SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	HIRLAM-C 3d phase (2021-2022) Special Project
Computer Project Account:	spsehlam
Start Year - End Year :	2021 - 2022
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) plus ~70 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 and impact of high-resolution and remote sensing data to be assimilated (esp. all-sky radiances, crowd-sourced observations and satellite surface observations)
- improvement of the 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 analysis and modelling system.
- development of hectometric resolution 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 Bologna 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 2021 to December 2022)

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 scientific development and implementation of the mesoscale analysis and forecast system Harmonie, and its associated ensemble prediction system HarmonEPS. A Harmonie Reference system is being maintained on the ECMWF HPC platform. The 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, the atmospheric forecast model, surface analysis and modelling, ensemble forecasting and code aspects during this special project period 2021-2022 are outlined.

A) Data assimilation

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

The focus of activities in 2021-2022 has been on bringing the Harmonie 4D-Var system to operational status. 4D-Var is presently run in several pre-operational suites and is found to generally outperform 3D-Var, at relatively slight extra computational cost by means of OpenMP optimization and the use of single precision in the trajectory computation. The application of single precision in the screening is still under investigation. 4D-Var has been enabled to run with all observation types which are routinely used in 3D-Var assimilation. Work is still ongoing to further enhance the 4D-Var system with e.g. GNSS STD, radar winds and cloudy radiances. Experiments with the aim to optimize 4D-Var settings for the control vector (e.g. for the control of LBC) and extension zone are continuing. Also, a variety of 4D-Var configurations is being tested in nowcasting ensemble setups, sub-km resolution models and continuous data assimilation approaches.

In parallel to the 4D-Var development, a hybrid Harmonie 3/4DEnVar system has been developed for research purposes, in two slightly different flavours. Aspects like the optimal ensemble size, spatial scale-dependent localisation lengths, use of full or hybrid EnVar, and spinup issues have been studied. Intercomparisons between the different methods are being done, both from a data assimilation and from an ensemble perspective.

In 2021, a Harmonie 3D-Var version was created within the OOPS code framework and tested successfully with conventional data. In 2022, this setup was expanded with the use of more non-conventional data in 3D-Var, and a start was made with studying a Harmonie 4D-Var implementation. After completing this, the remaining nowcasting-related assimilation algorithms (cloud initialization (Gregow, 2017) and field alignment/variational control (Geijo 2012,2019) will be added to the OOPS framework in 2023 and later. In the coming years the OOPS EnVar system will be assessed and further developed for operational use, Also, the exploitation of new control variables, e.g. for hydrometeors or for surface quantities, will be studied, to assess their relevance for assimilation in the nowcasting range and for the move towards coupled atmosphere-surface data assimilation.

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

At present, the 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 volume data, GNSS ZTD, GPS-RO, SEVIRI water vapour observations, Mode-S data, AMV's and scatterometer winds. Work is still ongoing on improving the quality control and bias correction for e.g. radar radial winds, GNSS STD and observations from private weather stations and smart phones. Continuous efforts are made to monitor and further enhance the impact of these data types, through improved data quality control, the application of more intelligent thinning or super-obbing strategies, enhanced bias correction, and careful tuning and optimization of observation statistics and structure functions.

Recently added satellites have increased data coverage for radiances (especially in the morning) and for scatterometer winds. The impact of radiance observations has been improved due to better varBC updating procedures and enhanced cloud detection. Also the use of low-peaking MW channels has been significantly enhanced by the means of dynamic emissivity maps. An all-sky approach has been implemented for the assimilation of MHS cloudy radiances; work is ongoing to fine-tune blacklisting and assess the sensitivity to e.g. model microphysics parameters. The use of the supermodding approach and the footprint operator, initially applied to scatterometer data (Mile et al. 2021), has now been extended to radiances (fig.1). In the preparation for the use of MTG-IRS data, KNMI is exploring alternative ways to use hyperspectral data, building on the work done by De Haan and Marseille (2015).

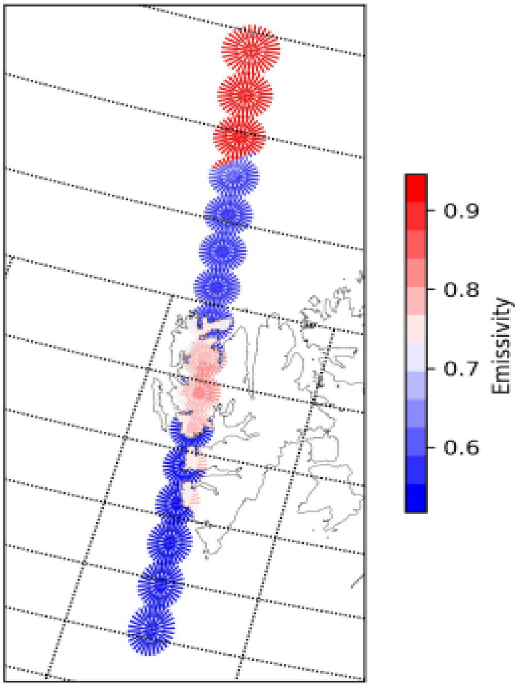

Fig. 1: Improved spatial representation of satellite radiances by a footprint operator applied to an AMSU-A single scan line over Svalbard. The figure shows the retrieved emissivity and how it changes when moving from south to north from sea to land to sea to sea ice.

The data coverage, quality and latency of Mode-S observations made available by EMADDC have all improved significantly. Both Mode-S wind and temperature data are now of a quality comparable to that of radiosondes and AMDAR data; because of their high spatiotemporal density over Europe, HIRLAM staff have begun to explore their use for verification of sub-km resolution models. After promising impact studies with GNSS slant delay data (positive impact up to +12h), a pre-operational run with the combined assimilation of zenith and slant total delays is under assessment. For radar data, the aim has been to develop a stable, high-quality ACCORD radar handling framework for both OIFS data and for the shorter-latency radar data available via Baltrad. A study has started on how best to handle different sensitivities of neighbouring stations in radar reflectivity assimilation. For assimilation of radar radial winds, AEMET experiments have shown that a very careful quality control of elevation data and choice of superobbing sizes are needed. Radar assimilation experiments with 4D-Var have shown that 4D-Var is able to improve the bias in relative humidity significantly with respect to 3D-Var.

Promising results have been obtained in studies of the assimilation of screen level parameters in the upper air analysis, and in an assessment of BUFR descent radiosonde data. Work on the collection, quality control and assimilation of third-party observations from private weather stations (PWS), smart phones (SPO), wind farms, boundary layer lidars/ceilometers, urban networks and car/road observations has continued. Data and quality control procedures for NetAtmo and WOW PWS observations have been made available for an ongoing Eumetnet intercomparison of quality control procedures for these data. DMI has set up a robust data flow for obtaining “depersonalized” SPO data and pre-process and apply them in assimilation in real-time runs. This pre-processing is still quite challenging (Hintz et al., 2021). The code to collect and pre-process SPO data can be added as a module in NMS weather apps. Careful intercomparisons are underway of the processing and relative impact of surface pressure observations from NetAtmo stations and smart phones, with the aim to better understand the differences in impact between these data sources.

A3. Optimization of data assimilation setups for the nowcasting range

For nowcasting, the focus is on moving towards sub-hourly cycling and assessing the challenges for assimilation on those timescales, particularly the issue of model spinup, in a common nowcasting branch. Technically, sub-hourly cycling has been enabled in the Harmonie code and scripts, and experimentation with it has started. For observations, the focus is on data sources with sufficiently short latency (10-20m): SYNOP,

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EMADDC Mode-S, radar (Baltrad), NetAtmo/WOW stations and various sources of (polar) satellite data. A comprehensive set of experiments is being carried out to systematically test and intercompare different data assimilation configurations in the nowcasting range: varying observations usage, different cycling strategies (e.g. sub-hourly vs hourly, continuous, overlapping windows) and initialization techniques aiming to reduce spinup (e.g. DFI, IAU), several data assimilation methods (3D- and 4D-Var, EnVar), and various assimilation strategies (use of ensemble information, background from long vs short cutoff, LBC treatment), plus several methods aiming to bring the model analysis closer to observations (cloud initialization (Gregow 2017), field alignment and variational control (Geijo 2012, 2019) techniques).

Problems with correlated observations become more pronounced at higher temporal and spatial resolution. For 4D-Var especially, temporal correlations are an issue to be tackled. For the handling of spatially correlated observations, error modelling approaches are being considered as a more sophisticated alternative to standard thinning or superobbing practices. New or improved SAF products are being tested for a better initialization of cloud characteristics and identification of multi-layer clouds.

One relevant issue is how to best take the large scales from the nesting model into account in the nowcasting range. For this, there presently are the LSMIX and Jk cost function approaches available. Ole Vignes has derived an alternative model cost term treatment, by combining nesting and nested model background into a single background cost term; first tests have shown the performance of this "mixed" cost term approach to be better for the short range (up to ~12h) in the summer, less clear results were obtained for a winter period. These investigations will be continued.

B) Atmospheric forecast model

B1. Studies to eliminate systematic model errors for clouds and fog:

A long-standing forecasting problem has been the prediction of fog under stable boundary conditions, especially over sea: 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 assumptions made in the ICE3 microphysics scheme on the density of cloud condensation nuclei. This experimentation has led to 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. This was done as a temporary pragmatic solution before the anticipated introduction in the coming years of near-real-time observed aerosol and (later) the second-moment microphysics scheme LIMA. 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 are being explored further in the context of SPP perturbations for HarmonEPS.

A more definitive solution is expected from the use of the second moment scheme LIMA and the introduction of aerosol parametrizations, in combination with near-real-time aerosol initialization from CAMS. However, there are still many aspects to experiment with, and tune, this setup. Work has started on a parametrization describing the fraction of aerosols which are active in condensation. 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. HIRLAM participation in the model inter-comparison experiments for the SOFOG3D IOP's may be very useful for the tuning of this aerosol activation.

A weakness of the Harmonie model has been its poor representation of open cell convection features observed in clouds, and the precipitation associated with them. A reduction of the too strong momentum mixing by the shallow convection scheme has led to a more realistic organization of open cell cloud structures, and the light precipitation associated with such clouds.

In the coming years, attention will shift more towards a long-standing problem in all NWP models: 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 will require 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 will be required to 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-radiation – microphysics- aerosol interaction:
A consistent dataflow has been developed for introducing a consistent use of both near-real-time and climatological aerosol information from global and regional CAMS data: 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. Presently, 11 types of aerosol can be retrieved. Case studies have shown that near-real-time aerosol information may have significant (beneficial) impact in individual cases on e.g. model snowfall amounts, dust attenuation of SW radiation, fog and precipitation. Longer-term impact studies for both near-real-time and climatological CAMS aerosol information are being carried out for several domains. Research is ongoing on a parametrization describing the fraction of aerosols which are active in condensation. 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. The added computational cost of using NRT aerosols is ~12-24% of the present forecast model cost.

The aerosol experiments have been done using the 1-moment ICE3 microphysics and the present default Harmonie radiation scheme. It is intended to redo them with the second moment LIMA scheme and with ECRAD, as soon as these schemes have been made available and sufficiently tested.

B3. Sub-km resolution modelling
Most HIRLAM services have implemented, and are running routinely, real-time sub-km (150-750m) horizontal resolution model setups, to discover the limitations which the present dynamics and physics parametrizations may have there. Some of these setups have reached operational status already. Many research avenues in the field of hectometric modelling are being explored, ranging from the creation of appropriately fine-scaled physiography (see section C3), sensitivity and grey-zone studies and developments on (quasi)3D-physics, to developing ideas on how to set up a common data-centric workflow for on-demand triggering of hectometric-scale LAM runs, and pursuing machine learning options for enhancing their computational efficiency.

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. Some experimental suites have shown noise issues in setups with resolution <500m; the optimal dynamics settings to handle these are being investigated.

In daily running nested model setups down to 100m resolution, the transition is being 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 for "intermediate" scales, scale-aware parametrizations are under development. 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 in 2023 work will start on an intrinsically stochastic turbulence scheme. Machine learning approaches have been selected with which to pursue this further.

Ideas have been developed to introduce computationally affordable quasi-3D physics schemes for radiation (pursued by HIRLAM). After introduction of the ECRAD radiation scheme in Harmonie, 3D cloud shading effects on radiation can be modelled using the SPARTACUS solver in ECRAD, in combination with machine learning. Also the possible use of process-dependent time-stepping and resolution for individual physics schemes is under consideration, primarily in order to reduce computational costs. This will be pursued in 2023 and onwards.

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. After successful initial tests over the Arome-Arctic, this combination of schemes is now being run in a pre-operational mode for several other European/Atlantic domains. This setup uses assimilation of screen level conventional and, over some domains, additional private weather station data. In general, the combination of new surface schemes results in an improved diurnal cycle for screen level parameter, warmer and dryer model

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behaviour during winter, and colder and wetter behaviour in summer. The new surface description gives positive-to-neutral results over most areas and seasons. However, there remains a problem with snow melting too fast in spring. This may be due the fact that a soil column can contain both snow-covered and snow-free surfaces. A separation of soil columns for snow-covered and snow-free fractions has been implemented to tackle this, and this setup is being tested.

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.

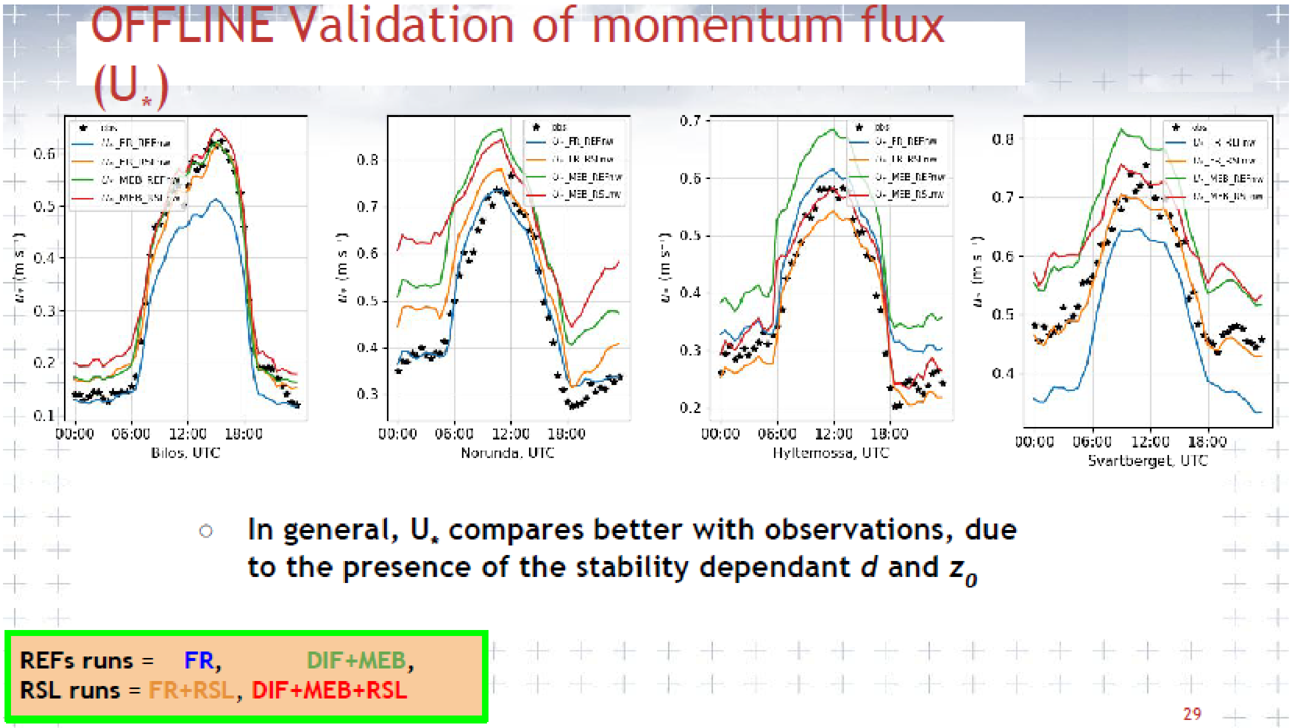

Fig.2: Validation of the impact of the Roughness Sublayer Scheme (RSL) on surface momentum flux against four ICOS forest sites (Bilos, Norunda, Hyllemossa and Svartberget, from left to right) in offline Surfex runs. The dark blue and orange curves represent the computed friction velocities modelled with the force-restore soil scheme without and with RSL, while the green and red curves are for U* computed by the many-layer soil and forest scheme without and with RSL. The runs with RSL generally compare better with observations. This is also seen for sensible heat fluxes. The impact of RSL on latent heat flux is small.

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 will be 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. This approach may be more realistic for the treatment of very heterogeneous urban landscapes in hectometric scale models.

A new parametrization for surface fluxes over the ocean, ECUME-6, has been tested. ECUME-6 in general was seen to lead to stronger fluxes of heat and moisture than its predecessor, to more accurate near-surface values and low-tropospheric profiles for temperature and humidity, and a lower bias in mean sea level pressure. However, the scheme was shown to overestimate the latent heat flux over sea, leading to cloud and radiation biases there, as confirmed by observed ocean fluxes from the EUREC4A campaign.

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

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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 maps 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, scientific developments have continued to focus on model perturbations using SPP. Presently, a set of 13 atmospheric parameters has been identified which has shown some appreciable impact on ensemble spread, five of them providing most of this impact. A version of SPP with these five parameters has entered operations in MetCoOp in August. After the decision to generate and apply the perturbation pattern in SPP only hourly rather than every time step, the computational cost increase of this new model perturbation setup could be limited to only +0.7%. Experiments have been done for all 13 atmospheric parameters with alternative parameter pdf distributions (uniform and shifted uniform vs the default lognormal distribution), and for studying the behaviour of correlated parameters (Frogner et al. 2022). For some parameters, ensemble spread, skill and bias behaviour have been shown to be quite sensitive to the assumed pdf distributions, particularly for cloud-related parameters (fig.3). Initial experiments using the same perturbation pattern for two correlated parameters resulted in less bias and better spread.

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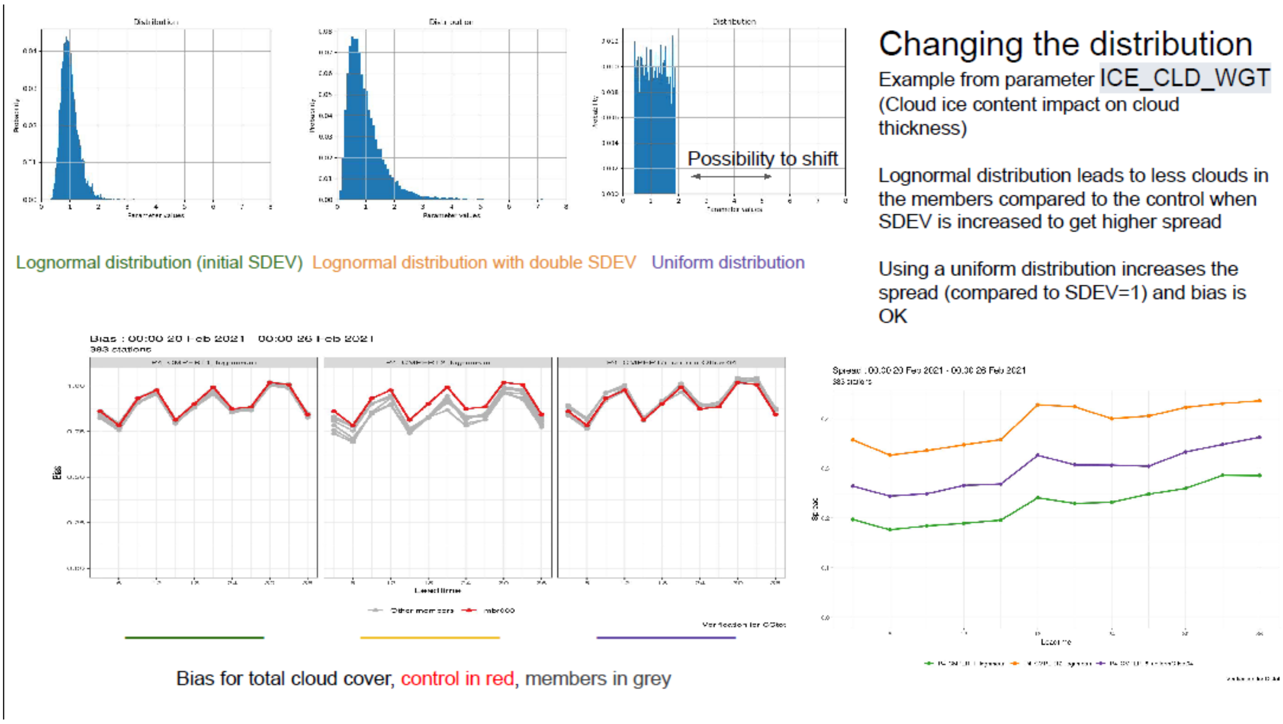

Fig. 3: The impact of changing the distribution of a cloud ice model parameter within SPP from lognormal top left, green curve in the right bottom figure of spread vs) to a broader lognormal distribution (top middle, orange) and a uniform distribution (top right, purple) on ensemble bias (left bottom) and spread (right bottom) versus lead time for total cloud cover. The uniform distribution gives a similar bias behaviour to the lognormal one but higher spread.

Several new mass-flux related parameters have been identified in the shallow convection scheme which affect the intensity of moist and dry updrafts. Experiments with these parameters over several seasons show appreciable impact during summer convective periods, moderately increasing ensemble spread for near-surface and cloud parameters and some improvements in CRPS, FSS and RMSE, without any systematic ensemble bias issues. Some parameters related to the shape of particle size distributions in the microphysics are still being experimented with. A start will be made soon with testing perturbations of hydrometeor fall velocities. Work has also started in 2022 on implementing perturbations for the first two surface parameters in SPP: the heat capacity of vegetation (CV) and minimum surface resistance (RSMIN).

For the perturbation of surface fields, a long-standing problem of drying of ensemble members with respect to the control has been cured by permitting soil wetness index (SWI) perturbations only in grid points where all perturbed SWI values are no closer to field capacity or wilting point than one standard deviation.

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. SP vs DP experiments with the five parameter SPP setup over four seasons are still ongoing. If the random number generation for the pattern generator is done in 64 bit, the SPP perturbation patterns in single and double precision are found to be reproducible. 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.

E) Computational efficiency, portability and system aspects

Various tests have been carried out for Harmonie-Arome in single vs double and mixed precision (SP/DP/MP), for the forecast model and for the 3- and 4D-Var data assimilation and ensemble systems, see sections A and D 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 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). This will later be implemented and tested in Harmonie-Arome as well. This type of emulation by ML will be extended to other parametrizations (e.g. quasi-3D radiation) in the future. 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 important to establish model performance on a range of different architectures. A "containerized" version of the model has been made and used to permit porting to a wide range of platforms for benchmarking purposes (involving CPU, GPU, AMD, ARM and mixed architectures). Kernels are being developed for smaller parts of the model, to facilitate faster detection and localization of computational performance problems and easier porting of code components, e.g. to university partners.

In 2022 a start was made with the refactoring of the forecast model code, needed for near-automated code adaptation tools to optimize use on GPU and other (mixed) architectures. These efforts, which should be largely finished during 2023, also permit a large cleanup of the main forecast model steering routines, and achieve a greater interoperability between the Arome-France, Harmonie and ALARO forecast models at the level of individual parametrizations schemes. The second step will then be to adapt the refactored code largely automatically for use on other HPC architectures. This is done in different ways for different parts of the code. For spectral transforms and machine learning emulation algorithms, hardware-optimized external libraries and API's will be used like the ECTRANS library developed by ECMWF. For grid point calculations, semi-automatic code transformation tools (LOKI, fxtrans) are being considered to generate hardware-specific code through e.g. loop re-ordering, memory layout etc. Application of these tools to make the refactored Harmonie codes ready for efficient use in GPU or mixed CPU-GPU architectures will be a main priority for 2023-2024.

List of publications/reports from the project with complete references

Jan Barkmeijer, et al., 2021: HARMONIE-AROME 4D-Var. *ALADIN-HIRLAM Newsletter* 16, p.20, www.umr-cnrm.fr/aladin/IMG/pdf/nl16.pdf

Y. Batrak, 2022: Parametrization of sea ice cover in short-range regional numerical weather prediction, Ph.D. thesis, Helsinki University.

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S. Contreras Osorio, et al., 2020, Impact of the microphysics in Harmonie-Arome on fog, *Atmosphere* 13(12), p.2127-2146

I.-L. Frogner, et al., 2022, Model uncertainty representation in a convection-permitting ensemble – SPP and SPPT in HarmonEPS. *MWR* 150, p.775-795, https://doi.org/10.1175/MWR-D-21-0099.1

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Future plans

A new special project has been requested for the final phase of HIRLAM-C, 2023-2025. In that final period, the main priorities will be:

- 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. Introduce and assess 3/4D EnVar, optimize nowcasting setupa, and work towards coupled data assimilation.
- Include new satellite (surface) observations and increase the use of very high resolution third-party data.
- Develop and assess hectometric scale and nowcasting (ensemble) setups, with focus on urban aspects
- Assess impact of more realistic descriptions of the microphysics, radiation, use of real-time aerosol, stochastic physics, roughness sublayer and surface physiography.
- Continue to build experience with machine learning in all parts of the Harmonie system.