A new implementation of digital filtering initialization schemes for HIRLAM

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Abstract

A new implementation of Digital Filtering Initialization (DFI) schemes has been made for the HIRLAM forecast system and preliminary version has been implemented in the reference system as a beta release (version 5.0.3). The motivations for the new implementation are three-fold:

1) Earlier DFI implementations require separate runs with forecast models using different namelists. They also involve unnecessary model state input/output (I/O). Errors often occur when making changes to the scripts. It is therefore desirable for the maintenance and development to have a simpler script for DFI, which activates only a single model run, with no extra I/O, as in the previous setup (version 5.0.2).
2) The earlier DFI implementations in HIRLAM contain many DFI-related statements in the main program, `GEMINI`, with the initialization step controlled at script level. This makes it difficult to understand and to modify. For further development, it is desirable to have a clean main program with only one subroutine call to DFI.
3) Many digital filter schemes have been tested since the first DFI implementation, but only the most effective one has been kept in the current reference model. Considering the fact that other DFI schemes may be more advantageous for different purposes, it seems useful to enable the choice of different schemes and filters.

In this technical report, we present the recoded initialization interface which addresses the above-mentioned issues. The new codes are validated with parallel assimilation runs. Since this report is mainly aimed for being used as a technical manual for users interested in DFI schemes in the HIRLAM system, we also examine some of the new features available in the modified code. For example it is shown that the incremental DFI schemes significantly improve the spin-up aspects for precipitation, with only moderately increased initial noise level.

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1 Introduction

In Numerical Weather Prediction (NWP) systems based on primitive equations, an adjustment procedure, called *initialization*, is often needed before the analyzed fields can be used as initial state for numerical integrations. There are several reasons for such a procedure. One of the most important reasons is to remove noise due to the imbalances in the analysis between the wind and mass fields. This noise, if remaining in the integration, could lead to numerical instabilities, degrade the forecast, and damage the subsequent data assimilation through noisy first-guesses. Another well-known reason for initialization is the construction of consistent fields for un-analyzed variables, *e.g.*, cloud water content. Furthermore, it is believed that the so-called spin-up problem in the early stage (0 - a few hours) of numerical forecasts of precipitation could be alleviated through a proper initialization step.

One of the widely used initialization schemes is the nonlinear normal model initialization scheme (NNMI), which sets the initial tendencies of the gravity waves to zero (Machenhauer, 1977). The first HIRLAM initialization scheme was such a NNMI scheme (Kållberg, 1990). An extension of NNMI, the implicit NNMI (INMI) as formulated by Temperton (1988), has been implemented and is still available as an option in the HIRLAM system (Källén, 1996).

Another widely used scheme is the Digital Filtering Initialization (DFI), which removes high frequency noises by applying digital filters. The first DFI implementation was made for HIRLAM (Lynch and Huang, 1991). Since then, many extensions of the original DFI have been proposed and there have also been many operational implementations worldwide. Since the main purpose of this work is a new implementation of DFI for HIRLAM and to revive some tested options, it is natural to include an overview of different extensions. As this report is technically oriented, the overview mainly covers the HIRLAM related versions.

1.1 A brief review of DFI

In the first version of DFI, the forecast model is integrated backward and forward in time from the analysis to produce a time series of model states, centered around the analysis time (Lynch and Huang, 1992). A digital filter with a span N is then applied to the time series and the filtered state at the analysis time is taken as the initialization result. Due to the irreversible nature of physical processes and horizontal diffusion, they are switched off during the DFI-integrations. Therefore the scheme is referred to as Adiabatic DFI (ADFI) in some later papers and also in this report. Comparing with the HIRLAM NNMI scheme (Kållberg, 1990), ADFI was shown to be more efficient in noise control and to lead to comparable forecast scores (Lynch and Huang, 1992).

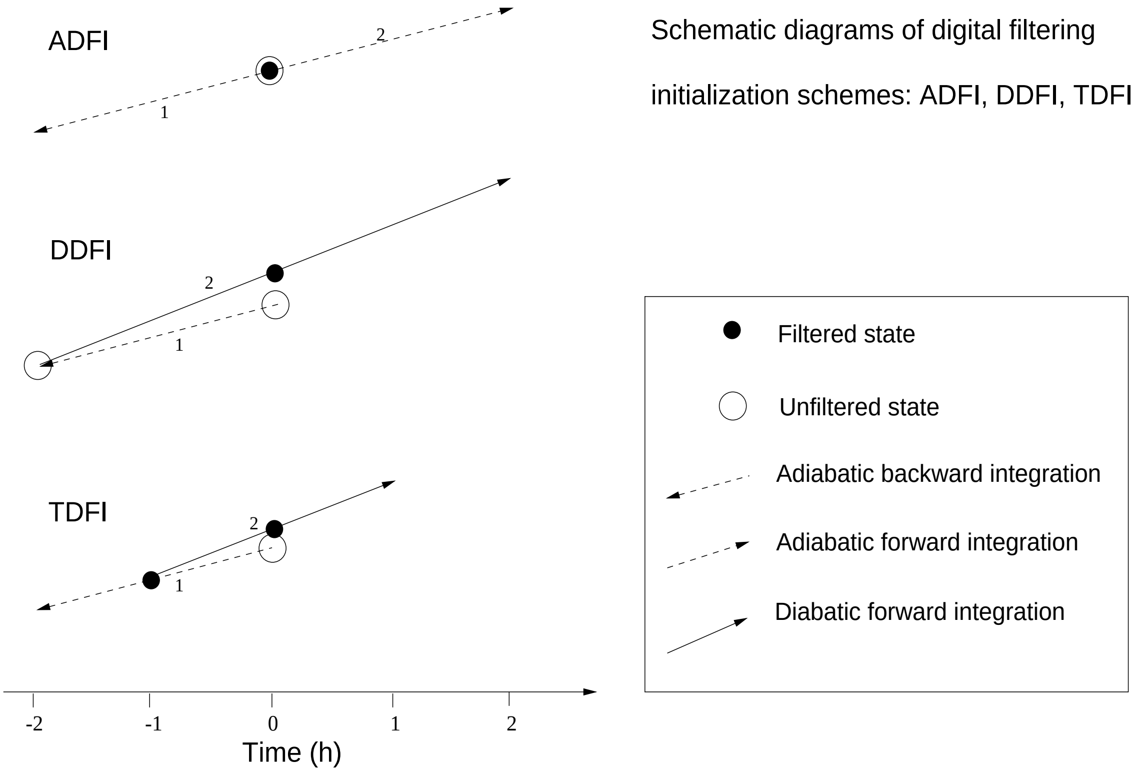

Figure 1: Schematic diagrams of the digital filtering initialization schemes.

The ADFI algorithm is:

$$\mathbf{X}_{ini} = \overline{\mathbf{X}_{ana}}^{ADFI} = h_{\frac{N}{2}}\mathbf{X}_{ana} + \sum_{n=1}^{\frac{N}{2}} h_{\frac{N}{2}-n}\left[\mathbf{X}_{ana}\right]_{-n}^{A} + \sum_{n=1}^{\frac{N}{2}} h_{\frac{N}{2}+n}\left[\mathbf{X}_{ana}\right]_{+n}^{A}$$

where $\mathbf{X}_{ini}$ is the initialized analysis, $\mathbf{X}_{ana}$ is the analysis and $[\mathbf{X}_{ana}]_n^A$ is the model state at time step n produced by adiabatic model integration from $\mathbf{X}_{ana}$ (indicated by the superscript A), where $n = -N/2, \cdots, +N/2$. Negative time steps are from backward model integrations and positive time steps are from forward model integrations. h_n are the filter coefficients.

A schematic diagram of ADFI is shown in Figure 1.

One of the special features of ADFI is that the time series passes the analysis exactly, which in most cases leads to desirable small changes (initialization increments). The major drawback of ADFI is that the adiabatic model used for initialization is not consistent with the diabatic model used later for the forecast. In principle, noise generated by diabatic processes could not be controlled by ADFI.

There are many extensions to the original ADFI, and these may be divided into five groups.

In the first group of extensions, physical processes are added to the model run which produces the time series to be filtered (Huang and Lynch, 1993). This scheme is referred to as Diabatic DFI (DDFI). A schematic diagram of DDFI is shown in the middle of Figure 1. In order for the time series to be centered around the analysis time, adiabatic integration backward in time is needed. Starting from the end of the backward integration, the full model with all diabatic processes is then integrated forward in time to produce a time series on which a digital filter is applied.

The DDFI algorithm is:

$$\mathbf{X}_{ini} = \overline{\mathbf{X}_{ana}}^{DDFI} = \sum_{n=0}^{N} h_n \left[[\mathbf{X}_{ana}]^{A}_{-\frac{N}{2}} \right]^{D}_{n}$$

where the superscript D denotes diabatic integration.

With DDFI, the same model is used both in the initialization and in the forecast. As expected, DDFI gives lower noise levels and a significantly smoother structure in the surface pressure tendency than ADFI. The major drawback of DDFI (and many later DFI schemes) is that the time series used in filtering does not pass the analysis state exactly (see the second diagram in Figure 1). This leads to large initialization increments, especially when the filter span is long. There are other problems due to the adiabatic backward integration. For example, in the HIRLAM system, all surface fields remain unchanged during adiabatic integrations. This means that the diabatic forward integration of DDFI always starts from a model state in which upper level fields (valid at `n=-N/2`) are inconsistent with surface fields (still valid at `n=0`).

It is tempting to design a scheme which does not need the adiabatic backward integration and therefore avoid all related problems. In such a scheme, the chosen digital filter is applied on a time series which is produced by a single diabatic forward integration from the analysis. The forecast will be launched from the filtered state (which may not be valid at `n=0`). To distinguish this scheme from other initialization schemes we will, in accordance with Lynch and Huang (1994), refer to it as Digital Filter Launching (DFL) [It is also called Digital Filtering Finalization (Fillion *et al.*, 1995)].

The DFL algorithm is:

$$\mathbf{X}_{start} = \overline{\mathbf{X}_{ana}}^{DFL} = \sum_{n=0}^{N} h_n \left[\mathbf{X}_{ana}\right]^{D}_{n}$$

where $\mathbf{X}_{start} = \mathbf{X}_{ini}$ only if the filter output is valid at the starting time. Attempts have been made on using a one-sided filter, *i.e.*, the filtered state is valid at the start or the end of the time series (Lynch and Huang, 1994). However, some phase shifts of those tested filters make the filtered state invalid at the analysis time. The search for a better filter is still on going (Lynch, 2000). On the other hand, if the output for the initialized state at the analysis time is not essential, DFL could be considered due to its efficiency and simplicity.

In the second group of the extensions, variables which are not analyzed are also filtered by DDFI (Huang and Sundqvist, 1993; Huang, 1996). For example, cloud water content (CWC) is a prognostic variable in many NWP models but not analyzed by the analysis and initialization schemes which provide the initial state for these models. A common practice has been to start the NWP model with the CWC forecast from a previous assimilation cycle (first-guess) or simply a CWC-free field, together with other analyzed fields like winds, geopotential, humidity and surface pressure. The imbalance between CWC and other fields could lead to an initial shock and spin-up problems in precipitation and related variables. Other examples include turbulent kinetic energy (TKE), rain water, snow content, vertical velocity (in non-hydrostatic models), etc. Since DDFI takes the full model into account, these non-analyzed variables are to some extent adjusted together with other analyzed variables during the DDFI process (Huang and Sundqvist, 1993; Huang, 1996).

The advantage of DDFI schemes in these extensions is obvious, *i.e.*, with almost no effort on code development and clear improvements on initial model performance of the aforementioned non-analyzed variables. However, one should be aware that these types of adjusted fields by DFI often have strong imprints of incomplete adjustment processes. Experience shows that such an adjustment (spin-up) process could take longer to complete than the filter span (a couple of hours) chosen for initialization purposes. Proper observations and analyses for these variables are still the ultimate solution for initialization issues.

On the implementation level, it is necessary to keep in mind that for the forward integration, moisture fields, such as CWC, often start with an initial dump and then gradually recover their magnitudes. The time series on which a filter is applied contain such dump-recover processes and therefore may lead to lower initialized values. Filters with a weight approaching zero towards the end of the filter span, *e.g.* the Lanczos window (Lynch and Huang, 1992), may reduce the negative impact of such dump-recover processes (Huang, 1996).

In the third group, the efficiency of the filter itself and the way the filters are applied are the main concerns. The computational cost for DFI, especially with diabatic processes involved, is quite significant if the originally proposed 6-hour span is used. When using shorter spans (3-hour or 2-hour), more efficient filters are required. The optimal filter (Huang and Lynch, 1993), the quick-start recursive filter (Lynch and Huang, 1994) and the Dolph filter (Lynch, 1997) are among the tested ones.

In addition to filters, there are schemes which also apply filters on the backward integration time series (Lynch and Huang, 1994; Lynch *et al.*, 1997). For the convenience of reference, we will refer to this type of schemes as TDFI (Twice Digital Filtering Initialization). A schematic diagram for TDFI is shown at the bottom of Figure 1. The HIRLAM reference initialization scheme is a TDFI scheme with the Dolph filter (Lynch *et al.*, 1999). The difference between TDFI and DDFI lies in where the diabatic integration starts. TDFI starts from a filtered state, which is obtained by applying the filter on the backward integration time series. This leads to a reduced forward integration length and a smoother start for the forward integration, compared to DDFI.

The TDFI algorithm is:

$$\mathbf{X}_{ini} = \overline{\mathbf{X}_{ana}}^{TDFI} = \sum_{n=0}^{N} h_n \left[\sum_{n'=0}^{N} h_{n'} \left[\mathbf{X}_{ana}\right]_{-n'}^{A} \right]_{+n}^{D} .$$

The benefit of the above-mentioned filters and schemes is evident from a computation-saving point of view. They have all been proved efficient in noise control. However, it is difficult to make a general statement on a particular filter and a particular scheme. In particular, the spin-up problem has not been given sufficient attention when new filters and new schemes are tested. The advantages and disadvantages of applying filters more than once also need further investigations.

In the fourth group, incremental (IDFI) approaches are investigated (Lynch and Huang, 1994). In this approach, it is assumed that the first-guess field is noise-free and that the filter should only be applied to the analysis increments. In order to filter the analysis increments, the proposed method is to apply DFI twice, one for the first-guess and the other for the analysis. The difference between the filtered analysis and filtered first-guess is then added to the un-initialized first-guess.

The IDFI algorithm is:

$$\mathbf{X}_{ini} = \overline{\mathbf{X}_{fgs,ana}}^{IDFI} = \mathbf{X}_{fgs} + \overline{\mathbf{X}_{ana}}^{FDFI} - \overline{\mathbf{X}_{fgs}}^{FDFI}$$

where FDFI could be ADFI, DDFI or TDFI ("F" denotes "Full" in contrast to "Incremental").

The advantages of IDFI, still to be demonstrated, are smaller initialization increments, fewer spin-up problems and preservation of fast developing modes in the first-guess. The disadvantages of IDFI are doubling of the computation time and the potential danger of a noisy first-guess. The latter would require special attention if IDFI is to be used operationally.

Finally, in the fifth group, the nature of DFI suits almost perfectly 4DVAR, the 4-dimensional variational data assimilation system, in which DFI could be used with virtually no extra cost as a penalty function to control noise during the minimization processes (Gustafsson, 1992; Polavarapu *et al.*, 2000; Gauthier and Thépaut, 2001). The HIRLAM 4DVAR already has this component and investigations will take place in the coming years.

1.2 Comments on the HIRLAM implementation

The very first implementation of DFI (ADFI) was done at the Department of Meteorology of Stockholm University (Lynch and Huang, 1991). The HIRLAM main forecast subroutine, `GEMINI`, was heavily modified and additional I/O introduced. A complicated script was made in which three forecast runs and two extra model state files were designed for ADFI. First, the HIRLAM forecast model is integrated backward in time and the filtered fields are stored (only half of the time series). At the end of the integration, the filtered fields are written out to an intermediate model state file. In the second integration the filtered fields are read and modified during the forward integration. At the end of the second run, the filtered fields are the final results of the initialization and written out to a model state file. The third is the forecast run that starts from the initialized model state. In later development of DDFI and TDFI, the hindcast results or the filtered fields from the hindcast are stored and then used as the initial fields for the forward DFI integration.

After a few years of development and testing, DFI-related updates were first tested in the HIRLAM reference system around 1995, but later removed due to their messy structure, excessive use of computation time and neutral impact on forecasts.

In 1999, another implementation was made and became the HIRLAM reference initialization scheme (Lynch *et al.*, 1999). Efforts were made to save computation time (use the effective TDFI with the Dolph filter) and to reduce the maintenance work (only one option is kept). However, the implementation strategy was the same as the very first one (Lynch and Huang, 1991), resulting in a major modification to `GEMINI`, unnecessary I/O and complicated scripts.

A schematic diagram of the previous HIRLAM reference setup is given in Figure 2. Two intermediate output files (IM, IN) were introduced. They are not really necessary and can easily become sources of error for script development and testing. The script expects three sets of namelists with same name (`NAMRUN`) in a given order. Many namelist parameters were set differently in backward DFI, forward DFI and forecast runs. This confusing structure lead to a messy script (`FORECAST`) and had caused many problems for experiments. The worst of all was the modification to `GEMINI`. One needs to have a thorough understanding of DFI in order to make changes to `GEMINI` for applications that have no relevance to initialization. Even for those who have been involved in HIRLAM DFI work at different stages, it remains a challenge to understand the data flow within `GEMINI`. This also partly explains why the previous HIRLAM reference system (prior to 5.0.2) only kept one option for initialization, *i.e.*, the TDFI with Dolph filter (Lynch *et al.*, 1999). In the following discussion, we refer the previous implemented DFI scheme in reference system as the TDFI-default.

As DFI is the HIRLAM reference initialization scheme, it is used extensively. Many people are using it and would like to understand how it works. A re-coding of DFI, aiming at a simpler structure of both run script and `GEMINI` (the main program), thus became necessary.

As the HIRLAM reference system should be applicable to all configurations at all HIRLAM member institutes, parameter tuning must be possible. The DFI-related parameters set by the reference system have been well-tuned only for a few system configurations. To enable systematic tuning for each configuration, the namelists should be easy to handle and each namelist variable should have a unique definition.

As we have discussed in the previous section, different DFI schemes have their own advantages and disadvantages. The current HIRLAM reference system is a TDFI scheme. However, other schemes may be preferable for other considerations in different applications, such as achieving an initialization increment that is as small as possible (ADFI) or

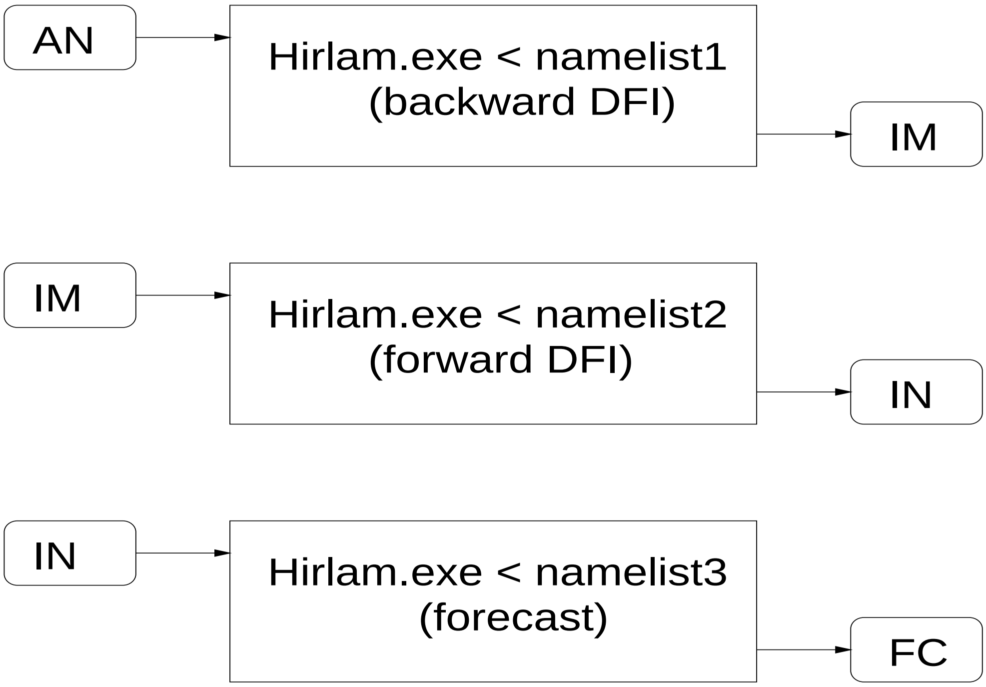

Figure 2: Schematic diagrams of a previous HIRLAM reference setup (prior to version 5.0.2).

avoiding filtering twice, etc.

The Dolph filter chosen by the HIRLAM reference system is a Chebyshev type filter (Lynch, 1997), while in many earlier implementations windowed-sinc filters [1] (*e.g.*, Lanczos window) have been used. Although the Dolph filter has been proven to be much more effective than those based on windowed-sinc filters, there are still reasons to revive and test windowed-sinc filters. If we only consider filter properties, windowed-sinc filters have a flat pass-band response and a much better stop-band attenuation than Chebyshev filters (Smith, 1999). In the actual DFI implementations in HIRLAM, it is difficult to design an optimal way to treat lateral boundaries and near surface fields in the DFI backward and forward integrations, which addresses the inconsistency issue properly. The windowed-sinc filters have vanishing coefficients close to the filter edges, which may alleviate such problems.

It has been found in some DFI implementations that a full DFI (FDFI) tends to smooth fronts too much and does not improve the model spin-up as it supposed to do. With the recent HIRLAM reference system, the model spin-up remains a concern for users who need the fields for the first hours and for people who try to improve moisture fields by cloud imagery (Per Undén, 2001, personal communication). One possible solution to

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[1] A windowed-sinc filter is a sinc function, $\frac{\sin ax}{bx}$, modified by a window, *e.g.* the Lanczos window $w_n = \frac{\sin[n\pi/(N+1)]}{n\pi/(N+1)}$. See Lynch and Huang (1992) for further explanations.

these problems is IDFI. As discussed in the previous section, the IDFI implementation requires an extra filtering on the first-guess. To do this with previous reference system would require extra file I/O and a increased complexity in both subroutine `GEMINI` and the script for forecast.

More arguments for a re-coding of DFI, aiming at a simpler code and scripts can be easily cited. Testing new initialization schemes and filters using the HIRLAM system could be made much easier (Peter Lynch, 2001, personal communication). Optimizing the HIRLAM performance, *e.g.* on the ECMWF computer systems, could benefit from such work (Gerard Cats, 2001, personal communication). Both for the system manager and for people developing initialization schemes, it is a clear advantage to have all initialization related programs separate from the rest.

2 The new implementation

Based on discussions in the previous section, it is not difficult to set out goals for the new implementation. In fact the re-coding of DFI has been under discussion for many years within the HIRLAM project. The general guidelines were agreed upon a few years ago. In short, we are aiming at

- a clean `GEMINI` subroutine - all DFI related statements should be removed except for a subroutine call to DFI;
- a simpler forecast script - no unnecessary I/O and only one namelist for the model run (`NAMRUN`);
- possibility for using different schemes and filters, completely controlled by a separate namelist (`NAMINI`).

2.1 The new approach

A schematic diagram of the proposed setup is given in Figure 3. As can be seen from Figure 3, there is no extra I/O of model states (IM, IN) during the initialization steps in the proposed setup. For some applications, the initialized state, IN, is needed. This could be achieved by simply writing out at forecast time 0. If IDFI is chosen, a first-guess file FG is also needed.

In this setup, the HIRLAM main subroutine `GEMINI` is only called once. All initialization (DFI or NMI) related code is removed from `GEMINI`, except two subroutine calls, one for DFI and one for NMI. These subroutine calls are controlled by two namelist parameters, `LDFI` and `LNMI`, which are the only initialization related parameters contained in `NAMRUN`. The modified `GEMINI` looks like the following:

```
      SUBROUTINE GEMINI
```

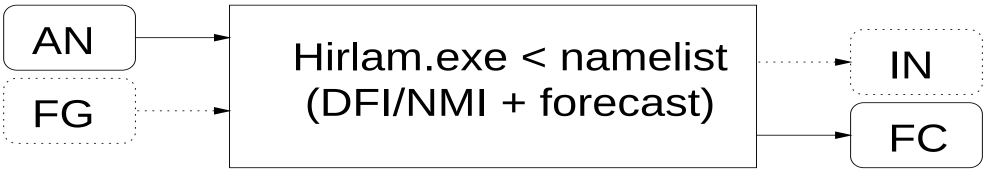

Figure 3: Schematic diagrams of the proposed setup.

```
....
IF(LNMI) CALL NMI
IF(LDFI) CALL DFI
....
END
```

As the main concern of this report is on DFI, we will only discuss DFI related issues in the following (a similar discussion could be made about NMI). The structure of `DFI` is

```
SUBROUTINE DFI
...
CALL RDNAMINI           ! READ IN NAMELIST NAMINI
CALL DFCOEF             ! CALCULATE DFI FILTER COEFFICIENTS
DO N=1,NITDFI
   IF(IDFI) THEN
      CALL INCDFI
   ELSE
      CALL FULDFI
   ENDIF
ENDDO
END
```

The options related to initialization are controlled by a separate namelist, `NAMINI`. These parameters are read in by subroutine `RDNAMINI` and communicated through a separate common block, `COMINI`. Among the main parameters in `NAMINI` and `COMINI` are:

```
IDFI               ! .TRUE. FOR INCREMENTAL DFI
NDFI               ! 1. ADFI; 2. DDFI; 3. TDFI; 4. DFL
NFILT              ! 1. LANCZOS; ...; 7. DOLPH; 8. QS
```

The choice of using FDFI or IDFI is made by setting parameter `IDFI` to `.FALSE.` or `.TRUE.`.

The choice of using ADFI, DDFI, TDFI or DFL is made by setting parameter `NDFI` to `1`, `2`, `3` or `4`.

The choice of filters is made by selecting parameter `NFILT` from `1` to `8`. The filter coefficients are then computed in the subroutine `DFCOEF`. This subroutine contains many choices of filters, from the Lanczos window (Lynch and Huang, 1992) to the Dolph filter (Lynch, 1997) and the quick start IIR filter (Lynch and Huang, 1994). New filters could easily be included in this subroutine, *e.g.* the one-sided boundary filter (Lynch, 2000). For most filters, the important parameters are the filter span, `TSPAN`, and the inverse of filter cutoff frequency, `TAUS`. See *e.g.* Lynch and Huang (1992) for a discussions of these parameters.

It may be useful to notice that the choices for `IDFI`, `NDFI` and `NFILT` are independent of each other, giving a great flexibility for testing. The default values are, however, set to: `IDFI=.FALSE.` (FDFI), `NDFI=3` (TDFI), `NFILT=7` (the Dolph filter), as in the previous HIRLAM reference version 5.0.2 (TDFI-default).

Depending on the namelist `IDFI`, `INCDFI` or `FULDFI` will be called by `DFI`. The structure of `INCDFI` is

```
      SUBROUTINE INCDFI
      ...
      CALL GETDAT           ! READ IN FIRST-GUESS
      ...
      CALL FULDFI           ! FILTER FIRST-GUESS
      ...
      CALL FULDFI           ! FILTER ANALYSIS
      ...
      UM(I,J,K) = FGSU(I,J,K)! CONSTRUCT INITIALIZED FIELD
     1         + DFANAU(I,J,K)! INI = FGS + (DFANA-DFFGS)
     2         - DFFGSU(I,J,K)!
      ...
      END
```

which applies `FULDFI` both to analysis fields and to first-guess fields sequentially, and then adds the increments to the unfiltered first-guess.

The real filtering work is done in `FULDFI`, in which the backward and forward integrations are performed. The approximate structure of `FULDFI` is

```
      SUBROUTINE FULDFI
      ...
      NBDTIM_ORIG=NBDTIM    ! SAVE ORIGINAL MODEL PARAMETERS
      ...
      DFTS(I,J)=TSM(I,J)    ! SAVE SURFACE ANALYSIS FIELDS
      ...
      CALL BDINIT
                            ! BACKWARD INTEGRATION
      CALL DIFHINI
      IF(NLEUL) THEN
        CALL EULER
      ELSE
        CALL SL2TIM
      ENDIF
```

```
 ...
 DFU(I,J,K)=DFU(I,J,K) ! FILTERING
1 + H(NSTEP)*UM(I,J,K) ! DFU = SUM H*U
 ...
 CALL DIFHINI
 CALL BDY_SWAP
                       ! FORWARD INTEGRATION
 IF(NLEUL) THEN
   CALL EULER
 ELSE
   CALL SL2TIM
 ENDIF
 ...
 DFU(I,J,K)=DFU(I,J,K) ! FILTERING
1 + H(NSTEP)*UM(I,J,K) ! DFU = SUM H*U
 ...
 NBDTIM=NBDTIM_ORIG    ! RESTORE ORIGINAL MODEL PARAMETERS
 ...
 TSM(I,J)=DFTS(I,J)    ! RESTORE SURFACE ANALYSIS FIELDS
 ...
 CALL BDY_SWAP
 END
```

The code structure of `FULDFI` resembles that of `GEMINI` due to a need for performing integration loop. Users must hence be aware of the future needs of necessary code adjustment in case that subroutines used by `FULDFI` and `INCDFI` are modified. Due to the HIRLAM coding style, the save and restore of some original input parameters are necessary as some of them are modified during model runs. Another comment should be made here as regarding to surface variables. It is not possible with the current HIRLAM code to obtain initialized surface fields, simply because the adiabatic backward integration is required and surface fields are not updated during the integration. As it is coded now, the surface fields cannot be filtered. The save and restore of them are just for this purpose.

2.2 Additional changes

Several additional changes have been introduced in the new implementation. Some of them are necessary in order to reproduce the TDFI results in the earlier versions.

McGrath and Lynch (1999) found that by excluding the model state at time step 0 the filtering results could be improved. Although this has not been found to be generally true for all our tests, we kept this feature and made it an option. The namelist parameter `NDFSFT` is the starting time step for applying the filter. We set `NDFSFT` to `1` as default, which should reproduce the earlier TDFI results. If one follows the arguments by Lynch *et al.* (1999), one could ignore a few more time steps by increasing `NDFSFT`. However, `NDFSFT` must be set to 0 if ADFI is used.

As with most limited area modeling systems, HIRLAM needs lateral boundaries and has a Davies-Kållberg type scheme (Davies, 1976). It has been shown by Huang (1991) that applying the lateral boundary relaxation scheme during DFI integrations could lead to unsatisfying filtering results in the boundary relaxation zone. In the TDFI-default, the number of grid points in the relaxation zone, `NBDPTS`, is set to 4, which due to the particular HIRLAM lateral boundary formulation gives no boundary relaxation at all. (On some computers this could lead to a crash, as `NBDPTS-4` appears in a denominator.) We introduced a new logical namelist variable, `NLBREL`, to switch on or off the lateral boundary relaxation scheme. When the scheme is on, `NBDPTS_INI` is the number of points in the relaxation zone during initialization, either with NMI or DFI.

As discussed in the previous sections, the horizontal diffusion should be considered as an irreversible process. This assumption has been used in many applications of DFI. On the other hand, if we only regard horizontal diffusion subroutines in a model as a control for numerical noise, it is also easy to accept the same control in the backward numerical integrations. The TDFI-default applies an implicit horizontal diffusion scheme in both forward and backward integrations. There is a detail of the TDFI-default, which may be worth mentioning. The order and the coefficients of the horizontal diffusion can be set differently in the DFI and in the forecast. In order to be able to select the same setup by using only one namelist, we have added all horizontal diffusion related parameters with suffices `_BWD` and `_FWD`, indicating parameters for backward and forward integrations, respectively. Their default values are set according to the TDFI of version 5.0.2.

There is a subtle feature of TDFI in the previous implementation for the first lateral boundary file handling. There is a flexibility in selecting the first lateral boundary file and in most implementations the analysis is chosen. As indicated in Figure 2, with TDFI, the first lateral boundary file differs in different steps of the integration runs.For the backward integration, it is the analysis. For the forward run, it is the filtered state from the backward run. For the final forecast, it is the initialized model state. In other words, the first lateral boundary file has been updated in the initialization step. Is this something to worry about? It could be. As we have discussed above, TDFI-default uses no lateral boundary relaxation during the backward and forward integrations. This may produce a sharp gradient in the relaxation zone. If this happens, the forecast in the first 6 hours (or 3 hours) could be influenced by the problematic lateral boundary file, although the average noise level shows an improvement. A new logical namelist variable, `LBDYSWAP`, is hence introduced in the new implementation. When `LBDYSWAP=.TRUE.` (as in the TDFI-default), the first lateral boundary is handled like before. When `LBDYSWAP=.FALSE.`, the first lateral boundary, whether it is analysis or some other file (*e.g.* ECMWF forecast), is kept unchanged. Here we would like to stress again that the impact of `LBDYSWAP` on the forecast should not be assessed by looking at the initial noise level.

Due to the lack of some physical processes (and horizontal diffusion in some implementations) during DFI time integrations, a shorter time step may be used to avoid numerical instabilities. A new namelist variable, `DTINI`, is included for this purpose. Based on the experience with the current reference system, we set its default value to be the same as that used in the forecast. (For the HIRLAM nonlinear normal mode initialization scheme, a short time step of 60s is used as default due to accuracy considerations.)

Finally, a new namelist variable `NITDFI` is added, giving the possibility of iterating DFI. This option could be very complicated to implement within the old code structure, and has become straightforward to add in the new code. In fact this parameter is added mainly because it is almost trivial to do so. It is well known that almost all nonlinear normal mode initialization implementations require iterations. However, we are not aware of any attempt on iterating DFI. With `NITDFI` systematic investigations could be performed.

2.3 Modifications to the script system

The above-mentioned code modification has been done based on the HIRLAM reference release 5.0.2, which features the mini-SMS script system. In connection with the new interface, modifications to several scripts under 5.0.2 have been necessary, *e.g.*, in the experiment description file, **`Env_expdesc`**, specification needs to be made for the options of `IDFI`, `NDFI` and `LNMI`, in addition to `LDFI` as was required before; in the input data file for the forecast model, **`FCinput`**, major changes have been made to produce single stream of namelist sets. Here `NAMINI` is placed at the last position of the namelist sets to be read by the forecast model. `NAMDFI`, which was previously required, is now gone. In **`Postpp`**, changes have also been made accordingly to accommodate the new sequence of namelist read-in.

The modified codes were introduced into the HIRLAM system as beta release 5.0.3 in June 2001 and have since become part of the new features in the official release version 5.1.

3 Experimental configuration and code validation

A number of data assimilation experiments have been configured to validate the code changes in the initialization interface, and to test the initialization schemes using the modified codes. The experiment is run at a 114 × 100 × 31 gridmesh and a 0.5 degree horizontal resolution, with the model domain, as shown in Figure 4, covering the whole European continent. Apart from the initialization schemes, the reference HIRLAM system is used in all runs. The experiments comprise an OI-based analysis at 6 hour intervals, followed by initialization and a 36 hour forecast. All the experiments are conducted on ECMWF computers.

In the parallel experiments that are designed solely for code validation purpose, the pre-revision code 5.0.2 and the modified code 5.0.3 are used for comparison. The experiments cover a 10-day period from Aug 18, 2000, 1800 UTC to Aug 29, 2000, 1200 UTC (Huang and Yang, 2001). In both runs the TDFI-default is used with the Dolph filter. It is expected that, given all initialization-related parameters being equivalent, the modified source code and scripts in 5.0.3 should be able to reproduce the results by the earlier model version, 5.0.2. An examination of the parallel results confirm that such is indeed the case, as reported in Huang and Yang (2001). Figure 5 here shows verification scores for the forecasted key surface and upper air parameters for the 10-day assimilation-forecast period, against observations of European radiosonde and synoptic stations (the

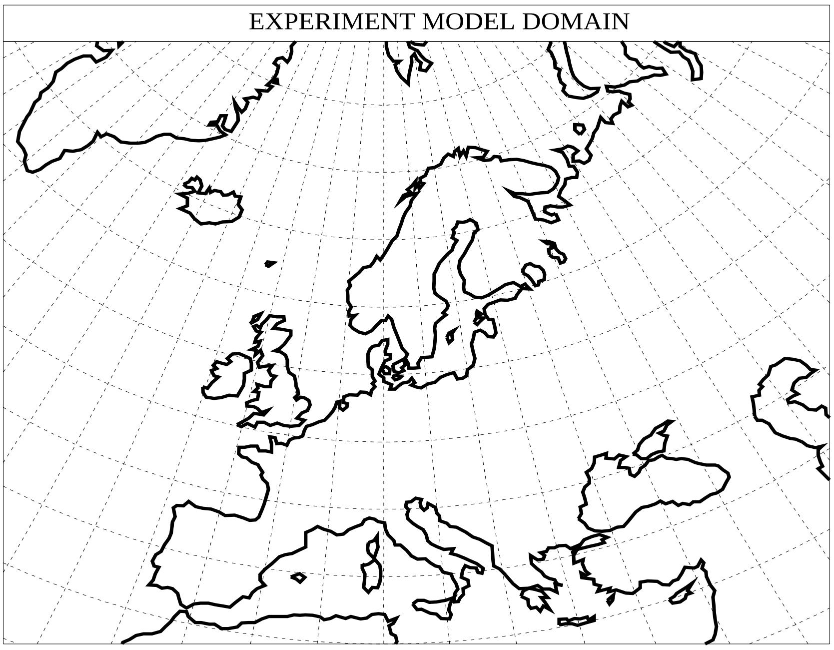

Figure 4: Model domain.

EWGLAM list). The tiny differences shown in the plots are attributed to the precision errors introduced in the grib input and output used in version 5.0.2. Thus the implementation of the new initialization interface is shown to be successful from a technical point of view.

4 Features of the initialization schemes

Using the new initialization interface contained in 5.0.3, a number of data assimilation experiments have been configured examining the impact of initialization schemes on forecasts. In Table 1, a summary of the tested initialization schemes is given with the default values for some key parameters in the implemented initialization schemes in 5.0.3.

Table 1: List of main DFI experiments

Scheme	`IDFI`	`NFILT`	`TSPAN`	`TAUS`	`NBDPTS_INI`	`LBDYSWAP`	`NDFSFT`
TDFI	.f.	7 (Dolph)	7200	10800	4	.t.	0
ADFI	.f.	1 (Lanczos)	21600	21600	8	.t.	0
DDFI	.f.	1 (Lanczos)	21600	21600	8	.f.	0
ITDFI	.t.	7 (Dolph)	7200	10800	4	.t.	0
IDDFI	.t.	1 (Lanczos)	21600	21600	8	.f.	0

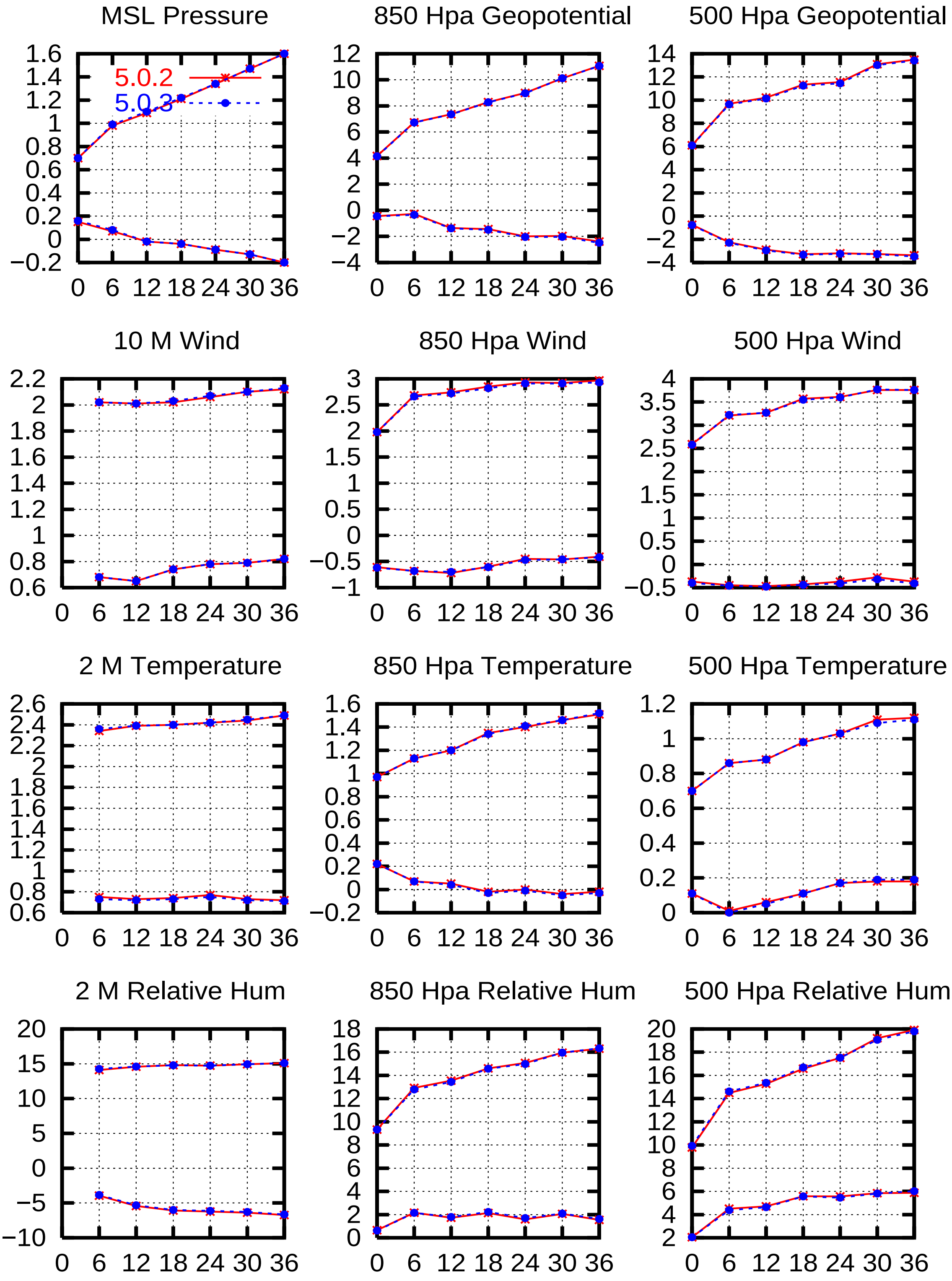

Figure 5: Observation verification in standard deviation (STD) and bias for mean sea level pressure, 10 meter wind, 2 meter temperature and relative humidity, and Geopotential height, wind, temperature and relative humidity at 850 and 500 hPa levels, for the forecasts from August 18 to August 29, 2000, with TDFI in HIRLAM 5.0.2 and the recoded TDFI in HIRLAM 5.0.3

Test runs have also been performed with INMI. For INMI, a parameter value of `NITER=3`, `MODES=4`, `NBDPTS_INI=4` are set as default. In addition, experiments with non-default configurations of various DFI schemes have also been performed for different lengths of periods to examine impact of the schemes under different circumstances.

4.1 Evaluation of initialization schemes in 5.0.3

Various data assimilation experiments have been carried out using several re-introduced initialization options, partly as a technical step to validate the new code. A period of 10-days, between December 1, 1999 at 00 UTC and 11 December 1999 at 00 UTC, is chosen for the parallel runs comparing forecasts initialized by INMI, ADFI, DDFI and TDFI. The first part of the period features the historical hurricane that severely affected Northern Europe, with the peak of the storm in the afternoon of Dec 3, when Denmark suffered devastating damage. Similar runs for the period have also been conducted using incremental DDFI (IDDFI) and TDFI (ITDFI), and are discussed at the end of this section.

Noise level

To evaluate the impact of initialization schemes on the resulting forecasts, we first examine several characteristic diagnostic quantities in the form of domain averaged statistics. The mean absolute surface pressure tendency N in hPa/3h, defined as

$$N = \frac{1}{IJ}\sum_{i=1}^{I}\sum_{j=1}^{J}\left|\frac{\partial p_s}{\partial t}\right|_{ij},$$

where p_s is the surface pressure and the summation denotes calculation over the whole domain, is a characteristic quantity which reflects directly the overall balance of the model states. The feature of noise control, as is best manifested by the time series of N, has traditionally been seen as a primary indicator of the efficiency of an initialization scheme. As is well known,the analysis procedure is often associated with a significantly increased noise level compared to the first-guess field, which, if not effectively damped, may require a considerable amount of time during forecast integration to reach a balance, and occasionally cause forecast failure. An initialization procedure, on the other hand, is expected to reduce such an imbalance substantially at the start of forecast. Figure 6a shows the time series of N for each time step of the first 6 hours of forecasts following initialization, during the 10 consecutive cycles starting on Dec 2, 1999 at 00 UTC. The initialization schemes in the comparison here are INMI, ADFI, DDFI and TDFI, each with their default parameter values as shown in Table 1. In Figure 6b, the same time series, but averaged for all 40 cycles of the experiment period, are plotted, for the integration time of up to 12 hour.

For the 10-day experiment period, tests indicate that without the initialization procedure, forecasts started directly from analysis fields would have an initial noise level, N, of around 7-12 hPa/3h for individual cycles (not shown here). Against that background, the Figure 6a confirms that all the tested initialization schemes have been effective in

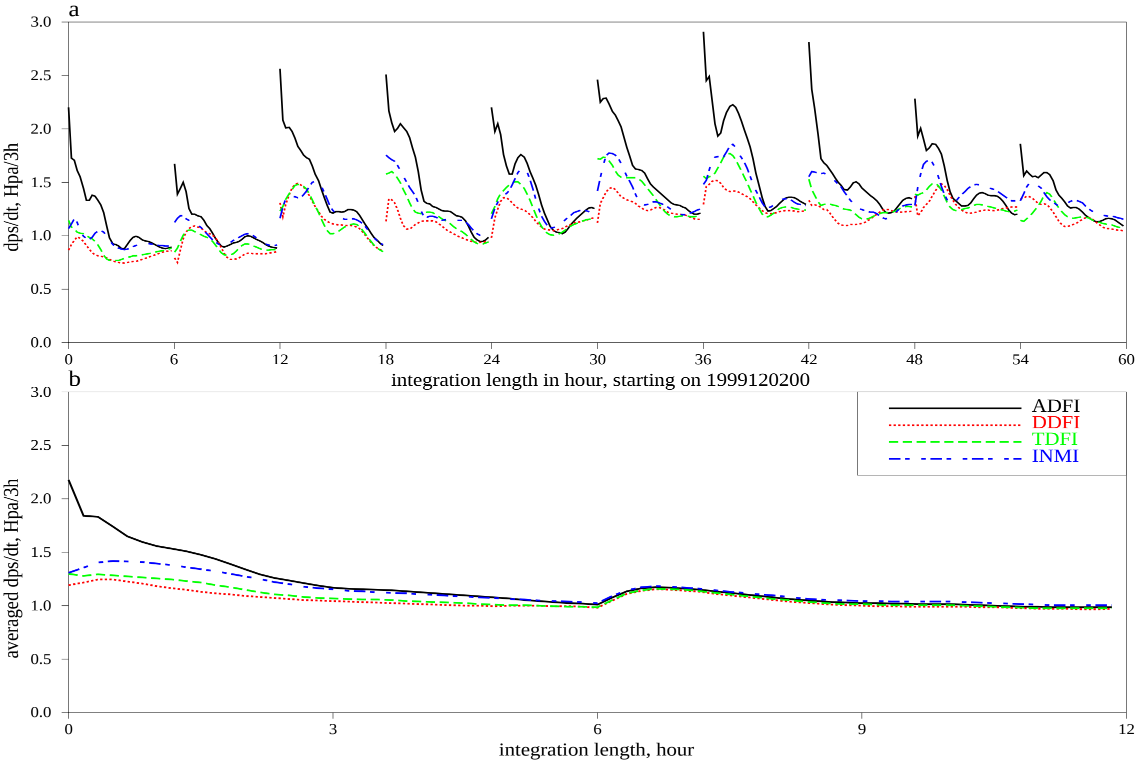

Figure 6: The time series of domain averaged mean surface pressure tendency N in hPa/3h, (a) for 10 consecutive 6 hour forecasts started on December 2, 1999 at 00 UTC. The forecasts are initiated by ADFI (solid line), DDFI(dotted line), TDFI (dashed line) and INMI (dash dotted line), respectively. (b), the time series of N in hPa/3h in the first 12 hour forecasts averaged from 40 cycles during 1999120106 - 19912011100.

damping initial noise. Among them, DDFI is shown to be most effective. On the other hand, ADFI, which includes only adiabatic processes during the initialization integration, is least effective in noise reduction. INMI seems to have generally higher initial noises than TDFI and DDFI most of the times, but occasionally it is also seen to cause deeper damping than DFI schemes. The averaged time series shown in Figure 6b seem to indicate that it takes around 3 hours for TDFI and DDFI-initiated forecasts to reach a “noise free” state, whilst for INMI and ADFI, the adjustment seems to take longer (close to 6 hours).

It is important to bear in mind, however, that it is not a goal to achieve as low a N level as possible by initialization. Indeed, filtering of high frequency components should not be overdone to cause loss of useful information contained in an analysis.

Moist spin-up features

Another important factor that measures impact of an initialization scheme is the spin-up feature in moisture fields. In a data assimilation cycle, the analysis procedure seldom deals directly with observation of moisture fields, such as liquid cloud water, cloud cover and precipitation. Furthermore, current HIRLAM analysis schemes (OI or 3DVAR) do not involve physical model as used in forecast system. Hence, there exists an intrinsic imbalance in the analyzed model state between, on the one hand, analyzed mass and wind fields, and on the other hand, un-analyzed moisture fields such as liquid cloud water, cloud cover and precipitation. It thus requires an adjustment period during which model fields gradually reach a quasi-balanced state. To investigate such an adjustment process following initialization steps, we examine the evolution of the domain averaged precipitation rate R.

Figure 7 shows the corresponding time series of Figure 6 but for the domain averaged precipitation rate. It demonstrates clearly that ADFI and INMI, which do not touch moisture fields during the initialization stage, experience a surge in precipitation during initial stage of forecasts, apparently due to imbalance between uninitiated moisture fields and initiated dynamic fields. Following the initial surge, both of the time series of the rain rate for ADFI and INMI go through a spin-down first, followed by a spin-up adjustment. The DDFI and TDFI-initiated forecasts are seen to start at a lower precipitation level and increase gradually during following hours. The initial low level of rain rate in diabatic DFI-initiated forecasts is attributed to the fact that, the spin-down process from the analyzed model state as seen in INMI and ADFI is now moved to the diabatic step during the DFI integration, and after DFI filtering the model state as a whole starts at a preliminary adjusted state which features less noise in moisture fields. Obviously, the spin-up process has not been completed during diabatic DFI integration and it continues during the initial stage of the following forecast. It appears that the efficiency of the DFI schemes in moisture spin-up is closely affected by the characteristics of the condensation schemes used in the forecast model. In Huang (1996) it was demonstrated that the DDFI-initiated forecasts have generally a more efficient spin-up feature than INMI. However, our experiments here indicate that DDFI forecasts tend to suffer a bit more severe moisture spin-up problem. Figure 7b shows that, on average, the spin-up process for precipitation fields requires 3 to 6 hours for all the initialization schemes and as such, the accumulated model predicted precipitation in the first 6 hours cannot be trusted.

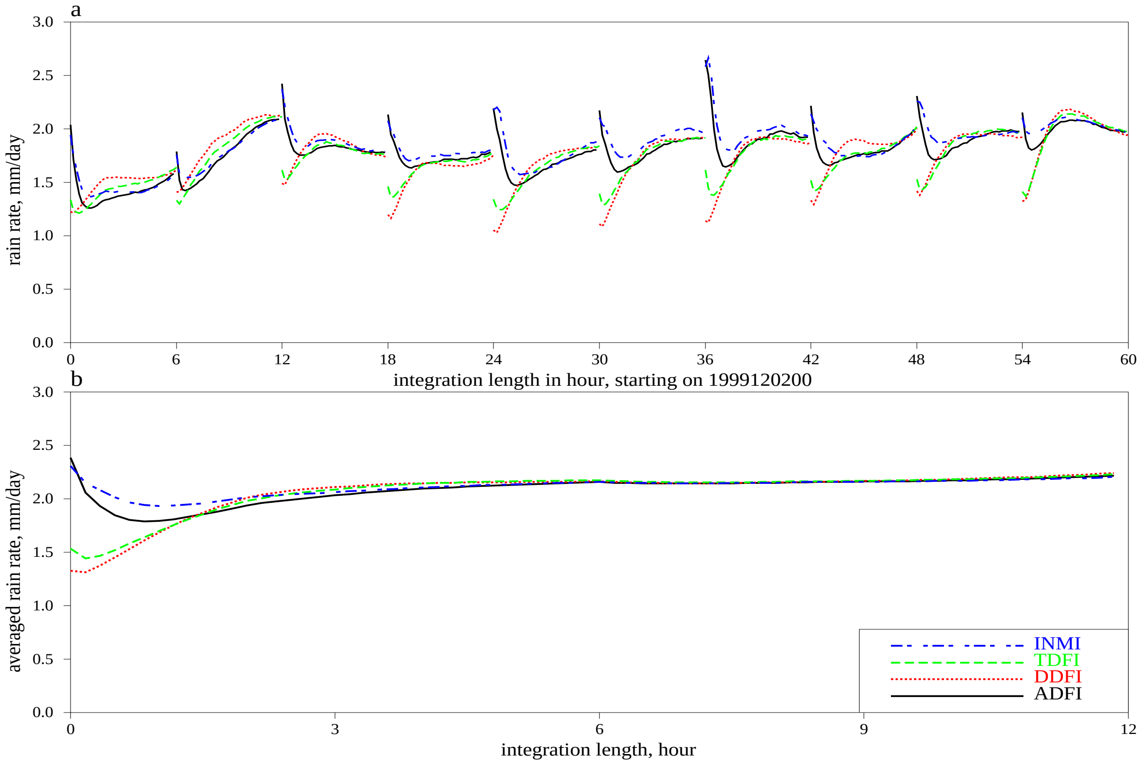

Figure 7: The time series of domain averaged precipitation rate R in mm/day, (a) for 10 consecutive 6 hour forecasts started on December 2, 1999 at 00 UTC. The forecasts are initiated by ADFI (solid line), DDFI(dotted line), TDFI (dashed line) and INMI (dash dotted line), respectively. (b), the time series of R in mm/day in the first 12 hour forecasts averaged from 40 cycles during 1999120106-19912011100.

Table 2: Analysis and initialization increments for cycle started on Dec. 3, 1999, 00 UTC

Experiments	u		v		T		q		ps	
	rms	max	rms	max	rms	max	rms	max	rms	max
ANA	2.0	-25.6	2.1	-27.1	0.8	6.6	1.6e-4	1.6e-3	89.5	-545.3
ADFI	0.4	5.5	0.5	10.9	0.1	-1.8	2.0e-5	-5.3e-4	31.2	149.1
DDFI	0.9	9.8	0.9	18.2	0.4	4.6	9.4e-4	2.7e-3	61.8	276.5
TDFI	0.6	7.4	0.6	13.6	0.2	3.2	6.5e-4	1.7e-3	39.8	-187.3
INMI	0.5	7.3	0.6	8.2	0.3	3.5	2.4e-6	-1.3e-4	54.0	230.9

Initialization increment

Obviously, for any initialization scheme, changes made by it should be relatively small, in comparison to those made by the analysis procedure over the first-guess, and that analysis should not be degraded by the initialization scheme. Table 2 presents the statistics of the initialization increments for the cycle started on December 3, 1999 at 00 UTC. The initialization increment is defined as the difference between the initialized field and input analysis, and represented here by the domain averaged RMS and maximum values in u, v, T, q and p_s. As a reference, the analysis increments, defined as the differences between the analysis and first-guess, are shown. In order to ensure a fair comparison, the parallel initialization and forecast runs for this particular cycle are based on the same analysis and lateral boundary condition.

Table 2 indicates that overall the changes introduced during initialization are indeed smaller than those due to the analysis, except for the specific humidity field, where the analysis does not bring substantial changes to moisture quantities. Instead, the initialization procedures cause significant adjustment in moisture fields toward balance with the other analyzed fields. Among the initialization schemes, the adiabatic scheme ADFI has the smallest increments, followed by INMI and TDFI. The contrasts shown here are in good agreement with the features depicted in earlier discussions about evolution of domain averaged quantities in the resulting forecasts.

Observation verification

Figure 8 shows the observation verification scores, represented by mean standard deviation and bias, of some chosen forecasted parameters for the above 10-day period, with forecasts initiated by INMI, DDFI and TDFI schemes. The observation data are those from European surface and sounding stations, using the EWGLAM list. One remarkable feature from Figure 8 is that the DDFI scheme clearly improves the negative bias of the MSLP and geopotential heights for this test period. However, except for that aspect, the differences in scores for forecasts with different initialization schemes are generally insignificant. Similar features have also been observed in parallel experiments for a number of other test periods, indicating generally small impacts of using different initialization schemes on forecast qualities.

4.2 Tunables in the initialization interface

As discussed in Section 2, the newly created namelist block `NAMINI` contains various initialization options, allowing for choices suiting user's particular needs. Different choices of tunables in `NAMINI` such as filter scheme (`NDFI`), filter type (`NFILT`), number of DFI iterations (`NITDFI`), filter span (`TSPAN`), filter cutoff window (`TAUS`), and full or incremental DFI (`IDFI`), have all been found to have significant consequences on initialization effects, in terms of degree of noise reduction on analysis input and the moisture spin-up feature following initialization. Additional tuning parameters as described in Section 2.2, such as `NBDPTS_INI`, `NDFSFT`, `NLBREL`, `LBDYSWAP` etc. have also shown impact on the initialization results to various degrees.

As an example, we demonstrate here a comparison of resulting 12 hour forecasts for a particular cycle on Dec 3, 1999 at 00 UTC, applying DFI initialization schemes with varying parameters. The results are again represented by the domain averaged noise parameter and precipitation rate.

In Figure 9, DDFI is applied with 5 different filter types (`NFILT`), with remaining parameters set to be the same as in the default DDFI combination. Among the tested filters, the Dolph filter (`NFILT=7`), currently used as default filter in combination with TDFI, distinguishes itself from other filters in both noise and precipitation curves. The forecast after Dolph filter is seen to have a slightly lower noise level than other forecasts. For precipitation, it has an unique initial V-shape, followed by a slightly smaller precipitation amount comparing to those from other types of filters.

In Figure 10, the impact of the choice of the cutoff period, `TAUS`, for DDFI filtering is demonstrated, where a value of 6 hours (default), 4.5 hours and 3 hours are chosen for `TAUS`, with a time-span of 6 hour. The figure indicates that while a longer cutoff window reduces more noise (shortest waves), it also reduces the initial precipitation level by a larger degree, which is undesirable.

In Figure 11, the benefit of iterating DFI is evaluated, by comparing three DDFI-initiated forecasts, one with filter span (`SPAN`) of 6 hours, with no iteration, (`NITDFI`=1), the second with a span of 3 hours, and the third with a span of 3 hours and an added iteration of DDFI (`NITDFI=2`). In terms of computation time the first and third set up are nearly the same. From the Figure 11, however, although the repeated application of DDFI improves noise reduction, it appears not as effective as simply doubling the filter span.

In Figure 12, the time series of N and R for two forecasts initialized by DFL (`NDFI=4`) are compared with a forecast initialized by the TDFI-default. The DFL tests are performed with the Dolph filter (`NFILT=7`) and the second order Quick-Start recursive filter (`NFILT=8`), respectively. The filter span is 2 hours. The Dolph filter output is valid at the center of the filter span, *i.e.*, at `t=1h`, while the Quick-Start filter output is valid at

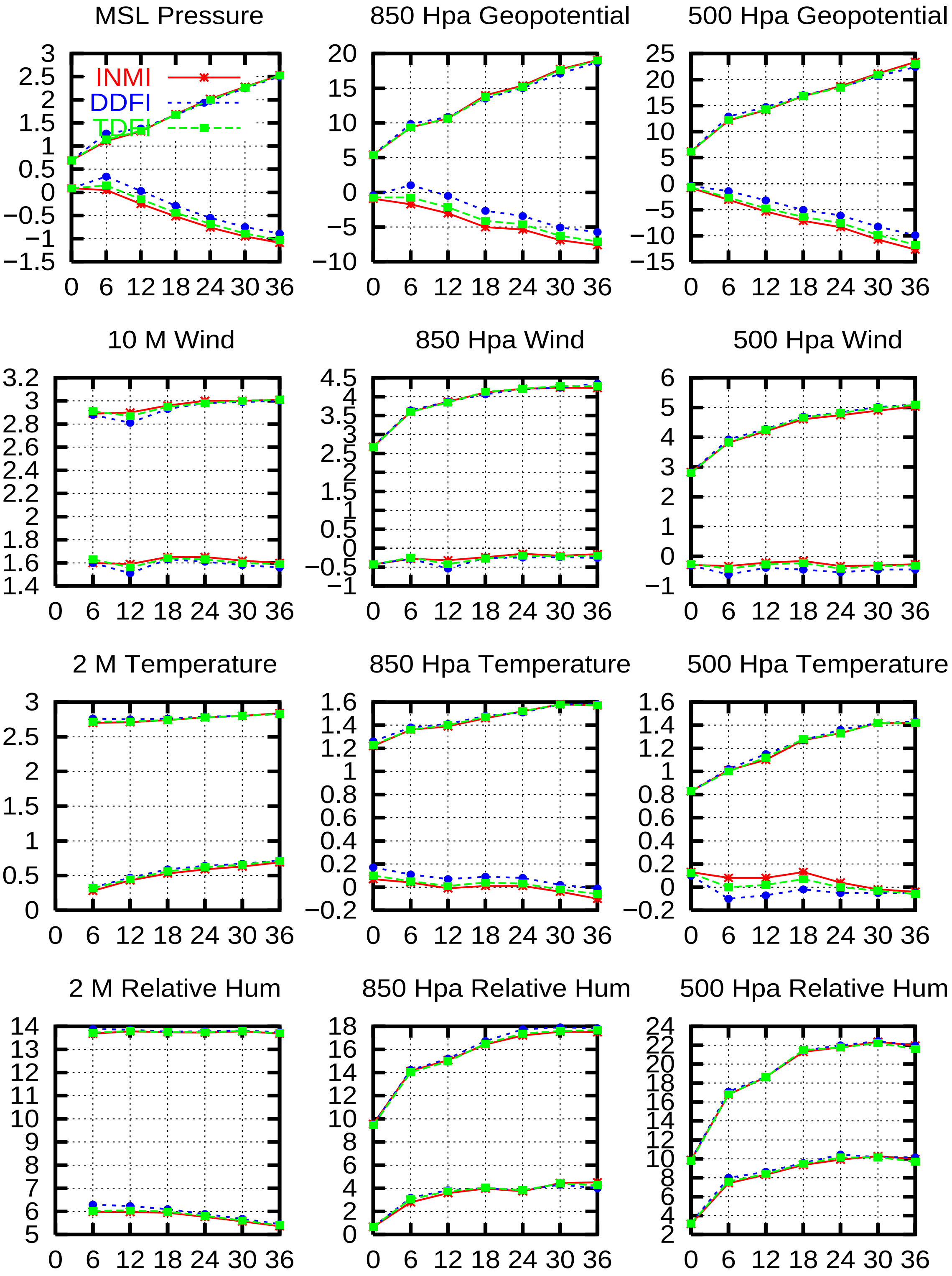

Figure 8: Observation verification, both standard deviation (upper group of curves in each panel) and bias (lower group of curves in each panel) for surface and upper air key parameters at 850 and 500 hPa, for the forecasts during December 1 and December 11, 1999, initiated by INMI scheme (solid line), DDFI (dark and short dashed line) and TDFI (light and long dashed line.

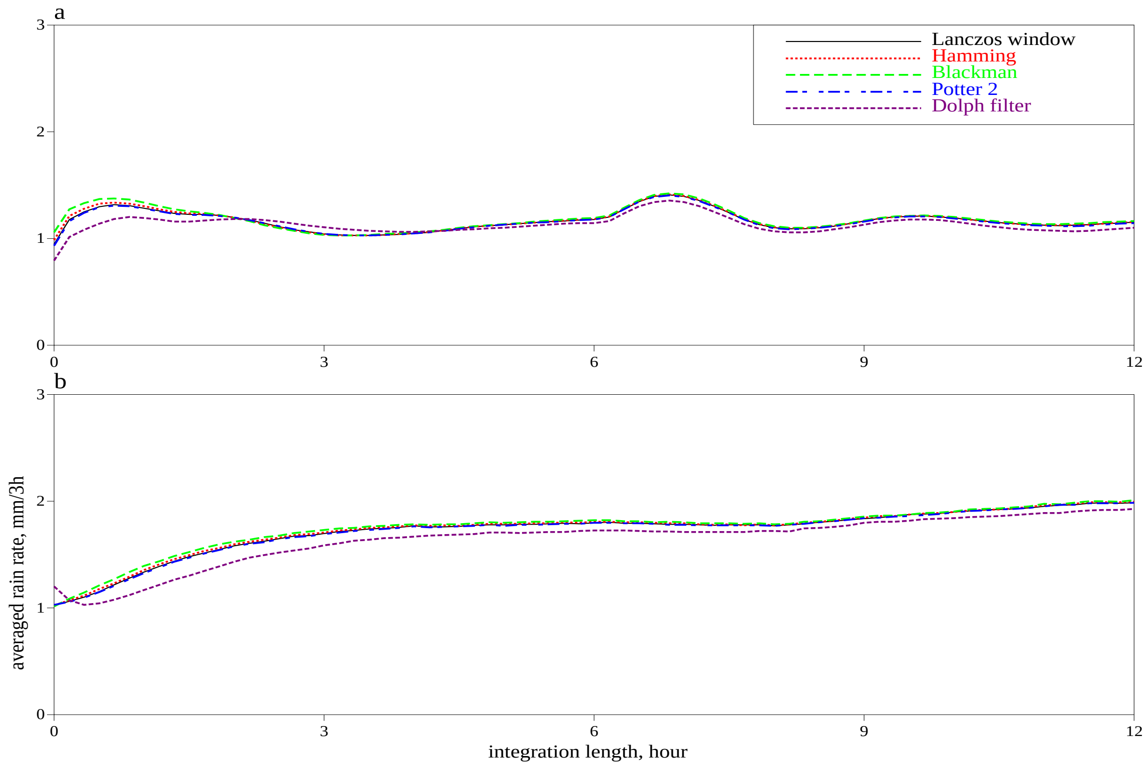

Figure 9: The time series of (a) N in hPa/3h and (b) R in mm/day, using DDFI with a Lanczos window sinc filter (solid lines), a Hamming window sinc filter (dotted line), a blackman window sinc filter (long sashed line), a potter 2 window sinc filter (dot dashed line) and a Dolph filter (short dashed line), respectively. The filter span is 6 hour and the filter cutoff period is 6 hour.

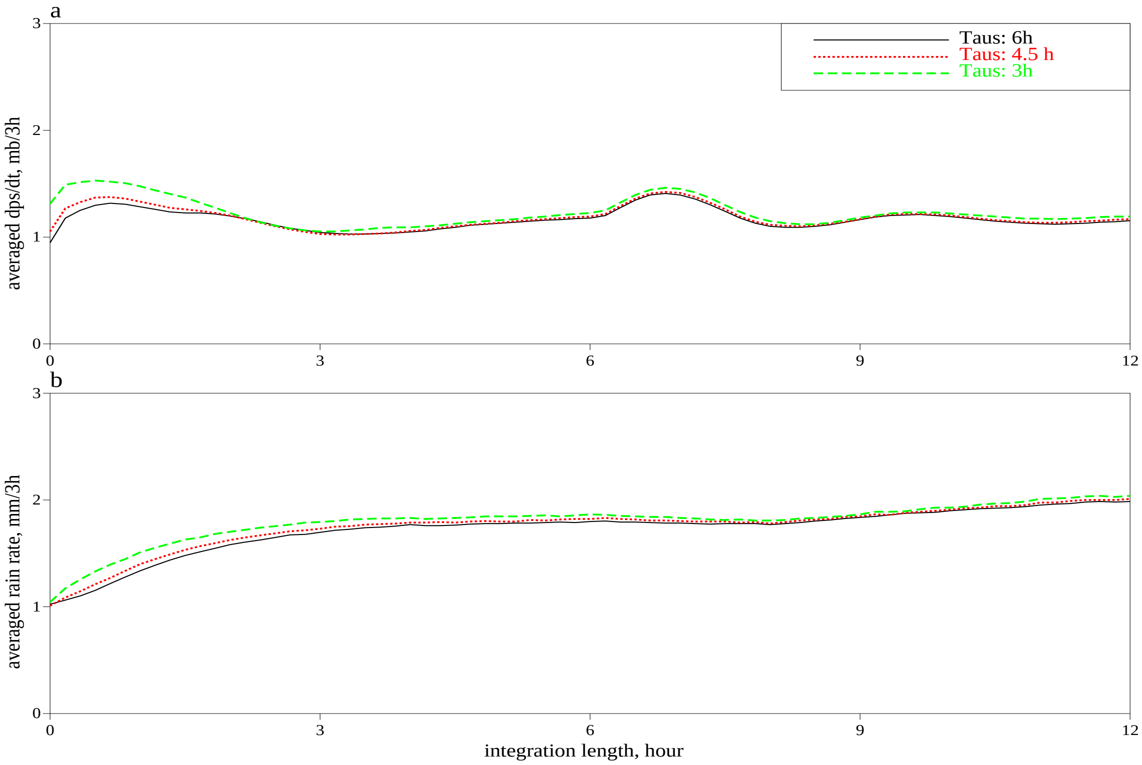

Figure 10: The time series of (a) N in hPa/3h and (b) R in mm/day, using DDFI with a Lanczos window sinc filter with a filter span of 6 hours. Three cutoff periods are compared: 6 hour (solid line), 4.5 hour (dotted line) and 3 hour (dashed line).

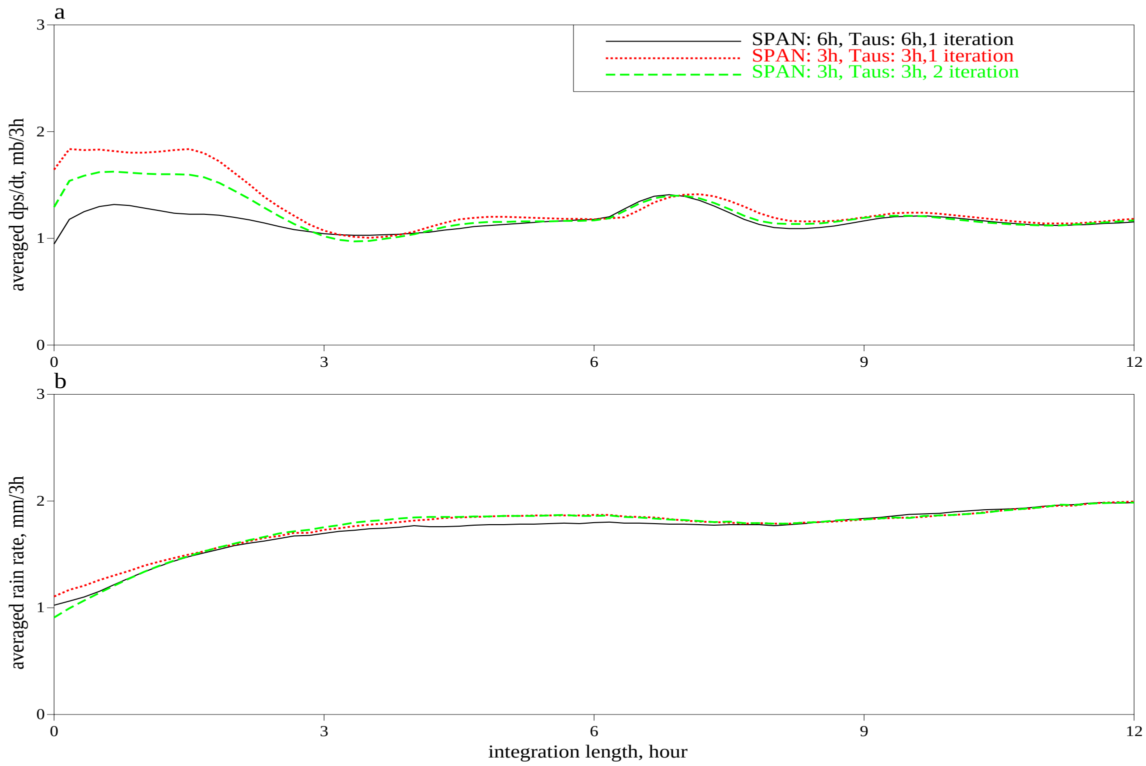

Figure 11: The time series of (a) N in hPa/3h and (b) R mm/day using DDFI with a Lanczos window sinc filter.

the end of the filter span with a time delay, *i.e.* at `t=2-0.6h`. Here the 0.6 h delay is calculated using

$$\delta = \frac{\tau_c}{\pi} M \sqrt{2^{1/M} - 1}$$

where δ is the time delay, τ_c is the cutoff time (here $\tau_c = 3h$) and M is the filter order (here $M = 2$). See Lynch and Huang (1994) for details.

We can see the DFL initiated forecasts start at later times than the analysis time, which means that there is no forecast between the analysis time and the forecast start time (here 1 h for the Dolph filter, 1.4 h for the QS filter). On the other hand, both N and R have similar values during the later forecasts. The advantages of DFL include: no need of backward integration; all model parameters are identical in DFL and in the forecast; for HIRLAM it makes the filtering of surface fields possible. As we mentioned earlier, once an efficient one-sided filter, producing a filtered state at analysis time, is found, the DFL scheme can also be used as a true initialization scheme.

Although in the implemented version 5.0.3 a default combination of initialization parameter values is selected for various filtering methods, it is not necessarily an optimal solution for different purposes. On the contrary, it is highly likely that better effects can be achieved with selection of non-default tunable values. But finding the best combina-

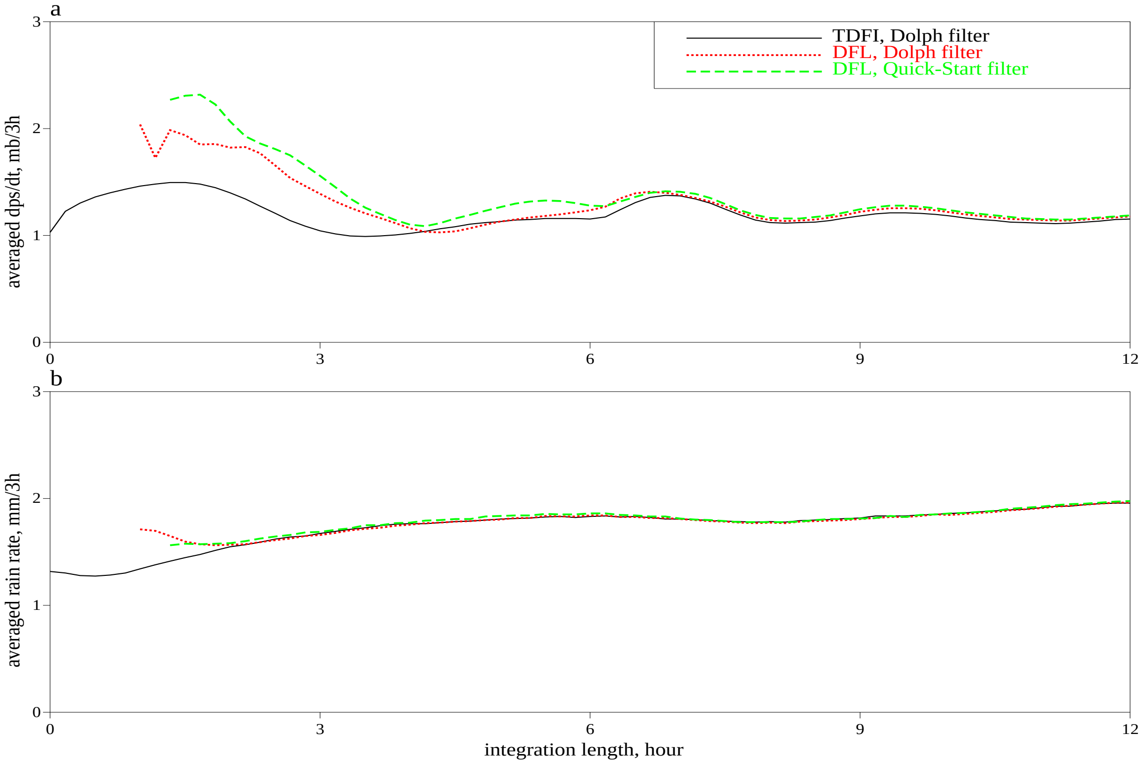

Figure 12: The time series of (a) N in hPa/3h and (b) R mm/day. The forecasts are initiated by TDFI (solid line), DFL-Dolph (dotted line) and DFL-QS (dashed line), respectively.

tion can only be achieved through extensive data assimilation testing. The new interface provides flexibility for users to explore optimal combinations which best fit their focus.

4.3 Incremental digital filtering initialization

With HIRLAM 5.0.3, the initialization procedure can also be applied in an incremental formulation, as discussed in Section 2. Data assimilation experiments have been performed using IDFI (`IDFI=.TRUE.`). Only some preliminary results are presented here. A more extensive report on incremental initialization will be presented in a forthcoming scientific report.

Figure 13 shows the corresponding plots for time series of N and R, similar to those shown in Figure 6a and Figure 7a, but for forecasts using full and incremental forms of DDFI and TDFI. In Figure 14, the corresponding mean 12-hour forecast time series are presented, averaged from 40 cycles covering the whole period. As expected, the forecasts initiated with incremental schemes are shown to have slightly higher initial surface pressure tendencies, which may be associated with the fact that the formulation does not touch the shorter waves contained in the first-guess field, whereas in a full DFI the latter are affected during filtering, to a varying degree. Overall the changes in the noise level is quite moderate. An examination of initialization increments for individual cycles also confirms that the incremental scheme indeed results in relatively small initialization increments compared to the full DFI schemes. The main visible benefits of the incremental approach, on the other hand, are very clearly demonstrated in the time series of the mean precipitation rate, where the severe initial damping of the moisture quantities in full DFI schemes is greatly alleviated in forecasts initiated by both of the incremental DFI schemes.

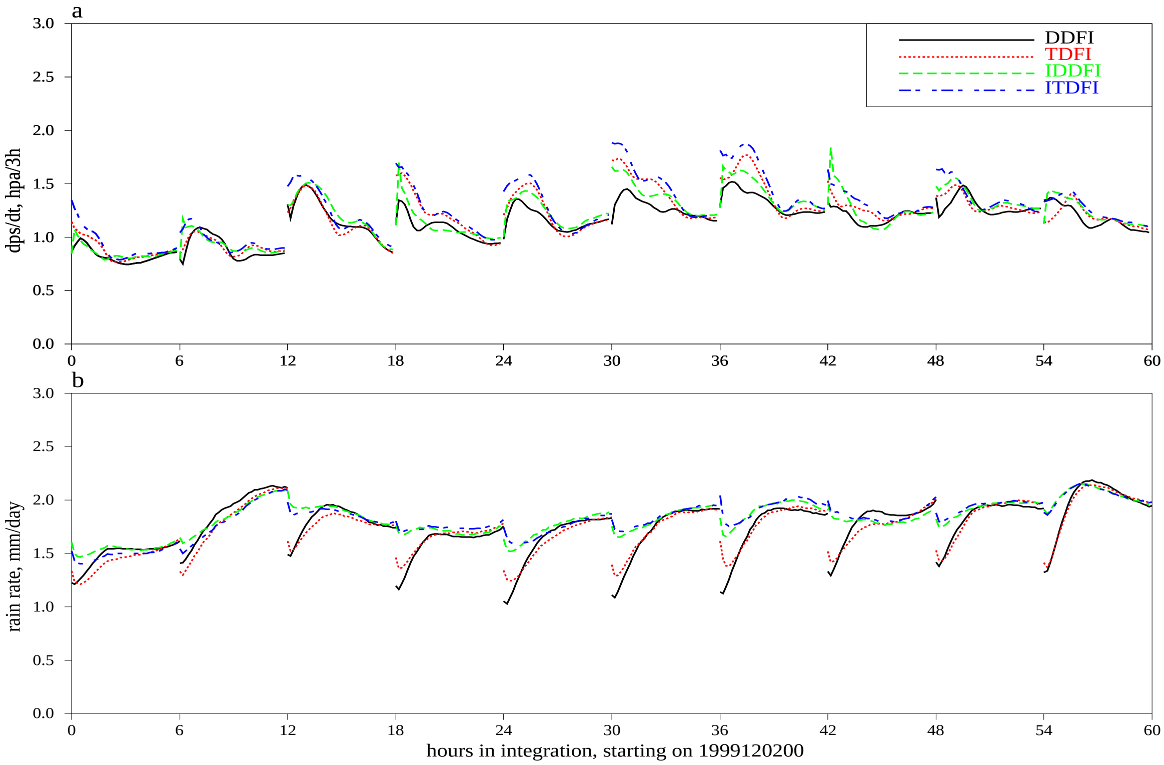

Figure 13: The time series of (a) N in hPa/3h and (b) R in mm/day for 10 consecutive 6 hour forecasts started on December 2, 1999 at 00 UTC.

5 Conclusions

In this work, we recoded the HIRLAM initialization interface which enhanced flexibility in the choice of initialization schemes. The new code eliminates the need of model state input and output during the initialization step. It also makes the interfacing structure between the main program and initialization subroutine simpler and more logical. For example, the choice of various initialization options and parameters has been made easier through the introduction of a special namelist for initialization.

In the modified initialization interface, various initialization schemes and options, many of which were tested in earlier HIRLAM research work, have been put back into the system. In particular, the incremental digital filtering initialization has been re-introduced as an option. Researchers who are interested in initialization problem should find it easier now to use the new code to explore different initialization options. It is also expected

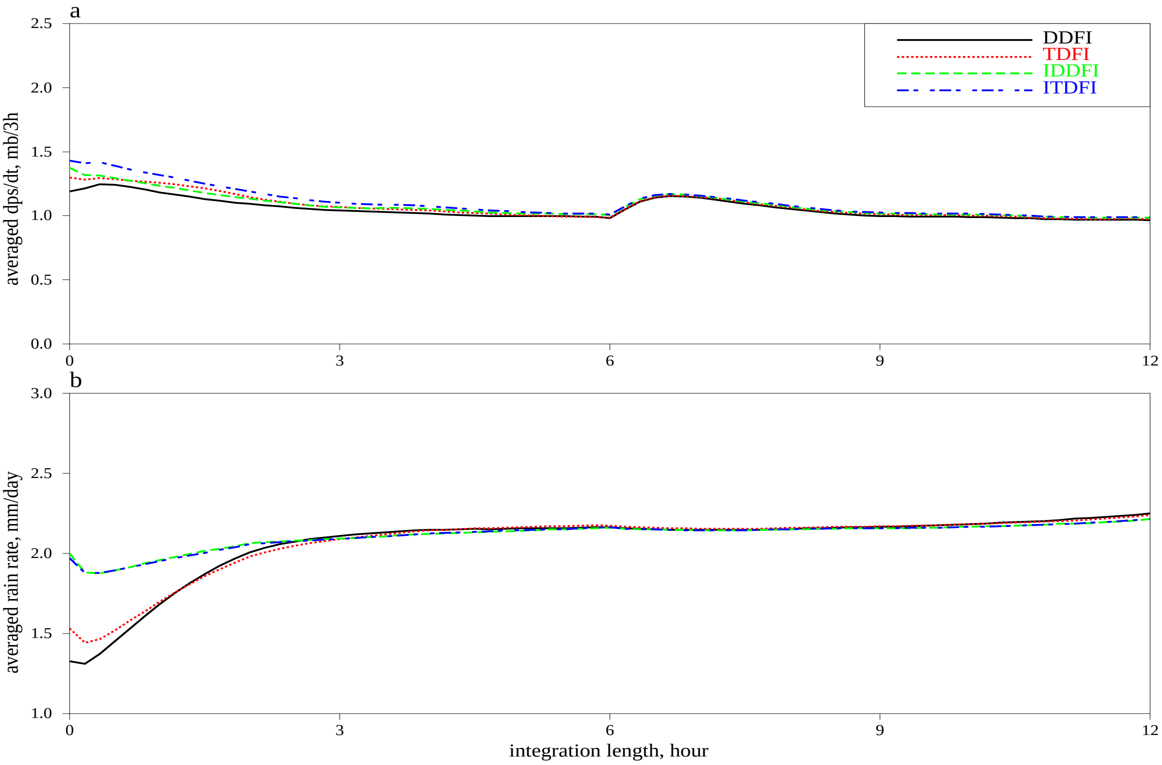

Figure 14: The time series of (a) N in hPa/3h and (b) R in mm/day, averaged from 40 forecasts cycles for the assimilation-forecast period during 1999120106 and 1999121100).

that the new code will make further improvement of the HIRLAM initialization procedure easier.

The validating data assimilation experiments for a 10-day period confirm that the new implementation of DFI can reproduce the results from the previous version (5.0.2). A set of parallel experiments using various initialization options has been carried out, partly for testing the new codes. Some description and discussions are made here to demonstrate the use of new codes in initialization applications. As an example, the report shows some results from parallel comparison of data assimilation runs examining the use of incremental DFI schemes, indicating that forecasts initiated with incremental DFI schemes improve significantly on spin-up aspects for precipitation, with only moderately increased initial noise levels. However, it has not been the intention in this work to examine in a thorough manner the different DFI options or to present optimal sets of tunable parameters for initialization. This work remains to be done by HIRLAM users in light of their own interests.

6 Acknowledgments

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7 List of symbols

$\overline{\mathbf{X}}^{DFI}$		Apply DFI on $\mathbf{X}$
$[\mathbf{X}]_{\pm n}^{A\ or\ D}$		Adiabatic (A) or Diabatic (D) model integration backward (-) or forward (+) in time from $\mathbf{X}$ up to step n
3DVAR		3-dimensional VARiational data assimilation
4DVAR		4-dimensional VARiational data assimilation
CWC		Cloud Water Content
DFI		Digital Filtering Initialization
	ADFI	Adiabatic DFI (Lynch and Huang, 1992)
	DDFI	Diabatic DFI (Huang and Lynch, 1993)
	FDFI	Full DFI, including ADFI, DDFI and TDFI
	IDFI	Incremental DFI (Lynch and Huang, 1994)
	TDFI	Twice-DFI (Lynch *et al.*, 1999)
DFL		Digital Filtering Launching (Lynch and Huang, 1994)
HIRLAM		HIgh Resolution Limited Area Modelling
I/O		Input/Output
N		The mean absolute surface pressure tendency hPa/3h
NNMI		Nonlinear Normal Mode Initialization
	INMI	Implicit Nonlinear Normal Mode Initialization
NWP		Numerical Weather Prediction
OI		Optimum Interpolation
R		Domain averaged precipitation rate in mm/h
TKE		Turbulent Kinetic Energy

References

Davies, H.C. 1976. A lateral boundary formulation for multi-level prediction models. *Quart. J. Roy. Meteor. Soc.*, **102**, 405–418.

Fillion, L., Mitchell, H.L., Richie, H. and Staniforth, A. 1995. The impact of a digial filter finalization technique in a global data assimilation system. *Tellus*, **47A**, 304–323.

Gauthier, P. and Thépaut, J.-N. 2001. Impact of the digital filter as a weak constraint in the pre-operational 4D-Var assimilation system of Météo-France. *Mon. Wea. Rev.*, Submitted.

Gustafsson, N. 1992. Use of a digital filter as weak constraint in variational data assimilation. *Pages 327–338 of: Proceedings of the ECMWF Workshop on Variational Assimilation, with special emphasis on three-dimensional aspects. Available from the European Centre for Medium Range Weather Forecasting, Shinfield Park, Reading, Berks. RG2 9AX, UK.*

Huang, X.-Y. 1991. *Diabatic digital filtering initialization of the HIRLAM model.* DM-Report 58, 23pp. University of Stockholm, Department of Meteorology/International Meteorological Institute in Stockholm, S-106 91 Stockholm, Sweden.

Huang, X.-Y. 1996. Initialization of cloud water content in a data assimilation system. *Mon. Wea. Rev.*, **124**, 478–486.

Huang, X.-Y. and Lynch, P. 1993. Diabatic digital filter initialization: Application to the HIRLAM model. *Mon. Wea. Rev.*, **121**, 589–603.

Huang, X.-Y. and Sundqvist, H. 1993. Initialization of cloud water content and cloud cover for numerical prediction models. *Mon. Wea. Rev.*, **121**, 2719–2726.

Huang, X.-Y. and Yang, X. 2001. Recoded initialization interface. *HIRLAM Newsletter*, **38**, 167–173. Available from SMHI, S–601 76 Norrköping, Sweden.

Kållberg, P. (Ed.). 1990. *HIRLAM forecast model level 1 documentation manual.* Available from SMHI, S-601 76 Norrköping, Sweden.

Källén, E. (Ed.). 1996. *HIRLAM documentation manual. System 2.5.* Available from SMHI, S-601 76 Norrköping, Sweden.

Lynch, P. 1997. The Dolph-Chebyshev window: a simple optimal filter. *Mon. Wea. Rev.*, **125**, 655–660.

Lynch, P. 2000. Boundary filters using half-sinc functions. *HIRLAM Newsletter*, **35**, 110–118. Available from SMHI, S–601 76 Norrköping, Sweden.

Lynch, P. and Huang, X.-Y. 1991. *Initialization of the HIRLAM model using a Digital Filter.* DM-Report 57,34pp. University of Stockholm, Department of Meteorology/International Meteorological Institute in Stockholm, S-106 91 Stockholm, Sweden.

Lynch, P. and Huang, X.-Y. 1992. Initialization of the HIRLAM model using a digital filter. *Mon. Wea. Rev.*, **120**, 1019–1034.

Lynch, P. and Huang, X.-Y. 1994. Diabatic initialization using recursive filters. *Tellus*, **46A**, 583–597.

Lynch, P., Giard, D. and Ivanovici, V. 1997. Improving the efficiency of a digital filtering scheme. *Mon. Wea. Rev.*, **125**, 1976–1982.

Lynch, P., McGrath, R. and McDonald, A. 1999. *Digital filter initialization for HIRLAM.* HIRLAM Tech. Rep. 42, 22pp. Available from Met Éireann, Glasnevin Hill, Dublin 9, Ireland.

Machenhauer, B. 1977. On the dynamics of gravity oscillations in a shallow water model with applications to normal mode initialization. *Beitr. Phys. Atmos.*, **50**, 253–271.

McGrath, R. and Lynch, P. 1999. Impact of the lateral boundaries on the digital filter initialization scheme in HIRLAM. *HIRLAM Newsletter*, **34**, 57–60. Available from Met Éireann, Glasnevin Hill, Dublin 9, Ireland.

Polavarapu, S., Tanguay, M. and Fillion, L. 2000. Four-dimensional variational data assimilation with digital filter initialization. *Mon. Wea. Rev.*, **128**, 2491–2510.

Smith, S.W. 1999. *The scientist and engineer's guide to digital signal processing. Second Edition.* California Technical Publishing. 650pp.

Temperton, C. 1988. Implicit normal model initialization. *Mon. Wea. Rev.*, **116**, 1013–1031.

List of HIRLAM Technical Reports.

1. Gustafsson, N., Järvenoja, S., Kållberg, P. and Nielsen, N.W. (1986). Baseline experiments with a high resolution limited area model. Copenhagen, November 1986.

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8. HIRLAM Workshop on Mesoscale Modelling—Copenhagen, Denmark, 3-5 September 1990. December 1990.

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11. Huang, X.-Y., Cederskov, A. and Källén, E. (1993). A Comparison between Digital Filtering Initialization and Nonlinear Normal Mode Initialization in a Data Assimilation System. June 1993.

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