

Assimilation of IASI Data into the Regional NWP Model COSMO-EU: Status and Perspectives

Marc Schwaerz and Reinhold Hess

Deutscher Wetterdienst, Offenbach, Germany

Abstract

This work will present a first setup of the assimilation of IASI data into the regional NWP model COSMO-EU of "Deutscher Wetterdienst" (DWD). The assimilation scheme is a combination of Nudging with a 1D-VAR step (utilizing the EUMETSAT NWP SAF 1D-VAR software package). The combination of these procedures should test and demonstrate the possible usage of observations which are connected to the model variables by non-linear operators (as IASI data are). The work will present the initial setup of the assimilation scheme for IASI data. The implementation of the bias correction scheme after Harris and Kelly (2001) is described, using two different layer thicknesses of the model, the total column water vapor, and the surface temperature as bias predictors. As forward model for the 1D-VAR step the new version of RTTOV (RTTOV-9-beta) was implemented. The work will show first impact experiments based on the described scheme focused on the used channel sets. Finally, the optimization of the used nudging weights and the inclusion of cloudy and partly cloudy measurements, respectively, the next steps planned, are addressed.

Introduction

The Infrared Atmospheric Sounding Interferometer (IASI), which is part of the core payload of the METOP series of polar orbiting operational meteorological satellites which are operated by EUMETSAT (first satellite METOP-A was successfully launched on Oct. 19, 2006), is providing a further significant improvement of vertical resolution of the state of temperature and humidity compared to existing operational satellites via a very high spectral resolution. Furthermore it will deliver ozone profiles and surface skin temperature as well as cloud parameters and column amounts of nitrous oxide (N₂O), methane (CH₄), and carbon monoxide (CO).

IASI is a Michelson type Fourier transform interferometer, which samples a part of the infrared (IR) spectrum contiguously from 645 cm⁻¹ to 2760 cm⁻¹ (15.5 μm – 3.6 μm) with an unapodized spectral resolution of about 0.5 cm⁻¹. The acquisition of information about the surface and the atmosphere is based on detection, recording, and analysis of electromagnetic (EM) radiation emitted by the earth mainly in the infrared range of the EM spectrum. The characteristics of the modification of radiation when passing through the atmosphere depends on the amount and properties of the atmospheric constituents. Therefore the information about the state of the atmosphere stored in the detected radiation may be retrieved from the measured spectrum.

Temperature profiles are obtained from observations in the absorption bands of carbon dioxide (CO₂), which is a relatively abundant trace gas of known and uniform distribution. Other atmospheric constituents absorbing in the thermal IR are H₂O (water vapor and temperature sounding), ozone (O₃ – ozone profiling), N₂O, CH₄, and CO (trace gas column amounts). The atmospheric window regions, where attenuation is minimal, are used to obtain surface and cloud properties. With the opportunity of

a very high spectral resolution at several wavelengths, the possibility of observing different layers can be established by taking into account that radiances measured in the center of an absorption band arise from the upper atmospheric layers, while measurements at the wings of a band will sense deeper into the atmosphere.

One of the primary objectives of the IASI instrument, according to the IASI science plan (*Camy-Peyret and Eyre (1998)*), is the improvement of the vertical resolution of temperature and water vapor profiles to about 1 km in the middle and lower troposphere as well as improving the retrieval accuracy to within 1 K in temperature and $\sim 10\%$ in humidity. This level of performance is greatly assisting numerical weather prediction (NWP) in delivering accurate and frequent temperature and humidity profiles for operational and research needs shown at the first IASI Conference (c. f. *Phulpin and Klaes (2007)*) and it will supply more accurate quantifications of climate variability, particularly contributing to our knowledge of the climate of the upper troposphere.

The main goal of this report is the presentation of the first setup of the assimilation of IASI data into the regional NWP model COSMO-EU of the German Weather Service (DWD). We are describing the preparation and preprocessing of the data for utilizing it in the COSMO-EU model. Then a short description of the optimal fusion of the data with the model output, i. e., the used forward model, the minimization scheme, as well as the two-step assimilation framework – *IDVar* followed by nudging is given. The next section provides some very preliminary comparison results between the routine-run of COSMO-EU at DWD and an experiment where IASI data were assimilated. Finally, a short outline of the planned activities for a first tuning campaign of the described setup is provided.

Data Preparation and Preprocessing

In comparison to conventional infrared (IR) and microwave (MW) nadir looking sounder data like data from HIRS (20 channels) or AMSU-A/B (20 channels) the full IASI spectrum contains 8461 channels. Hence, it is clear that the current data preparation and preprocessing setup of the COSMO-EU satellite data assimilation system has to be changed essentially. Here we have to attach importance to an intelligent design of the processing steps as well as on an effective and robust channel selection scheme.

Data Preparation and Preprocessing outside COSMO-EU

Data preparation and preprocessing outside the COSMO-EU model contains the following steps:

- The data conversion from the BUFR format to netCDF format. This is provided by an external program since DWD decided to transfer the handling of observational data from the BUFR format to netCDF to get the possibility to out-source work resulting from e. g., changes in the BUFR format.
- A rough quality control step where the different IASI quality flags provided by the IASI level 1c data are used in a first implementation.
- The selection of observed IASI data according to the COSMO-EU region. This selection implies that the assimilation of data from the IASI instrument or more general of data from the METOP satellite can only be used in the 0:00 UTC and 12:00 UTC assimilation run (except some observations near the North Pole which lie inside the COSMO-EU domain). This is due to the fact that METOP is in a sun-synchronous orbit and crosses the equator at 9:30 local time at the ascending node.
- The deselection of IASI measurements over land using the land-sea mask of the COSMO-EU model to avoid the not yet solved problem of land surface emissivities.

- The selection of an optimal subset of channels which is sufficiently sensitive to the retrieved variables.

The last point is crucial due to the fact that the conversion of the radiances (distributed by EUMETSAT) to brightness temperatures has a high computational cost. At this initial setup the implementation of this last point was performed by selecting only those channels which are distributed via the GTS system too. The selected subset was obtained by applying the information content theory (c. f. *Rodgers (2000)*) to different spectral regions to get a well distributed subset of channels for each atmospheric constituent (e. g., CO₂, H₂O) and for all atmospheric variables of interest (e. g., temperature, water vapor, or surface skin temperature), respectively (*Collard and Matricardi (2005)*).

Preprocessing inside COSMO-EU

Since the following preprocessing steps will need information from the state of the model itself, i. e. a first guess of the atmospheric state obtained from the model is needed, these steps have to be integrated directly into the COSMO code:

- The setup of a cloud detection scheme: Since currently no IR data are assimilated at DWD a new cloud detection scheme for IR data has to be implemented. As a first step the IASI Level 2 cloud flags are used. Since they are currently delivered only for each second IFOV of the overall 120 IFOV's of one IASI scan line only each second measurement can be qualified. Of course this reduces the number of selectable IFOV's per EFOV by two. Hence, as a second step currently the cloud detection algorithm of *McNally and Watts (2003)* has been integrated into the COSMO-EU code. It is provided as a stand alone package by NWP-SAF *Collard (2006)*. This scheme has been implemented but is currently not used. Initially, only cloud-free pixels will be used. As a second step, the usage of all channels which are sensitive at heights above the cloud top is planned.
- The implementation of a new, more general bias correction scheme: The implementation of the bias correction scheme for ATOVS data is based on the scheme of *Eyre (1992)* and uses AMSU-A channel 4 and 9 as predictors. We decided to implement the bias correction scheme based on *Harris and Kelly (2001)* which uses predefined model parameter as bias predictors. Hence, the calculation of the bias correction coefficient and the bias correction itself were generalized to an arbitrary number of predictors. Figure 1 shows a first preliminary plot of bias corrected radiances. The first guess statistics for the bias prediction coefficients used to correct the bias for the radiances shown in this plot were quite small. We have chosen a period between January 10 2008 and February 1 2008 to calculate them. For the computation only those measurements were taken into account which were specified as cloud free by the IASI Level 2 cloud flags. The usage of the IASI Level 2 cloud flags reduces the number of iterations in obtaining meaningful bias correction coefficients. Unfortunately, the chosen period was quite cloudy over Europe (at least for infrared instruments) one can see from the plot that the bias correction coefficients are usable in this first preliminary setup except for some channels (dark) which could not be corrected well.
- The implementation of a quality control scheme which exploit the difference in brightness temperature between the bias-corrected measurements and the first guess. This has to be tuned to get an optimal state for the finally resulting analysis field. Due to the fact that it is not clear how good the IASI Level 2 cloud flags are and how good the bias correction is working the maximal difference value is currently set to the very conservative value of 5 K difference in brightness temperature.

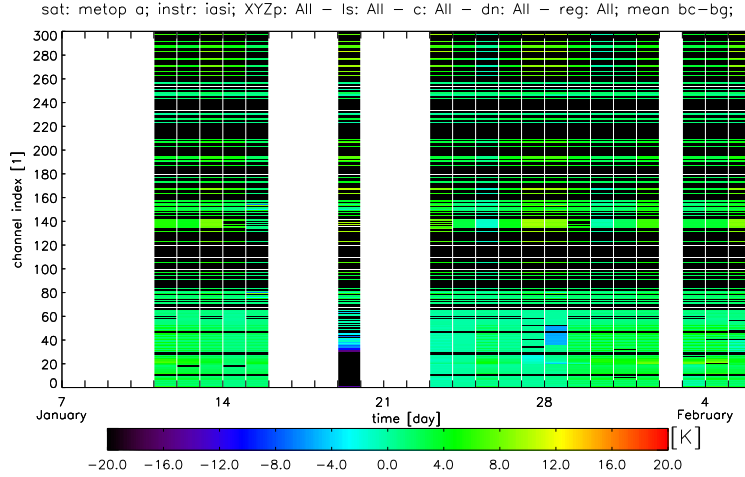


Figure 1: Observed minus bias corrected measurements for about one month of IASI data and all monitored channels. One can see that for those channels currently used in the minimization process (lower third of the channels) the bias correction works more or less well whereas for the humidity and surface channels this can not be said. (Hence, the bias correction coefficients have to be updated.)

Nudging and 1DVar – ”NudgeVar”

Nudging

In general, Nudging or Newtonian relaxation denotes the adjustment of the prognostic variables of a model towards prescribed values within a given time window. This technique can be found in detail in e. g., *Anthes (1974)*, *Davies and Turner (1977)*, or *Stauffer and Seaman (1990)*. The adaption of the nudging technique to the COSMO model is described in *Schraff and Hess (2002)*.

Nudging means the introduction of a relaxation term into the model equations, i. e., the time dependency of the prognostic variables are given by:

$$\frac{\partial}{\partial t} \Psi(\mathbf{x}, t) = F(\Psi, \mathbf{x}, t) + G_{\Psi} \sum_{k(obs)} W_k(\mathbf{x}, t) [\Psi_k^{obs} - \Psi(\mathbf{x}_k, t)], \quad (1)$$

where F denotes the dynamics and physical parameterization of the model, Ψ_k^{obs} the value of the k^{th} observation influencing the grid point \mathbf{x} at time t , and \mathbf{x}_k the location of the observation. G_{Ψ} is a constant which is called the nudging coefficient, and W_k is an observation dependent weight which in almost all cases takes values between 0 and 1. The difference $[\Psi_k^{obs} - \Psi(\mathbf{x}_k, t)]$ between observed and model value is called observation increment. The complete additional term is the so called nudging term determining the analysis increment, i. e., the impact of the measurement on the model state.

A single observation in the nudging process is not used at the correct observation time only, but it is used at regular intervals with an exponentially increasing impact starting from 1.5 h before observation time and exponentially decreasing impact until 0.5 h after the observation time for satellite data (c. f. Figure 2). Thus, equation 1, the so called *nudging equation* describes a continuous adaption of the state of the model towards the observations during the forward integration of the model which is illustrated in Figure 3).

1DVar

Since there is no possibility to directly use the radiance measurements of satellites in the nudging process a 1DVar assimilation step has to be performed prior to it to transform the radiances from measurement space into model space.

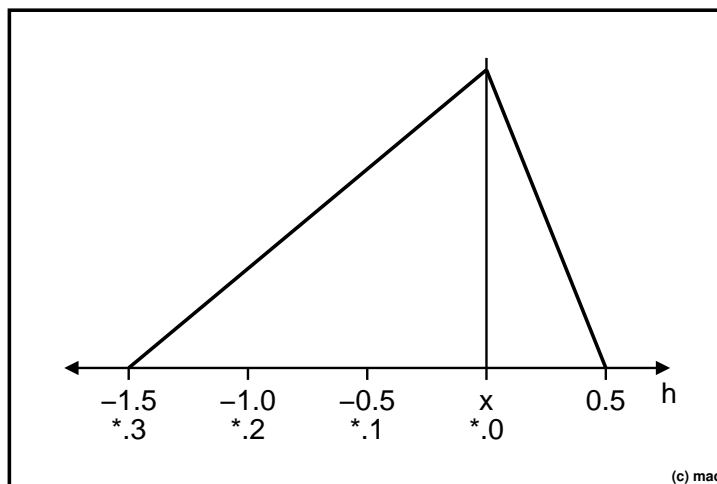


Figure 2: A single satellite observation is used at regular intervals with an exponentially increasing impact starting from 1.5 h before observation time and exponentially decreasing impact until 0.5 h after the observation time. Note that this means that during a 3 hours "NudgeVar" we have to account for observations which occur at most half an hour before the start of the assimilation and at most one and a half hour after it.

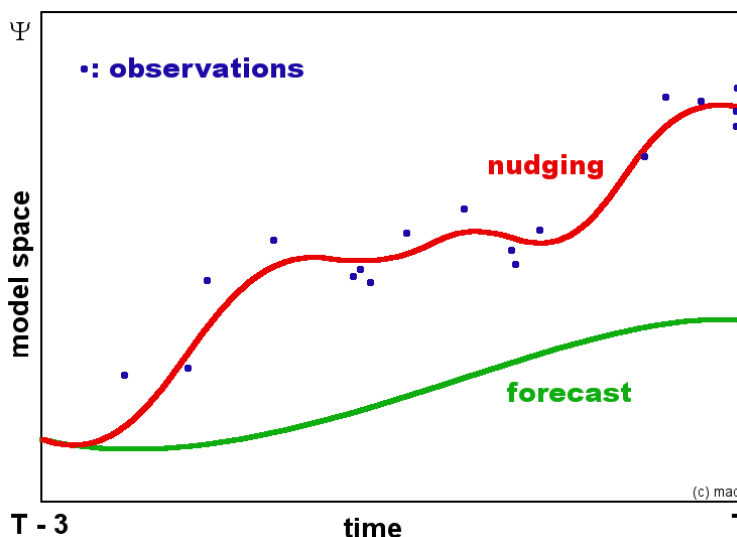


Figure 3: The Figure sketches the influence of the observations on a free forecast process. It illustrates the influence of the nudging term which forces the model trajectory towards the observations.

The *IDVar* scheme is implemented in the following way:

- As forward model the new version of RTTOV, RTTOV-9.0 beta (c. f. *Saunders and Matricardi (2007)*), was implemented and will be replaced by the final version after it is released.
- The background errors are obtained by utilizing the NMC-method (c. f. *Parish and Derber (1992)*) and were calculated for the COSMO consortium by F. Di Giuseppe. This method derives the background error covariance matrices by analyzing the analysis minus forecast differences for different forecast times but for the same point in time.
- As mentioned above, the bias correction is applied after *Harris and Kelly (2001)* using total column water vapor, surface skin temperature (SST), and two different kinds of layer thicknesses (1000 hPa to 300 hPa and 200 hPa to 50 hPa) as predictors.

- Since the radiative transfer calculation, i. e. RTTOV needs a meaningful state above the top of COSMO-EU currently IFS/ERA-40 climatological profiles (c. f. *Uppala et al. (2005)*) are appended. In the next few months it is planned to replace this scheme by using ECMWF analysis fields with a meaningful transition between these two models.
- It has to be mentioned that in a first step satellite measurements will only be used if their ground pixels are over sea and if the cloud detection has flagged them as cloud free.
- The minimization scheme utilized here is based on the M1QN3 algorithm (c. f. *Gilbert and Lemarechal (1989)*) as supplied by the NWP-SAF.

First preliminary experiment

The assimilation setup described above is currently tested for the period between January 10 2008 and February 10 2008 which has not been finished until now. Hence, only preliminary results can be shown here.

In order to show that the implementation works and that changes in the assimilation scheme are showing an – at least weak – impact in the forecast a one day case study from this experiment was extracted.

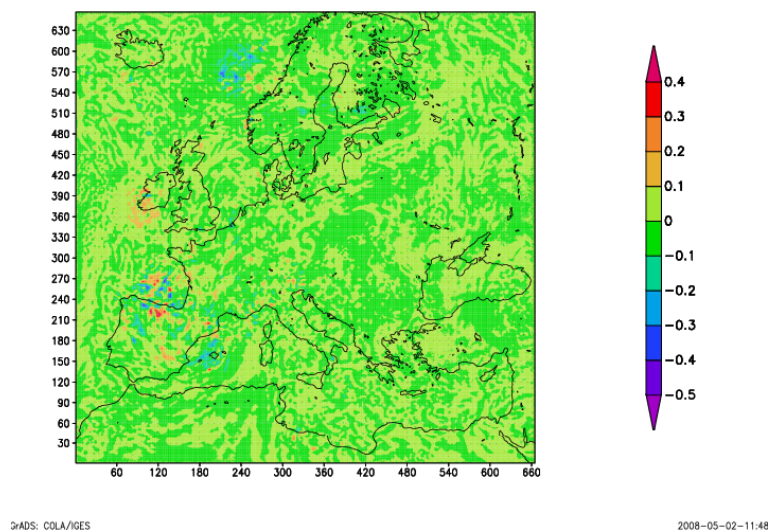


Figure 4: Analysis difference of 500 hPa temperature of the routine-run of COSMO-EU at DWD and the experiment where the IASI data were assimilated, after one day of assimilating IASI data, i. e. for January 12 2008.

Figure 4 shows the analysis difference in 500 hPa temperature of the routine-run of COSMO-EU at DWD and the experiment where the IASI data were assimilated after one day of assimilating IASI data, i. e. for January 12 2008. I have chosen this day for presenting the differences between routine and experiment since it gives us the opportunity to see the impact of the of the data on the forecasts without too much difference in the starting analysis fields. Those are still correlated since the assimilation of IASI data started a day ago only. Due to the fact that the period around January 10 was quite cloudy there were not many regions where IASI data were assimilated – only in the Bay of Biscay and in the West of Norway and Ireland.

The strong impact over the Iberian peninsula is not resulting from the assimilation of measurements over land but of the model since the assimilation window was 3 hours in this case. The other larger differences (orange and light blue spots) over land can also be explained by a drifting of the assimilated information via the model trajectory since the assimilation of IASI data already has started 24 hours ago, as mentioned above.

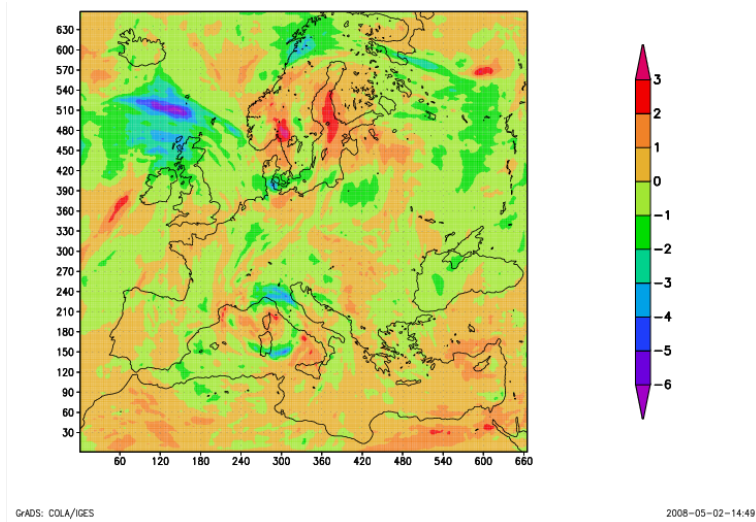


Figure 5: Difference between Analysis and 24 h forecast 500 hPa temperature of the routine-run of COSMO-EU at DWD.

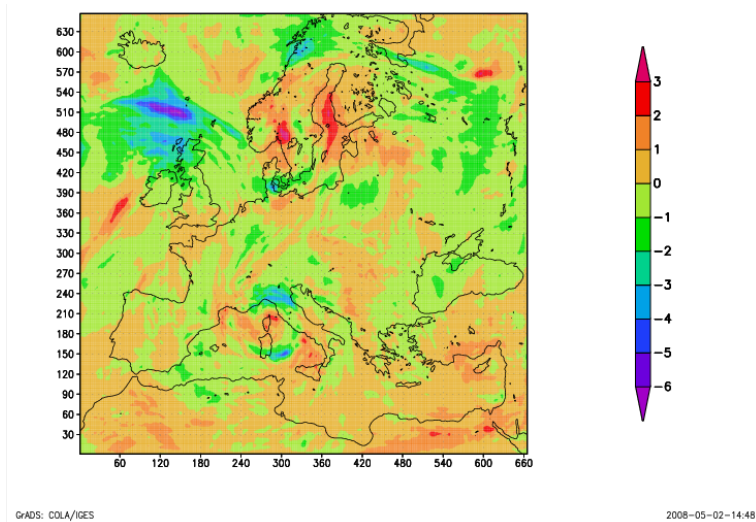


Figure 6: Difference between Analysis and 24 h forecast 500 hPa temperature of the experiment where the IASI data were assimilated.

Figure 5 and 6 are showing the forecast minus analysis differences between the routine-run (Figure 5) and the experiment (Figure 6). This first view does not allow us to figure out the differences between the two forecasts although a more closer view (c. f. Figure 7) is showing them. Figure 7 shows the differences between the 24 h forecast started from the experiment, i. e. the analysis where the IASI data was assimilated and the forecast started from the analysis field obtained by the routine-run. We can see that there are point-wise differences west of the British Islands and that there is a wide area of forecast differences at the South-western Alps and the France and Corsica and Sardinia. But due to the fact that currently there are only three forecast runs ready there is no possibility to check whether the impact of the IASI data on the forecast quality is positive or negative at this first preliminary setup.

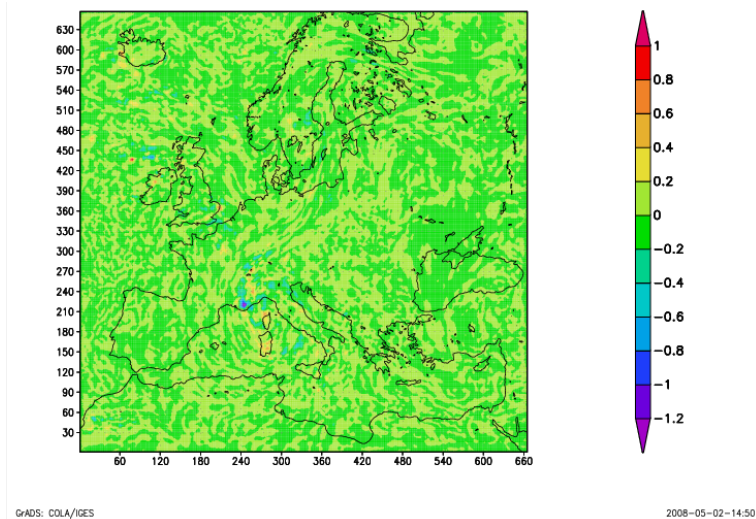


Figure 7: 24 h forecast differences of 500 hPa temperature of the routine-run of COSMO-EU at DWD and the experiment where the IASI data were assimilated.

Summary and Outlook

Summarizing it can be said that the technical implementation of the *IDVar*/nudging – the so called "NudgeVar" – scheme for the assimilation of IASI data within the COSMO model has been finished in its first setup. The following implementation steps have been performed until now:

- The data preparation and preprocessing outside the COSMO-EU model which contains the steps of data conversion from the BUFR format to netCDF format, the selection of the observed IASI data according to the COSMO-EU region, the deselection of IASI measurements which lie over land, as well as the selection of an optimal subset of channels which is sufficiently sensitive to the retrieved variables.
- The preprocessing inside COSMO-EU which contains the implementation of a cloud detection scheme (preliminary until now via the usage of the IASI Level 2 cloud flags), the implementation of a new, more general bias correction scheme, and the implementation of a quality control scheme which exploit the difference in brightness temperature between the bias-corrected measurements and the first guess.
- The generalization of the COSMO code to handle more than one instrument-set per satellite, which has been implemented partly, but has to be finished as a next step.
- The upgrade of RTTOV – from version 7 to the new version RTTOV-9 beta.

Currently a first test of this preliminary implementation scheme is in progress.

The remaining steps to declare the implementation of the usage of IASI data within the COSMO-EU model as complete (in its first setup) are the usage of the cloud detection algorithm of *McNally and Watts (2003)* (it has been implemented but is not used until now) and one or two further iterations in the determination of the bias correction coefficients.

As next steps the tuning of this initial setup of the currently described assimilation scheme for the regional model COSMO-EU for IASI measurements is planned:

- The implementation of AAPP to get a more enhanced preprocessing (due to the fact that measurement information from other instruments on board of METOP scanning the same or at least

almost the same region on surface is taken into account too by AAPP) and a good cooperation of the different instruments on board of the METOP satellite during the assimilation.

- A tuning of the error model to get an optimal final state estimate which then can be nudged into the model.
- An optimal setup for the profiles added at above model top of COSMO-EU as well as an smooth transition between them and the COSMO-EU has to be found to minimize the impact of inconsistent stratospheric (and mesospheric) states on the troposphere.
- The selection of an optimal subset of channels of the IASI spectrum combining a possible seasonal dependency of the channel subset with a slightly modified selection procedure compared to that described above (c. f. *Collard and Matricardi (2005)*) has to be performed.
- In addition, a redefinition of the optimal nudging weights as well as of the used background covariance matrix should be investigated.

As mid- and long-term perspectives the comparison of the impact on COSMO-EU forecasts of the IASI Level2 Product with the *IDVar* scheme described above is planned. In addition, the inclusion of cloudy observations is intended and the applicability of IASI measurements over land will be tested.

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