SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	HIRLAM-C 1st phase (2016-2018)
Computer Project Account:	spsehlam
Start Year - End Year :	2016 - 2018
Principal Investigator(s)	J. Onvlee
Affiliation/Address:	KNMI Utrechtseweg 297, P.O.Box 201, 3730 AE De Bilt, the Netherlands
Other Researchers (Name/Affiliation):	The HIRLAM-C project leaders (Daniel Santos/AEMET, Roger Randriamampianina (Met Norway), Lisa Bengtsson (SMHI), Sander Tijm (KNMI), Patrick Samulesson (SMHI), Inger-Lise Frogner (Met Norway), Bent Hansen Sass (DMI)) and research team (~70 scientists)

The following should cover the entire project duration.

Summary of project objectives

The main goals 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

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

Experience with the Special Project framework

Administrative aspects like application and reporting procedures are straightforward and user-friendly.

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. Research efforts are focused on the development, implementation and further improvement of the mesoscale NWP model Harmonie and its associated ensemble prediction system HarmonEPS. The aim is to enhance the quality of Harmonie and HarmonEPS for the accurate prediction of severe weather at a target horizontal resolution of 0.5-2.5km and 65-90 levels. The Harmonie system is being developed within the IFS framework in close cooperation with the Aladin consortium. 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 research, evaluation and testing of the deterministic Harmonie Reference System. The Special Project computational resources are primarily used to develop and experiment with new elements for this Reference System, and evaluate their meteorological performance.

Below, the main research activities are outlined that have taken place on the deterministic Harmonie model in this project phase (January 2016 - December 2018). One additional focal point within HIRLAM-C in these three years has been the development of the convection-permitting HarmonEPS ensemble forecasting system and preparations for its operational use. For those activities, separate special project resources have been used, and they will not be described in this report.

<u>A) Atmospheric data assimilation:</u>

Work has been carried out on the following topics:

1. Optimal use of high-density observations in 3D- and 4D-Var
2. Development and optimization of flow-dependent assimilation methods: Introduction of 4D-Var and development of 3D-Var/LETKF and 3D-Var/hybrid EnVar
3. Development of data assimilation setups suitable for the nowcasting range (including the integration of non-variational initialization methods into the variational assimilation system)

The progress made in these areas has been as follows:

<u>A1. Optimal use of high-density observations in 3D- and 4D-Var:</u>
At present Harmonie uses as default a 3D-Var assimilation system, which assimilates conventional data and cloud-free radiances from AMSU-A, AMSU-B and MHS. A focal point in the past three years has been to prepare several types of spatially and temporally dense observations for routine assimilation in the Harmonie Reference system and operational Harmonie setups in the HIRLAM services: radar radial wind and reflectivity volume data, GNSS ZTD, IASI cloud-free radiances, SEVIRI water vapour observations, Mode-S EHS data, geostationary and polar AMV's and ASCAT winds. All these data types have been enabled in the Harmonie assimilation system and shown positive impact. Much work is now being done more or less continuously to further improve data quality control, to apply more intelligent thinning or super-obbing strategies, introduce and enhance variational bias correction, and perform 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 developed for mountainous regions. For radial wind data, alternatives for the Baltrad de-aliasing procedure have been tested, such as the He at al. (2012) algorithm, which was found to give more satisfactory results. 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, 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 so-called supermodding method has been introduced to account more explicitly for the spatial footprint of satellite data, and the added value for this approach has been demonstrated for ASCAT and AMV data. In 2019 and onwards, this work will likely be extended to radiances.

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 and the use of emissivity atlases. 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 experimentation on the best way to handle cloudy radiances from ATOVS, SSMI/S and SEVIRI.

For GNSS data, efforts have focused on operational implementation and enhancement of VarBC. 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. 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. Since then, the slant delay observation operator has been refined further, and impact studies with this setup will continue in 2019. An impact study of radio occultation GNSS data has shown these data to have potential improve the mesoscale analysis.

The drift information in BUFR-format radio sonde data has been shown to have clear added value. Impact studies of E-AMDAR humidity observations have been done with positive outcomes. First experiments have started with the bias correction of aircraft data.

A fast growing and highly promising data source is meteorological information from non-NMS networks or crowd-sourced data, such as amateur weather stations, road observation networks, smart phones, and observations from offshore wind energy farms and hot air balloons. Experience has been and is being gained with the use of such data for both validation of (sub-km) resolution model runs and assimilation.

In the coming years several 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/ceilometers is likely to increase. Preparations have begun to incorporate these new data into the Harmonie analysis and assess their impact.

The fast growth in the range of observations which can be assimilated in the Harmonie analysis system, has necessitated the development and introduction of new tools for routine monitoring of these observations and for the assessment of their relative impact on the model analysis and forecast. In particular, the monitoring of radiances has been greatly enhanced, and new impact assessment scores like FSO and MTEN have been introduced.

A2. Development and optimization of flow-dependent assimilation methods: Introduction of 4D-Var and development of 3D-Var/LETKF and 3D-Var/hybrid EnVar

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 potential for improving 3D-Var performance. However, it should be recognized that the 3D-Var method has strong inherent limitations. A main aim in the past three years therefore has been the development and preparation for operational use of a more sophisticated, flow-dependent, Harmonie 4D-Var system.

By the end of 2018, 4D-Var has been tested extensively on operational model domains, and has been extended to work together with the full variety of high-resolution observations which are available for 3D-Var, e.g. radar, SEVIRI and Mode-S. Impact studies have consistently shown the good potential of 4D-Var to enhance the quality of the model analysis and short-range forecasts over that of 3D-Var, particularly also in critical weather situations. The option of using multiple outer loops in 4D-Var has been enabled around end 2018, and this together with efforts to optimize MPI parallelization has made the system computationally efficient enough to permit its use in operational settings. In the coming years, the work on 4D-Var will be continued with a view to implement it

within HarmonEPS setups and compare its performance there with that of 3D-Var, to apply and assess 4D-Var also in the nowcasting range, and to further improve its computational performance with OpenMP parallelization.
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/ETKF system and a hybrid 3D-EnVar scheme. First experiments with the use of both systems in relatively small mesoscale ensembles have shown promising results as compared to operational 3D-Var. Experiments have been, and are being, done to test the sensitivity of the scheme to e.g. ensemble size, perturbation spatial scales and domain extent. A start was made with the preparation of a clean setup for inter-comparison of these schemes against standard 3D- and 4D-Var, and against each other.

A3. Development of data assimilation setups 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 (RUC) mode at update frequencies of 15m-1h, using high-frequency 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, which results in the analysis being of less quality than earlier forecast runs. For many variables spinup is relatively short (significantly less than 1h), but it can reach up to several hours for moisture.

Experiments to compare the impact of 3D-Var rapid updating systems with that of less frequent updating with a more sophisticated technique such as 2- or 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 most promising of them turned out to be the rapid refresh approach and the overlapping window or continuous 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). The ambition is to achieve an ensemble perturbation and cycling strategy suitable for use at nowcasting time scales before the end of the HIRLAM-C programme.

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 assimilation 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). To improve this further, a different balance formulation has been developed, the so-called variational constraints (VC) method, 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 imaging observations (Gregow 2017). 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 (mostly in-situ) 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 was shown to result in a more realistic initialization of moisture profiles (e.g. fig.2), and in 2019 testing of this setup has started in pre-operational mode.

B) Atmospheric forecast model

Research activities and experimentation have focused on the following topics:

1. Studies to eliminate systematic model errors for clouds and boundary layer behaviour
2. Improved description of the radiation – microphysics – cloud – aerosol interaction.
3. Dynamics developments
4. Preparations for increased horizontal and vertical resolution

The progress made in these areas has been as follows:

B1. Studies to eliminate systematic model errors for clouds and boundary layer behaviour:
In the past three years, efforts on this have concentrated on finding the root causes of, and alleviating, model problems seen with too little and too late initiation of deep convection in several severe convection events, an over-prediction of fog, the representation of temperature minima under winter-time very stable boundary layer conditions, and underestimation of stratiform precipitation and open cell convection events.

The convection and low cloud/fog representation problems both have been shown to have multiple causes. Several misses of severe convection events were shown to be associated with an unrealistic description of climatological evapotranspiration in the ECOCLIMAP-v2.2 physiographic database, and a use of too strong increments in the surface data assimilation. In other cases, the initiation of supercell formation was hampered by the fact that the HARATU turbulence scheme was observed to mix in too much dry air from above into the boundary layer. A first set of updates in the HARATU scheme was made accordingly which already led to a more realistic transport of moisture and turbulent energy from sub-cloud to cloud layers and a better daily cycle for humidity and clouds. A second set of changes was made at the end of 2018 concerning the free atmospheric length scale, the mixing of momentum and moisture near inversions and the statistical cloud scheme. Initial results with this second upgrade in 2019 showed a clear positive impact on the model representation of both deep convection and low cloud behaviour.

Another contributing factor to the problems seen in the lack of stratiform precipitation from the dispersal of the anvil in the dying-out stages of deep convection, and in the poor ability of the model to represent open cell convection lies in the microphysics. The ICE3 microphysics scheme lets too much solid precipitation form in the form of graupel and too little snow, and super-cooled liquid water is underestimated. Several in-depth 1D studies have confirmed that when these things are addressed, more realistic descriptions of the stratiform precipitation and open cell convection can be achieved.

To improve model stable boundary layer behaviour, several approaches have been followed: alternative turbulence formulations such as that by Zilitinkevitch et al. (2008); sensitivity studies on the impact of the near-surface CANOPY scheme of sub-levels between the lowest model level and the surface; and assessment of the impact of increased vertical resolution in the boundary layer. By the end of 2018, these studies had not yet resulted in clear improvements.

B2. Improved description of the cloud - radiation – microphysics - aerosol interaction:
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 adapted to provide a more 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. Orographic parametrizations of the effects of e.g. slopes have been included in the radiation scheme.

The benefits of using an improved aerosol climatology (CAMS rather than Tegen et al.) on radiation and clouds have been confirmed. This was followed by studies on the impact of using real-time aerosol information from CAMS. Experiments have started 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, and started with the inclusion of hydrophilic organic material and black carbon. A beginning has been made both with in-depth case studies and longer-term experiments on the impact of these parametrizations. In several case studies so far, a clear beneficial impact was seen in the use of real-time, rather than climatological, aerosol information. Later, experimentation will start with the two-moment LIMA microphysics scheme, as compared to the present ICE-3 microphysics.

B3. Dynamics developments

The main emphasis in the dynamics research in the past years has been on:

- the development of a vertical finite element (VFE) discretization. A VFE formulation has been assessed and documented; however, at it gave no appreciable added value over the finite differencing approach, it was decided not to implement it operationally.
- the inter-comparison of linear vs higher-order (quadratic and cubic) grids; the latter are computationally cheaper than linear grids, but at the noticeable loss of some resolution (particularly for e.g. near-surface winds). The use of non-linear grids is therefore considered mostly in the context of creating affordable high-resolution (sub-km) models and ensembles.
- the investigation of stable dynamics settings (time stepping, use of predictor-corrector vs SETTLS schemes, vertical level definition, etc.) suitable for use in models with sub-km horizontal resolution, and the behaviour of gravity waves at such resolutions.

B4. Preparations for increased vertical and horizontal resolution

At present, the Harmonie forecast system is generally run operationally at 2.5km horizontal resolution and with 65 layers in the vertical. Since 2017, efforts to prepare the model for operational use at higher horizontal (sub-km) and vertical (~90 levels) resolution have rapidly picked up speed. Model domains were set up for relevant areas (environments of airports, urban areas, regions with complex orography and/or land-sea transitions). Real-time model suites at horizontal grid spacings ranging from 300m to 1000m have been set up over a variety of domains in Denmark, Greenland, Iceland, Faroer Islands, Norway and Ireland, and others are in preparation over Sweden and Spain. A beginning has been made with testing the impact of vertical resolution increase to 90 levels, making use of the experience already gained by Meteo-France, the main aims being to look into the impact of the greater resolution on boundary layer winds and fog.

Initially, for the sub-km resolution domains the focus was on creating numerically stable model setups at 500-750m horizontal resolution (e.g. time step and vertical level definition, quadratic or cubic vs linear grid, stability issues near steep orography) and on providing an appropriately detailed surface characterization. More recently, also physics parametrizations (esp. the handling of shallow convection, turbulence and the use of orographic parametrizations for radiation and momentum), data assimilation (e.g. derivation of fine-scale structure functions) and cycling strategies, ensemble forecasting and computational performance assessment have begun to receive attention. In October 2018, the first 750m resolution setup, over the Tassilaq area in Greenland, became operational.

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. At hectometric resolutions, it will be important to compare the model with large eddy simulation (LES) models for validation purposes. For this, the option has been enabled to nest an LES scheme from Delft University into Harmonie-Arome.

C) Surface analysis and modelling

Developments in this area have focused on the following topics:

1. Enhanced use of satellite surface observations in combination with more advanced surface assimilation algorithms
2. Improving the sophistication of the surface model components
3. Coupled atmosphere – sea (surface) modelling

The progress made on these topics has been as follows:

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 operationally at present to assimilate conventional surface and screen level observations. It has been a high priority in the past three years to enhance the surface analysis system with more advanced methods which will permit the use of a wide range of satellite surface observations. A set of simplified extended Kalman filters (SEKFs) has been developed for soil, snow, sea ice and lakes, which will replace the OI system in the next Harmonie Reference System version (Cy43h). Preliminary experiments with these SEKF's in combination with conventional and a variety of satellite observations such as ASCAT soil moisture have shown better results than achieved with OI. Also, in the past three years experience has been gained with the acquisition and assimilation of satellite data such as ASCAT and SMOS products for soil moisture and LAI, MODIS data for lake water temperature and ice fraction assimilation, and several different satellite products for sea ice and snow extent and depth. In 2019, the SEKF's will be introduced into the Harmonie Reference in combination with the new Surfex diffusion soil (DIF) and explicit snow (ES) snow schemes. At a later stage, a variety of satellite observations of the soil, sea surface and inland waters, and snow- and ice-covered surfaces will be added progressively to the surface assimilation.

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 few years have included the development of a multiple energy balance approach for vegetation- and snow-covered surfaces, of a simple sea ice scheme which since then has been made more sophisticated (through a more realistic ice thickness evolution and treatment of snow on ice), and extensions to the Flake lake model (e.g. 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. These schemes and the ways in which to tune them have been assessed thoroughly, together with researchers from the regional climate modelling community. 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 (see fig.3 for an example of the improvements seen in the multi-layer ES snow scheme wrt the present bulk snow scheme D95). In 2019, the full set of schemes will be tested in combination with each other, and also together with the new surface data assimilation. A start has been made with testing the combination of surface schemes in climate mode, with the aim to identify, and where possible reduce, potential surface model biases.

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 various weaknesses, local as well as larger scale. Examples of situations in which local improvements proved necessary, are the albedo of volcanic sands and characteristics of the vegetation in Iceland, the LAI climatology (see section B1), and unrealistic assumed tree heights in Scandinavia (which led to local biases in low level wind speed). A local high-resolution sand-and-clay database over Scandinavia was shown to be a significant improvement there over the HWSD global sand-and-clay database.

C3. Coupled atmosphere – sea surface modelling

Within the first half HIRLAM-C programme, this has been a longer-term goal of relatively low priority. First experiments started several years ago in Norway with coupling Harmonie with the sea surface through one- and two-way inline coupling with the WAM wave model. Next, a coupled atmosphere-wave model, making use of an OASIS coupler and the wave model WaveWatch3, has been set up at SMHI. The indications for both systems were that the impact of two-way coupling was quite beneficial.

D) Code efficiency and scalability

An important task to achieve is the optimization of code efficiency and scalability, with a view to use on very massively parallel hardware platforms. The main bottleneck for scalability, in Harmonie as in most other forecast models, is the need for I/O to read initial data and to write out forecast fields at required intervals. Removal of the present use of intermediate formats and the introduction of an I/O server are developments aiming to reduce these problems. The best way to improve the parallelization of a computer code on the longer term is to restrict as much as possible the need for communications among processors, particularly in the context of semi-Lagrangian interpolations and spectral transforms. Efforts have been made together with the IFS/AAAH partners to ensure that I/O and as many computations as possible take place in grid point space, thus reducing the need for spectral transforms. Plans to assess the impact of more efficient "localized" dynamics options were already mentioned above (section B3). Cost reductions can be achieved by the use of an I/O server, developed by Meteo-France. Optimizations made by HIRLAM staff include speedups in e.g. the microphysics, shallow convection and turbulence schemes have reduced costs by ~10%.

In terms of parallelization, several existing and potential bottlenecks can be identified. One of the weakest points in the model is the relatively poor parallelization of the surface model and surface assimilation; although this has been improved, further optimization in this area remains needed. MPI parallelization has been implemented successfully in the multiple outer loop 4D-Var setup, but OpenMP thread parallelization for 4D-Var remains to be done. The 3- and 4DEnVar system which are presently under development are inherently better parallelizable, and have been demonstrated to be computationally significantly more efficient.

A cooperation with the Barcelona Supercomputing Center has started in the fall of 2018 with the aim to clearly establish which parts of the code are the most limiting factors in terms of efficiency and scalability, and how to tackle this. HIRLAM staff have started to investigate the option to use single rather than double precision in Harmonie, and assessing its computational and meteorological consequences. A beginning has also been made with studies to assess how best to optimize code performance on mixed CPU/GPGPU computer architectures, both in the context of externally funded projects (e.g. ESCAPE) and in cooperation with hardware providers like Bull.

E) Use of Harmonie in re-analyses and regional climate modelling:

A growing number of regional climate modelling (RCM) groups in Hirlam member states has begun to explore the use of Harmonie for re-analysis and climate modelling purposes. Increasingly, Harmonie-Arome has been used in long re-analysis and/or climate runs, e.g. in Finland, Netherlands, Ireland and Sweden; one example is the 35-year MetEireann MERA re-analysis (Gleeson et al. 2017). In the context of the Copernicus project CARRA preparations have been made for a large re-analysis effort over the Arctic. A climate branch has been developed for Harmonie (called HCLIM) based on Cy37h, and later this has been upgraded to include atmospheric and surface model improvements introduced in Cy40h1 and Surfex-v8, respectively.

Figures:

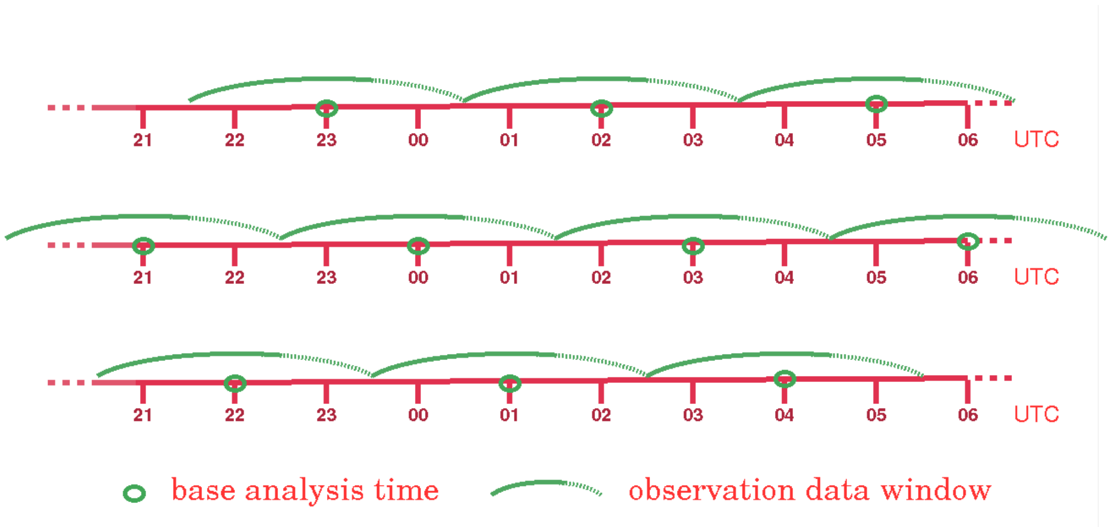

Fig. 1: Overlapping time window strategy used in the present COMEPS ensemble. Hourly analysis is enabled in DMI's COMEPS ensemble system through the use of 3 parallel suites, each using a 3-hourly data assimilation cycling but with a base time which is consecutively shifted by 1h between the three members. 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.

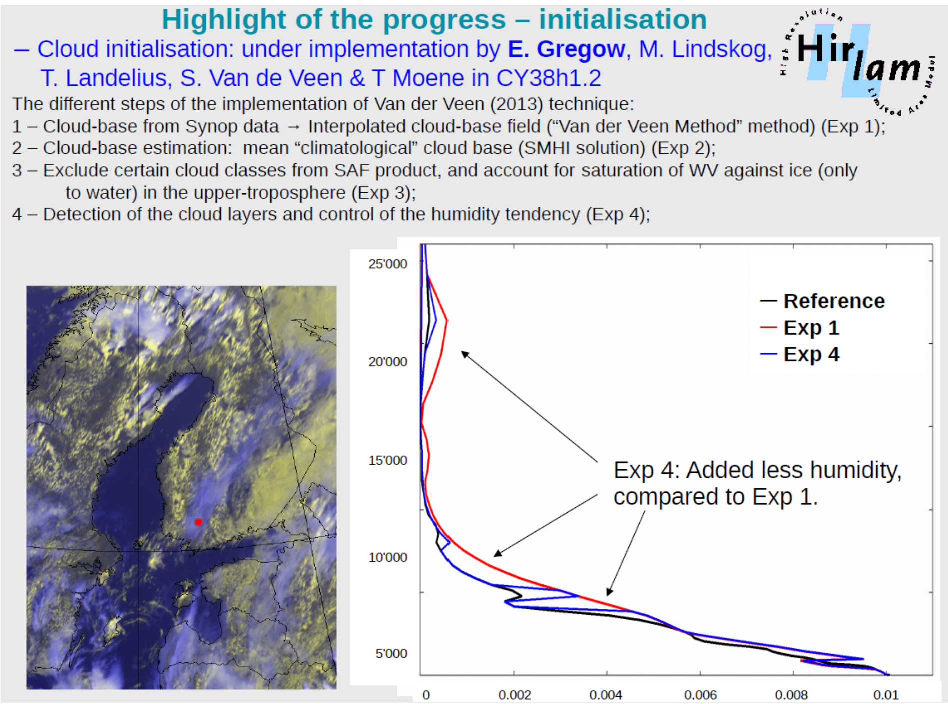

Fig.2: Example from experiments over Finland aiming to improve the original cloud initialization algorithm through a better use of available cloud type and cloud layer information from the NWC SAF. The original cloud initialization method generally resulted in too humid vertical profiles (red curves in right panel) wrt observations (black curves) at a radiosonde site (at the location of the red dot in the left panel). Making use of the additional NWC SAF cloud information results in more realistic initial moisture profiles (blue curve).

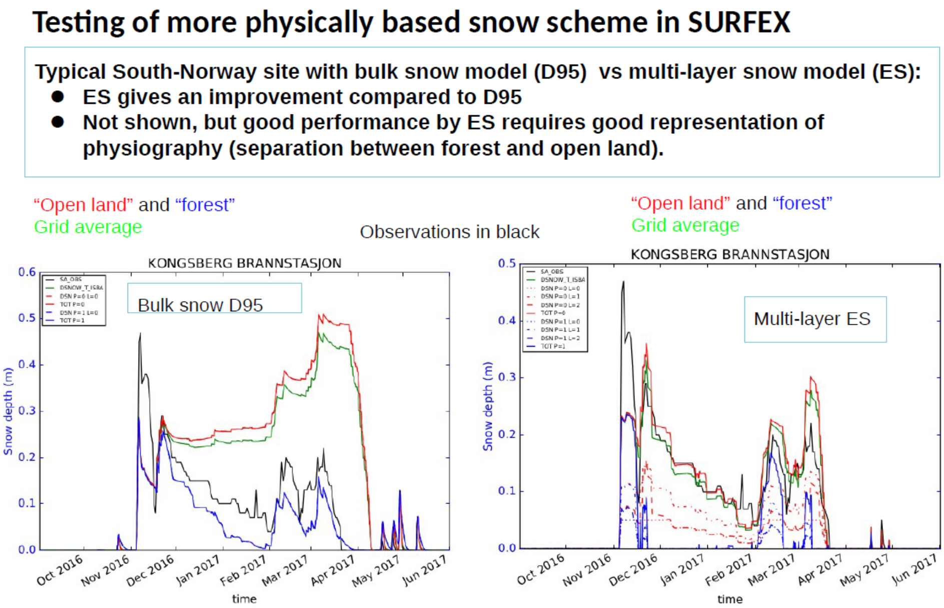

Fig.3: Results for a comparison of the snow depth representation of the present bulk snow model D95 (left panel) versus the new multi-layer snow scheme ES (right panel), for a station in southern Norway during the winter season of 2016-2017. Black curves indicate snow depth observations; the green curves represent the grid-averaged value of model snow depth at the station location, while the red and blue curves indicate the model snow depth for the "open land" and "forest" patch for this grid point, respectively. Neither the grid-average nor the open land or forest patches in the D95 scheme can adequately represent the reduction in snow depth after December 2016. The multi-layer ES scheme gives a far better description of the snow depth evolution.

List of publications/reports from the project with complete references

Bengtsson, L. and Körnich, H.,2016. "Impact of a stochastic parametrization of cumulus convection, using cellular automata, in a mesoscale ensemble prediction system". QJRMS Vol.142: 1150–1159. doi: 10.1002/qj.2720

Bengtsson, L., et al., 2017. "The Harmonie-Arome model configuration in the ALADIN-HIRLAM NWP System", MWR 145, pp.1919-1935 , DOI: 10.1175/MWR-D-16-0417.1

Boone, A., P.Samuelsson, S. Gollvik, A. Napoly, L. Jarlan, E. Brun, and B. Decharme, 2017: "The Interactions between Soil-Biosphere-Atmosphere (ISBA) land surface model with a multi-energy balance (MEB) option in SURFEXv8 - Part 1: Model description". Geoscientific Model Development, vol.10, pp.1-30. doi:10.5194/gmd-10-1-2017

Bruijn, E.I.F. de, S. de Haan, F.C. Bosveld, B. Wichers Schreur and A.A.M. Holtslag, 2016: "Observing Boundary-Layer Winds from Hot-Air Balloon Flights", Wea. and Forec. Vol.31, 1451-1463, doi:10.1175/WAF-D-16-0028.1.

Gleeson, E., Toll, V., Nielsen, K. P., Rontu, L., and Mašek, J., 2016. "Effects of aerosols on clear-sky solar radiation in the ALADIN-HIRLAM NWP system", Atmos. Chem. Phys., 16, 5933-5948, doi:10.5194/acp-16-5933-2016.

Gleeson, E., Whelan, E., and Hanley, J., 2017: "Met Éireann high resolution reanalysis for Ireland", Adv. Sci. Res., 14, 49-61, doi:10.5194/asr-14-49-2017.

Gregow, E., 2017, "Harmonie – MSG cloud data assimilation experiments", ALADIN-HIRLAM Newsletter 10, pp 22-29.

Gustafsson, N., et al., 2018. "Survey of data assimilation methods for convective-scale numerical weather prediction at operational centers", QJRMS,2018, doi:10.1002/qj.3179

Kheyrollah Pour, H., Choulga, M., Eerola K., Kourzeneva E., Rontu L., Pan F., Duguay C.R., 2017: "Towards improved objective analysis of lake surface water temperature in a NWP model: preliminary assessment of statistical properties". Tellus A 69. DOI:10.1080/16000870.2017.1313025

Landelius, T., Dahlgren, P., Gollvik, S., Jansson, A., Olsson, E., 2016. "A high resolution regional reanalysis for Europe. Part 2: 2D analysis of surface temperature, precipitation and wind". QJRMS 1477-870X. http://dx.doi.org/10.1002/qj.2813

Marseille, G.-J., Barkmeijer, J., de Haan, S., and Verkley, W., 2017: "Assessment and tuning of data assimilation systems using passive observations",QJRMS vol.142, pp.3001-3014,doi:10.1002/qj.2882

Marseille, G.-J. and Stoffelen, A, 2017: "Toward scatterometer winds assimilation in the mesoscale Harmonie model", IEEE Journal Selected Topics Appl. Earth Observations Remote Sensing, doi:10.1109/JSTARS.2016.2640339.

Mottram, R., Nielsen, K. P., Gleeson, E., and Yang, X., 2017: "Modelling Glaciers in the Harmonie-Arome NWP model", Adv. Sci. Res., 14, 323-334, https://doi.org/10.5194/asr-14-323-2017.

Müller, M., et al., 2017: "AROME-MetCoOp: A Nordic Convective-Scale Operational Weather Prediction Model". Wea. Forecasting, 32, 609–627, doi: 10.1175/WAF-D-16-0099.1.

Napoly, A., et al., 2017: "The Interactions between Soil-Biosphere-Atmosphere (ISBA) land surface model and Multi-Energy Balance (MEB) option in SURFEX - Part 2: Model evaluation for local scale forest sites". Geoscientific Model Development, **10**, 1621-1644, doi:10.5194/gmd-10-1621-2017

Nielsen, K.P., Gleeson, E., 2018: "Using Shortwave Radiation to Evaluate Clouds in Harmonie-Arome". Atmosphere. 2018.

Rontu L, Wastl C, Niemelä S, 2016. "Influence of the details of topography on weather forecast ? Evaluation of HARMONIE experiments in the Sochi Olympics domain over the Caucasian mountains". Frontiers in Earth Science 4, 16 pp. http://dx.doi.org/10.3389/feart.2016.00013.

Rontu, L., Gleeson, E., Räisänen, P., Pagh Nielsen, K., Savijärvi, H., and Hansen Sass, B., 2017: "The HIRLAM fast radiation scheme for mesoscale numerical weather prediction models", Adv. Sci. Res., 14, 195-215, https://doi.org/10.5194/asr-14-195-2017

Samuelsson, P., Homleid, M., Aspelien, T., Andrae, U., 2018. "Two patches in Cy40 Harmonie-Arome, and modified tree height and snow roughness length for the MetCoop domain.", ALADIN-HIRLAM Newsletter 10. pp.107-115

Soci, C., Bazile, E., Besson, F., & Landelius, T.,2016. "High-resolution precipitation re-analysis system for climatological purposes". Tellus A, 68. doi:http://dx.doi.org/10.3402/tellusa.v68.29879

Toll, V., Gleeson, E., Nielsen, K.P., Männik, A., Mašek, J., Rontu, L., Post, P., 2016. "Impacts of the direct radiative effect of aerosols in numerical weather prediction over Europe using the ALADIN-

HIRLAM NWP system". Atmospheric Research, vol. 172–173, p.163–173. doi:10.1016/j.atmosres.2016.01.003

Valkonen, T., Schyberg, H., Figa-Saldana, J., 2016: "Assimilating advanced scatterometry winds in a high-resolution limited area model over Northern Europe", IEEE Journal of Selected topics in Applied Earth Obs. and Remote Sensing vol.99, pp.1-12, doi: 10.1109/JSTARS.2016.2602889

Yang, X., Feddersen, H., Hansen Sass, B., Sattler, K., 2017: "Construction of a continuous mesoscale EPS with time lagging and assimilation on overlapping windows", ALADIN-HIRLAM Newsletter 8, pp.112-118, http://www.umr-cnrm.fr/aladin/meshtml/nl8.pdf

Future plans

The special project HIRLAM-C 1st phase (2016-2018) has ended December 2018. A new project (HIRLAM-C 2d phase (2019-2020)) has been applied for, and granted, for the second half of the HIRLAM-C programme period, with updated scientific goals.