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The DMI-HIRLAM upgrade in June 2004

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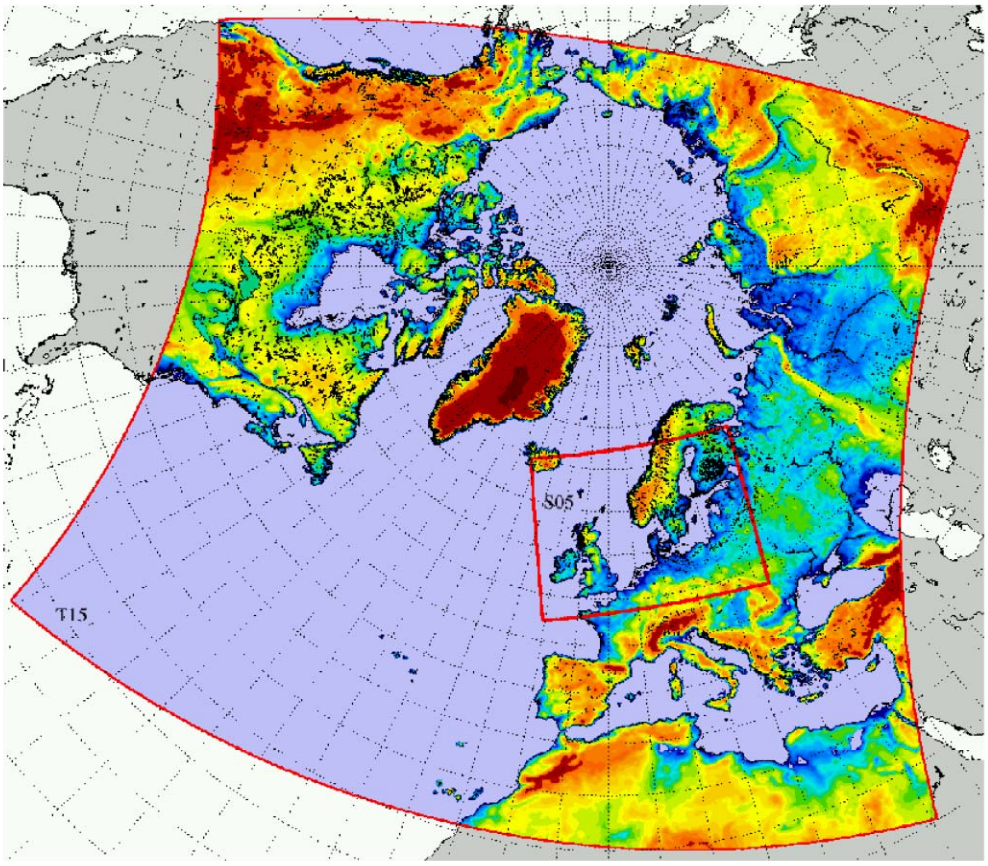

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Contents

Abstract

This report describes the main features in the major upgrade of DMI's operational forecast system DMI-HIRLAM on June 14 2004, in which the horizontal domain for the main forecast production, was enlarged substantially and several key components of the operational system, i.e., forecast, climate generation and surface analysis modules, were changed to be based on the recent reference HIRLAM version 6.3. A significant amount of adaptation work has been performed to ensure computational efficiency as well as quality in meteorological performance. Operational experience as well as parallel experiments in hindcast mode for historical episodes demonstrate generally improved performance with the new system. In this report, the main emphasis is to document the new features in the upgraded operational suite as compared to the previous one, as well as the differences between the reference HIRLAM and the new DMI-HIRLAM due to local adaptation.

Resume

Denne rapport beskriver de væsentligste ændringer, der er foretaget i DMI's prognose model. Denne version har siden 14. juni 2004 afløst DMI-HIRLAM-GEDN som den operationelle model og er blandt andet karakteriseret ved, at modelområdet er blevet øget betydeligt. Derudover er modellen blevet ændret eller udskiftet på en lang række andre områder, her i blandt prognose modellen, klima genereringen og overfladeanalysen, hvor koden nu er baseret på reference HIRLAM version 6.3. For at udnytte DMI's computer faciliteter optimalt og for at forbedre prognosemodellens kvalitet, er der foretaget en del DMI specifikke kodetilrettelser. Operationel erfaring og historiske testkørsler har vist, at disse ændringer har ført til en generel kvalitetsforbedring af prognosemodellen. I rapporten, vil foreskellene mellem den nuværende og forgående operationelle model samt de tilrettelse, der er blevet foretaget i forhold til reference HIRLAM 6.3, blive dokumenteret.

Introduction

Since early 2003, DMI's meteorological research division (FM) has committed substantial resources to implement the main components of the recent reference HIRLAM system (REF-HIRLAM) into DMI's operational forecast suite DMI-HIRLAM. The implementation involves mainly changes in climate generation, surface analysis and forecast model. Since 1997, DMI's operational suite (hereafter referred to as DMI-HIRLAM-GEDN, where "G", "E", "D", "N" denote the triply nested model domains in the previous operational DMI-HIRLAM. see detailed description of the system in Sass et al. 2002), which originated from the earlier versions of the REF-HIRLAM 3 in 1996, has undergone many developments and resulted in significant improvement in forecast quality and efficiency. Many deviations occurred during the process and DMI-HIRLAM as a whole became substantially different from the recent REF-HIRLAM. Meanwhile, numerous new features have been developed in the recent REF-HIRLAM (Undén et al. 2002), such as the new surface analysis scheme including land surface assimilation, a more advanced implementation of the Semi-Lagrangian advection and implicit horizontal diffusion schemes, a Digital Filtering Initialization (DFI) scheme, and several updates in physical parameterization for turbulence, radiation, and surface processes. REF-HIRLAM also features an implementation of parallelization using MPI in its forecast model. These features add weight to the argument for cost-effectiveness of DMI-HIRLAM to base its forecast model on REF-HIRLAM, rather than partial adaption of REF-HIRLAM features into DMI-HIRLAM. On the other hand, it has been obvious, that various adaptations have had to be made during the process of changing the operational suite to a system based on REF-HIRLAM, both from a technical point of view and to the meteorological performance. The new DMI-HIRLAM was officially launched in June 14, 2004, and was based primarily on REF-HIRLAM 6.3 with local adaptations. The new DMI-HIRLAM has been observed, from both the pre-operational and operational experiences, to compare favorably in many respects to the previous version. This is also quantitatively demonstrated by using standard verification measures for parallel hindcast runs and comparisons in extreme storm cases, as well as from examination of prediction for sea level height with the storm surge model driven by the predicted surface wind in the DMI-HIRLAM. (See verification reports for winter episodes in Petersen et al. (2005) and summer episodes in Kmit et al. (2005)).

In this report, the focus has been to document the main differences between the new DMI-HIRLAM and the previous one, and various modifications made to the REF-HIRLAM during the local adaptation.

Domain configuration

Prior to the June 2004 upgrade, DMI's operational suite, DMI-HIRLAM-GEDN, consisted of forecast runs on 4 domains in a triply-nested structure (Figure 1), with the "G" domain covering a large area of western part of the northern hemisphere at 0.45° resolution on a 202$times$190 grid (hereafter referred to as "G"); The "G" uses ECMWF Boundary Condition (BC) forecast frames as lateral boundaries and provides, in turn, its hourly forecasts for "E" and "N" as lateral boundaries. The run on "E" domain, with a grid of 272$times$282 and 0.15° resolution, was DMI's main production suite for short-range forecasts up to 54 h for western Europe. The "N" domain, with a 194$times$210 grid and 0.15° resolution, is designed for forecasts in Greenland. Finally, the run on the "D" domain, with a grid of 182$times$170 and 0.05° resolution, provides forecasts up to 36 h for the Danish area, using hourly forecasts from "E" as lateral boundaries. All these runs are done at a vertical grid of of 40 levels.

The new DMI-HIRLAM merges now "G", "E" and "N" into a "T" domain (T15) with a grid mesh of

610$times$568 and 0.15° resolution (Figure 2). The T15 domain is almost equivalent to that of "G" but with 3 times higher horizontal resolution. The use of the T15 domain for the main forecast production implies approximately an increase of domain size by a factor of 3, relative to the combined domain size of "E" and "N" at same resolution (0.15°). Meanwhile, the "D" domain has been enlarged to the "S" domain (S05) with a grid mesh of 496$times$372, which more than doubles the size of the previous "D" domain. The S05 domain now covers the entire Baltic Sea and the North Sea, and has hence become the host model for DMI's high resolution oceanographic storm surge model, Mike21.

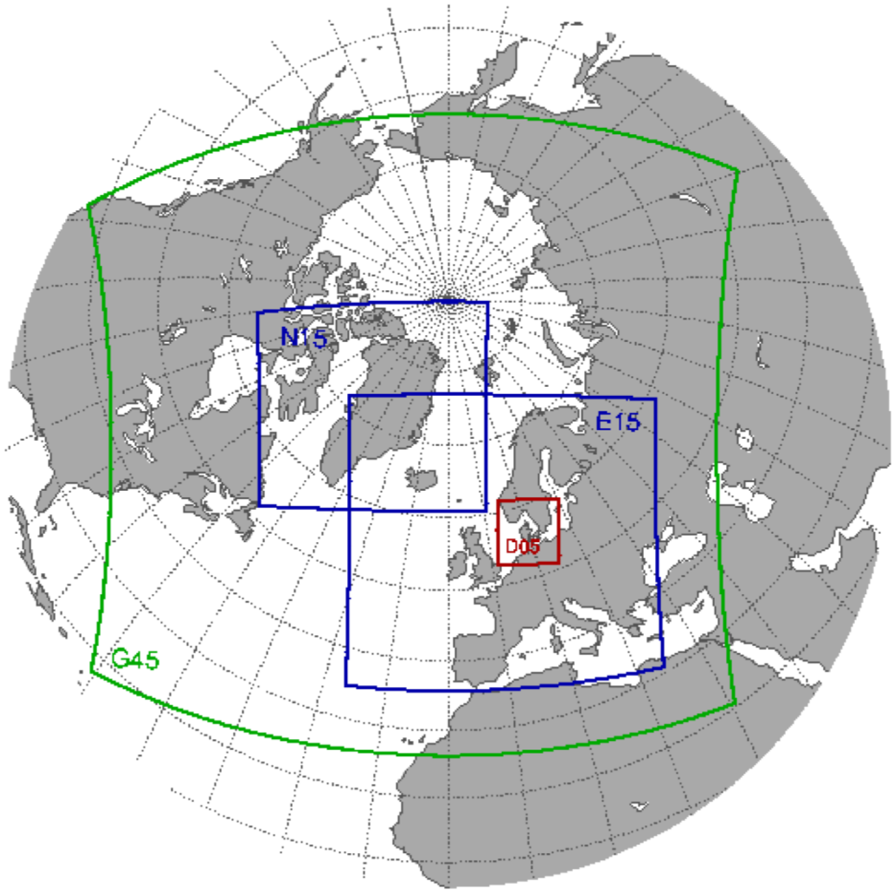

Figure 1: The DMI-HIRLAM-GEDN nested model domain, which had been operational from October 1997 until June 2004. DMI-HIRLAM-G (marked in the lower left corner with 'G') is the outermost model area and run with 0.45° grid-spacing, DMI-HIRLAM-E ('E' on figure) 0.15° as well as DMI-HIRLAM-N ('N'), while DMI-HIRLAM-D ('D') was run with 0.05° grid-spacing.

Besides the change in model domains, the new DMI-HIRLAM with T15 and S05 (hereafter referred to as DMI-HIRLAM-TS) differs from the DMI-HIRLAM-GEDN in many aspects. Due to the increased domain size, the forecasts at 0.15° and 0.05° grid-spacing are now extended to 60 and 54 h, respectively. In Appendix A, the operational scheduling of DMI-HIRLAM-TS, as well as a rough estimate of resource usage of the operational suite, is given.

In DMI-HIRLAM-TS, T15 is now the outermost domain and it uses ECMWF-BC frames at 3 hour interval as lateral boundaries. In DMI-HIRLAM-G, BC data are requested only for every other level (in total, 30 levels), whereas in T15, full vertical resolution (60 level) BC data are requested. Information from 47 of the 60 ECMWF vertical levels are used in interpolation to DMI-HIRLAM

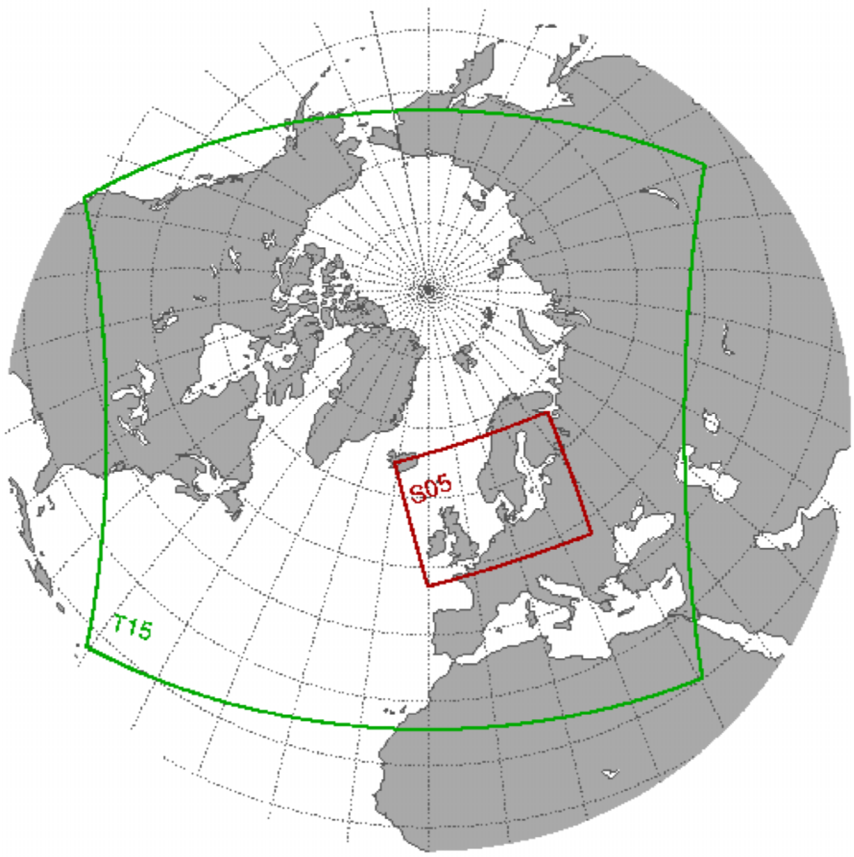

Figure 2: The DMI-HIRLAM-TS forecast domain which has been operational since June 2004. DMI-HIRLAM-T15 (marked in the lower left corner with 'T15') is the outermost model area with 0.15° grid-spacing. DMI-HIRLAM-S05 ('S05' on figure) runs with 0.05° grid-spacing.

with 40 levels, the remaining 13 levels are not used because they are located higher up in the atmosphere than the model top (10 hPa) in DMI-HIRLAM. The benefit of using full, instead of reduced, vertical resolution of ECMWF BC data in T15 was demonstrated in a parallel comparison in which improvement in MSLP rms scores has been observed (not shown here). A 3 or 6 hours forecast from previous cycle, depending on assimilation interval, is used as a first guess in the ISBA surface analysis. It updates surface quantities such as surface temperature and water content in the soil layer. The modified first guess from the ISBA analysis is then used as a first guess in the upper-air 3D-VAR analysis. Final analysis from 3D-VAR is used together with the ISBA-modified first guess through Incremental Digital Filtering Initialization (IDFI) to initialize the forecast (see more details in the section about initialization).

Implementation of the main components of REF-HIRLAM has required a substantial amount of work. Much of the adaptation were technical in nature. In addition, during the pre-operational parallel runs, some deficiencies in REF-HIRLAM were identified, often associated with poorer meteorological performance in comparison to DMI-HIRLAM-GEDN. Modification of various model elements and numerical experiments have thus been necessary. In the following sections, more detailed descriptions of the features in DMI-HIRLAM-TS, both in contrast to those in DMI-HIRLAM-GEDN and to those in REF-HIRLAM, are given.

Climate generation

The climate generation procedure used in DMI-HIRLAM-GEDN differs in several respects from the one in REF-HIRLAM, such as the original data resolution, orographic smoothing scheme, and differences related to the use of ISBA surface scheme in REF-HIRLAM. As a result, the climate constant fields generated by DMI-HIRLAM-GEDN cannot be directly applied to the system based on REF-HIRLAM. Thus the climate generation module in REF-HIRLAM has been implemented in the DMI-HIRLAM-TS suite. During this process, several modifications were found to be necessary and more details can be found in Sattler (2004a). Among the main modifications, the following can be mentioned:

1. In the DMI-HIRLAM implementation, smoothed orography using Raymond filtering has been used. The implemented filtering scheme differs from REF-HIRLAM versions up to 6.2.2. In addition, in order to avoid artificial features associated with numerical filtering (e.g., grid-point islands along coastlines), the resulted orographic fields are adjusted using correlation relations in the filter process[1].

2. An improved scheme to derive orographic roughness has been implemented. The scheme results in a more reasonable orographic roughness distribution in areas such as Greenland (Sattler 2004b)[2]. As Figure 3 demonstrates, using the scaling in DMI's implementation, the maximum of the z_0 value is less than 10 m in the T15 domain, whereas the corresponding maximum is about 55 m in the REF-HIRLAM implementation. The differences in the z_0 values here are associated with slightly different implementations of the recent tuning of the turbulence scheme in the HIRLAM community.

3. In REF-HIRLAM, the soil type "sand" has been assigned to many parts of Europe, such as areas in northern Europe including large parts of Denmark, where it is dominated by assigned tile types of either low vegetation or forest (Figure 4, upper panel). This has been found to be associated with unrealistically low soil moisture in dry periods (such as those in March/April for Denmark), and hence unrealistically active diurnal cycles in 2 m temperature (T2m, too warm on sunny days and too cold during clear nights). A modification of the soil type from "sand" to "loam" for such areas in the climate generation procedure has thus been implemented (Figure 4, lower panel), which has resulted in a better T2m fit.

With the above mentioned exceptions, the new climate generation system is equivalent to the REF-HIRLAM 6.3.6, released in Feb 2005.

Surface analysis

In DMI-HIRLAM-GEDN and older versions of REF-HIRLAM, no surface analysis was performed. Instead, the time varying surface quantities such as soil temperature, humidity and snow depth are cycled from the previous forecast (first guess), with the exception of the sea surface temperature (SST) and ice cover. The latter are derived, using simple linear interpolation, from the ECMWF "analyses" available two times a day at 00 and 12 UTC, which themselves are based on NCEP global analyses.

In DMI-HIRLAM-TS, the surface analysis based on the scheme "Interaction between Soil, Biosphere and Atmosphere" (ISBA), as implemented in REF-HIRLAM has been adopted (Undén et

[1] This scheme in DMI-HIRLAM-TS is later adopted in REF-HIRLAM 6.3.5.

[2] This scheme, together with the Raymond filtering of orography as in (1), was later implemented i in the REF-HIRLAM climate generation in 6.3.5, but in DMI's implementation, different scaling factors for orographic roughness has been applied compared to those in REF-HIRLAM.

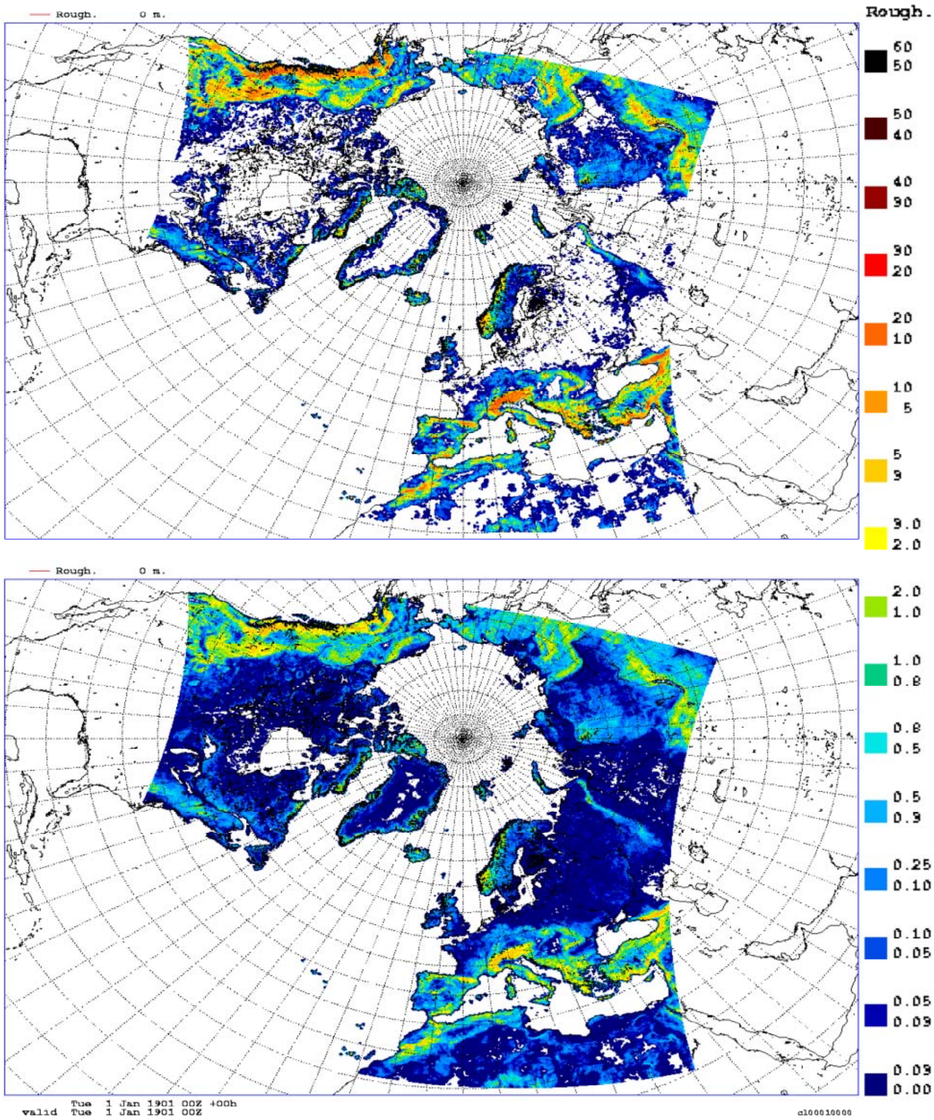

Figure 3: Orographic roughness for the T15 domain using climate generation and scaling options as implemented in REF-HIRLAM (6.3.5a) (upper panel) and DMI-HIRLAM (lower panel). White area represents flat areas with practically no orographic roughness.

al. 2002). With the REF-HIRLAM implementation, surface properties are classified into 5 tile types: water, ice, bare soil, low vegetation and forest, with different soil features prescribed under land tiles. The primary observation data source in the surface analysis is conventional SYNOP observations from LAND and SHIP. From the observed screen-level temperature and dew point temperature, SST and snow depth, the near surface prognostic quantities are modified with an Optimal Interpolation (OI) method, except for the analysis of SST and snow depth. These are analysed using a successive correction method.

Some code modifications have been necessary in order to assimilate SYNOP and SHIP observations with DMI's BUFR data format. For analysis of sea surface features, the disseminated ECMWF analysis data at 0.5° resolution, is used. Another data source for the SST analysis is SHIP SYNOP observations. No data from DRIBU is used. In the original REF-HIRLAM, the ECMWF SST analysis is treated as a pseudo-observation at 2° resolution, and the ice concentration information

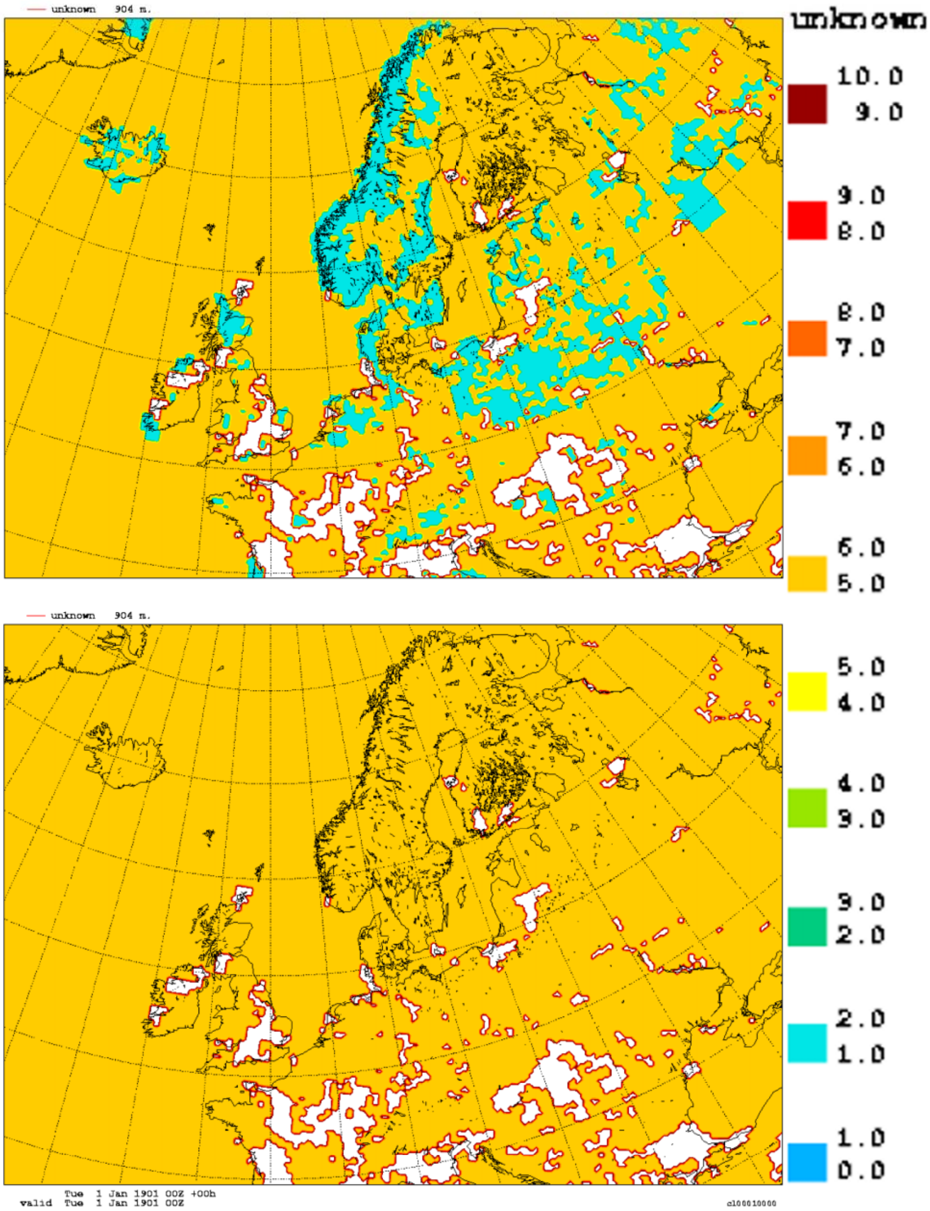

Figure 4: Soil property assigned to tile type 'low vegetation', as determined by the REF-HIRLAM climate generation (upper panel) and by DMI's modification (lower panel). In the latter, the soil feature is changed from pure sand (light blue color) to mixture of sand and loam (orange color) for European 'low vegetation' areas. White areas in the plots represent those classified with other tile types, i.e., bare soil or forest.

from ECMWF or observation data are not used. Rather, a diagnosis is made to derive ice cover according to the analyzed SST. However, the pre-operational runs with T15 and S05 indicated often unsatisfactory SST analyses and accordingly unrealistic ice cover diagnoses in winter periods, especially along the coast of Greenland. In fact, comparison of such obtained ISBA analyses of SST and ice cover with those of the disseminated SST and ice concentration data or analyses from various data sources (such as satellite images etc.) indicated little advantage (and often, on the contrary, a negative impact) in analysing SST and ice cover. Thus modifications were made so that the interpolated ECMWF SST is treated directly as background and only SHIP observations are assimilated in the analysis using a successive correction scheme. For ice cover, instead of diagnosing it from the analyzed SST, it is completely determined by the interpolated ECMWF ice cover data, and final adjustment of the SST is made according to the ice cover. Figure demonstrates an example of the modified SST analysis procedure in DMI-HIRLAM-TS. For T15 analysis cycle 2005041300, first an interpolation of the disseminated ECMWF SST field at 0.5 ° resolution (Figure a) is made to obtain the SST field in the T15 grid. Note that a source code modification was made in the horizontal interpolation procedure in order to extrapolate the ECMWF SST field to all points with water tiles (Figure b). This is to avoid data holes within the model area over tiles with fraction of waters (e.g., along coast lines). The interpolated/extrapolated ECMWF SST field is then used directly in the ISBA analysis as background. A successive algorithm is then applied to assimilate SHIP SST data to obtain an SST analysis. Finally, the analysed SST value is modified so that areas with ice cover, according to ECMWF ice analysis, are assigned fixed values (Figure c). Parallel experiments validating the correction to the ISBA SST and ice analyses confirmed the significant improvement in the resulted T2m forecast for Greenland for March 2004 (see Figure 3 in Yang 2004).

With the above-mentioned exceptions, the ISBA analysis scheme in DMI-HIRLAM is equivalent to that of REF-HIRLAM 6.3.0.

Upper air analysis

For T15, HIRLAM 3D-VAR (HIRVDA) is used with the FGAT option for upper air data assimilation. In principle the same version of HIRVDA software is used in DMI-HIRLAM-TS as in DMI-HIRLAM-GEDN, except that the first guess in the 3D-VAR procedure is now the output of the ISBA analysis, and "lisba" and "lwriteall" are now specified as TRUE in the name-list. The main features in the implemented 3D-VAR scheme in T15 include a 3 h assimilation cycle (with the exception of short cut-off runs at 06 and 18 UTC). A low-resolution increment is used in the 3D-VAR minimization. Assimilation of conventional observation data, SYNOP, SHIP, DRIBU, TEMP, PILOT, AIREP and satellite data, ATOVS (NOAA-15/16 AMSU-A) and Quikscat wind data, is done. As for DMI-HIRLAM-GEDN, the forecast error statistics are the vertically interpolated ones derived from the SMHI 31-level structure functions, using seasonal adjustment a scaling factor of around 0.6 for standard deviation of surface pressure, temperature and ageostrophic winds.

The HIRVDA analysis scheme as installed in DMI-HIRLAM is equivalent to the corresponding version in REF-HIRLAM 6.3.2.

Forecast model

Code-wise the forecast module is mainly based on REF-HIRLAM 6.1.2 with subsequent revisions similar to those in the later releases of 6.3. Several important revisions have been made to tune the turbulence scheme, and the final implemented turbulence parameterisation in DMI-HIRLAM-TS resembles its counterpart in REF-HIRLAM, 6.3.5, see more details below [3].

Technical adaptation and parallelization

The adaptation of the forecast model based on REF-HIRLAM involved many technical efforts. First, a script system in similar style as that used in the previous DMI-HIRLAM-GEDN was constructed. Running REF-HIRLAM requires a separate script for preparing lateral boundaries, which was not necessary in DMI-HIRLAM-GEDN where the interpolation of initial and lateral boundary files was done on the fly during forecast. The technical adaptation also includes creation of GRIB conversion facility between the internal REF-HIRLAM GRIB format (ASIMOF) and DMI's GRIB format. Comparing to the GRIB format adopted in DMI-HIRLAM-GEDN and other HIRLAM-related

[3] The dynamic core related to the SL scheme was further updated for DMI-HIRLAM-TS in Jan 2005, making the dynamic aspect equivalent to the REF-HIRLAM 6.3.4.

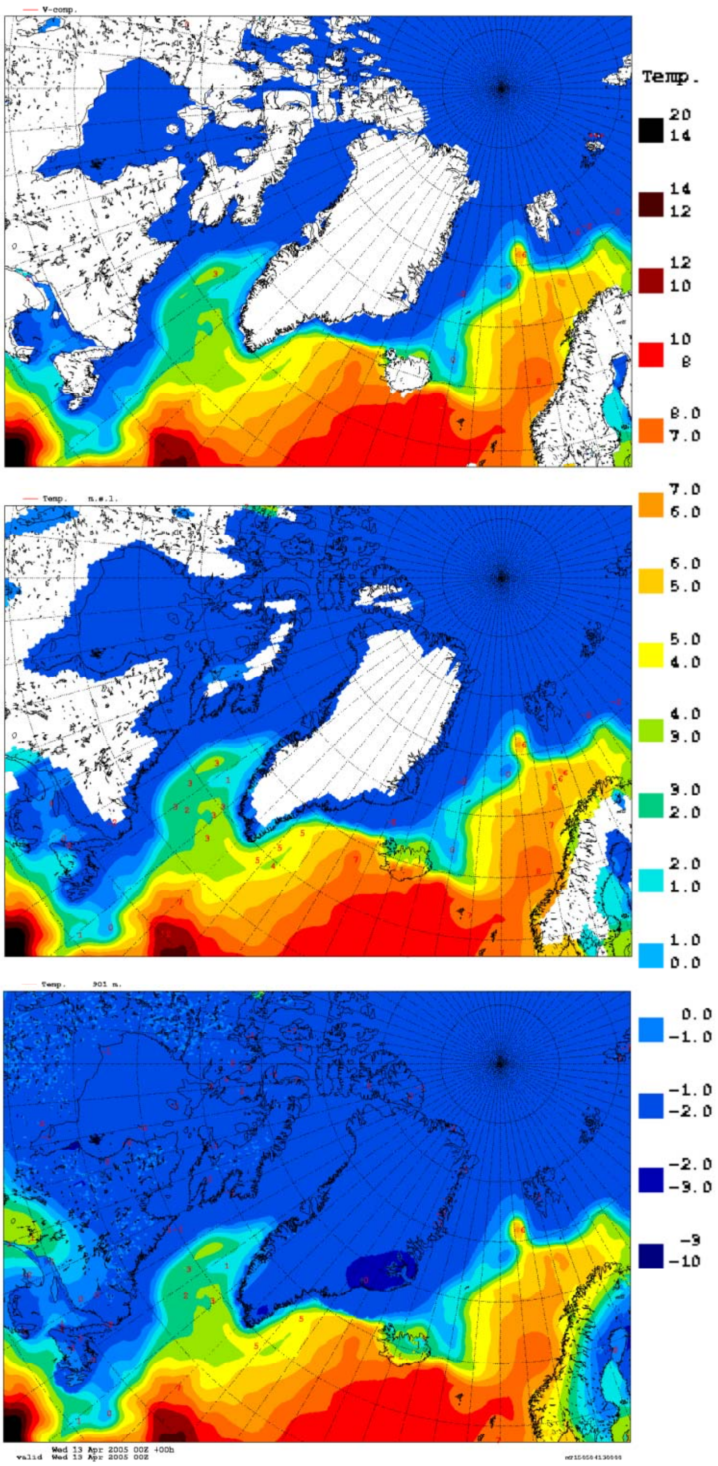

Figure 5: Sea surface temperature for the area centered around Greenland for: ECMWF data at 0.5° resolution, valid at 12 UTC on 20050412 (upper panel); the interpolated and extrapolated SST on T15 grid (middle panel); the final T15 analysis valid at 00 UTC on 20050413 (lower panel).

applications, the ASIMOF GRIB format in REF-HIRLAM differs mainly on two aspects. In an ASIMOF file, the first record always contains the vertical coordinate parameters and occupies GRIB parameter number 254. Secondly, the file can contain any number of administration headers, depending on number of fields to be written into the data base. The first header is located in the top of the file while the next is located after the next 100 entries (fields). Each header contains pointers to individual entries in the data base (as well as a pointer to the next administration header). This makes searching the data base for specific entries very efficient.

Significant amount of work has been devoted to improve the efficiency of the forecast code in REF-HIRLAM on the NEC SX-6 platform. The NEC SX-6 computer as installed at DMI is a multi-node, a total of 8, clustered system, in which processors on a single node share memory, while the inter-node memory structure is distributed. The code optimization work includes those with OpenMP, MPI options or both (Boerhout 2004, Korsholm and Petersen, 2003). Certain parts of the code, such as the Helmholz solver and the horizontal diffusion scheme, have been difficult to parallelize using OpenMP, and could not parallelize well with MPI either. These involve mainly those that perform swapping and data communication in connection with FFT. Through close cooperation with NEC-EUROPE, the structure of these subroutines have been efficiently optimized. The modification reduce significantly the data distribution among different nodes. This, in combination with a re-arrangement of data structure, improves substantially the performance of the system, especially at increasing number of processors. The code modifications and performance tests have been documented in Boerhout (2004) and most of those have since been adopted in the recent release of REF-HIRLAM.

In November 2004 the input/output handling scheme in DMI-HIRLAM was optimized by the implementation of the HIRLAM Gribfile Server (HGS). A brief summary of the HGS workings is given in Appendix C. For operational DMI-HIRLAM-TS, currently 3 nodes, a total of 24 processors, are allocated for forecasts. Among them, 2 processors are allocated for asynchronous I/O, 4 for lateral boundary processing, file conversion and post-processing for verification purposes, and the remaining 18 processors are used for forecast integrations. With such a configuration, a 60 h T15 forecast now takes about 30 min, and a 54 h S05 forecast takes about 40 min.

Dynamics

In DMI-HIRLAM-TS, the semi-Lagrangian advection scheme (SL) and 6th order implicit horizontal diffusion are used. These differ from the method used in DMI-HIRLAM-GEDN, in which a modified Eulerian advection scheme with differential time stepping for dynamics and physics and, a 4th order implicit diffusion scheme are used. The use of SL advection enables a relatively long time-step for DMI-HIRLAM, which is 6 minutes for both dynamics and physics in T15 and 2 minutes in S05. In T15/S05, 4 passive boundary points are chosen in the rotated X-direction in connection with the SL scheme. Sensitivity tests on the varying widths of lateral boundary relaxation zone have been performed, with no significant sensitivity found. In T15 and S05, a boundary relaxation width of 12 and 16 grid points are chosen, respectively.

It is noteworthy that the use of SL advection in DMI-HIRLAM-TS has been numerically very stable. Extensive sensitivity tests on varying time-stepping revealed generally insignificant impact on stability and forecast quality (Lindberg and Yang, 2004). The stability feature in the new system seems to be more superior than in the DMI-HIRLAM-GEDN, in which occasional instabilities were experienced, presumably as a consequence to the interaction of Eulerian advection and the model physics, which may become unstable in certain convective situations. The improved stability in DMI-HIRLAM-TS based on SL advection has also manifested itself in the general tendency observed from operational experience: that the upper air fields in DMI-HIRLAM-TS appear more smooth than the ones in DMI-HIRLAM-GEDN at the same horizontal resolutions.

The recent implementation of the Canadian MC2-type lateral boundary relaxation in REF-HIRLAM 6.2.5 has shown to eliminate effectively the spurious precipitation pattern at lateral boundaries, although not completely. For nested runs, the problem seems to become worse when cloud water is interpolated from the host model, and for S05 runs, there are indications of potential instability. Omitting cloud water from initial and lateral boundaries seems to avoid unrealistic moisture convergence at the lateral boundaries. Thus in S05, cloud water information from host analyses of T15 is not used.

Physical parameterization

During the pre-operational test of the new DMI-HIRLAM, the parameterization of vertical diffusion went through several major modifications in order to achieve satisfactory forecast quality. The main focus was to overcome the general problem of insufficient PBL vertical mixing under stable conditions, which is often associated with insufficient filling of lows in their maturing stage. Initially, a modification proposed by Colin Jones (personal communication), which was the earlier version of the CBR tuning implemented in REF-HIRLAM 6.2.5, was tested. The modification was found in general to improve observation verification scores, but degrade severely forecast skills of extreme storm events such as the Danish storm, Dec 3, 1999. The modification was also found to be associated with unrealistically active diurnal T2m cycles in winter, as manifested by a severe degradation of STD of T2m. In the final, implemented version, a modification of the turbulence parameterisation combining several recently proposed tunning schemes in the HIRLAM research community, has been adopted, the result of which is rather close to the updated version in the REF-HIRLAM 6.3.5. Among the implemented new features, the parameterisation of the turning of surface wind vector based on original ideas of Tijm (2003) and Nielsen (2004), using the formulation of Sass and Nielsen (2004), and a general increase in the vegetation roughness according to De Rooy (2004), were included. Largely due to the improvement in the parameterisation of vertical diffusion, a general reduction of surface wind bias and STD has been observed, consistently, in DMI-HIRLAM-TS in comparison to those in DMI-HIRLAM-GEDN. For most of the periods, this is also accompanied with improved scores in MSLP.

Comparing to DMI-HIRLAM-GEDN, the surface parameterization scheme in the new DMI-HIRLAM is very different. The previous HIRLAM surface scheme makes distinctions between sea, ice and land. In the new scheme based on ISBA, three grid tile types for land surface are introduced (bare soil, low vegetation and forest). The old scheme basically solves the heat equation for soil layers, using fluxes from the atmosphere as input to the surface energy budget, and climate values as lower boundary conditions. In the ISBA scheme, a force restore approach is applied in a complicated parameterization for soil processes. The calculation of surface fluxes and diagnostic quantities such as 2 m temperature and 10 m wind in the new surface scheme differs from those in the previous DMI-HIRLAM.

Initialization with Incremental DFI

In DMI-HIRLAM-GEDN, Nonlinear Normal Mode Initialization (NNMI) has been used as an initialization scheme. The physical principle behind an NNMI is as follows: the algorithm works to calculate the high frequency gravity wave mode and delete it, to avoid spurious developments in forecasts following the analysis procedure. Figure 6 shows a result of an NNMI initialization for the U-component at level 25 (about 850 hPa) in a normal G45 cycle for 2005041400, where the original and initialized analyses, as well as analysis increment (analysis minus first guess) and initialization increment (initialized analysis minus original analysis) are shown. As seen from the figure, the initialization increment is insignificant compared to the 3DVAR analysis increment and most visible in areas close to lateral boundaries.

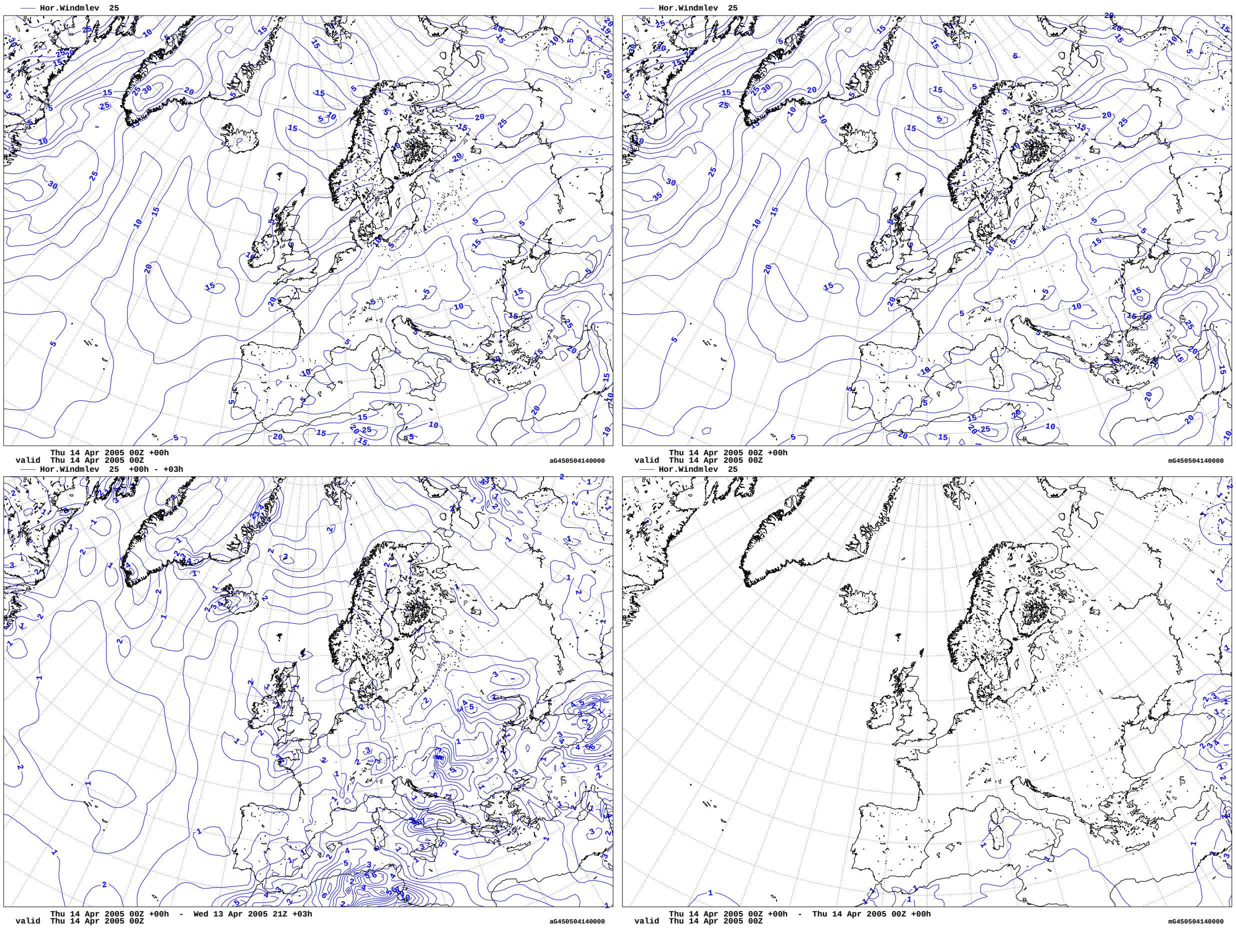

Figure 6: U-component at level 25 for G45 cycle 2005041400 from the (a) analysis, upper left, (b) initialization after NNMI, upper right, (c) analysis increment, lower left, (d) initialization increment, lower right. The contour interval is 5 m/s in (a), (b) and (c), and 1 m/s in (d).

Since 2000, REF-HIRLAM adopted the DFI scheme as its initialization scheme, with the purpose of achieving better noise control and stability (Lynch et al. 1999). The DFI scheme was later found to over- damp and often degrade moisture spin-up in the forecast. Thus Incremental DFI was tested and found to be effective in overcoming the moisture spin-up problem, while retaining other advantages of a normal DFI (Yang and Huang, 2002). The scheme became the default one in REF-HIRLAM 6.2.2 in 2004.

All forecast suites in the new DMI-HIRLAM apply IDFI but with different options. In a normal T15 forecast, initialization of main prognostic quantities is achieved through manipulation of both the analysis (ana) and ISBA-modified first guess (sfa) with following algorithm:

$$\mathbf{X}_{ini} = \mathbf{X}_{sfa} + \overline{\mathbf{X}_{ana}}^{DFI} - \overline{\mathbf{X}_{sfa}}^{DFI} \tag{1}$$

Where **X** denotes model variables Ps, U, V, T, Q, CW, TKE, and DFI refers to DFI filtering. In DFI filtering, a Dolph "TDFI" filter with a 2 hour period and 3 hour cut-off is applied (Lynch et al. 1999). The "T" above refers to the fact that the DFI filtering is done twice, first in the wake of a two hour backward, adiabatic integration, second in the wake of a two hour forward, diabatic integration. The implied TDFI filtering property as used in REF-HIRLAM is shown in Figure 7.

With incremental DFI, a normal DFI is applied to the analysis and first guess separately in order to obtain low-pass filtered increments for prognostic model states. The increments are then added to the

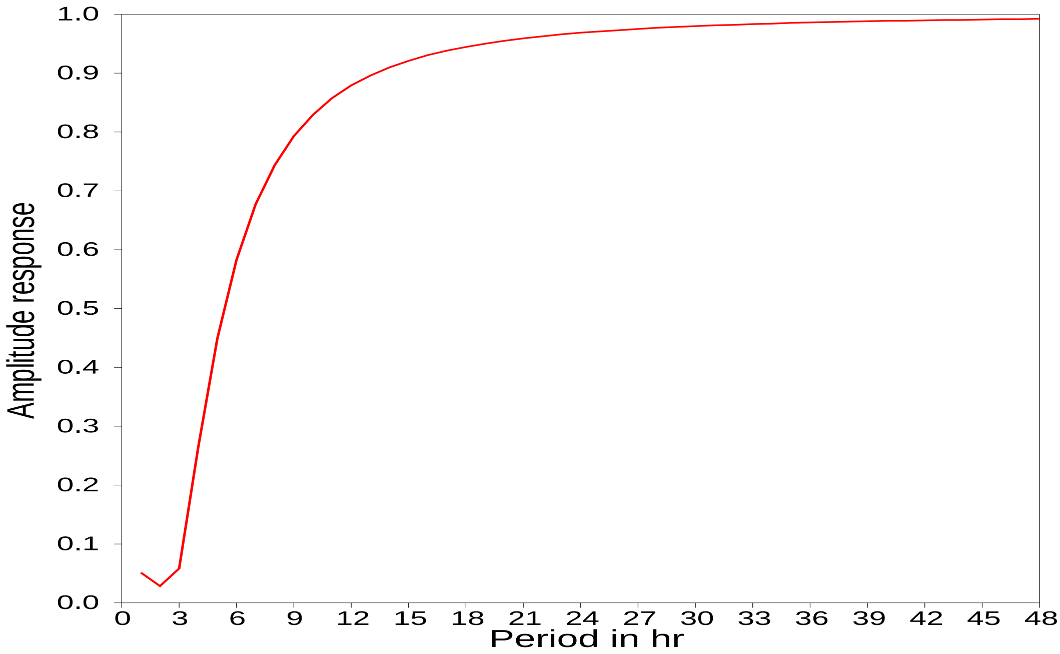

Figure 7: Filtering property of the DFI scheme as implemented in REF-HIRLAM, represented by the frequency response, as a function of the period, for a Dolph filter with a filter span of 2 hours and a cut-off period of 3 hours.

first guess field. There are two primary assumptions behind the incremental application of DFI: first, it is assumed that the DFI scheme retains only noise-free and meteorologically significant (large scale) features; second, the first guess is well balanced (with little noise). The application of IDFI in DMI-HIRLAM has been successful. Figure 8, demonstrates the result of IDFI initialization for T15 for the same situation as shown in Figure 6. As seen from the figure, analysis increments indicate correction of U-field at resolution of about 0.5 °, (due to the use of coarse resolution in the 3D-VAR minimization in T15, which is chosen in view of the used background error structure function at 0.5° resolution). The result of IDFI initialization, on the other hand, was mostly a short-scale initialization increment mainly in mountainous areas, indicating successful removal of small scale and noisy features by IDFI. Note that both the length scales and magnitudes of the initialization increment appear to be smaller than the analysis increment in the figure, which is desirable.

The canceling effect in the IDFI algorithm provides a rather effective remedy to avoid excessive DFI filtering on large scales. In Figure 9, examples of statistics from a whole month in August 2004 for T15 and S05 are shown in terms of domain averaged noise and moisture spin-up properties (rain rate, cloud cover and cloud water content) for forecast lead-times up to 48 hours. The results indicate generally well-balanced model states during the forecast, and the moisture spin-up feature in T15 and S05 appear to be satisfactory.

Coupling of large scale analyses in a blending scenario

A unique feature in the DMI-HIRLAM-GEDN system is the blending procedure in which information from the analysis, first guess, lateral boundary, and (when applicable) large scale analysis, is extracted, followed by the NNMI procedure to initialize the forecast. In REF-HIRLAM, no similar blending practice has been implemented. In the adaptation of REF-HIRLAM to DMI-HIRLAM-TS, the IDFI scheme has been extended further to the coupling application with the

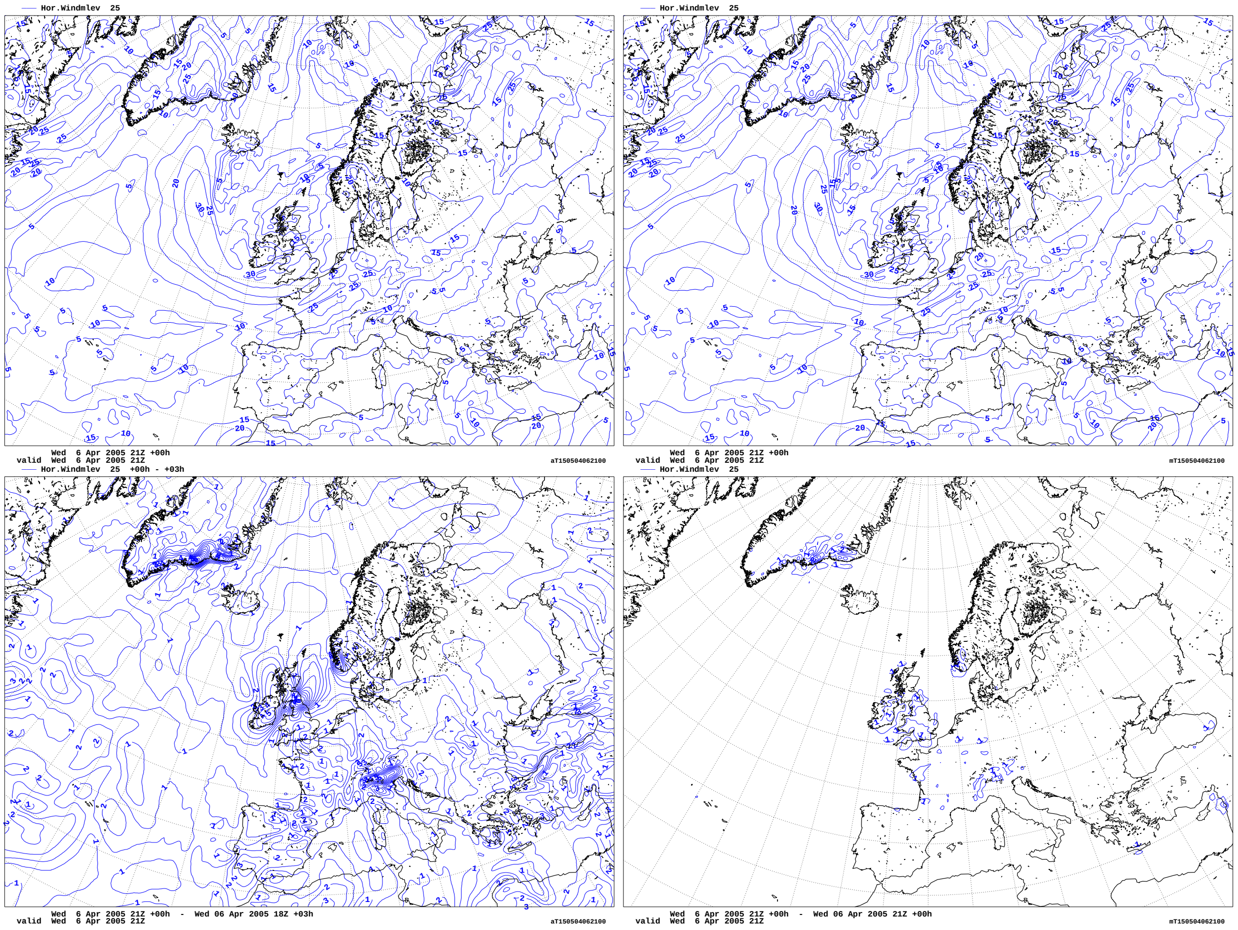

Figure 8: U-component at level 25 for T15 cycle 2005041406 from (a) analysis, upper left, (b) initialization after IDFI, upper right, (c) analysis increment, lower left, and (d) initialization increment, lower right. The contour interval is 5 m/s in (a) and (b), and 1 m/s in (c) and (d).

goal of extracting useful information from the large scale analysis.

Generally speaking, due to limitations in the domain size, a high resolution model cannot resolve as many large scale features as a model with a larger domain (but typically with a coarser resolution). This has been found to be the case, in particular, when comparing HIRLAM's analysis with the ECMWF global analysis. The latter is generally with a higher quality, due to a more advanced data assimilation system (4D-VAR with a long data cut off and more observation data assimilated). On the other hand, for very high resolution models such as S05, it is argued that no obvious benefit can be expected due to the limited domain size and network density of the currently assimilated observations. Thus it becomes natural to use an interpolated, coarser resolution analysis, T15, to initiate the S05 forecast.

In DMI-HIRLAM-GEDN, a blending of the analysis increment between the large scale (ECMWF) analysis and the higher resolution (HIRLAM) analysis or first guess has been used for several years with success. In fact, this is one of DMI's key innovative features within the HIRLAM community. The basic philosophy applied in the previous DMI-HIRLAM-GEDN is to extract the large scale analysis increment and add it to HIRLAM's analysis or first guess before initialization. Since the ECMWF analysis is not available in a normal DMI-HIRLAM forecast due to operational time constraints, a re-assimilation procedure, in which the assimilation cycle is restarted daily at 00 and 12 UTC, was introduced to utilize the high quality ECMWF analysis. By using ECMWF analysis,

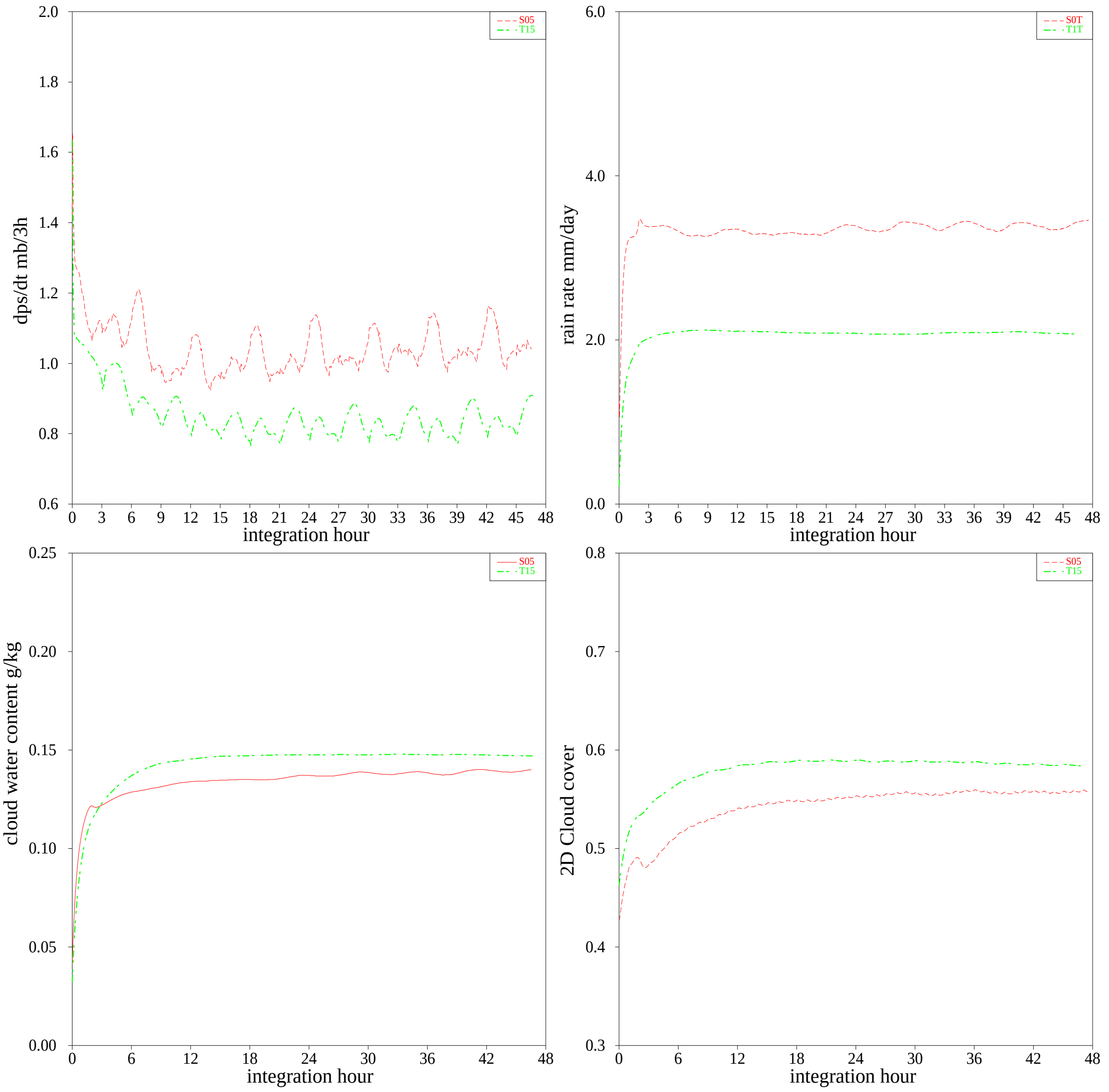

Figure 9: Averaged time series of domain averaged quantities from archived T15 and S05 forecasts in August 2004, for (a) mean absolute surface pressure tendency, upper left, (b) rain rate, upper right, (c) cloud water content, lower left and (d) cloud cover, lower right).

late arriving observations and ECMWF lateral boundaries, the first guesses for later cycles are improved. In the re-assimilation step for DMI-HIRLAM-G, ECMWF and HIRLAM analyses are blended so that the large scale analysis increment from ECMWF is extracted. An approximate procedure is applied in which a thinning of input data is first performed, by reading in both analyses at a coarser resolution (around 180 km for DMI-HIRLAM-G). An analysis increment is then obtained at that resolution, and interpolated back to the HIRLAM-G resolution and added to the original HIRLAM analysis. The effect of such a blending procedure can be demonstrated in Figure 10, in which again the initialization of the level 25 U-component is shown for cycle 2005041400 in the re-assimilation cycle. Note that the "increment" in Figure 10d is now the result of both analysis blending and initialization, in which changes in the large scale can be observed. A somewhat similar scenario exists in the coupling of "E" and "D". Since no upper air analysis is performed for "D", the above blending algorithm is extended to the "E" and "D" coupling, in which "large scale" information from the "E" analysis is blended with the first guess in "D" before NNMI initialization. Figure 11 shows the corresponding initialization of the level 25 U-component for

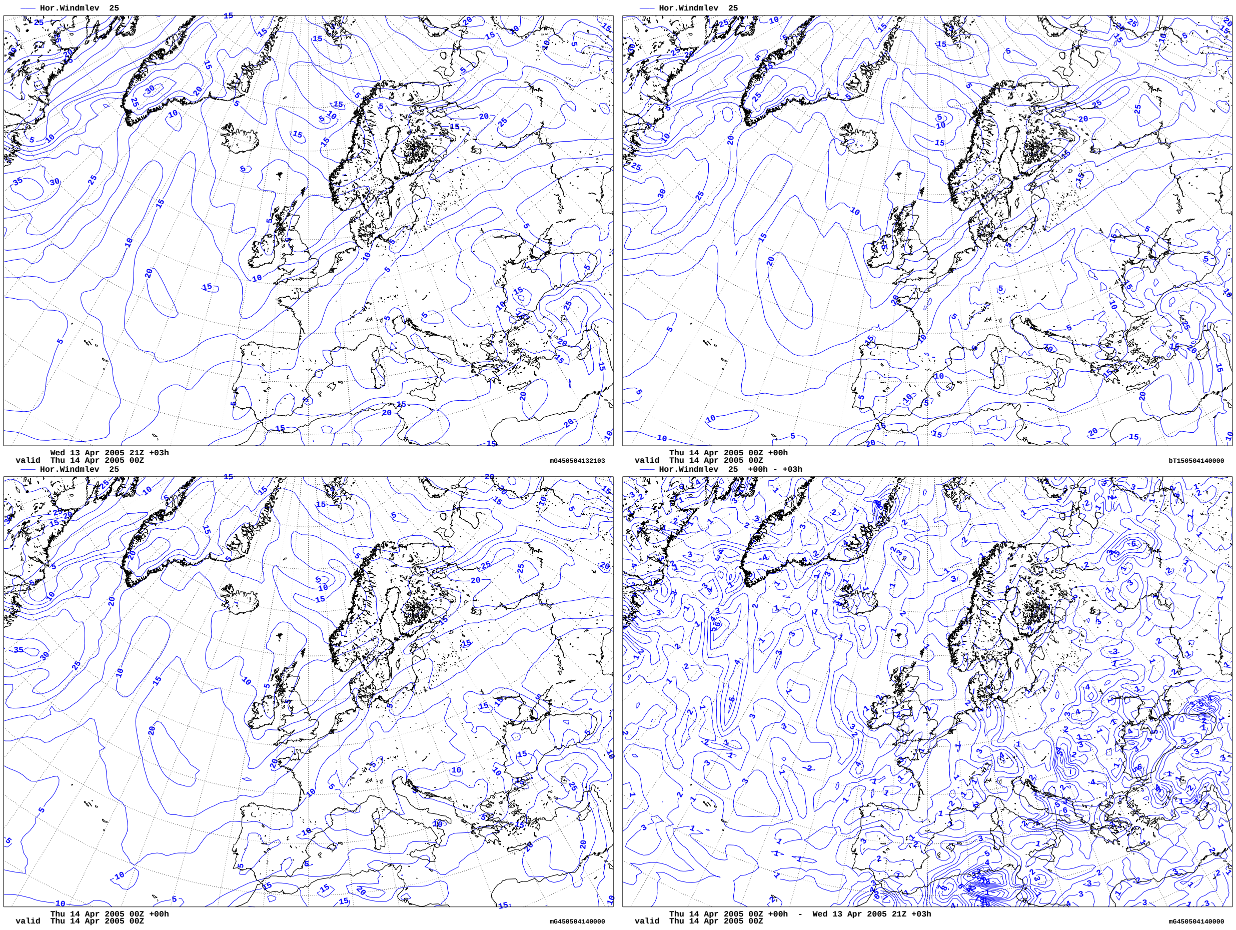

Figure 10: U-component at level 25 for G45 re-assimilation cycle 2005041400 from (a) first guess, upper left, (b) interpolated ECMWF analysis, upper right, (c) NNMI-initialized analysis after blending, lower left, (d) initialization increment relative to the first guess, lower right. The contour interval is 5 m/s in (a), (b) and (c), and 1 m/s in (d).

cycle 2005041400 with "D". Note also that the "increment" in Figure 11d now is relative to the first guess. Since the first guess is well balanced, the final "increment" as shown in Figure 11d contains mainly "large scale" increment from the "E" analysis.

In DMI-HIRLAM-TS, an alternative approach is adopted in which the IDFI algorithm is used to extract most of the resolvable scale information from the interpolated ECMWF analysis, supplied by the (balanced) HIRLAM first guess for the remaining, unfiltered scales. The simplified approach is represented in the following expression:

$$\mathbf{X}_{ini} = \mathbf{X}_{sfa} + \overline{\mathbf{Y}_{ana}}^{DFI} - \overline{\mathbf{X}_{sfa}}^{DFI} \qquad (2)$$

Where $\mathbf{Y}$ denotes the values from the interpolated large scale analysis.

The net effect of using IDFI in the coupling of the ECMWF analysis and the HIRLAM T15 first guess can be seen in Figure 12, in which the initialization of the level 25 U-component is shown for cycle 2005041400 in connection with the re-assimilation. Note that in this case no T15 analysis has been used directly, and the "increment" in Figure 12d shows the result of blending the ECMWF analysis with the ISBA-modified T15 first guess, the effect being large scale changes. This is satisfactory and it compares well with the effect shown in Figure 10d using the

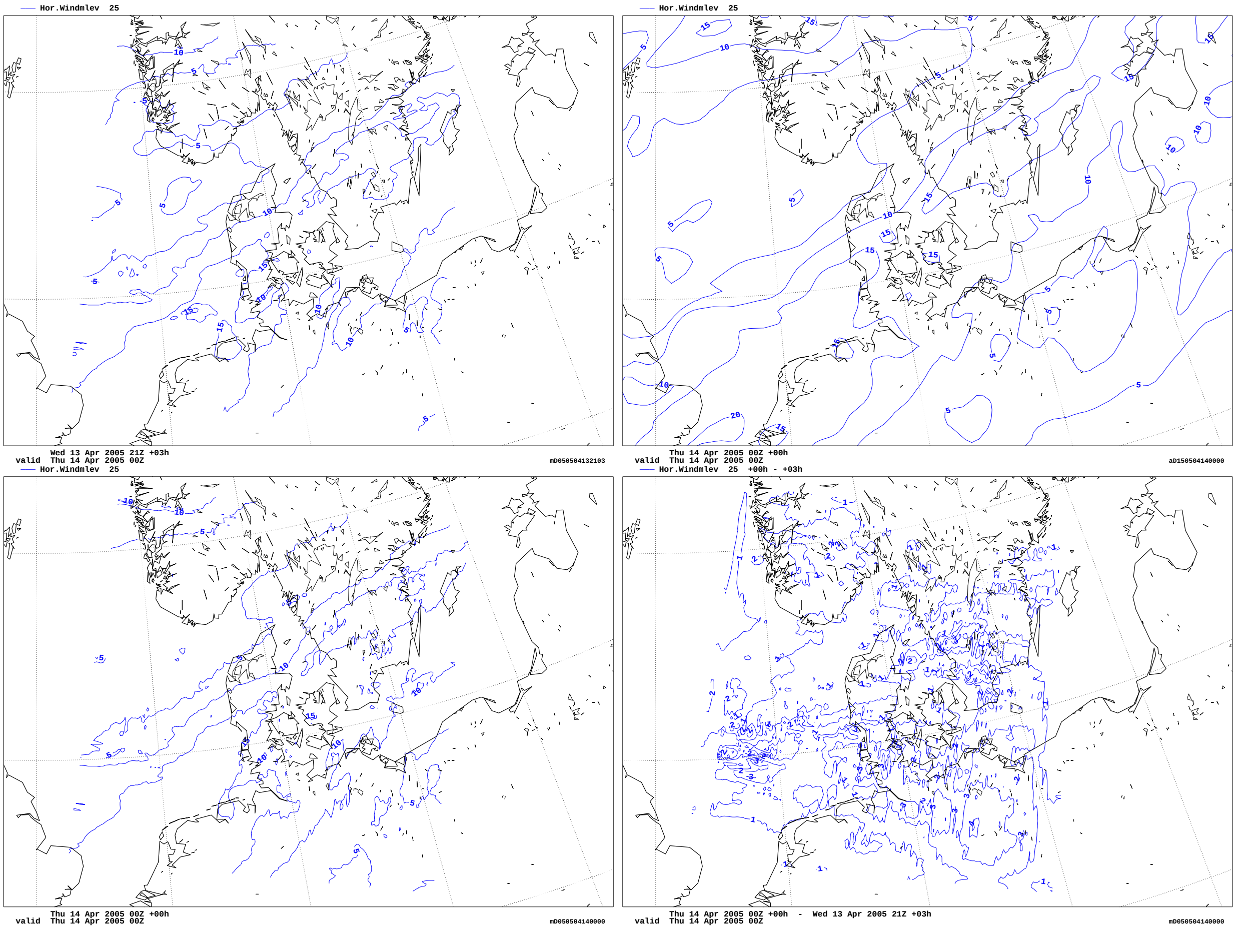

Figure 11: U-component at level 25 for D05 cycle 2005041400 from (a) D05 first guess, upper left, (b) interpolated D15 analysis, upper right, (c) NNMI-initialized analysis after NNMI, lower left, d) initialization increment relative to D05 first guess, lower right. The contour interval is 5 m/s in (a), (b) and (c), and 1 m/s in (d).

DMI-HIRLAM-GEDN blending scheme. Note that the plots shown in Figure 10 have 3 times coarser resolution ("G") than those in Figure 12 (T15).

Following the same principle, the algorithm can be applied to the internal nesting scenario between T15 and S05, where no analysis is available for S05. Instead, an interpolated T15 analysis is used, together with the ISBA-modified S05 first guess to initialize the forecast through the above IDFI algorithm. Again, the basic hypothesis behind both of the blending applications in T15, using the ECMWF analysis, and in S05, using T15 analysis, is that the analysis increment needed to update the initial state of the nested models is best captured by the analyses of host models which cover larger domains albeit with coarser resolution. On the other hand, the first guess of the (higher resolution) nested model can provide a reasonably balanced initial state for smaller scales which are not sufficiently resolved by the host model analysis. Figure 13 shows the result corresponding to Figure 12 for blending of the T15 analysis with the ISBA-modified S05 first guess. Again, similar to the case in DMI-HIRLAM-D coupling (Figure 11) and the T15 coupling to ECMWF analysis (Figure 12), the final increment in Figure 13d represent mostly large scales.

Application of the IDFI scheme to the above coupling situation is very simple in practice: a replacement of nested analysis by the large scale analysis in IDFI will do. Note that a source code modification has been introduced in such a coupling scenario to ensure that the surface variables

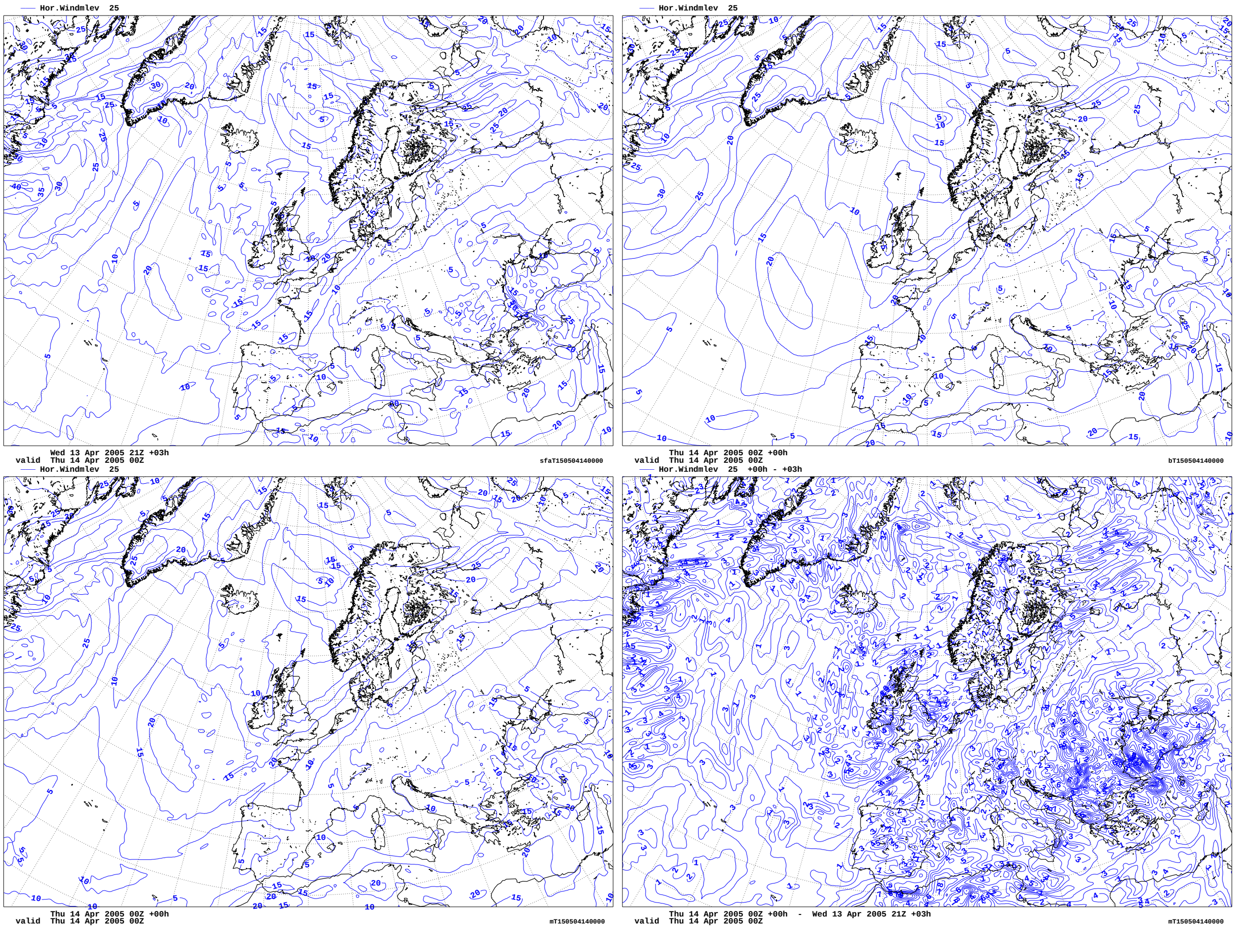

Figure 12: U-component at level 25 for the T15 re-assimilation cycle of 2005041400 from (a) the T15 first guess, upper left, (b) interpolated ECMWF analysis, upper right, (c) initialization after IDFI, lower left and (d) initialization increment relative to the first guess, lower right. The contour interval is 5 m/s in (a), (b) and (c), and 1 m/s in (d).

from the ISBA-modified first guess are used at the end of the initialization. This is because, with the current REF-HIRLAM interpolation tools, the interpolated large scale analysis normally contains only climate records for surface quantities, rather than adequate surface information[4]. The source code correction for this was implemented in REF-HIRLAM 6.3.4. To enforce it, set "INCMOD" to 2 in the forecast name-list.

It is not straightforward to validate the adequacy of the procedure applied in the above coupling strategy based on IDFI. Conceptional experiments, however, have been performed to confirm the benefit of coupling ECMWF analysis with the above algorithm. In Figure 14, it is shown that data assimilation runs for a two week winter episode using the above mentioned IDFI scheme showed clearly better MSLP and upper air scores when the ECMWF analysis is used, instead of HIRLAM's own.

[4]Recently, Met.no introduced a correction in the REF-HIRLAM interpolation software to add an option to interpolate surface fields. This will enable use of interpolated surface fields from coarse resolution HIRLAM ISBA analyses in case that no such analysis in performed for the nested model.

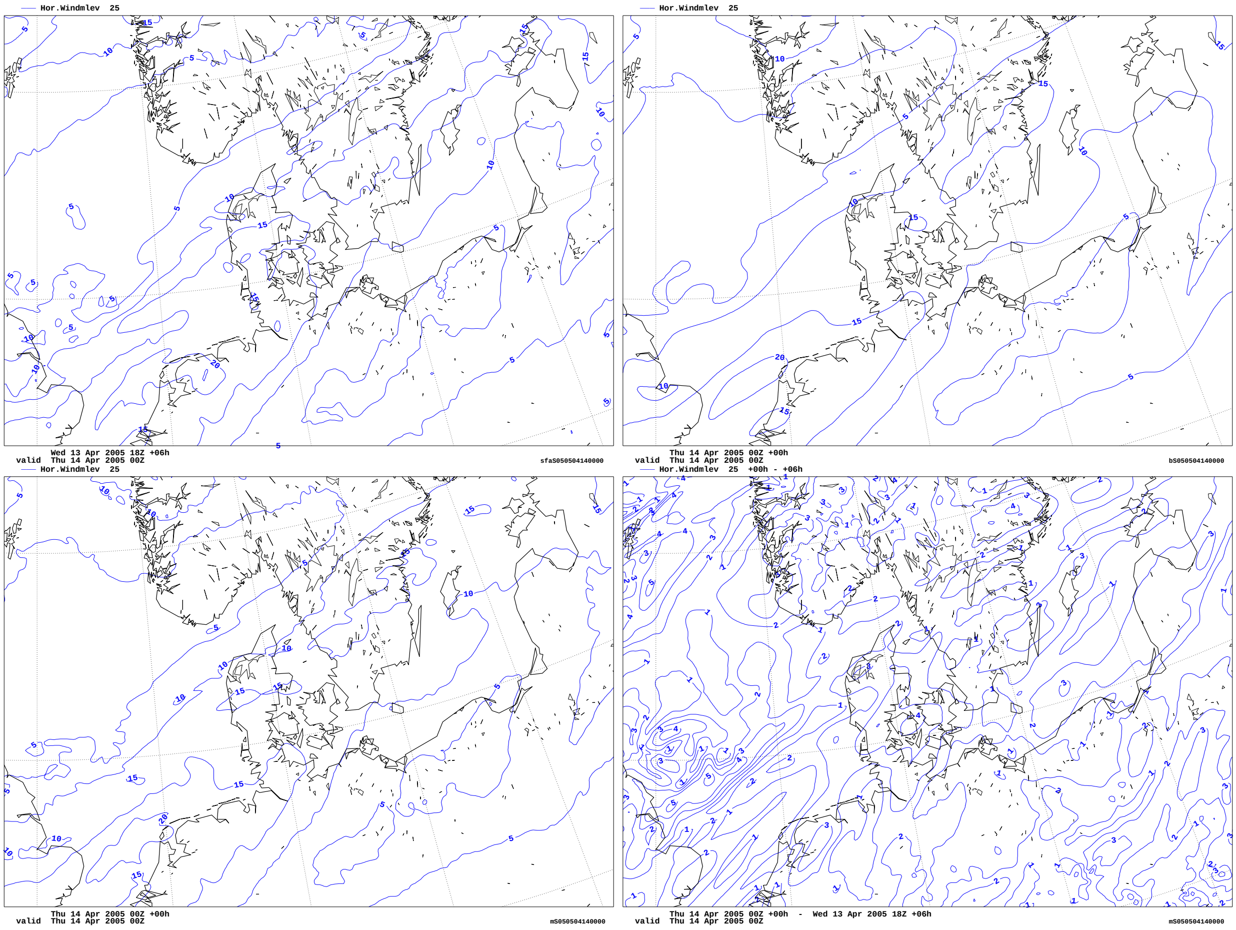

Figure 13: U-component at level 25 for S05 cycle 2005041400 from (a) the S05 first guess, upper left, (b) interpolated T15 analysis, upper right, (c) initialization after IDFI, lower left, d) initialization increment relative to the S05 first guess, lower right. The contour interval is 5 m/s in (a), (b) and (c), and 1 m/s in (d).

Scripts, code management, post-processing and verification

In order to achieve maximum continuity in DMI's operational environment and to meet the requirements of applications using DMI-HIRLAM, efforts have been made to create script, post-processing, verification and graphic display modules as close as possible to those in DMI-HIRLAM-GEDN.

cvs-based HIRLAM source code management

In connection with adoption of Ref-HIRLAM to DMI-HIRLAM, a cvs-based code management system has been developed and implemented[5]. The basic principle of the scheme is to have the main components of the HIRLAM source code version-controlled by cvs, and maintained through a common cvs server. In the first DMI-HIRLAM implementation on DMI's internal cvs server, the HIRLAM source code consists of 2 cvs repositories: first the cvs import of the REF-HIRLAM version 6.2.1 (hirlam_src), second the DMI local changes relative to the REF-HIRLAM 6.2.1 (dmiref_src). Among them, the source code included in dmiref_src will have precedence over those in hirlam_src during compilation. Note in the installed source code for REF-HIRLAM 6.2.1, the upper air analysis code, HIRVDA, has been incorporated, which enables a single-step compilation of

[5] The cvs-based code control system is an extension of the recent HIRVDA system and is scheduled to become the REF-HIRLAM standard in 2005

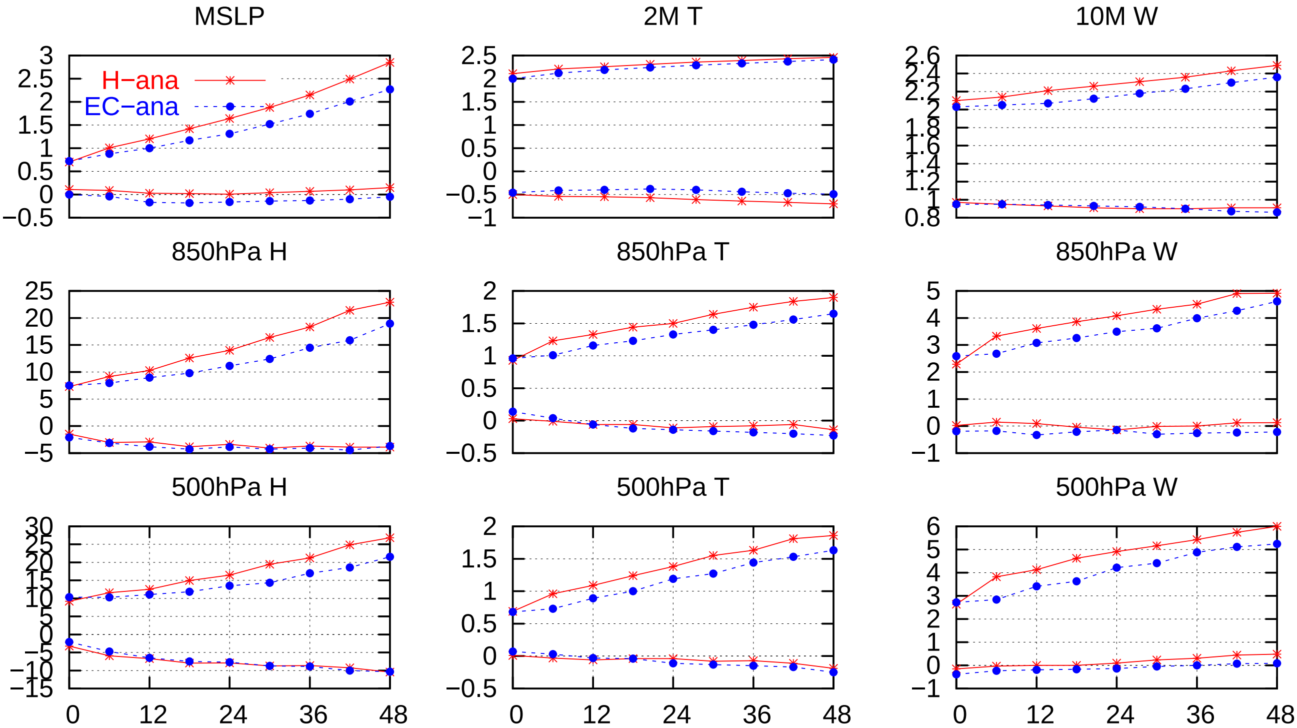

Figure 14: Observation verification scores of key parameters averaged for forecasts using IDFI algorithm with HIRLAM analysis (H-ana, in red) and with interpolated ECMWF analysis (EC-ana, in blue), respectively. The scores have been averaged for the 15-day episodes between Jan 23 and Feb 7, 2002. The plotted STD and BIAS errors are model errors in comparison to EWGLAM observations. The experiment is done on IBM/HPCD using REF-HIRLAM 6.3.7 on the RCR (Regular Cycle Reference HIRLAM) domain with a 0.2 ° grid-spacing.

all necessary executables needed in DMI-HIRLAM. At DMI, all the installed DMI-HIRLAM cvs repositories can be conveniently browsed online via an internet browser http://cvs.dmi.dk/cgi-bin/cvsweb. For DMI's HIRLAM developers, the cvs-based DMI-HIRLAM source code system has been found to be convenient to use for applications in checking-out, local source code modification, committing and compilation.

Script system

The script system consist of a number of Perl scripts which covers the needs for both operational and historical runs using the forecast system. It includes the following main modules:

Preparation of initial and lateral boundary files
Surface analysis
Upper air (3DVAR) analysis
Forecast
Post-processing

Post-processing, diagnosis and verification

The post-processing module above is DMI specific. It includes mainly extraction of model data onto observation space for verification purpose (i.e., the creation of Q files in grid format), as well as conversion of the surface and pressure level outputs from internal REF-HIRLAM ASIMOF grib format to those in DMI's grib format. The latter is required for most 'downstream' applications such as graphic display, input for storm-surge, road condition and air pollution models, etc.

The field and observation verification for DMI-HIRLAM-TS outputs, including those for precipitation forecast, follows the procedure adapted from the existing DMI-HIRLAM algorithm. Due to the changing in REF-HIRLAM associated with ISBA scheme using tile structure, extra calculation have been introduced in the forecast code to output tile-averaged quantities such as soil temperature, fraction of land, screen-level temperature, specific humidity and wind. To calculate verification scores of temperature and humidity at 2 m, tests have been made to test use of either grid-averaged quantities (e.g., PAR/TYP/LEVEL as 11/105/2 for T2m) or land fraction averaged quantities (e.g., PAR/TYP/LEVEL as 140/105/2 for T2mland), for comparison to in-situ observations. The results often indicate that the verification results of T2m are quite sensitive to the choice of verification strategy. In spite of this, it has been decided to apply the traditional grid-average method in the output and verification steps. This is mainly to keep operational continuity in terms of applying the same method to determine T2m and RH2m. For observation verification at the analysis time, the statistics are calculated using those derived from initialized fields.

Source code modifications in REF-HIRLAM have also been introduced to implement DMI-specific diagnostic quantities for forecast output, such as calculation of visibility, wind gust, the daily maximum and minimum of T2m, etc.

The algorithm to calculate 2 m visibility follows the one as described in Petersen and Nielsen (2000), which was first introduced in DMI-HIRLAM-GEDN in 2002. In the present DMI-HIRLAM, the lowest model level is at about 30 m. In order to estimate the amount of cloud water at 2 m, a somewhat empirical function depending primary on relative humidity and 10 m wind is used. With diagnosed amount of cloud water and precipitation intensity, the 2m visibility can be calculated using empirically determined extinction coefficients for snow, rain and cloud water.

The calculation of 10 m wind gust follows that of Nielsen and Petersen (2001). Its general formulation is based on similarity theory and depends on surface layer stability, as given by

$$G_u = 1 + \gamma_u(c_b\frac{w_*}{U} + c_n\frac{u_{*0}}{U}) + \gamma_s c_n\frac{u_{*0}}{U} \quad (3)$$

where G_u is the wind gust,U is the mean flow, γ_s and γ_u are stability indicators (0 or 1), u_{*0} is the friction velocity, w_{*0} is the convective friction velocity and c_b and c_n are constants.

Additionally, maximum and minimum 2 m temperature and maximum and minimum 10 m wind are stored every 12 hour according to the WMO standard. That is, these are offset to the present value when the forecast time pass 06 and 18 UTC and updated whenever the forecast-ed 2 m temperature or 10 m wind exceed the maximum or minimum value. Note that if the forecast is launched at 00 and 12 UTC the maximum and minimum valid for the first 6 hours will not be the maximum for the last 12 hours but only for the last 6 hours.

The algorithm to diagnose MSLP and geopotential height has been modified (Feddersen, 2004). The method is based on the corresponding ones from DMI-HIRLAM-GEDN (Sass et al. 2002). This is found to be necessary in order to obtain comparable, reliable verification scores such as those in DMI-HIRLAM. It is found that the modification of the MSLP calculation procedure results in smoother MSLP fields then in REF-HIRLAM (e.g., less noisy around mountainous areas).

Summary

Through intensive efforts of DMI staff in the past years, a major upgrade to DMI's operational NWP suite, DMI-HIRLAM, has been accomplished and launched successfully in June 2004. The new

DMI-HIRLAM is radically different from the earlier one, DMI-HIRLAM-GEDN, due to significant changes involving most components of the operational suite. Among those, the most important change is the fact that the forecast model is now based on the recent release of REF-HIRLAM. With the introduction of the T15/S05 suites, DMI's main forecast production is now performed at finer resolution on larger domains and with an extended time range. In addition, a surface analysis module has been introduced, which enables frequent update of near-surface thermodynamic features using screen-level observations. An incremental DFI initialization is now applied in DMI-HIRLAM, replacing the NNMI scheme in DMI-HIRLAM-GEDN. In that connection, an innovative feature in the coupling scenario has been successfully implemented in which the IDFI scheme is used in coupling/nesting scenarios. In such a scenario, a host analysis is coupled, together with the nested model first guess to drive the fine resolution forecast. Improvements in the numerical scheme and physical parametrization have been applied in the forecast model, allowing further improvement in the overall forecast qualities. The implementation of the new DMI-HIRLAM has been possible thanks to the recent enhancement of DMI's supercomputer facility with NEC SX-6 vector platform, which also implies extensive technical work in order to improve computational efficiency of various modules in the DMI-HIRLAM. In terms of meteorological performance, the new suite has been found to maintain, and in many aspects to increase, the forecast skill over the previous DMI-HIRLAM-GEDN.

Improvements have been made to many aspects of the new NWP suite during the adaptation phase of the REF-HIRLAM to the pre-operational system. Monitoring parallel runs revealed several key shortcomings associated with the recent REF-HIRLAM, and remedies for some of these aspects have hence been implemented. For the climate generation procedure, corrections related to the inadequate treatment of the high resolution database, the orographic smoothing, the derivation of orographic roughness, have been proposed and implemented. In addition, a modification of the climate generation procedure changing the soil type "sand" to "loam" for part of the European area has been implemented in order to get a more accurate description of soil moisture, and hence screen level temperature and humidity, for dry periods (such as those in early spring 2004). In the ISBA surface analysis procedure, modifications have been made to rely more strongly on the twice daily disseminated ECMWF SST and ice concentration data, i.e., the ECMWF SST is now treated as background and only observations from SHIP-SYNOP are assimilated. For ice cover, instead of diagnosing it from the analyzed SST, it is completely determined by the interpolated ECMWF ice cover data, and adjustment of the SST is made according to the ice cover. This has been found to be beneficial for the forecast scores in and around Greenland in winter, especially for T2m. Many parallel experiments have been made to identify and reduce the long-standing HIRLAM deficiency in terms of insufficient filling of lows in their decaying stages. As a result, the recently proposed parameterization of surface stress vector turning by Tijm (2003), Nielsen (2004) and Sass and Nielsen (2004) has been implemented, which seems to have resulted in significant improvement in general forecast scores. From the standard observation verifications since June 2004, it is found that the new DMI-HIRLAM scores are often better than those of DMI-HIRLAM-GEDN. This is especially the case for MSLP rms, bias in 10 m wind speed, as well as scores in precipitation forecasts. More systematic evaluation of the DMI-HIRLAM performance in comparison to the DMI-HIRLAM-GEDN can be found in Petersen et al. (2005) and Kmit et al. (2005), where the two systems are compared for historical episodes in hindcast mode.

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Leif Laursen provided organization support at FM in migration from DMI-HIRLAM-GEDN to DMI-HIRLAM-TS throughout the process. Jan Boerhout, NEC, contributed with important code improvements on parallelization of REF-HIRLAM forecast model which has been critical to ensure

satisfactory scalability of the model on the NEC SX-6.

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Appendix A: Operational schedule and resource usage

Compared to DMI-HIRLAM-GEDN, T15 in the new DMI-HIRLAM-TS suite is executed with similar schedule to "G" in DMI-HIRLAM-GEDN, performing four 60 hour forecasts daily, at 00, 06, 12 and 18 UTC, supplemented by two re-assimilation cycles initiated at 00 and 12 UTC, respectively, see Table 1. For normal forecast runs, the observation cut-off time is about 1 hour 40 minutes. For lateral boundaries, the 3-hourly ECMWF forecast frames from BC-suite are used. In the re-assimilation runs, all available observation data and the most recent boundaries (full fields ECMWF analysis or forecast frames) are used. The guaranteed delivery time of the 36-hour T15 forecast for each cycle is 2 hour 15 minutes after synoptic time. S05 performs 54 hour forecasts 4 times a day on synoptic hour, using T15 analysis and hourly forecasts from same cycle are used as initial and lateral boundary data.

Table 1: Operational schedule of DMI-HIRLAM which lists regular launch time of T15 and S05 runs. T_E in the table denotes a restart using the ECMWF analysis.

Launch Time (UTC)	T15 Cycle	S05 Cycle
01:37	T00 +60 h	
02:30		S00 +54 h
ECMWF-BC 00 UTC		
07:37	T06 +60 h	
08:30		S06 +54 h
ECMWF-BC 06 UTC		
11:45	T_E00 +05 h	
	T03 +05 h	
	T06 +05 h	
	T09 +05 h	
13:37	T12 +60 h	
14:30		S12 +54 h
ECMWF-BC 12 UTC		
19:37	T18 +60 h	
20:30		S18 +54 h
ECMWF-BC 18 UTC		
23:50	T_E12 +05 h	
	T15 +05 h	
	T18 +05 h	
	T21 +05 h	

The following table lists approximate information about resource usage for DMI-HIRLAM-TS. Note that the task "Post-processing" in the table includes interpolation of hourly T15 model level output to S05 domain, the grib-format conversion from ASIMOF to DMI-format, and extraction of model forecast onto observation point according to a specified SYNOP and TEMP station lists ("q"-files) for observation verification purpose.

Table 2: Resources used for long T15/S05 forecasts (60/54 h) and T15 reassimilation cycle (5 h forecast) on NEC SX-6. Values listed are maximum ones.

		T15 60 h forecast	S05 54 h forecast	T15 5 h forecast
BC boundary interpolation	elapse time	3 min	0 min	0.5 min
	nr of cpu	4	0	4
	ram	22 Gb	0	22 Gb
	disk	1.6 Gb	0	246 Mb
Surface analysis	elapse time	1.5 min	1 min	1.5 min
	nr of cpu	1	1	1
	ram	6.3 Gb	6.0 Gb	6.3 Gb
	disk	292 Mb	155 Mb	292 Mb
3D-VAR	elapse time	4 min	0 min	0 min
	nr of cpu	8	0	0
	ram	9 Gb	0	0
	disk	200 Mb	0	200 Mb
Forecast	elapse time	29.5 min	41.5 min	5 min
	nr of cpu	20	20	20
	ram	44 Gb	35 Gb	44 Gb
	disk	30 Gb	10 Gb	2.2 Gb
Post processing	elapse time	29.5 min	41.5 min	5 min
	nr of cpu	4	4	4
	ram	24 Gb	24 Gb	24 Gb
	disk	10 Gb	9 Gb	1.8 Gb
Entire suite	elapse time	38 min	43 min	7 min
	nr of cpu	24	24	24
	ram	55+ Gb	40+ Gb	55+ Gb
	disk	42 Gb	19 Gb	4.7 Gb

Appendix B: Chronicle of the recent DMI-HIRLAM-TS upgrade since June 2004

14/6-04 DMI-HIRLAM-T15 and DMI-HIRLAM-S05 became operational.

15/6-04 Bug fix in (post-processing) calculation of geopotential height in pressure level files.

29/6-04 Bug fix in calculation of Richardson number in the CBR scheme.

27/7-04 Change in vegetation roughness and thermal roughness over land to improve W10m as well as T2m and RH2m scores.

16/11-04 Various changes

- Changes in ISBA
- I/O handling (HIRLAM Gribfile Server or HGS)
- No more re-assimilation of DMI-HIRLAM-S05 (6 hour cycle instead of 3 hour)

19/11-04 Change in time steps due to noise when maximum wind speed is more than 100 m/s.

- DMI-HIRLAM-T15: 360 s $\rightarrow$ 300 s.
- DMI-HIRLAM-S05: 120 s $\rightarrow$ 90 s

21/12-04 Revised climate generation (a bug-fix).

18/1-05 Changes in semi-Lagrangian advection and time-stepping.

- DMI-HIRLAM-T15: 300 s $\rightarrow$ 360 s.
- DMI-HIRLAM-S05: 90 s $\rightarrow$120 s.

Appendix C: DMI-HIRLAM-TS output and archive list

Following past practice, selected data in several categories are archived for each DMI-HIRLAM-TS cycle. These include:

- observation data
- lateral boundary data
- history data (analysis, initialized analysis and forecasts)
- pressure level data
- surface level data
- interpolated forecast data in observation space (for verification)
- log messages from assimilation and forecast runs.

A typical forecast run with DMI-HIRLAM-TS outputs three types of GRIB-data: those in history file (model level data), which contains all the information needed to (re-)initiate a forecast integration; pressure level data, which contains output fields interpolated to key pressure levels (1000 hPa, 950 hPa, 925 hPa, 850 hPa, 700 hPa, 500 hPa, 300 hPa, 250 hPa, 100 hPa); and surface level data, which contains single level fields for surface level or accumulated diagnostic fields such as total cloud cover and accumulated precipitation. The analysis and first guess data are archived in ASIMOF-GRIB format, while the pressure and surface level data are in DMI-GRIB format in order to be used by DMI-HIRLAM's "downstream" applications. The run-time ASIMOF-GRIB output are placed in the /sx6opr/hiropr/refhirlamT/database/tmp/gdb/$model$date$time where $x represents a variable name. The names of the output files follow the convention of the reference system: (model level files) hi$date_$time+$forecasthour, (pressure level files) ba$date_$time+$forecasthour.p and (surface files) ba$date_$time+$forecasthour.ul. After conversion to DMI-GRIB format, files are placed in /gdbopr/94/$abbr/$model/$date$time/$forecasthour, where $abbr is either ML (model level), PL (pressure level) or SF (surface). Some original ASIMOF-GRIB files are saved for later usage (but not moved), these are named [am]$model$date$time$forecasthour. The converted files are then archived later.

Model level data includes values of T, U, V, Q, CW and TKE, and p_s at every grid point on an Arakawa C grid. Other variables included in model level output can be found in following table along with the parameters contained in the pressure level files:

Pressure level data

variable	unit	parameter number, level type
Mean sea level pressure	hPa	001,103
u-component of wind	m/s	033,100
v-component of wind	m/s	034,100
Geopotential	J/kg	006,100
Temperature	K	011,100
Relative humidity	fraction	052,100

Model level data

variable	unit	parameter,level type,level
u,v-components of wind on model level	m/s	033/034,109
Temperature on model level	K	011,109
Specific humidity on model level	kg/kg	051,109
Specific cloud condensate on model level	kg/kg	076,109
Turbulent kinetic energy on model level	J/kg	201,109
Total cloud cover	fraction	071,109
Surface pressure	Pa	001,105,0
Surface geopotential	m^2/s^2	006,105,0
u,v-components of wind at 10 m, average or over 5 tiles	m/s	033/034,105,10/801/802/803/804/805
10 m u,v over sea	m/s	033/034,102,10
Fraction of land	fraction	081,105,0
Fraction of water,ice,bare ground,low vegetation soil,forest	fraction	081,105,901/902/903/904/90 5
Surface temperature over 5 tiles	K	011,105,901/902/903/904/905
Deep soil temperature over 5 tiles	K	011,105,951/952/953/954/955
Surface specific humidity over 5 tiles	kg/kg	051,105,901/902/903/904/905
Climatological deep soil temperature	K	011,105,998
Temperature at 2 m, over 5 tiles	K	011,105,801/802/803/804/805
Surface temperature averaged over tiles	K	011,105,0
Maximum 2 m temperature	K	015,105,2
Minimum 2 m temperature	K	016,105,2
Temperature at 2 m, over land	K	011, 103, 2
Specific humidity at 2 m, over 5 tiles	kg/kg	051,105,801/802/803/804/805
Averaged temperature at 2 m, grid average	K	011,105,2
Averaged temperature over land cover at 2 m	K	140,105,2
Averaged specific humidity at 2 m, grid average	kg/kg	051,105,2
Averaged specific humidity over land cover at 2 m	kg/kg	141,105,2
Soil wetness/Surface moisture over 5 tiles	m	086,105,901/902/903/904/905
Deep surface moisture over 5 tiles	m	086,105,951/952/953/954/955
Climatological deep soil wetness	m	086,105,998
Water equivalent of snowpack (snow cover) over 5 tiles	m	066,105,901/902/903/904/905
Background albedo	fraction	084,105,0
Climatological roughness length	m	083,105,0
Roughness length over sea	m	083,105,702
Snow albedo over 5 tiles		190,105/901/902/903/904/905
Snow density over 5 tiles		191,105 /901/902/903/904/905
Wind gusts	m/s	191,105,1
10 m wind speed over sea	m/s	191,102,0
Minimum 10 m wind speed	m/s	191,105,9
Maximum 10 m wind speed	m/s	191,105,11
Ustar	m/s	191,105,0
Planetary boundary layer height	m	238,105,0
Water on canopy layers over 5 tiles	kg^2/m^2	192,105,901/902/903/904/905
Surface soil ice	m^3/m^3	193,105,901/902/903/904/905
Deep soil ice	m^3/m^3	193,105,951/952/953/954/955
Soil type over 5 tiles		195,105/901/902/903/904/905
Surface vegetation type over 5 tiles		199,105 901/902/903/904/905
Convective precipitation	kg/m^2	063,105,0
Stratiform precipitation	kg/m^2	062,105,0
Surface sensible heat flux, average or over 5 tiles	J/m^2	122,105,0/901/902/903/904/905
Momentum flux average and over 5 tiles	N s/m^2	128,105,0/901/902/903/904/905
Surface latent heat flux, average or over 5 tiles	J/m^2	121,105,0/901/902/903/904/905
Visibility	m	18,105,2

Surface level data

variable	unit	parameter,level type,level
Surface pressure	Pa	001,105,0
Surface geopotential	m^2/s^2	006,105,0
Surface temperature over land	K	011,105,0
Water equivalent of accumulated snow depth	kg/m^2	065,105,0
Water equivalent of snowpack	m	066,105,0
2 meter dew point temperature	K	017,105,2
Relative humidity at 2 meters	Fraction	052,105,2
Total accumulated precipitation	kg/m^2	061,105,0
Average (2D) 2 meter temperature over land	k	140,105,2
Average (2D) 2 meter specific humidity over land	kg/kg	140,105,2
10 m wind speed over sea	m/s	191,102,0
Wind gusts	m/s	191,105,1
Minimum 10 m wind	m/s	191,105,9
Maximum 10 m wind	m/s	191,105,11
Maximum 2 meter temperature	K	015,105,2
Minimum 2 meter temperature	K	016,105,2
Fog	m	070,105,2
Level 40 temperature	K	011,109,40
Roughness length over sea	m	083,102,0
Mean sea level pressure	Pa	001,103,0
u-component of wind at level 40	m/s	033,109,40
v-component of wind at level 40	m/s	034,109,40
u-component of wind at level 39	m/s	033,109,39
v-component of wind at level 39	m/s	034,109,39
u-component of wind at 10 m above ground	m/s	033,105,10
v-component of wind at 10 m above ground	m/s	034,105,10
u-component of 10 m wind over sea	m/s	033,105,10
v-component of 10 m wind over sea	m/s	034,105,10
Visibility	m	018,105,2
Temperature at 2 m	K	011,105,2
Specific humidity at 2 m	kg/kg	051,105,2
Depth of the boundary layer	m	067,105,0
Total cloudiness	fraction	071,105,0
Low clouds	fraction	073,105,0
Medium clouds	fraction	074,105,0
High clouds	fraction	075,105,0
Convective precipitation	kg/m^2	063,105,0
Stratiform precipitation	kg/m^2	062,105,0
Evaporation	kg/m^2	057,105,0
Surface sensible heat flux	J/m^2	122,105,0
Surface latent heat flux	J/m^2	121,105,0
Global (downwelling) shortwave radiation	J/m^2	117,105,0
Surface downwelling longwave radiation	J/m^2	115,105,0
u-component of surface momentum flux	N s/m^2	124,105,0
v-component of surface momentum flux	N s/m^2	125,105,0
T.O.A. net shortwave radiation	J/m^2	113,008,0
T.O.A. shortwave radiation	J/m^2	117,008,0
T.O.A. net longwave radiation	J/m^2	114,008,0
Precipitable water	kg/m^2	054,105,0
Cloud condensate	kg/m^2	076,105,0

Appendix D: Implementation of the HIRLAM Gribfile Server

The writing of output files and reading of input files to and from disk are presently among the most time consuming operations in the DMI-HIRLAM forecast. During a typical DMI-HIRLAM-T15 forecast the model reads a first guess ($\sim$300 Mb), an analysis ($\sim$200 Mb) and boundary files ($\sim$14.5 Mb) except for the 00 file which is $\sim$14 Mb every three hours and write out three types of output files every hour (see Appendix C). Since a model level file has a size of $\sim$300 Mb it is clear that input/output (i/o) constitutes a severe constraint on the execution time. A typical time-step in T15 with no i/o needs approximately 2 seconds while a typical i/o step lasts for approximately 10 seconds. A typical 60 hour DMI-HIRLAM-T15 forecast lasts for approximately 2000 seconds when executed on 20 processors (plus four for post-processing). In addition to the long real time of the i/o steps all reading and writing are done sequentially by the master process and constitutes a severe bottleneck in the system preventing scalability.

In November 2004 DMI upgraded the i/o handling in DMI-HIRLAM by implementing the HIRLAM Gribfile Server (HGS). Prior to this a substantial amount of work was carried out in order to optimize and consistently adapt HGS to DMI-HIRLAM.

The first HGS implementation (Boerhout (2001)) was developed for running on shared memory platforms, while a MPI version was developed separately by Jussi Heikonen (CSC) and Kalle Eerola (FMI). A version merging the shared memory HGS and the MPI version was realized in 2003 (Vignes (2002)) making HGS more portable and suitable for implementation in reference HIRLAM. In addition HGS was optimized in 2004 in a collaboration between DMI and NEC-Europe (Boerhout (2004)).

The general rationale behind HGS is the following. A set of dedicated servers are allocated for i/o purposes only (reading/writing, GRIB decoding/encoding). This allows the model computations to continue while the i/o is done asynchronously. This have the obvious advantage that the computational processes are not idle while i/o is being carried out. During a typical input and output sequence the following general steps are executed. Well before the input file is needed it is decoded and preread into memory asynchronously by HGS. When the model needs the input fields they are read from memory segments instead of from disk, thereby saving time. When the fields have been used for the last time the memory segment is released and reused for the next i/o operation. Similarly, during the output phase output is written to a memory segment instead of to disk. When this is done HGS will encode and write the contents of the memory segment asynchronously to disk. Such a setup obviously requires a lot of synchronization and message passing between the HGS's and between the HGS's and the computational processes. For a more detailed account the above references are recommended.

Executing a DMI-HIRLAM-T15 forecast with three processors allocated for HGS (not an optimal number) and three for post-processing leaving 18 computational processors (everything else similar to the above mentioned run) and comparing to the above mentioned forecast, shows that an i/o time steps needs now approximately 3 seconds while a non i/o step needs for approximately 2.5 seconds. Hence a time step without i/o lasts a bit longer due to the fact that fewer processors are employed for computations, but this is more than compensated by the large gain during the i/o steps. This leaves an execution time of approximately 1600 seconds and a gain of approximately 20 %. In the present operational system two processors are allocated for HGS.

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