SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	July 2017-June 2018
Project Title:	HIRLAM-C 1st phase (2016-2018) 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 Jan 2016
Expected end date:	31 Dec 2018

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)	11 MSBU	11 MSBU	12 MSBU	8.0 MSBU (by 21 May)
Data storage capacity	(Gbytes)	20.000	20.000	20.000	20.000

Summary of project objectives

The main areas of attention are:

- introduction and optimization of flow-dependent assimilation techniques (4D-Var, 3/4DEnVar)
- development and introduction of data assimilation techniques more suitable for the nowcasting range
- increasing the range of remote sensing data to be assimilated (esp. all-sky radiances and satellite surface observations)
- a more sophisticated and consistent description of the radiation-cloud-microphysics-aerosol interaction, winter stable boundary layer conditions
- a more sophisticated surface analysis and modelling system.
- Preparations to increase the operational horizontal and vertical model (ensemble) resolution to ~1km resolution, and research on developments required to run the system at hectometric resolutions.

Summary of problems encountered (if any)

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

Summary of results of the current year (from July 2017 to June 2018)

The HIRLAM-C research Programme, which has started in January 2016 and end in December 2020, is a continuation of the research cooperation of the previous HIRLAM projects. The members of HIRLAM-C are 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, in particular to enhance their quality for the accurate prediction of severe weather at a target horizontal resolution of 0.5-1km. The Harmonie system is being developed within the IFS framework in close cooperation with the Aladin consortium. Following the past Hirlam practice, a Harmonie Reference system is being maintained on the ECMWF HPC platform. The emphasis in the HIRLAM-C Special Project at ECMWF is primarily on experimentation, evaluation and testing of the deterministic Harmonie Reference System. The Special Project computational resources are used mainly to experiment with newly developed model components and evaluate their meteorological and technical performance in beta-releases, before releasing them as Reference. Below, the main research and testing activities (undertaken jointly with Aladin partners) in the fields of data assimilation, the atmospheric forecast model, surface analysis and modelling and code efficiency from the past year are outlined. A focal point within HIRLAM-C in the past three years has been the development of the convection-permitting HarmonEPS ensemble forecasting system and preparations for its operational use. For these activities, a separate special project exists ("Probabilistic forecasting for short range in Europe"), and they will not be described here.

A) Atmospheric data assimilation:

A1: Optimal use of high-density observations in 3D- and 4D-Var:

At present Harmonie uses as default a 3D-Var assimilation system, which routinely assimilates conventional data and cloud-free radiances from AMSU-A, AMSU-B and MHS. Additionally, in the past three years several types of spatially and temporally dense observations have been prepared for operational use: radar radial wind and reflectivity volume data, GNSS ZTD, IASI cloud-free radiances, SEVIRI water vapour observations, Mode-S EHS data, AMV's and ASCAT winds. All these data types have shown positive impact after improved data quality control, the application of more intelligent thinning or super-obbing strategies, variational bias correction, and careful tuning and optimization of the observation statistics and structure functions.

For radar data, stricter quality control procedures have been introduced, and improved beam blocking corrections have been introduced for mountainous regions. A pre-processing system (called PREP-OPERA) has been made to handle radar data from the OPERA data hub, and as a consequence more and more OPERA radar volume data are being introduced in local Harmonie suites.

The ingest procedure for AMV data has been adapted to handle both geostationary and polar AMV observations, and both AMV data as provided by the EUMETCAST system and locally processed ones. Local AMV processing was shown to be beneficial for the impact of these data on forecasts in the nowcasting range. A study to assess whether it is beneficial to account explicitly for the spatial footprint of AMV data is still ongoing.
Studies have been carried out on the handling of lower-peaking ATOVS and IASI channels, which have led to adaptations in the blacklisting of these channels. The use of alternative predictor sets in the variational bias correction for clear-sky radiances has been, and is being, studied. A start has been made with studies on the best way to handle cloudy radiances from ATOVS, SSMI/S and SEVIRI.

GNSS slant delays have been implemented in the assimilation system. After application and improvement of a variational bias correction for these data, a positive impact could be shown. The amount of GNSS data suitable for assimilation over Scandinavia has increased a lot through the use of the NGAA processing center, and this has proven beneficial in the model analysis over this domain. An impact study of radio occultation GNSS data has shown potential of these data to improve the mesoscale analysis. The drift information in BUFR-format radio sonde data has been shown to have clear added value. A start has been made in the past year with impact studies of E-Amdar humidity observations.

In the coming years new sources of high-resolution remote sensing observations will become available, such as ADM/Aeolus and MTG, and also the availability of observations from e.g. polarimetric radars or boundary lidars is likely to increase. Preparations are being made to incorporate these new data into the Harmonie analysis and assess their impact. A fast growing data source is meteorological information from non-NMS networks or crowd-sourced data, such as road observation networks, hot air ballloons, amateur weather stations and smart phones. Experience has been and is being gained with the use of these data for both validation of very high (hectometric-scale) resolution model runs and assimilation.
The growth in the range of observations which can be assimilated in the Harmonie analysis, has necessitated the development and introduction of improved tools for routine observation monitoring and for the assessment of their relative impact. In particular, the monitoring of radiances has been greatly enhanced, and impact assessment scores like MTEN and FSO have been introduced.

Until now, the impact of introducing new high-resolution observations in the Harmonie 3D-Var has generally been positive but limited in both size and duration. It has therefore been attempted to enhance the performance of the 3D-Var algorithm in several ways. Activities on 3D-Var optimization have included the inter-comparison of various methods for generating structure functions in terms of impact, spin-up and the noisiness of increments; experiments with EDA on small scales in combination with several methods of accounting for the large scale; and testing the impact of different methods for estimating optimal thinning distance. Several of these approaches have shown some potential for improving 3D-Var performance. However, it should be recognized that the 3D-Var method has strong inherent limitations. A main aim therefore has been the preparation for operational use of a more sophisticated Harmonie 4D-Var system. In the past three years, 4D-Var has been tested extensively on large model domains (~1000x1000 grid points), it has been extended to handle multiple outer loops, and has been enabled to work together with all high-resolution observation types which are presently operationally assimilated in 3D-Var. Impact studies with individual observation types such as Mode-S and SEVIRI have shown the good potential of the 4D-Var system to enhance the quality of the model analysis over that of 3D-Var, particularly also in critical weather situations. In the combination of 4D-Var with radar data, there are still problems to be overcome. In the coming years, 4D-Var experiments will be carried out with the full range of observations which presently can be handled by the 3D-Var system, impact assessment studies will be done in comparison with 3D-Var, and it will be assessed how to improve the 4D-Var computational performance.

A2. Development of data assimilation suitable for the nowcasting range

For nowcasting, one would like to assimilate the latest observations fast and frequently. Experiments have therefore first been done with the 3D-Var system in rapid update cycling mode at update frequencies of 15m-1h, using observations such as radar, GNSS, Mode-S and locally processed AMV's with very short cutoff times. A downside which has been demonstrated for these RUC setups, is that model spinup effectively puts a lower limit on cycling frequency, and even when spinup is relatively short (generally significantly less than 1h, but occasionally several hours for moisture), there may still be a problem with a lack of balance in the model for some time after the assimilation. Experiments to compare the impact of 3D-Var rapid updating systems with that of less frequent updating with a more sophisticated technique such as 3-hourly 4D-Var have started recently. Also, to enhance the performance of 3D-Var itself in the nowcasting range, several cycling and initialization strategies have been, and are being, tested which should give greater weight to the most recent observations: the rapid refresh approach and the overlapping window cycling strategy used in the DMI COMEPS ensemble, which permits efficient use of the most recent observations in combination with relatively long assimilation windows (fig.1). Both the rapid refresh and the overlapping window approaches have shown promising results in the nowcasting range. Ultimately, the ambition is to achieve an ensemble perturbation and cycling strategy suitable for use at nowcasting time scales.

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. For this reason, a so-called field alignment technique (by which displacement errors are first identified and corrected for, after which a "normal" 3D-Var analysis is performed) has been developed which is of potentially great interest for application in the nowcasting time range, using radar observations. The field alignment method developed for adjusting analyses to the patterns of radar reflectivity and velocity data, was shown to be beneficial, particularly in the nowcasting range but with relatively short impact (~6h); this was believed to be related to balance problems. To improve this, a different initialization formulation has been developed, the so-called variational constraints (VC) method (Geijo, 2017), with the aim to achieve a better handling of analysis increments and a faster balancing of the model. The field alignment of radar wind data produces wind pseudo-observations, which are then submitted to the VC scheme to reduce imbalances. First results seem promising, but further investigations are needed.

A good description of the 3D structure of clouds in the atmosphere is an essential component for nowcasting. A cloud initialization technique has been introduced using MSG observations. This method was shown to be very beneficial at times, but the weak point in the original algorithm was the initialization of the model cloud base from observations. It has been shown that the original cloud initialization algorithm, which generally resulted in a too moist model atmosphere, can be improved by using a wider range of cloud information at various levels in the atmosphere. A more sophisticated use of e.g. the NWC SAF cloud type and cloud mask information results in a more realistic initialization of moisture profiles. However, the main challenge for this method remains to achieve an accurate estimate of the cloud base.

A3. Development and optimization of ensemble assimilation methods: LETKF and 3/4D-EnVar:
For both global NWP models and for LAM models such as Hirlam, it has been demonstrated that ultimately the strengths of ensemble and variational approaches can and should be combined, to the mutual benefit of the model analysis and its probabilistic forecasting ability. The primary longer-term aim in data assimilation algorithmic development therefore has been to design and build a flexible algorithmic framework for 3/4D ensemble variational assimilation (3/4DEnVar) for Harmonie, suitable for both assimilation and ensemble forecasting purposes. The starting point for this has been the construction of a hybrid 3D-Var/LETKF scheme. First experiments with the use of the LETKF system in a small (10-member) mesoscale ensemble have shown promising results. Experiments are now continuing to test the sensitivity of the scheme to e.g. ensemble size, perturbation spatial scales and domain extent. In the past year, also a 3/4D EnVar setup has been created, and this is being readied for wider experimentation as well.

B) Atmospheric forecast model

B1. Studies to eliminate systematic model errors for clouds and boundary layer behaviour:
Model parametrization studies have primarily focussed on eliminating systematic model biases in surface fluxes, in (low) clouds and visibility, and under winter-time stable boundary layer conditions. These studies have led to some improvements, e.g. in the removal of a bias in radiative fluxes, and in precipitation and near-surface wind behaviour, but have also uncovered a number of compensating errors and model issues, particularly related the triggering of severe convection. These studies will be continued in the coming years. It has been attempted to improve model stable boundary layer behaviour, in particular for low-wind winter conditions, through alternative turbulence formulations and testing of the near-surface sublevel approach in the canopy scheme of SURFEX, but with little success. Present work in this field is focussing on e.g. improvement of the surface description (see paragraph C), assessment of the influence of increasing model vertical resolution, and experimentation with the choice of lowest model level height.

B2. Improved description of the cloud-radiation – microphysics- aerosol interaction:
The fog and low cloud and surface flux studies involve alternative formulations of the turbulence and radiation schemes, the cloud microphysics (first and second moment schemes), and a more realistic and consistent treatment of the radiation – cloud - aerosol interaction. The present spectrally detailed radiation scheme is not run at every time step, due to its cost. A comprehensive radiation inter-comparison study has been done against several alternative schemes (HLRADIA, ACRANEB2; Rontu et al. 2017) which are less spectrally detailed but cheaper and run more frequently; this was believed to be important for a realistic description of the cloud-radiation interaction and cloud evolution within the model. The ACRANEB and spectral radiation schemes appears to give rise to a similar forecast quality. Orographic parametrizations of the sub-gridscale effects of slopes and vegetation have been included in the radiation scheme, with a slight but consistently positive effect. Work on a sub-grid-scale parametrization for momentum is underway. Systematic studies have been undertaken to assess the practical importance of parametrizing direct and indirect aerosol effects on radiation fluxes, cloud development and cloud-radiation interactions. The existing radiation, cloud and microphysics schemes have been, and are being, adapted where necessary in order to provide an internally consistent treatment of cloud-radiation-surface-aerosol interactions (through harmonization of e.g. sub-grid scale assumptions on different water species, CCN, and cloud overlap assumptions). Several avenues have been explored to improve, or provide competitive alternatives for, the ICE3 microphysics parametrizations. The benefits of using an improved aerosol climatology (from MACC rather than Tegen et al.) on radiation and clouds have been confirmed earlier. This was followed up by a study of the impact of using real-time aerosol

information from CAMS. Experiments are being carried out with cloud-aerosol interaction parametrizations for individual aerosol types, using prescribed daily CAMS aerosol fields to update the 3D number density of cloud droplets Nc. Meteo-France and Algerian staff have included a parametrization for dust, while HIRLAM staff have incorporated parametrizations for sea salt and sulphate. Case studies to investigate the behaviour of these parametrizations are ongoing (e.g. fig.x).

B3. Dynamics developments:

The main emphasis in the dynamics research has been on increasing the accuracy and computational efficiency of the dynamics code, with a view to prepare the model for future use at hectometric resolutions and on massively parallel computer systems. Issues which have been considered in this context are the development of a vertical finite element (VFE) discretization, introduction and testing of non-linear (cubic, quadratic) spectral grids, assessing the numerical stability and physics-dynamics interaction on 1km- and sub-km scales (see below under 4.), and alternative methods of boundary condition treatment and nesting.

B4. Preparations for increased vertical and horizontal resolution

At present, the Harmonie forecast system is generally operationally run at 2.5km horizontal resolution and with 65 layers in the vertical. Since 2017, efforts are being made to prepare the model for operational use at higher vertical (~90 levels) and horizontal resolution (~1km), and to assess model behaviour at the hectometric scale in research mode. For the operational resolution upgrade, in particular the vertical resolution increase is likely to require substantial re-tuning of the model physics, and use will be made of the experience already gained by Meteo-France at these resolutions. All relevant model aspects are being considered: dynamics settings and numerical stability aspects (e.g. vertical level definition, cubic vs linear grid, stability issues with the semi-implicit time stepping, and the possible need for tuning the Semi-Lagrangian Horizontal Diffusion (SLHD) scheme), and physics parametrizations (esp. the handling of shallow convection and turbulence), but also surface modeling and characterization, data assimilation and cycling strategies, ensemble forecasting and computational performance. In regions with steep orography, the impact of use of sub-grid orographic parametrizations for radiation and momentum will be assessed.

Experiments are being set up for relevant areas (environments of airports, urban areas, regions with complex orography and/or land-sea transitions; see e.g. fig.2). Real-time model suites at resolutions of 300-1000m resolution have already been set up over a variety of domains in Denmark, Greenland, Iceland and the Faroer Islands, and others are in preparation over Ireland, Sweden and Spain. In verification against available local data, the high-resolution models generally show benefits e.g. for wind speed forecasts in domains with steep orography, but also localized convective events appear to be represented better. A beginning has been made with testing the impact of vertical resolution increase to the Meteo-France 90 level settings, with as main aims to look at the impact of the greater resolution on boundary layer winds and fog. Also, 3D-Var cycling experiments have started on some of the high-resolution domains. At hectometric resolutions, it will be important to compare the model with large eddy simulation (LES) models for validation purposes. For this, an LES scheme from Delft University is being nested into Harmonie-Arome. Appropriate (local) high-resolution physiographic information will need to be introduced for most of these domains to ensure an accurate description of the surface at hectometric resolutions.

C) Surface analysis and modelling

C1. Enhanced use of satellite surface observations in combination with more advanced surface assimilation algorithms

For the surface analysis, a simple OI approach is being used at present, to assimilate conventional surface and screen level observations only. It has been a high priority to enhance the surface analysis system through the introduction of a wider range of satellite surface observations in combination with more advanced assimilation methods. Preparations have been made to replace the

OI system in the next version of the Harmonie Reference System (Cy43h) with a set of (simplified) extended Kalman Filters ((S)EKF's) for soil, snow, sea ice and lakes. Preliminary experiments with (S)EKF in combination with conventional and satellite observations such as ASCAT soil moisture have shown better results than achieved with OI.
Impact studies have taken and are taking place with assimilation in the (S)EKF's of a variety of satellite observations of the soil, sea surface and inland waters, and snow- and ice-covered surfaces: e.g. ASCAT and SMOS products for soil moisture, MODIS data for lake water temperature and leaf area index, and several different satellite products for sea ice and snow cover and depth. In the coming years these satellite data will be introduced progressively.
In parallel, some research efforts have focussed on the exploration and development of more powerful envisaged future assimilation methods such as EnKF and particle filters.

C2: Improving the sophistication of surface model components

For surface modelling, the main focus has been on improving the description of Northern, Arctic and Antarctic conditions in Harmonie. Key issues have been the handling of snow, ice, forest, lakes and sea ice. Activities of the past years have included the introduction of a multiple energy balance approach for vegetation- and snow-covered surfaces, the development and operationalization of a simple sea ice scheme which since then has been made more sophisticated (with more realistic ice thickness evolution and treatment of snow-on-ice; see fig.3), and extensions to the Flake lake model (with snow-on-ice parametrizations and an improved lake database and lake climatology). In the new Surfex-v8 package, in addition to these schemes also a more sophisticated diffusion soil scheme and more realistic snow schemes have become available, and these are being experimented with. So far the results of the each of these individual schemes (the diffusion soil scheme (DIF), the extended snow scheme (ES), the snow-over-vegetation scheme (Mass Energy Budget (MEB)), the adjusted lake model FLAKE and the sea ice scheme (SICE) have been quite positive.They now need to be tested in combination with each other, and also in relation to the new EKF surface data assimilation. A start has been made with testing the combination of surface schemes in climate mode, with the aim to evaluate, and where possible reduce, model biases. In particular the new diffusion soil scheme has many more degrees of freedom than the presently operational force-restore scheme, and thus it will need to be carefully tuned. In this context, sensitivity studies are ongoing to deliver optimal settings e.g. for the vegetation parameters in the DIF scheme.

A necessary condition for a good performance of the surface modules is that the physiographic data used there accurately represents local conditions. The present physiographic database ECOCLIMAP-2 contains local weaknesses which, when discovered, are dealt with on a case-by-case basis. Examples of situations in which local improvements proved necessary, are the albedo of volcanic sands and characteristics of the vegetation in Iceland, and unrealistic assumed tree heights in Scandinavia (which led to local biases in low level wind speed). A high-resolution sand-and-clay database over Scandinavia was shown to be a significant improvement there over the HWSD global sand-and-clay database. A Short-Time Augmented Extended Kalman Filter (STAEKF) scheme has been implemented to make local adjustments to e.g. the (in some places suspect) LAI climatology fields provided by ECOCLIMAP. The actual tuning of the LAI fields, however, still remains to be done.

C3: Coupled atmosphere – sea surface modelling

First experiments started several years ago in Norway with coupling Harmonie with the sea surface through one- and two-way coupling with the WAM wave model. The indications were that the impact of two-way coupling was quite beneficial. More groups have become active in this field now, also experimenting with coupling with ocean models. It has been jointly concluded that the best way forward appears to make use of an OASIS-type coupler for the wave and ocean models. For the wave models, experiments are ongoing with coupling Harmonie to the WAM and

Wavewatch-3 wave models; for the ocean model, experiments with coupling Harmonie with the NEMO model are just starting up.

D) Code efficiency and scalability

An important task to achieve is the optimization of code efficiency and scalability, with a view to use Harmonie on very massively parallel hardware platforms. The best way to improve the Harmonie parallelization on the longer term is to restrict as much as possible the need for communications among processors. The aim is that as many computations as possible will take place in grid point space, reducing the need for spectral transforms. To assess the impact of more efficient and "localized" forecast model options, experiments have been done together with ALADIN partners on alternative Helmholtz solvers and on multi-grid physics. In terms of parallelization, several existing and potential bottlenecks can be identified. In the physics, optimizations have been carried through in the microphysics, shallow convection and turbuluence schemes, leading to a speed-up of the forecast model by ~6%. One of the weakest points in the model was the relatively poor parallelization of the surface model and surface assimilation, and although this has been improved, further optimization in this area remains needed. From the point of view of scalability, the 4D-Var code (with its multiple outer loops) is one of the potentially most troublesome issues. This was an important motivation for the planned future move to a more inherently parallellizable 3- and 4DEnVar system. Another option is to implement the Gaussian quadrature approach (Stappers, Ph.D Thesis, 2014) for 4D-Var, which would eliminate the need for (poorly scalable) multiple outer loops. Comprehensive profiling of the code at the introduction of every new cycle is necessary to clearly establish which parts of the code are the most limiting factors in terms of efficiency and scalability. The Harmonie model is regularly being benchmarked on as massively parallel machines as are available to the consortium. Studies to assess how best to optimize code performance on mixed CPU/GPGPU computer architectures are being undertaken both in the context of externally funded projects (e.g. ESCAPE) and in cooperation with e.g. the Barcelona Supercomputing Center and hardware providers like Bull.

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Figures:

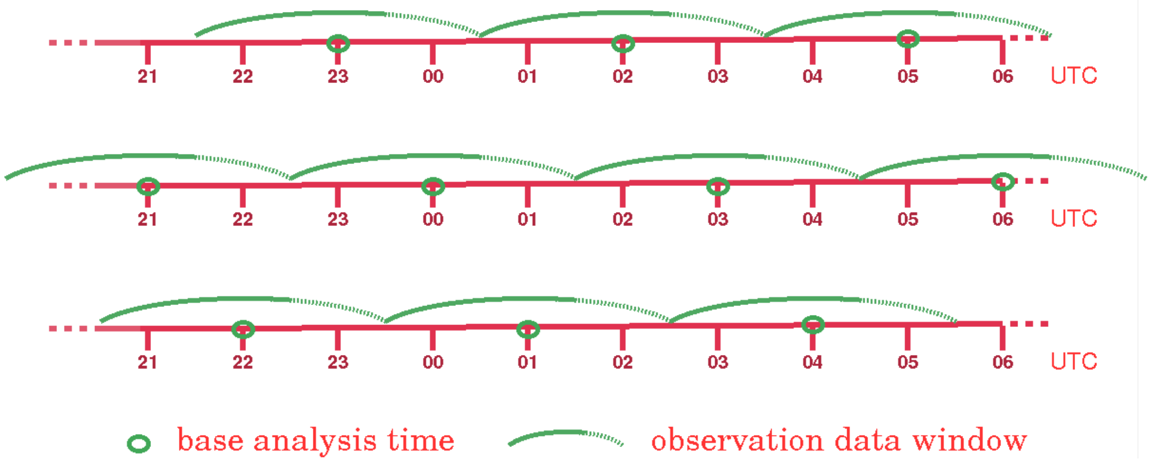

Fig. 1: Overlapping time window strategy used in the present COMEPS ensemble. Hourly analysis is enabled in DMI's COMEPS ensemble system through the use of 3 parallel suites, each using a 3-hourly data assimilation cycling but with a base time which is consecutively shifted by 1h between the three members. This way, every hour, a 3D-VAR analysis is launched with a 3h observation window. As the three consecutive assimilation cycles are mutually independent, the repeated use in observations in overlapping time windows between the three consecutive suites is not a problem, as it would be for the traditional deterministic 3D-Var approach. In the envisaged future nowcasting ensemble system, the three consecutively hourly shifted suites with a 3h observation window each will be replaced by a set of 6 suites, shifted in base time by 10m between consecutive members, and using a 1h observation window. This system is aimed to assimilate rapidly delivered observations within a cutoff time of ~15m: mainly radar, surface observations and aircraft data.

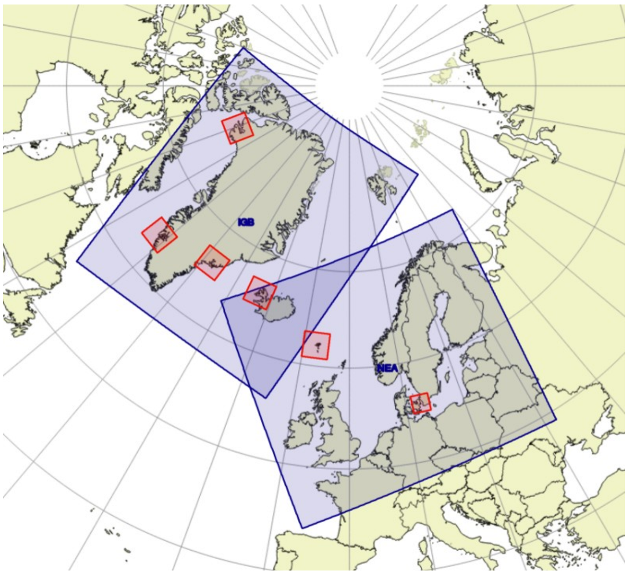

Fig.2: Some of the high-resolution testing domains at 300m, 500m or 750m resolution under study by DMI and IMO staff. Additional high-resolution domains have been or are being set up e.g. in Norway, Sweden, Spain and Ireland.

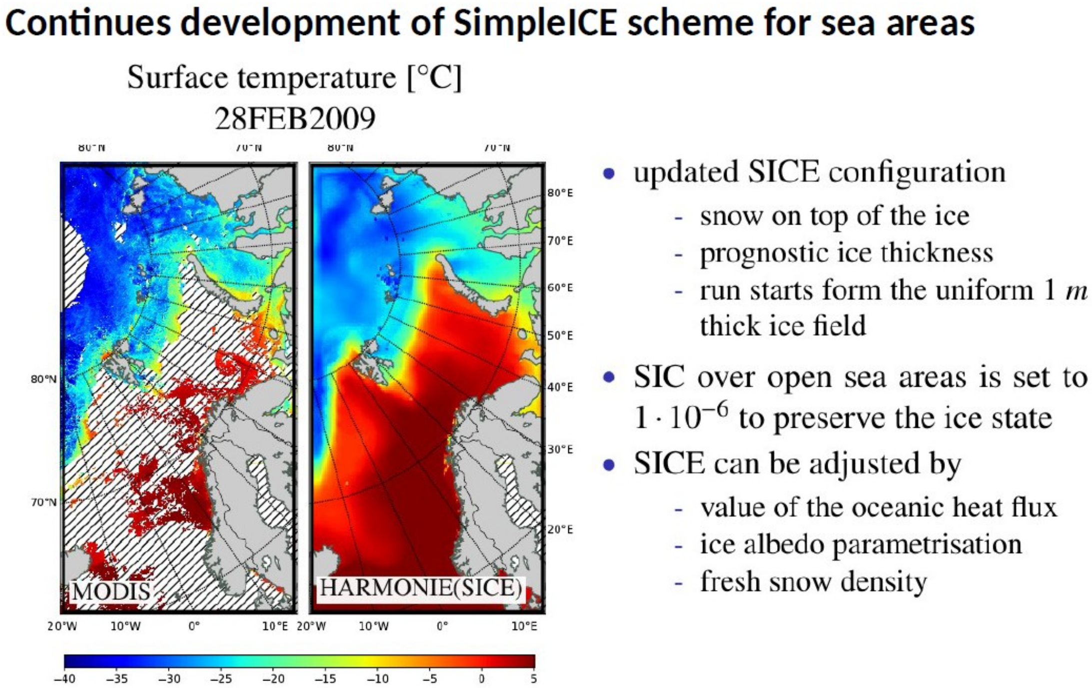

Fig.3: Description of recent updates made in the sea ice scheme SICE, which now includes a dynamically evolving ice thickness and treatment of snow over ice.

Summary of plans for the continuation of the project

(10 lines max)

The period of the present project ends in December 2018. A new project proposal has been submitted for the second half of the HIRLAM-C programme period (the years 2019 and 2020), with updated scientific goals.