Proceedings for the 2018 EUMETSAT Meteorological Satellite Conference, 17-21 September 2018, Tallinn, Estonia

INVESTIGATING THE ASSIMILATION OF MSG/SEVIRI WATER VAPOUR RADIANCE DATA TO EXTRACT WIND INFORMATION WITH AN ENSEMBLE KALMAN FILTER

Marc Pondrom, Christina Köpken-Watts, Andreas Rhodin

Deutscher Wetterdienst, Frankfurter Straße 135, 63067 Offenbach am Main, Deutschland

Abstract

The impact of geostationary clear sky water vapour radiances (CSRs) of the Spinning Enhanced Visible Infra-Red Instrument (SEVIRI) on board Meteosat 8 and 10 on specific humidity, temperature and wind analyses and forecasts of the operational global ensemble variational assimilation system of the German Weather Service (DWD) has been investigated. The study uses on the one hand a set of observing system experiments performed under idealised conditions with synthetic observations ("twin experiments"), and on the other hand impact experiments with real data. In both cases, the verification scores show that the assimilation of CSRs from the two water vapour (WV) channels at 6.25 and 7.35 µm improve the forecast skills for all three dynamic variables, especially in the high and middle troposphere and in the region covered by MSG 1 and 3. The different results obtained from the idealised experiments show that the improvement is due to the interaction between specific humidity, temperature and wind through the model dynamics and physics during the forecast step as well as through the improved spatial correlations and cross-correlations between variables of the updated background error covariance matrix derived from the ensemble.

INTRODUCTION

Water vapour radiances measured by satellite instruments not only contain information about the water vapour distribution in the atmosphere but also on the wind field through the displacement of the water vapour structures. This information can be exploited through the direct tracking of these movements, done e.g. in the derivation of so-called water vapour atmospheric motion vectors, but also in a data assimilation (DA) system. For 4Dvar, it has been shown that through the so-called "tracer effect" meaningful wind increments are derived from assimilating a sequence of water vapour radiances benefitting the forecast quality [Peubey and Mc Nally, 2009]. In how far such wind information through tracking can also be obtained in an ensemble assimilation system context has not been studied extensively. For the use of Level 2 products, [Liu *et al.*, 2009] have shown that the assimilation of Atmospheric Infrared Sounder (AIRS) specific humidity retrievals with a Local Ensemble Transform Kalman Filter (LETKF) improves both the humidity and wind analysis

The current study investigates this further, but using the clear-sky radiances from the geostationary MSG-1,3/SEVIRI instruments in the operational global hybrid variational and ensemble (EnVar and EnVar+LETKF) data assimilation system (DA) of DWD. To analyse the behaviour of and the results in the ensemble DA, the current study uses water vapour (WV) radiances both in idealized and real data experiment setup. The study focuses on WV radiances from the SEVIRI instruments Meteosat 8 and 10 as it is done in the context of a EUMETSAT fellowship program and as a

preparation for the use of radiances from the future MTG IRS instrument.
In section 2, we describe the operational ensemble DA system of DWD used in the study. Section 3 and section 4, respectively, present the results obtained from the idealised set of experiments and the studies involving real data. Finally, a summary and discussions are given in section 5.

OPERATIONAL ENSEMBLE DATA ASSIMILATION AT DWD

The technical framework for the investigation on MSG/SEVIRI CSR is the operational global ICON/EnVar numerical forecasting system (figure 1). ICON [Zängl *et al.*, 2015], operational since January 2015, is a non-hydrostatic model formulated on an icosahedral grid which runs currently at 13 km resolution with 90 vertical σ-z-levels (model top at 70 km / ~2.6 Pa). Higher resolution forecasts are provided at 6.5 km for a European domain using two-way nesting (ICON-EU, see Fig. 1, left panel). The global hybrid Ensemble Variational (EnVar) data assimilation, operational since January 2016, is based on a global Local Ensemble Transform Kalman Filter [Hunt *et al.*, 2007] running at lower resolution (40 km) with an ensemble size of 40 members. The cycling interval is 3h, providing the first guess for the LETKF and in addition the ensemble B-matrix with flow dependent background errors. This ensemble B-matrix is used in a weighted average with a climatological B-matrix in the coupled full resolution (13 km) deterministic 3DVar (Fig. 1, right panel). Since the ensemble size is not large enough to provide meaningful correlations at large distances, a localisation is used with length scales of 300 km horizontally and 0.3 to 0.8 scale heights in ln(p) (from surface to model top) in the vertical. The observation processing and quality control are performed only once in the EnVar context and used in the ensemble LETKF analysis. Global ensemble forecasts, the ICON-EPS (40 members based on the analysis ensemble), are operational since December 2017 and produce forecasts up to 120 h (00, 12 UTC) and additionally 3-hourly 24 h forecasts used as boundaries for the high-resolution regional ensemble (COSMO-EPS).

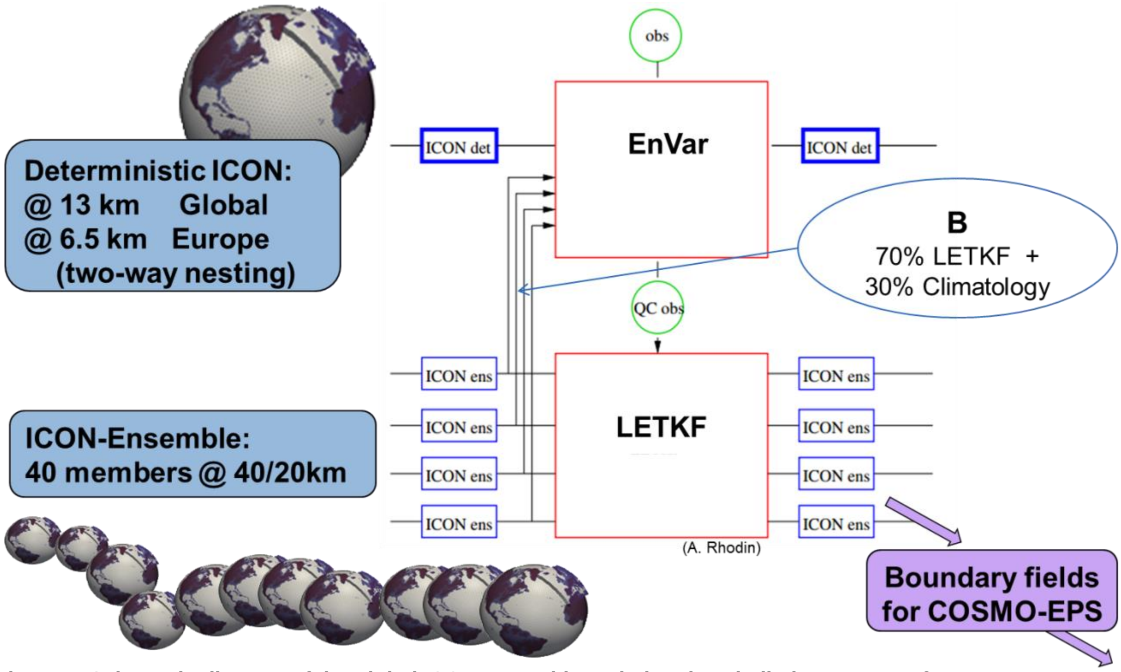

Figure 1: **Schematic diagram of the global ICON ensemble variational assimilation system of DWD.**

TWIN EXPERIMENTS

In this section, the impact of CSRs on the temperature, humidity and wind analysis and forecasts is investigated, based on assimilation experiments performed under idealised conditions with the global hybrid (LETKF+EnVar) system of DWD. After describing the setup of the framework for the idealised experiments, we present the main results and draw out the conclusions from the study.

Experimental design and verification methods

A setup of a framework for idealised experiments has been prepared wherein the integration of the model has been performed undisturbed, i.e. without an assimilation cycle. This model run is denoted as ‘nature run’ and regarded as the ‘truth’ in subsequent assimilation experiments. In this ‘nature run’, a trajectory of the atmospheric development fully consistent with the model formulation has been generated and all the observations – conventional and remote sensing (including the WV CSRs, AMSU-A, IASI radiances and atmospheric motion vectors (AMVs)) – have been processed. None of the data have been actively assimilated, but their model equivalents have been computed which have been used as synthetic observations in a subsequent set of experiments, the so called “twin experiments” (figure 2).

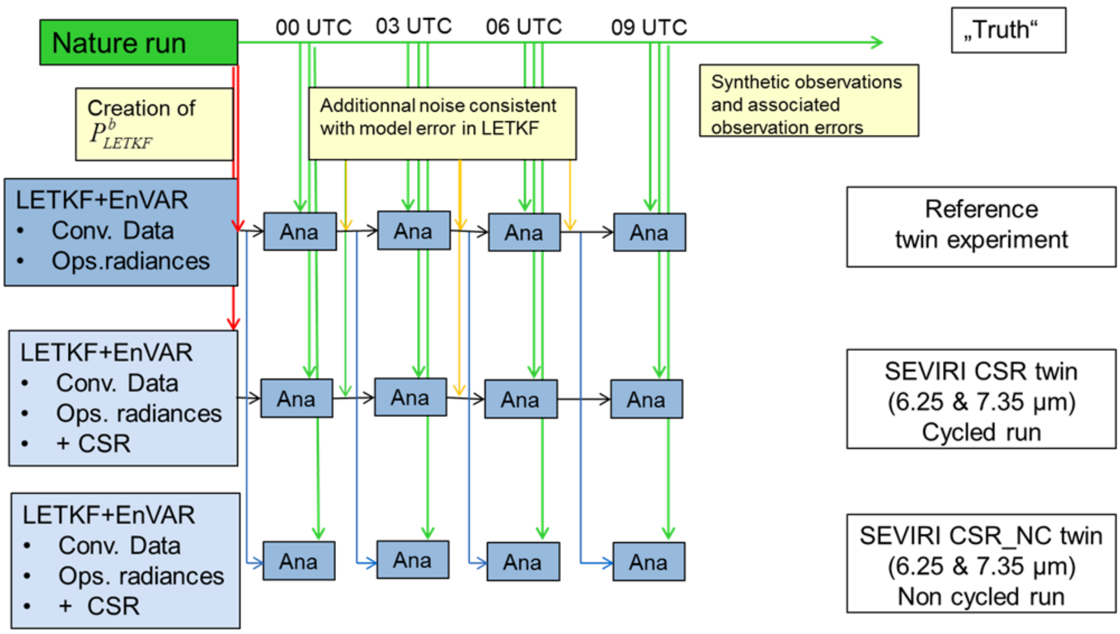

Figure 2: **Illustration of the reference and CSR twin experiment setups. AMVs (VIS, IR, clear-sky WV) are assimilated in all three LETKF+EnVAR experiments. The operational radiances in this context are AMSU-A and IASI temperature channels, but no WV radiances. In the first CSR twin experiment (cycled run) SEVIRI CSRs are assimilated in addition to all the observations used in the reference twin experiment. The CSR twin experiment non cycled run is performed under the same conditions as the CSR cycled run but the background is provided by the first guess from the twin experiment.**

The twin experiments (LETKF+ EnVar) have been performed using the synthetic observations from the nature run. Before using them in the assimilation system random noise consistent with the assumed observation error has been added. Furthermore, the short range model forecasts (deterministic trajectory and ensemble mean) providing the background in the assimilation experiment have also been disturbed with noise consistent with the assumed model error in the LETKF. In the reference twin experiment (also called ‘control’ in the following), conventional data, radio-occultations, AMVs and AMSU-A and IASI radiances are assimilated, but no WV radiances or channels. In the CSR twin experiment (cycled run), the synthetic WV CSR radiances from Meteosat 8 and 10 are assimilated additionally. In a subsequent non cycled run, SEVIRI CSRs have likewise been assimilated, but the background has been provided by the first guess from the reference twin experiment so that adjustments in temperature, humidity and wind fields and background error covariances caused by model dynamics and physics in response to the CSR data are excluded.

As the full EnVar+LETKF runs are very costly, especially in terms of available disk space, the reference and CSR twin experiments have been performed for two weeks (1-15 August 2017). Two weeks are deemed sufficient for this idealised setup where several noise effects present in real data experiments do not occur, especially forward model error and inconsistencies between the assumed/modelled background and observation error covariances and real model and observation errors. Also, the nature run is available for a direct verification of the results.

Analysis verification scores

We evaluate the performance of the CSR runs by comparing the accuracy of the analyses and forecasts from the reference and the CSR assimilation twin experiments in terms of RMSE w.r.t the nature run fields. These comparisons show the way the assimilation of water vapour channels from geostationary satellites improve the forecast skill in an ensemble variational context.

Figure 3 shows the time evolution of the global average RMSE of the analysis of temperature (left panels), humidity (middle panels) and wind (right panels) at 500 hPa (top panels) and 300 hPa (bottom panels). When WV CSRs are assimilated, the RMSE is significantly smaller not only for humidity, but also for the temperature and wind fields (CSR cycled run, yellow lines, versus control, red lines). In the non-cycled run (grey lines), however, the improvements for humidity are smaller, and more significantly, there are only marginal improvements visible for temperature and wind fields.

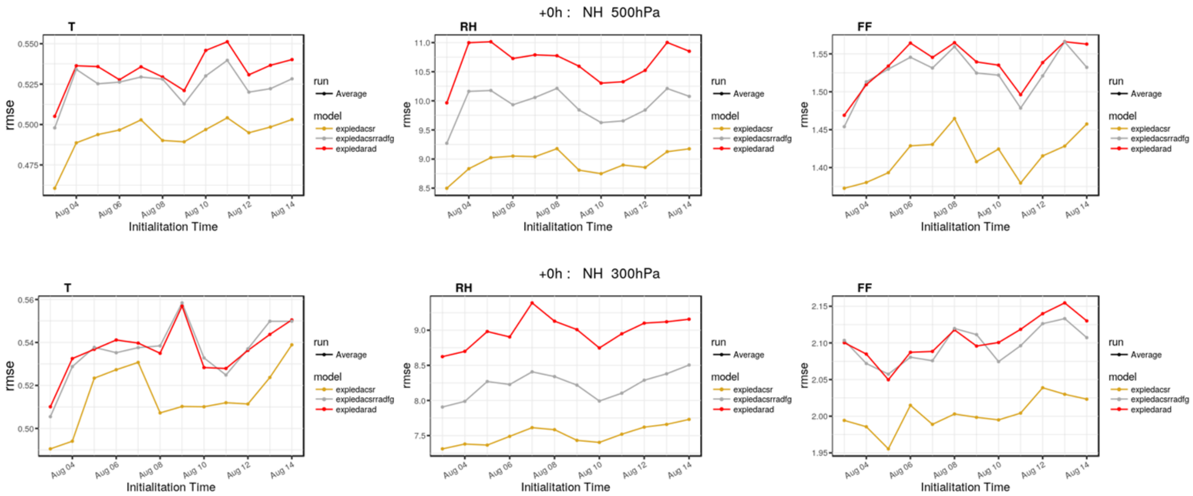

Figure 3: **Time evolution of the 500 hPa (top) and 300 hPa average RMSE for the analysis of the (left) temperature [K], (middle) relative humidity [%] and (right) wind speed [m/s]. The control run (red line), CSR cycled twin experiment run (yellow line) and CSR non cycled twin experiment runs (grey line) are shown. Here and in the following figures, the analysis verification is made against the analysis from the nature run.**

A summary of results for various variables at different height levels for several geographical areas is given in the so-called ‘score cards’ showing the relative difference of the RMSE for the analyses of the cycled and non-cycled CSR assimilation versus the control twin experiment (Fig. 4). The assimilation of SEVIRI water vapour channels in the EnVar+LETKF cycled run (left panel) leads to a significant improvement in the quality of the temperature, humidity and wind analysis in the Tropics and Mid Latitudes at all levels. But in the case of the CSR non cycled run, we mostly observe a reduction of the humidity analysis RMSE in the Tropics, the Southern and the Northern Mid Latitudes with only small improvements in temperature (lower troposphere in the tropics) and very small improvements in winds. The much larger positive impact observed in the case of the cycled CSR assimilation run for temperature, humidity and wind analysis, and especially the consistent and very large improvements also for temperature and wind, are due to the interaction of those dynamic variables through the model physics and dynamics during the forecast step. This results in better first guess background fields for all variables and in improved spatial correlations and cross-correlations between variables in the updated background error covariance matrix from the LETKF which in turn improve the analysis step. Current experiments address splitting these two effects.

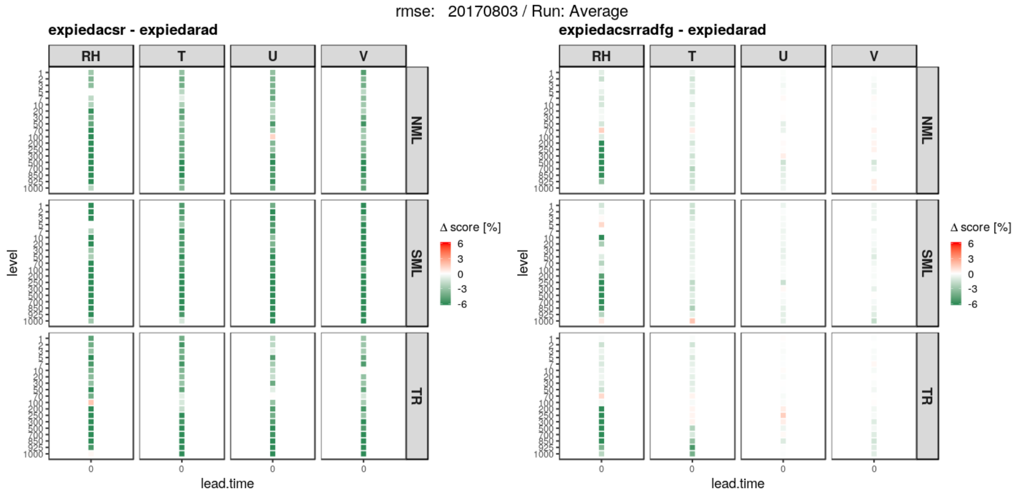

Figure 4: **'Score cards' showing the relative difference of the time averaged analysis RMSE between the CSR cycled run and the control run (left panel) and the CSR non cycled run and the control run (right panel). Results are displayed as height profiles for different variables in columns and for north and south mid latitudes (NML, SML) and tropical regions in the rows.**

Since the temperature and wind analysis show similar behaviour in the results, we focus on the humidity and zonal wind analysis for the following. A closer look at 500 hPa, the approximate altitude of the peak of SEVIRI weighting function at 7.35 µm (figure 5), shows that the improvement in the quality of humidity and wind analysis due to the assimilation of water vapour clear sky radiances is significant especially in the Tropics and Mid Latitudes with a reduction of up to ~40-50% of the specific humidity analysis RMSE (top left panel) and of up to ~10-15% of the zonal wind analysis RMSE (top right panel) in the case of the CSR cycled run. Whilst the reduction is most pronounced within the areas covered by MSG 1 and 3, significant improvements are spread throughout the tropics and mid-latitudes around the whole globe in the cycled run. In the non-cycled CSR assimilation run, the reduction of ~20-30% of specific humidity analysis RMSE from the CSR is limited only to the region covered by the MSG satellites, as expected. The neutral impact on the quality of the zonal wind analysis confirms the essential role played by the model integration and the improved spatial correlations and cross-correlations between variables of the updated background error covariance matrix.

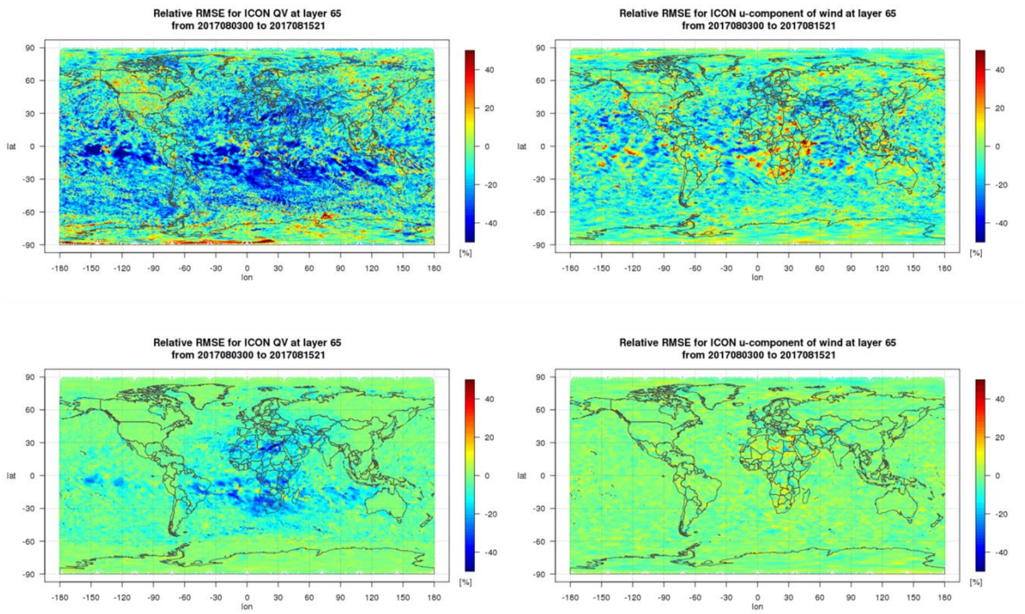

Figure 5: **500-hPa specific humidity (left) and zonal wind (right) analysis RMSE (versus nature run) displayed as relative RMSE difference between the CSR cycled run and the control runs (top), and between the CSR non cycled run and the control run (bottom).**

Observation verification scores

The twin experiments performed under idealized conditions (i.e. without model biases, outliers, etc.) have made it possible to evaluate directly in terms of analysis scores (versus the nature run) the ability of the combined variational and ensemble based data assimilation system to extract wind information from the movement of water vapour structures observed in time sequences of MSG. However, such a verification procedure cannot be used when performing assimilation experiments under real conditions and using real data, because the true state of the atmosphere is not known. To ease the comparison of the twin experiment verification results with the later real data experiments, another standard verification procedure is thus performed here, by using different types of observations (radiosondes, AMVs, etc.), and computing the statistics (mean, standard deviation, root mean square error, number of assimilated data) of the difference between observations (O) and first guess (model equivalent of the 3h forecast or background B). The resulting O-B departure statistics obtained in the case of the CSR twin experiment are then compared to those obtained for the reference twin experiment. Figure 6 shows a significant reduction of the O-B standard deviations due to the assimilation of SEVIRI CSR together with an increase in the number of data used for temperature (left panels) and humidity (middle panels) from radiosondes, as well as for AMV wind, and thus an improvement in the accuracy of the analysis and forecasts.

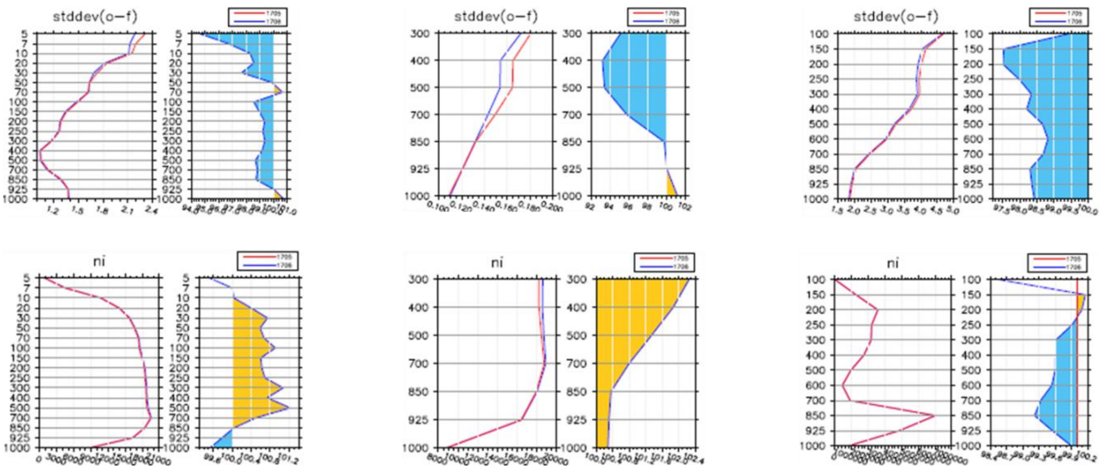

Figure 6: **Standard deviation of the first guess departures from temperature of radiosondes (top left panel), relative humidity of radiosondes (top middle panel), wind AMVs (top right panels), and corresponding number of assimilated observations (lower panels) for the CSR cycled run (blue line) and the control run (red line). On the right-hand side of each panel, the blue shaded area indicates a decrease of the standard deviation (or number of data used) with respect to the reference twin experiment and the yellow shaded area an increase.**

ASSIMILATION EXPERIMENTS WITH REAL WV RADIANCE DATA

In parallel, the system has been prepared for the assimilation of real data, including aspects like the setup of data monitoring and bias correction (using two layer thickness predictors at 900-300 hPa and 200-50 hPa in an online cycling bias correction update scheme). A subsequent experiment has been conducted for the four month period of November 2017 – February 2018 with the operational ICON/EnVar assimilation system of DWD. In this section, we briefly describe the setup of the SEVIRI WV assimilation experiments performed before presenting the main results obtained.

Setup of the observing system experiment

To evaluate the benefit of the inclusion of SEVIRI clear sky radiances into the ensemble variational assimilation system, two distinct 4 month experiments have been performed for 1st November 2017 – 28th February 2018. In the reference experiment, all operational data (conventional and satellite observations) have been assimilated, including water vapour channels from IASI, MHS and ATMS. In the real CSR data experiment, in addition to all the data assimilated in the reference experiment, both SEVIRI water vapour channels at 6.25 and 7.35 µm have been introduced in ICON/EnVar but without any update of the background error covariance matrix, i.e. the error correlations from LETKF are provided by the reference experiment. The CSR have been assimilated over sea and land, with satellite zenith angles up to 60° and an additional threshold of 3K on the 12 µm window channel departures to exclude potentially remaining cloud contamination.

Observation verification scores

The results are presented in terms of relative differences of O-B departure statistics (standard deviations in the upper panels and number of assimilated data in the lower panels) between CSR assimilation and reference experiments for a selection of other assimilated data types: MHS (channels 3, 4 and 5), temperature and humidity from radiosondes, as well as AMV winds. In the case of MHS (figure 7), the pronounced reduction of the standard deviation (left and middle panels of top row) coincides precisely with the region covered by METEOSAT 8 and 10 (upper right panel). The decrease in standard deviation while more MHS data are actively assimilated (number of used data, lower left and middle panels) confirms the benefit of real SEVIRI CSR data for improving the representation of humidity fields. Similar positive impact is visible in WV channel radiances from ATMS, IASI and passively monitored GMI, AMSR-2 data (not shown). The O-B departure statistics for the temperature (figure 8, left panels) and humidity (figure 8, middle panels) from radiosondes, as well as for the AMV winds (figure 8, right panels), show that the introduction of SEVIRI water vapour channels to ICON/EnVar has a positive impact on the quality of the temperature, humidity and wind analysis/forecasts in the troposphere. The improvement in this real data experiment is small (only a few tenths of %) compared to the results of observation departure statistics in the twin experiments (~7% for humidity radiosondes and ~3% for wind AMV) and forecast verification scores give similar results (not shown). The smaller impact can be explained by other humidity radiances (from IASI, MHS) already being assimilated, by the presence of biases in model and observations, data outliers, inaccuracies of the radiative transfer and in the modelled/assumed background and observation error covariance matrices. Also, in this EnVar experiment, the covariance matrices have not been updated, hence reducing the positive impact from the CSR information. Moreover, the applied quality control checks were more stringent for this implementation of real data leading to a reduction in the used data coverage. Nevertheless the experiment shows a clear benefit due to the assimilation of the WV CSR from METEOSAT 8 and 10. This led to the inclusion of SEVIRI water vapour channels at 6.25 and 7.35 µm in further pre-operational experiments and to their operational use in July 2018.

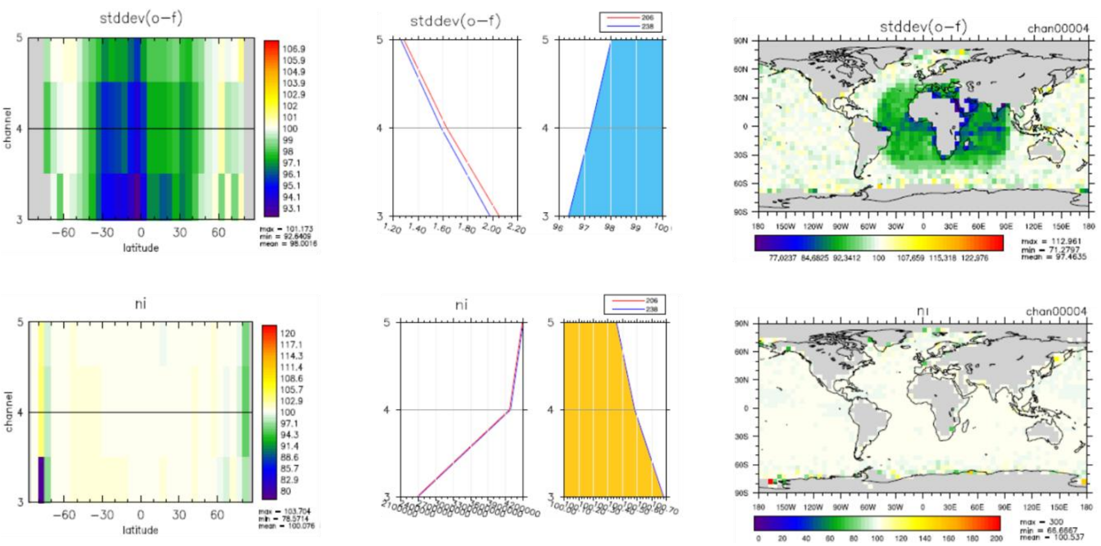

Figure 7: **Standard deviation of the first guess departures (top panels) from MHS brightness temperatures (channels 3, 4 and 5) and number of data assimilated (lower panels), represented on a zonal mean (top left panel), globally channel by channel (top middle panel) and horizontally for channel 4 (top right panel), and corresponding number of assimilated observations for the CSR cycled run (blue line) and the control run (red line). On the right-hand side of middle panels, the blue shaded area indicates a decrease of the standard deviation / number of data used with respect to the control run, and the yellow shaded area an increase. On the left and right panels, blue to green colours indicate a decrease, and yellow to red colours an increase.**

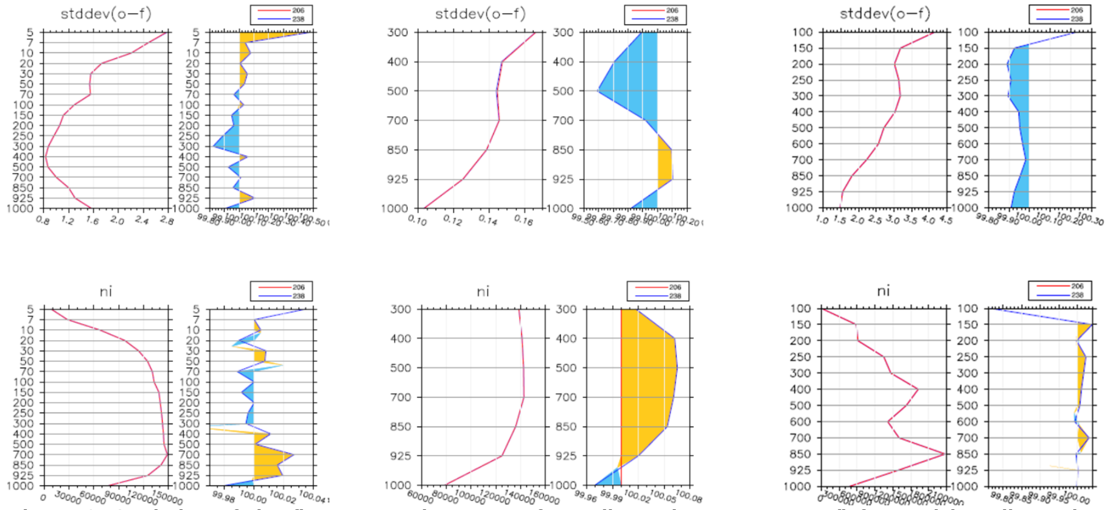

Figure 8: **Statistics of the first guess departures for radiosonde temperature (left panels), radiosonde relative humidity (middle panel) and AMVs winds (top right panels) for the CSR (blue line) and control (red line) runs.**

SUMMARY AND DISCUSSION

This study has demonstrated the added value of assimilating MSG/SEVIRI clear sky radiances in the ICON EnVar+LETKF global assimilation system of DWD by performing assimilation experiments under idealised conditions and with real data. The idealised experiment setup has shown that the improvement in the quality of the temperature, humidity and wind analysis/forecasts are due to the interactions between the variables through the model dynamics during the forecast step, but also through improved spatial correlations and cross-correlations in the background error covariance matrix used during the analysis step. An additional twin experiment is being performed to further investigate the relative importance of these two effects. Also, the height assignment and vertical localization in LETKF will be investigated in this context. Important additional benefit is expected from the introduction of a 4D-EnVar at DWD.
After the performance of clear sky radiance assimilation experiments with real SEVIRI data showing a small positive impact in the analysis and forecasts, the water vapour channels at 6.25 and 7.35 µm are assimilated operationally at DWD since the beginning of July 2018. Currently, work is ongoing to further analyse and tune the quality control checks with the aim to increase the amount of operationally assimilated data. Additionally the assimilation of geostationary water vapour clear sky radiances will be extended to GOES (Imager and ABI) and Himawari (AHI) data.

Acknowledgements

This research was supported by EUMETSAT within the framework of the Fellowship Program. The authors also want to thank colleagues, especially Harald Anlauf and Robin Faulwetter, for their support.

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