensitive model parameters. For nowcasting purposes, ML algorithms have been developed on semi-transparent cloud removal and fog detection. Fully data-driven ML models for mesoscale forecasting, like Neural-LAM (https://github.com/joeloskarsson/neural-lam) and Bris (https://arxiv.org/pdf/2409.02891) are being explored and developed by several of the HIRLAM services in the context of the ECMWF ML pilot project, and fall outside the scope of this special project. Investigations to assess the ability of these ML models to represent basic physics processes in the atmosphere as compared to NWP models have recently begun.

F) Computational efficiency, portability and system aspects

Testing of single vs double precision has led to the adoption of single precision in large parts of the Harmonie-based model configurations. Options to further optimize the computational efficiency of 4D-Var (e.g. assessing the impact of using single precision in screening and trajectory computations) are being pursued in parallel with a more extensive and targeted quality assessment.

In order to make the Harmonie code suitable for use on new/mixed computer architectures, the Fortran code has been refactored for all default schemes and options within the Harmonie forecast model. Work is still ongoing on refactoring some remaining non-default options, which should largely be finished by the end of this year, excepting possibly some of the aerosol-related codes. The application of near-automated code adaptation tools on specific architectures has made it possible to derive GPU-enabled codes, however, this doesn't necessarily make these codes faster or more energy-efficient compared to CPU-based machines, for which codes have already been highly optimized. Further work will concentrate on making the refactored codes work together with a variety of compilers, to enhance their portability, and on further attempts to optimize computation efficiency for GPU's on a few specific machines.

The latest official Harmonie-Arome release, Cy46h1.1.1, has been made in March 2025, and the development suite is now based on Cy49T2h. A validated alpha-release Cy49T2h is expected to be made around July 2025. Most new elements in Cy49T2h-alpha (and Cy49-DEODE) have already been successfully ported and technically validated in Cy50T1. Major new elements brought into Cy49T2h have been:

- the refactored Harmonie physics codes;
- Surfex-v9 related changes and the new high-resolution physiographic datasets;
- 4D-Var scheme under OOPS, OOPS changes related to observations, all-sky assimilation;
- the scale-aware convection scheme, cloud-aerosol-radiation related changes, the wind farm parametrization;
- the recent additions to SPP physics perturbations;
- plus many technical changes such as the use of cmake for compilation, adaptations to permit sub-hourly cycling, single precision, and updated technical/user/scientific documentation.

The Harmonie testbed, which is routinely run to technically test all new Harmonie code contributions, was broken this spring and has only recently been recovered. Because of this, the meteorological testing of new Cy49T2h components, which was expected to be done on ATOS with Spsehlam SBU resources, has been delayed. This, in combination with the delays in the testing of the new 17-parameter SPP setup for HarmonEPS, has resulted in only very few Spsehlam resources being used in the first half of 2025. However, the regular testbed runs will be resumed soon, and with the planned computationally intensive SPP testing after the summer (see section D), it can be expected that the special project resources will be fully used again this year.