SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	HIRLAM-C 2d phase (2019-2020) Special Project
Computer Project Account:	spsehlam
Start Year - End Year :	2019 - 2020
Principal Investigator(s)	J. Onvlee
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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)
- improvement of the model behaviour for low clouds, fog and stable boundary layer conditions
- increasing the range and impact of high-resolution and remote sensing data to be assimilated (esp. all-sky radiances, OPERA radar data, crowd-sourced observations and satellite surface observations)
- a more sophisticated and consistent description of the radiation-cloud-microphysics-aerosol interaction and winter stable boundary layer conditions
- a more sophisticated surface analysis and modelling system
- definition of and experimentation with sub-km resolution nowcasting (ensemble) setups
- and achieving enhanced computational efficiency, scalability and portability

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

No problems worth mentioning. Excellent support from ECMWF as usual.

Experience with the Special Project framework

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

The automated submission procedures for application and reporting have been a step forward.

Summary of results

The HIRLAM-C research programme (January 2016 - December 2020) is a research cooperation of the national meteorological institutes of Denmark, Estonia, Finland, Iceland, Ireland, Lithuania, Netherlands, Norway, Spain and Sweden, with Meteo-France as associated member. Within HIRLAM-C, research efforts are focussed on the development, implementation and further improvement 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 are primarily used for experimentation with, and evaluation of the performance of, 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 efficiency during the past year are outlined.

A) Data assimilation

A1: Optimal use of (high-density) atmospheric observations:
During this second phase of the HIRLAM project, the Harmonie model used as default a 3D-Var assimilation system, which assimilates conventional data and cloud-free radiances from AMSU-A, AMSU-B, MHS and IASI. Additionally, it was possible to assimilate optionally several types of spatially and temporally dense data: radar radial wind and reflectivity volume data, GNSS ZTD, SEVIRI water vapour observations, Mode-S data, AMV's and scatterometer winds, and data from private weather stations. The main focus in the years 2019-2020 has been on continuous efforts for all these data types to improve data quality control and variational bias correction, the application of more intelligent thinning or super-obbing strategies, and careful tuning and optimization of the observation statistics and structure functions.

Work has continued to improve and homogenize the preprocessing of various types of observations. Many HIRLAM services have tested and implemented the Scalable Acquisition and Prep-Processing (SAPP) system to handle standard as well as non-conventional data types (e.g. Mode-S, crowd-sourced data). The development has begun of a more homogeneous way of handling OPERA data to permit use of radar data from a wider range of countries, using the HOOF homogenization tool developed by LACE and the PrepOpera algorithm developed by HIRLAM for super-obbing of the radar data. During the COVID-crisis, due to the scarcity of AMDAR aircraft observations, Mode-S observations have become a very valuable addition to the European observation network. The number of Mode-S data being exchanged through EMADCC has increased significantly, The preprocessing of Mode-S data in EMADCC has been adapted to derive temperature data with greater accuracy. The quality of these data now has become similar to those of AMDARs and radiosondes, and bias correction of Mode-S temperature data no longer appears to be needed.

The work on the assimilation of new radiances from Metop-C, FY-3C and FY-3D, including the tuning of VarBC, has been successful. Positive impact has been seen from these data, partly because of the improved daily coverage, and many services have started to use these data operationally. Options to use more low-peaking channels and emissivity atlases have been investigated, with mixed success. Similarly, impact assessments have been carried out for scatterometer winds from Metop-C and HY2B. These data were shown to be of good quality, and are being introduced in various HIRLAM services. Real-time Aeolus Horizontal Line of Sight (HLOS) observations showed good impact in Harmonie, despite their relatively small data volume. Work has been done to derive a bias correction for these data. To take into account the footprint of scatterometer data relative to the effective model resolution, an improved supermodding approach has been implemented and optimized in the 3D- and 4D-Var observation operator for ASCAT winds. As a next step, the assimilation team has started to apply supermodding to radiances.

The assimilation and bias correction of surface pressure and screen level parameters in the atmospheric analysis has been investigated. Also, an assessment has been made of the potential use of descent radiosonde data. In both cases, promising results have been obtained over several domains, so these data sources will be included in the Harmonie atmospheric assimilation system in the near future.

Third-party data from e.g. private weather stations (PWS), smart phones, wind turbines, and road observations are of increasing interest, as the greater spatial density of such data with respect to standard meteorological observing networks permits better identification of fine-scale weather features, in particular also over urban areas. PWS data have been shown to have a good potential to improve short-range forecasts by direct assimilation, provided that sufficient attention is paid to their quality control and bias correction. Investigations on further extending the range of observed parameters assessed from PWS's and optimizing their quality control with machine learning techniques are continuing. Even for the WOW-network, where

PWS's are of less homogeneous quality than e.g. NetAtmo stations and bias correction is far more challenging, the addition of quality-controlled and bias-corrected WOW observations to a standard SYNOP network was shown to add value in short-term forecasts (Chen et al. 2021). In general, for mobile data sources such as phones or cars, quality control has been shown to be a complex issue requiring very careful attention. Additionally, privacy concerns may be an issue for several types of crowd-sourced data. For smart phone data therefore a processing has been developed which "depersonalizes" these data in accordance with privacy constraints, albeit at some cost to their spatial resolution.
In the context of Copernicus re-analyses for Europe and the Arctic, a European setup, CERRA, has been prepared for operations and been shown to be an improvement with respect to its predecessor UERRA. The CARRA (Copernicus Arctic Regional Re-Analysis) setup for the Arctic has entered operations.

A2: Development, operationalization and optimization of flow-dependent data assimilation methods.
There have been two main objectives in this area: prepare 4D-Var for operational use, and, for the longer term, continue the development and start deployment of (hybrid) ensemble assimilation methods.
The 4D-Var objective has been achieved as intended. Many longer runs and case studies have been performed with multi-incremental 4D-Var with different combinations of high-resolution observations, in order to test the best settings for this system. Tests have shown that the use a larger than default extension zone (200-300km) in the minimization step (in order to better represent horizontal error correlations in the assimilation) gives more realistic results. The use of multi-incremental 4D-Var has been enabled for the full set of observations which can be used in the Harmonie 3D-Var, and impact assessment experiments with adding progressively all these observation types have been performed for several domains. Optimal settings have also been derived for the choices for outer loops and resolutions, time windows, control variables, etc. (Barkmeijer et al. 2020). 4D-Var was shown to outperform 3D-Var consistently in meteorological terms, and also to be able to make better use of observations.

The 4D-Var computational performance has been improved to achieve an operationally affordable setup. The MPI parallelization of the code has been enhanced, and efforts on a more effective OpenMP parallelization are ongoing. Studies with single, double and mixed precision setups have shown that much of the 4D-Var code can be run at single precision, reducing computational costs by ~30%. In 2021, 4D-Var will be implemented in Harmonie-Arome and enter operations.

4D-Var has also been tested in the nowcasting range. In near-real-time runs with multi-incremental 4D-Var in nowcasting mode, hourly 3D-Var, hourly 4D-Var and 4D-Var with overlapping windows are now being intercompared. Several adaptations (a correction for a recently discovered wrong use of LBC data and the introduction of control of LBC at the beginning of the time window) have been made to further improve the 4D-Var performance in the first few hours of the forecast. At a later stage, it is intended to test 4D-Var also at higher (750m/90L) resolution.

On a longer term, an ensemble assimilation system is envisaged. Two alternative ensemble assimilation methods, an LETKF and a hybrid EnVar system, have been developed for this and introduced as options for experimentation. The hybrid EnVar system can make use both of observation perturbations and of perturbations in the B-matrix (so-called B_{rand} perturbations). Both setups have been upgraded in 2020 to the latest Harmonie pre-operational cycle (Cy46h). Longer inter-comparison experiments against operational 3D-Var have given some positive results so far, but also some options for improvement which require further elaboration. Following this, in 2021 a set of intercomparisons will be performed to test hybrid EnVar/B_{rand} and LETKF against each other and against standard 3D- and 4D-Var.

A3. Optimization of data assimilation setups for the nowcasting range
For nowcasting, one would like to assimilate the latest observations fast and frequently. However, limits are put on this by model spin-up in the first hour or two of the forecast. In 2019 and 2020 several avenues have been explored to achieve this. Above, the experiments to test whether 4D-Var configurations may be better able to handle spin-up have already been mentioned. The continuous or overlapping window cycling strategy used in COMEPS (Yang, 2018) has permitted efficient use of the most recent observations in an ensemble in combination with relatively long assimilation windows. For 3D-Var, DMI has set up and begun testing a nowcasting version of its COMEPS Harmonie ensemble system with six parallel suites with base times consecutively shifted by 10 minutes, short cut-off times and with hourly or two-hourly assimilation cycling of frequently available observations. A start has been made with creating a setup for sub-hourly cycling. In 2021 and onwards, this setup will be applied to 3D-Var, but also in a 4D(En)Var framework.

At high spatial and temporal resolutions, it becomes increasingly important for the analysis system to be able to correct for position and phase errors of fine-scale atmospheric features. Present variational methods are not well versed in handling such non-additive errors. In earlier years, the field alignment (FA) method has been developed, by which displacement errors of e.g. the modelled precipitation or wind field with respect to radar 3D data can be identified and corrected before 3D-Var takes place. FA is mainly beneficial in the nowcasting range, showing e.g. a significant reduction of errors in wind fields in the first 6 hours of the forecast. To reduce the problems of model imbalance in the nowcasting range, a new initialization formulation has been developed. The introduction of this so-called variational constraints (VC) method (Geijo and Escriba, 2018) has been shown to achieve a better handling of analysis increments and a faster balancing of the model. VC and FA together appear to act in a complementary manner to enhance model performance in the nowcasting range. The FA/VC codes are being upgraded for integration in the most recent Harmonie cycle.

A good description of the 3D structure of clouds is an essential ingredient for nowcasting. The cloud initialization (CI) method was developed to permit a more sophisticated use of NWC SAF cloud products (cloud type, mask and microphysics) from MSG and polar satellites to adjust 3D humidity in model analyses and nowcasts (Gregow, 2017). The CI scheme has been shown to have a beneficial impact on cloud scores, and has become operational in MetCoOp; but it has shown weaknesses in situations of clouds at multiple levels in the atmosphere, and it has had little success in removing persistent erroneous fog from the model analysis. In 2021 it will be studied if the scheme can become more successful in these situations by limiting CI adaptations to a few model levels or by applying it only conditionally, in case of erroneous model clouds.

B) Atmospheric forecast model

B1. Studies to eliminate systematic model errors for clouds and boundary layer behaviour:
Coordinated experimentation has been performed in the past two years with the aim to understand the (multiple) causes of observed poor model behaviour for convection and low clouds: the timeliness and initiation of deep convection, the description of stratiform precipitation and open cell convection, too persistent fog in the model, a negative cloud frequency bias and a too high model cloud base in fog situations. Several clear avenues of improvement were identified and pursued for improving the representation for convection, low clouds and fog.

One cause of problems with the model triggering convection too little and too late has turned out to be the unrealistic description of climatological evapotranspiration in ECOCLIMAP2.2, in combination with a too strong impact of the surface assimilation. A new physiographic database, ECOCLIMAP-SG, was shown to offer a significant improvement in this respect.

Initiation of supercell formation in the early evening sometimes did not happen. This appears to be caused by too much dry air being mixed by the HARATU turbulence scheme from above into the boundary layer, which may then have become too dry to permit convective initiation. A set of changes in the cloud and turbulence schemes, involving reduced mixing from the cloud layer, changes in the free atmospheric length scale, and several adaptations affecting the mixing of momentum and moisture near inversions, led to a positive impact on the representation of deep convection and precipitation, but also of low clouds.

In stable boundary conditions, fog has long been a significant problem. Generally, fog was shown to build up too quickly, have a too large extent (especially over sea), be too dense (too much cloud water), and cool too much over sea. Fog layers in the model already start to cool strongly when the fog layer is still quite shallow, much more than observed. An increase in model vertical resolution in the boundary layer did not alleviate this problem. Detailed well-observed case studies showed that fog evolution is extremely sensitive to the amount and evolution of cloud condensation nuclei (CCN), and to the way in which the cloud emissivity is formulated in the long-wave radiation parametrization. The best solution will be to combine the use of near-real-time CCN density values derived from CAMS, with the use of the aerosol parametrizations and the new second-moment microphysics scheme LIMA which permits CCN densities to evolve. This combination will become available for testing in Cy46h1 in 2021. In the operational 1-moment ICE3 microphysics scheme, fixed values for CCN densities were assumed over sea, land and urban areas. It has been shown, however, that fog problems can be reduced strongly by a drastic reduction of the fixed values of CCN density in the lowest km or so of the atmosphere (in agreement with observations), in combination with a change in cloud emissivity in the long-wave radiation parametrization. Due to the thus diminished overprediction of cloud water in the model, less fog occurs over sea, and it no longer quickly grows and spreads (e.g. fig.2). The proposed changes in CCN density values also result in removing the present negative bias in SW radiation, and in much better behavior of precipitation in e.g. the Norwegian coastal and mountainous areas. However, they have not yet fully solved the issues with fog over sea, and some retuning may still be needed to ensure that e.g. summer convection behavior of the model is not degraded.

Another long-standing problem has been the underestimation of temperature minima at night during very stable boundary layer conditions. This behaviour is very sensitive to the value adopted for the maximum Richardson number. Optimizing this value leads to more accurate night time temperature minima under stable to very stable conditions, and improvements have also been seen for fog.

A third weak point is the balance between “cold” and “warm” hydrometeors in mixed-phase clouds and the way in which they interact with the development of convection. In both 1D and 3D experiments, it was shown that the ICE3 microphysics scheme lets far too much solid precipitation form in the form of graupel and too little in snow. This may lead to an underestimation of cold pool formation. Elements of the Thompson microphysics scheme have been implemented in the standard ICE-3 scheme. This leads to a more realistic division of precipitation between snow and graupel, more supercooled liquid water and less ice, and more production of snow and freezing drizzle. It also provided a more realistic description for the stratiform precipitation which is formed from the dispersion of the anvil in the dying-out phase of the deep convection life cycle, and a better representation of open cell convection and precipitation in mountainous areas.

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

Work has continued on quantifying the benefits (and costs) of using aerosol parametrizations in combination with near-real-time aerosol information from CAMS on clouds and radiation. Experiments are being carried out with cloud-radiation-aerosol interactions for a variety individual aerosol types, using prescribed daily CAMS global 137 level aerosol fields. Cy43h2 has been adapted to include NRT 3D mixing ratio aerosol fields from CAMS in the cloud and microphysics schemes, and in the hlradia radiation scheme: ~11 types of aerosol, including sea salt, hydrophilic black carbon, organic matter, sulfate, nitrate and ammonium. Aerosol wet deposition has been included.

For the radiation scheme, CAMS mass mixing ratios for the individual aerosol types are combined with prognostic model specific humidity fields for each time step, grid point and level, with prescribed inherent optical properties. From these, e.g. the optical depth AOD and transmission are calculated for the aerosol mixture. Sensitivity studies have been done for the simple hlradia scheme, showing clear impact on short-and longwave radiative fluxes. Work remains to be done to include the inherent optical properties and mass mixing ration CAMS fields also in the radiation schemes IFSradia and ACRANEB2.

Rather than assuming cloud condensation nuclei concentrations to be constant, the microphysics scheme has been updated to calculate CCN concentrations from the CAMS mixing ratio fields assuming log-normal size distributions. These are then used in the auto-conversion, cloud droplet sedimentation and cloud liquid collision processes. One month of verification (September 2019) has been carried out with and without aerosol parametrizations in the radiation and microphysics schemes. The ETS of precipitation and the bias in RH2m improved, at the cost of a degradation in T2m bias as function of forecast length. This may be due to the fact that the dependence of the mass extinction of hydrophilic species on humidity was originally ignored. Including this dependence bring the global radiation and direct normal irradiance in closer agreement to observations. Studies over Norway have shown that including the aerosol forcing from NRT CAMS fields leads to a much improved representation of coastal and mountain precipitation, reducing the customary coastal dry bias and the wet bias over the mountains significantly.

The use of aerosol information in this way increases the cost of Cy40h runs with 14%. This will need to be confirmed for Cy43h2.1 as well, and work will need to be done with the aim to optimize the aerosol code further (e.g. by not using the CAMS fields for every time step).

B3. Sub-km resolution modelling

At present, the Harmonie forecast system is generally operationally run at 2.5km horizontal resolution and with 65 layers in the vertical. Efforts have been made to investigate and optimize model performance at higher horizontal (300-750m) and vertical (90L) resolutions. A recommended setup of the model has been prepared for sub-km experimentation: dynamics settings, manner of nesting, vertical resolution and level definition, and the use of continuous (overlapping windows) assimilation. This setup has been used in subsequent testing. A critical aspect for all partners is the (sometimes poor) quality of the ESA-CCI-based surface characterization (orography and physiography), and the proven need to optimize this using local high-resolution databases. It will require a significant effort to do this consistently across European borders. Some issues with climate generation and the use of sub-hourly output remain to be solved in the short term.

More efforts will be required to e.g. arrange for sub-hourly input (observations and boundaries), and to determine the proper scales of the B-matrix corresponding to the model resolution. The use of single precision in high resolution models still remains to be investigated.

Tornadoes are a phenomenon which seems to be occurring increasingly in Europe. At 2.5km resolution, Harmonie is not able to adequately represent such fine-scaled features. However, in 1km resolution runs over the US, it was shown that Harmonie is able to represent the typical “hook echo” structure which is characteristic for the larger-scale flow around tornadoes. Updraft helicity, which is known to be a good indicator for tornado occurrence, will be included as a parameter in the model post-processing.

C) Surface analysis and modelling

C1: Improving the sophistication of surface model components

A critical aspect for surface modelling is the quality of the surface characterization, and the need to optimize this at sub-km scales using local high-resolution databases in a consistent manner. In Surfex v8.1, a new and spatially more detailed (resolution 300m) version of the physiographic database, ECOCLIMAP-Second Generation, which contains physiographic information which has been more directly obtained from ESA/CCI satellite observations. Much effort has been done in the past two years to assess the strengths and weaknesses of ECOCLIMAP-SG and the consequences of applying it for model performance. The main characteristics of ECOCLIMAP-SG in comparison to its predecessor ECOCLIMAP-v2 have been described in Samuelsson et al. (2020). The description of coastal and urban areas and the yearly cycle of evapotranspiration are clearly represented in a more realistic manner in ECOCLIMAP-SG, although some weaknesses have been identified as well, which partly remain to be addressed. It has therefore been decided to adopt ECOCLIMAP-SG as the new physiographic database in Cy43h2. The significant differences between the old and new databases made it necessary to assess very carefully for which aspects of the surface model parameters retuning was appropriate, and to optimize those parameters to use in combination with ECOCLIMAP-SG (e.g. modified heat capacity, maximum Richardson number, stomatal resistance and the vegetation roughness formulation). One serious weakness of ECOCLIMAP-SG is that in pixels which in reality have mixed low, middle and high vegetation, pixel values are assigned only to the dominant vegetation type. This introduces systematic biases in near-surface parameters into the model for which temporary fixes have had to be found until more permanent solutions can be introduced. In addition, ECOCLIMAP-SG can still benefit from quite many local adaptations, and introducing these will require a significant effort also in the coming years.

The new Soilgrids sand/clay database and updated Global Lake Database (GLDB) have been tested successfully and have become default.

For surface modelling, the Surfex system of parametrizations is used in Harmonie. Operationally, use is still made of a 3-layer fore-restore soil scheme and a simple snow module. Experiments with the new many-layer diffusion soil, extended snow and snow-over-vegetation schemes have shown the added value of these more advanced schemes. However, their introduction needs to be done in combination with more advanced schemes for soil and snow assimilation, which are being finalized for pre-operational testing (see section C2 below). This combined introduction is in preparation in 2021.

The ECOCLIMAP-SG validation efforts over various have highlighted the issue that present Monin-Obukhov similarity theory falls short in describing the complexity of heterogenous canopies. In order to deal with this, alternative diagnostic formulations for screen level parameters and flux formulations from roughness sublayer theory (Hartmann and Finnigan 2007) are being investigated.

The sea ice scheme SICE has been extended with sea ice drift. Updates have been made in the FLAKE lake model and the GLDB lake database. An orographic parametrization for turbulence, OROTUR, has been implemented. Also, a parametrization describing the creation of turbulent wakes in and behind wind farms over sea, based on the method of Fitch et al. (2012), has been introduced and validated successfully against floating lidar and platform observations (fig.3). Also, required metadata on wind turbine and farm characteristics have been collected for most wind farms present and planned on the North Sea until 2030.

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

One of the main objectives in HIRLAM-C is to replace the very unsophisticated OI surface analysis system with more advanced assimilation methods, in combination with using a wider range of satellite surface observations. The focus in the past two years has been to finalize preparations for the introduction of a set of simplified extended Kalman Filters (SEKF's) for soil, snow, and sea ice. As described above, these SEKF's will be used in combination with the new diffusion soil and extended snow schemes. For the horizontal spatialization, the new gridpp OI scheme will replace the present CANARI scheme, because of its more modern and compact code base, and its proven ability to handle a variety of crowd-sourced data from e.g. private weather stations. The introduction of the SEKF assimilation schemes has been delayed to 2021. This is partly due to the need for retuning surface model components caused by the introduction of ECOCLIMAP-SG, partly to the wish to study the impact of an alternative set of control variables and the remaining need to optimize cycling and assimilation time window settings.

In parallel, some research efforts have focused on the exploration and development of more powerful envisaged future assimilation methods such as EnKF and particle filters. For experimentation, an EnKF is already being run with AMSR-2 and SMOS radiance observations. In the coming years, the design of a coupled surface-atmosphere data assimilation system will be considered.

In addition to conventional near-surface observations, crowdsourced data and satellite observations will progressively be introduced. Positive impact has been seen from the assimilation of crowd-sourced data from private weather stations (Bremnes et al. 2019) and smart phones (Hintz et al. 2019). Presently, the bias correction of these data is still being investigated. Experiments with assimilating a variety of snow products from e.g. H-SAF and CryoClim showed positive impact, primarily during the melting season. Impact studies have already been performed or are ongoing involving ASCAT, SMOS, MODIS, and H-SAF retrieval products of soil, vegetation, sea surface and inland waters properties and snow- and ice-covered surfaces. These will be added progressively to the surface assimilation after the introduction of the SEKF schemes. Following this, the aim is to also include raw satellite radiances and Sentinel-S SAR data in the analysis of soil moisture, soil temperature and snow.

D) Probabilistic forecasting:

A scientific description of the HarmonEPS system, its various implementations and its options in detail, has been published (Frogner et al, 2019). Work has continued on assessing a variety of perturbation methods in model physics, surface, initial and boundary conditions for HarmonEPS. Also, the HarmonEPS system has been upgraded from Cy40h to Cy43h2.

In the work on model perturbations, many efforts have been made to investigate whether the quite limited impact seen from SPPT perturbations could be enhanced, but without success. Work on SPPT has therefore finally been abandoned, and the focus will shift completely to stochastic parameter perturbations (SPP), which have shown consistently to add value in terms of increased spread and skill to other perturbation types. The number of physical parameters to be perturbed has steadily increased to cover most model parametrizations, and the effect of using different distributions and spatial and temporal scales for different parameters has been studied. In ensemble members, the tendency was seen for them to be drier than the control. The cause for this has been studied but not yet found, this will remain under investigation.

The continuous cycling approach originally developed at DMI (Yang 2018) has shown to be a powerful instrument to enable increased (double or even triple) ensemble size, as well as earlier delivery of ensemble products and less jumpiness between ensemble runs. It is gradually being introduced in most operational HarmonEPS setups. EDA is presently being used for initial condition perturbations. In the coming years, more detailed inter-comparisons will be made for EDA and two alternative mechanisms for IC perturbations: LETKF and hybrid EnVar/Brand. In preparation for this, the hybrid EnVar and LETKF development branches have been ported to the most recent pre-operational cycle, Cy46h.

In 2020, the work on surface perturbations has been intensified by new staff members. Experiments with perturbing surface fields like SST, soil moisture and LAI have shown to lead to improved spread for near-surface parameters, but to have little impact at higher levels in the atmosphere.

A high-priority target is to achieve affordable high (sub-km) resolution nowcasting ensembles, which are computationally highly demanding considering the tight time constraints for nowcasting. One important element for achieving this which has been experimented with extensively, is the overlapping window approach. Another element which has been investigated is the replacement of the linear grid by quadratic or cubic grids, which are computationally 30-50% more efficient, at the loss of some effective resolution. A third way would be to single precision in ensemble members while using double precision still for the control. This is being studied during 2021.

E) Code efficiency, scalability and portability

Various code adaptations have been made to permit use of single precision for Harmonie-Arome. The option of single versus double precision has been tested in several services. Both the Reference 3D-Var and forecast model can be run mostly in single precision, which has so far been tested successfully for almost all available observation types. For most variables, verification scores are indistinguishable between single and double precision, with the exception of a small bias in mean sea level pressure and a slight tropospheric cooling in single precision runs, the causes of which are still under investigation. When going from double to mixed precision, typical 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). Work has started to test 4D-Var in mixed precision.

Efforts have continued to improve the computational efficiency of 4D-Var through a better use of MPI and OpenMP parallelization. The Barcelona Supercomputing Center has been performing a general assessment of the computational efficiency of Harmonie. Both at the code and compilation level, a number of clear potential gains have been identified. This first assessment has been followed up with the optimization of Harmonie efficiency along these lines on the existing and new ECMWF platforms, which will continue into 2021.

Given the increasing heterogeneity of HPC architectures, it is important to establish model performance on a range of different architectures. At KNMI a first investigation has been made on the performance of Harmonie on a cluster of ARM chips, the advantage of ARM architectures being their high energy efficiency. Harmonie could be made to work on an ARM cluster without any recoding, at the cost of somewhat greater time-to-solution but also significantly less energy-to-solution. Experiences have also been gained with new AMD-based architectures at DMI.

DMI staff have managed successfully to build the necessary components of the Harmonie suite onto a container, with a view to test the possibility to run Harmonie in the "cloud". Independently, staff from Met Norway managed to port the MUSC single column model code onto a virtual machine. With such steps it is aimed to make the Harmonie system more portable and usable to a wider community for research purposes.

Figures:

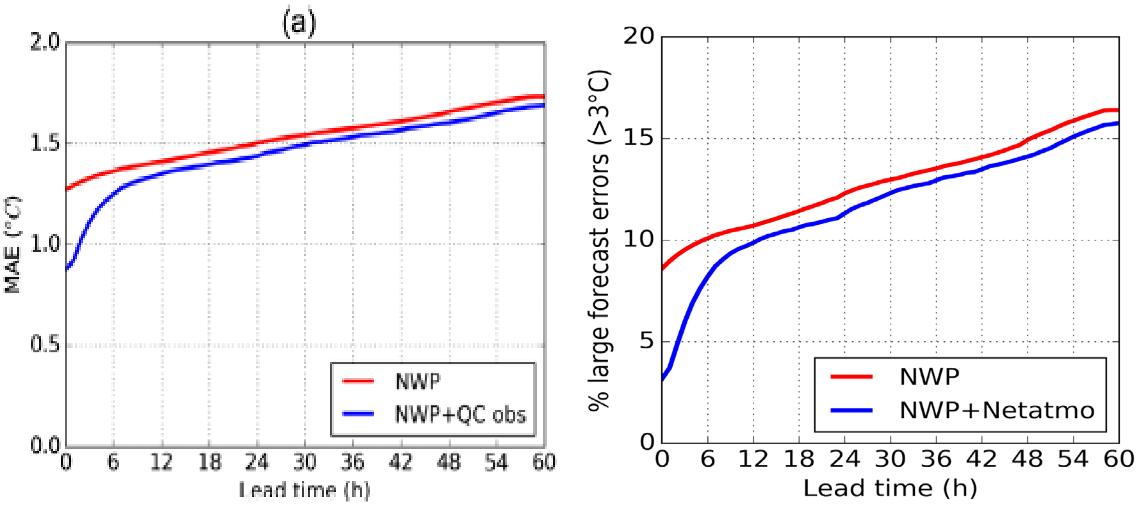

Fig. 1: Impact of the inclusion of quality-controlled Netatmo private weather station data in the postprocessing of Harmonie forecasts of T2m for Norway (taken from Nipen et al. 2019). Normally, observations from the observation network of Met Norway are used for statistical adjustment of Harmonie forecasts and thus obtaining a so-called "gridded truth". In the experiments by Nipen et al., quality-controlled Netatmo data have been added to those of Met Norway's own network. The left figure shows the mean absolute T2m error as a function of lead time, the right figure the percentage of large forecast errors (>3 degrees) vs lead time. The blue curves represent the model results when quality-controlled Netatmo are included in the postprocessing of Harmonie forecasts, on top of the observations from the Met Norway surface network only (red curves). The Netatmo data provide clear added value in the post-processing throughout the forecast range, but particularly in the first 6 hours of the forecast. In direct assimilation, it has been more difficult to demonstrate their added value in terms of traditional scores, but spatial structures have been shown to be more realistic.

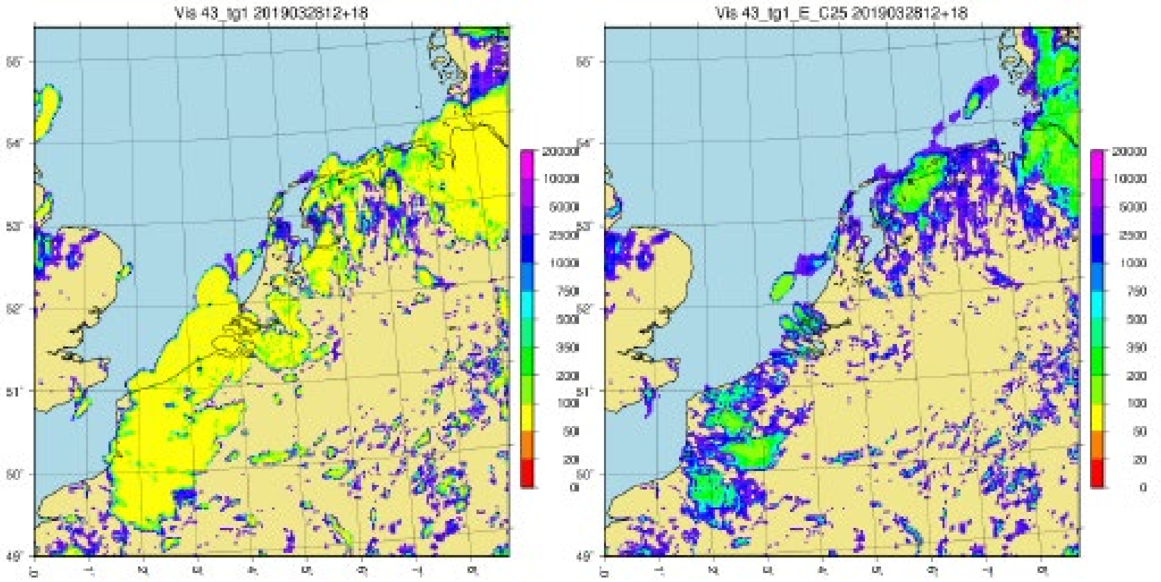

Fig.2: Improvement of fog forecasts through changes in cloud emissivity and CCN density as seen in a testcase on 28 March 2019 over the North Sea. In this test case, the model showed the rapid formation of dense fog over a large area above the North Sea, which did not occur in reality. Both the thickness and extent of the fog in the model grew fast, in contrast to what was seen in satellite imagery. The left figure shows the +18h visibility forecast from the Harmonie pre-operational model Cy4tg1, in which the erroneous fog over the North Sea is clearly present (yellow-coloured structure). The right figure shows the same forecast but with reduced cloud emissivity in the long-wave radiation parametrization and a reduction in the CCN density in the model. In this configuration the fog formation over sea is far less extensive, and it no longer grows quickly in horizontal extent and thickness after its original formation, in agreement with observations.

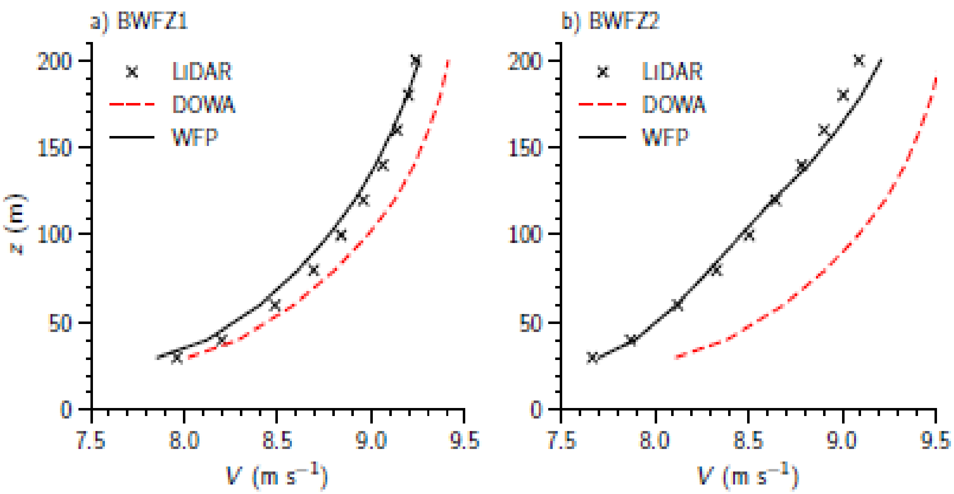

Fig. 3: Verification of the impact of the Fitch et al. 2012 wind farm parametrization (van Stratum et al. 2019) on Harmonie boundary layer wind profiles in the area around the Borssele wind farm. The left and right picture show the vertical wind profiles from the model for in comparison to observations from two nearby lidars BWFZ1 and BWFZ2, downstream of the wind farm in cases of the usually south-westerly wind flow for that area. The red dotted curve represents profiles from the model without wind farm parametrization, the black curve the profiles for the model including wind farm parametrization under south-westerly flow conditions. The crosses represent the lidar observations. Use of the wind farm parametrization clearly gives a more realistic representation of wind profiles in the boundary layer downstream of the wind farm, and more accurate energy predictions (not shown here). The spatial impact of the parametrization on the wind field can extend well beyond the immediate vicinity of the wind farm (order several tens of km, not shown here).

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Future plans

The HIRLAM-C programme has been extended with two years to December 2022. It has therefore been decided to apply for a new 2-year project HIRLAM-C phase 3 (2021-2022), and this has been granted.