Analysis and forecast impact of the humidity observing system

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Abstract

The paper presents the results from Observing System Experiments (OSEs) with the ECMWF data assimilation and modelling system for investigating and evaluating the impact on both analysis and forecast of satellite observations sensitive to humidity. A large number of satellite instruments are currently assimilated into Numerical Weather Prediction (NWP) systems; therefore, OSEs can provide, not only, a valuable reference for classifying which observations dominate the humidity analysis and forecast, but also a good indication for evaluating the strategy used to assimilate the data within the NWP system.

In this paper we test the separate and combined impact of the main humidity observing systems using data from Microwave Imagers (SSMIS, TMI, AMSRE), Microwave Sounders (MHS) and Infrared Sounders (HIRS, AISI, AIRS, GEOS): Microwave Sounders (MWSs) and Infrared Sounders (IRSs) data are assimilated in clear-sky conditions only, whilst Microwave Imagers (MWIs) observations are treated in the all-sky approach, where clear and rain-cloud affected scenes are considered in the same stream.

The results show that each tested data type contributes to the moisture analysis. The all-sky assimilation, bringing additional information on water vapour, cloud and precipitation into the system, dominates the relative humidity analysis in the lower troposphere (1000-600 hPa). MWSs and IRSs have more impact in the middle troposphere (600-200 hPa). MWIs also improve the global medium-range Total Colum Water Vapour (TCWV) forecasts. Root mean square of the differences between independent TCWV observations derived by the Envisat MicroWave Radiometer (MWR) and TCWV forecasts from the ECMWF system, shows that MWIs improve the entire 4-day and 2-day forecast range in the Tropics and in the Northern hemisphere respectively.

Observing system experiments

One-month OSE was run from 31 July to 31 August 2011, using the ECMWF 4D-Var data assimilation system at T255 horizontal resolution (~78 km) and 91 model levels. In the minimization, analysis increments at T159 resolution (~128 km) and T95 (~208 km) are computed and added to the T255 background fields using the incremental 4D-Var method. The 37r3 cycle of the Integrated Forecast System (IFS) was used throughout. Its standard configuration, where a large number of observations are assimilated (comprising conventional data and, for the largest part, satellite observations), provides the Control assimilation experiment used as reference in all the comparisons performed. Currently, the high-resolution analyses and forecasts are produced at T1279 resolution (~16 km), but for sake of efficiency, the OSEs presented in this paper were run at lower resolution. Among all the conventional data and satellite radiances assimilated directly in 4D-Var, at ECMWF, microwave imagers observations are the only one to be assimilated in the all-sky approach (Geer et al. 2009, Bauer et al. 2010, Geer et al. 2010, Geer et al. 2011), where clear, cloudy and precipitating scenes are treated in the same stream. The study presented in this paper is also an evaluation of the benefit brought by the all-sky assimilation to the humidity analysis and forecast.

Beside the Control experiment (Exp 0), in order to assess the impact of each observing system, four additional experiments were run in the same period. In each experiment one main humidity observation type was withheld from the Control as follows:

Exp 1: **MWIs** data withheld (sensors: SSMIS, TMI, AMSRE).

Exp 2: **MWSs** data withheld (sensor: MHS).

Exp 3: **IRSs** data withheld (sensors: HIRS, IASI, AIRS, GEOS).

Exp 4: **Baseline:** All data above withheld.

OSEs are well known to be complicated to interpret due to the analysis uncertainty of the full assimilation system itself. In order to better understand which differences between each humidity observing system are significant and reduce the intrinsic error of the assimilation Control experiment, an additional sixth experiment, slightly different from the Control, was run. The new Control experiment (Control*) is an exact copy of the original Control, but the first analysis was initialized with different initial conditions.

The impact of the separate (MWIs, MWSs, IRSs) and combined (MWIs + MWSs + IRSs) humidity observing systems in all comparisons in the following, has been estimated in terms of the root mean square (RMS) of analysis differences:

$$RMS_{humidity\_observing\_system} = RMS(AN_{Control} - AN_{Exp}) - RMS(AN_{Control} - AN_{Control^*}), \qquad (1)$$

where AN is the humidity analysis produced twice daily (00 or 12 UTC) by the variational assimilation system. The second term on the right side of the equation can be interpreted as an estimation of the humidity analysis uncertainty of the full assimilation system.

A detailed description of which observations have been withheld by the Control experiment (Sensor, Satellite, Channels) is provided in Table 1.

Humidity observing system experiments		
Control (Exp 0)		
Full operational observation system		
MWIs (Exp 1)		
Sensor	***Satellite***	***Channels withheld (GHz)***
SSMIS	DMSP17	19V&H; 22V; 37V; 91V
TMI	TRMM	19V&H; 22V; 37V; 85V
AMSRE	AQUA	19V&H; 24V&H; 37V
MWSs (Exp 2)		
Sensor	***Satellite***	***Channels withheld (GHz)***
MHS	NOAA18	183.3 ± 1.0; ± 3.0; ± 7.0
MHS	NOAA19 Metop-A	183.3 ± 3.0; ± 7.0 183.3 ± 1.0; ± 3.0; ± 7.0
IRSs (Exp 3)		
Sensor	***Satellite***	***Channels withheld***
HIRS	NOAA17 NOAA19 Metop-A	7.33; 6.52 (µm) 7.33; 6.52 7.33; 6.52
IASI	Metop-A	1367.05; 1384.27; 1392.95; 1395.28; 1407.06; 1421.06; 1422.27; 1990.04; 1994.41; 2014.91 (cm^{-1})
AIRS	AQUA	1251.40; 1316.10; 1339.70; 1342.30; 1367.80; 1392.20; 1514.0 (cm^{-1})
GEOS	GOES 11 GOES 13 METEOSAT 7 METEOSAT 9 MTSAT-2	6.7 (µm) 6.7 6.2 6.2; 7.3 6.8
Baseline (Exp 4)		
All satellite data above withheld		
Control* (Exp 5)		
Copy of the Control experiment (Exp 0), but first analysis initialized with slightly different initial conditions		

Table 1: Definition of the six humidity OSEs

Relative humidity analysis impact

The impact of the separate (MWIs, MWSs, IRSs) and the combined (MWIs + MWSs + IRSs) humidity observation systems on the analysis of relative humidity has been evaluated in terms of RMS of analysis differences computed according to equation 1. All the OSEs were run for the period of 31 July to 31 August 2011. The initial 5-day period has been estimated as a reasonable time to allow for the system to spin up and eliminate the effect of having a different observation system in each experiment. Therefore, all following results exclude the initial five days from the calculation and refer to the period of 5 to 31 August 2011.

Figure 1 and Figure 2 summarize the main result of this study displaying respectively the observing systems impact on the vertical profile of relative humidity and along zonal cross sections.

The combined OSE (Baseline experiment) can be interpreted as the total humidity impact from satellite humidity observations. It can be considered as a case limit when the satellite humidity observing system is completely denied from the assimilation. Figure 1 shows clearly the importance of satellite observations on the estimate of moisture: the denial of all satellite humidity observations generates the highest RMS values in each geographical region considered (the furthest line to the right in each plot). The analysis of the humidity profile, when satellite radiances are removed by the assimilation, appears to be globally constrained to within 1 and 5% (left panel).

Figure 2 shows also that the impact on the humidity estimation from all the satellite sensors (bottom right panel) is well spread out globally with evident latitude dependencies. This geographical feature can be explained by the fact that conventional observations have not been removed by the Control experiment. The sparsity of conventional observations over the Southern Hemisphere and Tropics makes satellite data dominant at these latitudes, where RMS impacts are observed to be greater than 6%. On the contrary, in the lower and middle troposphere from 30 to 60 degrees latitude in the Northern Hemisphere, where radiosonde coverage is generally good, the RMS appears to be reduced with values less then 3%.

The OSEs observing systems investigated separately, MWIs, MWSs and IRSs, have a different impact on the moisture estimation with both height and latitude dependencies (Figure 1 and Figure 2). MWIs completely dominate the humidity analysis in the lower troposphere, between 1000 and 600 hPa, with a second peak of sensitivity to the moisture estimation at about 200 hPa in the deep tropical convection area. The impact on the analysis of moisture brought by the MWIs all-sky assimilation is clearly displayed in Figure 1: when microwave observations are removed by the assimilation, RMS values, between 1000 and 800 hPa, are comparable to those produced by the baseline experiment for any geographical area. Geostationary and Infrared Sounders, instead, have impact on the middle-upper tropospheric humidity, between 600 and 200 hPa, at middle and high latitude in both the Hemispheres. MWSs show a similar impact like the IRSs, mainly at high latitude in the North Hemisphere, but not as significant.

These results are relatively consistent with OSEs obtained using a previous cycle of the ECMWF assimilation system (Andersson et all. 2007). However, microwave imager observations are now assimilated directly in 4D-Var (Bauer et al. 2010, Geer et al. 2010), where clear, cloudy and precipitating scenes are treated in the same stream. The additional impact of MWIs on the relative humidity analysis can be explained with the beneficial inputs of the all-sky assimilation approach, where the assimilation of cloudy and rainy conditions brings additional information on water vapour, liquid cloud and precipitation into the system. Microwave imager observations are currently assimilated only over ocean and restricted from -60 to 60 degrees latitude and this is the explanation of the geographical impact displayed in Figure 2 (top left panel). The slight impact of the MWSs with respect to the other two observation types, instead, can be justified considering the fact that the number of microwave sounders observations denied from the assimilation (sensors and channels) are not as many as the other two OSEs.

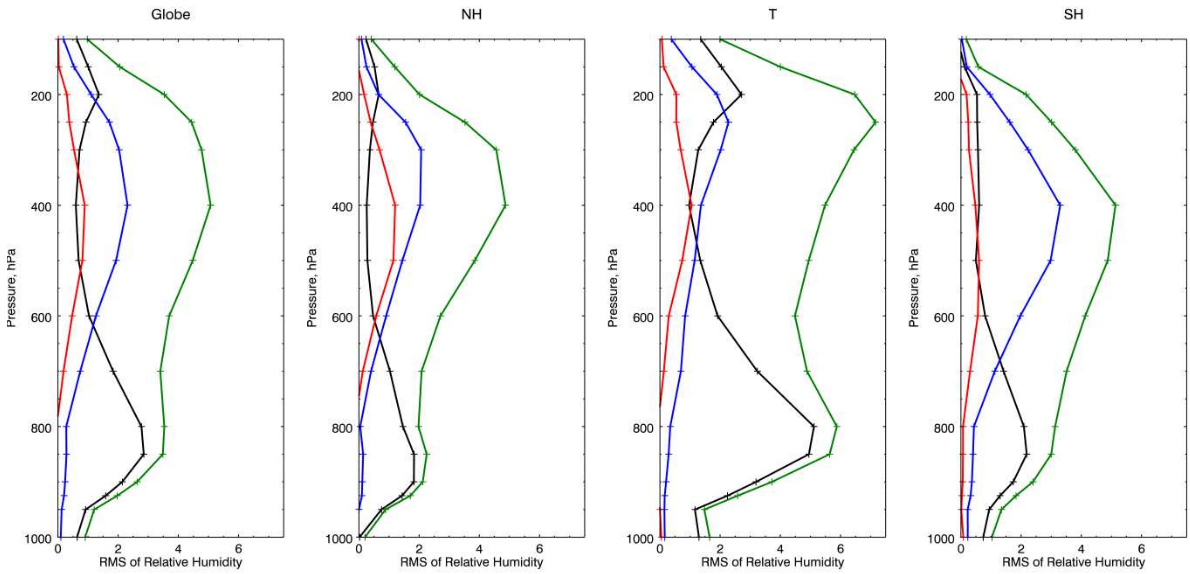

Figure 1: RMS of the relative humidity analysis differences computed according equation 1 considering the analysis produced at 12 UTC for each of the OSEs investigated: MWIs, black, MWSs, red, IRSs, blue, full satellite observing system (MWIs + MWSs + IRSs), green. Four geographical regions are displayed (from left to right): the whole Globe, North Hemisphere (20°, 90°), Tropics (20°, -20°), South Hemisphere (-20°, -90°).

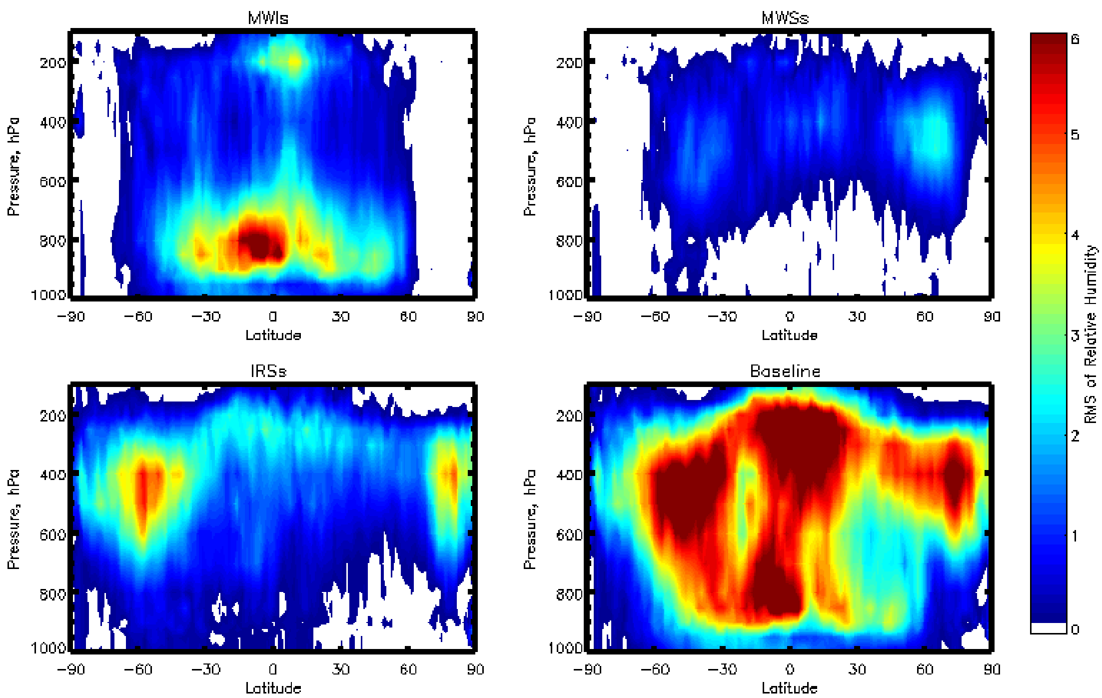

Figure 2: As Figure 1, but along zonal cross sections: MWIs, top left, MWSs, top right, IRSs, bottom left, full satellite observing system (MWIs + MWSs + IRSs), bottom right.

The OSEs impact can be additionally studied by analysing brightness temperature departure statistics. Figure 3 and 4 show, respectively, MetOp-A MHS brightness temperature departure statistics for the Control experiment (Exp 0) and the experiment when MWIs are withheld (Exp 1), and for the Control experiment and the experiment when IRSs are removed (Exp 3), both for the Tropics. When MWIs are denied from the Control experiment, deterioration in standard deviation is observed for both background and analysis departures from assimilated MHS channel 5 data. MHS channel 5 (183.0 ± 7.0 GHz) is the microwave sounder channel more sensitive to the lower troposphere (with a peak of sensitivity at about 900 hPa). The detected deterioration in standard deviation is therefore an additional confirmation of the impact of microwave imager observations on the lower tropospheric humidity. Figure 4, instead, shows deterioration in standard deviation from assimilated MHS channel 3, 4 and 5 data. MHS channel 3 and 4 (183.0 ± 1.0 and 183.0 ± 3.0 GHz) are sensitive to the middle-upper troposphere (with a peak of sensitivity at about 500 and 700 hPa respectively). The more pronounced standard deviation deterioration for channel 3 and channel 4 confirms that infrared sounder observations control the moisture estimation in the upper levels of the atmosphere.

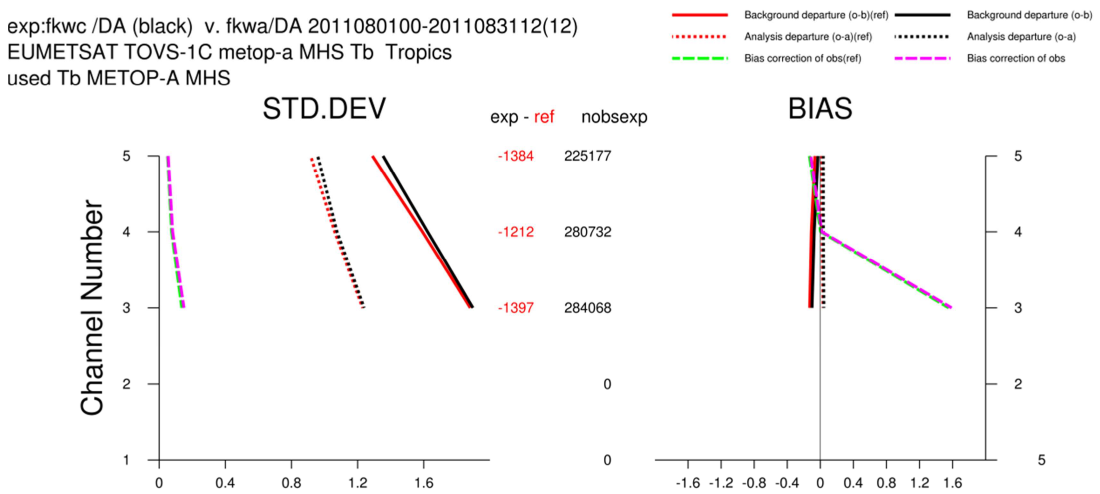

Figure 3: MetOp-A MHS brightness temperature departure statistics for the Control experiment (Exp 0), red, and the experiment when MWIs are withheld (Exp 1), black, for the Tropics: background departure, solid line, analysis departure, dotted line, bias correction, dashed line. MHS channel numbers are displayed on the y axis: 183.0 ± 1.0, channel 3, 183.0 ± 3.0, channel 4, 183.0 ± 7.0, channel 5. Statistic is computed over 1-31 August 2011.

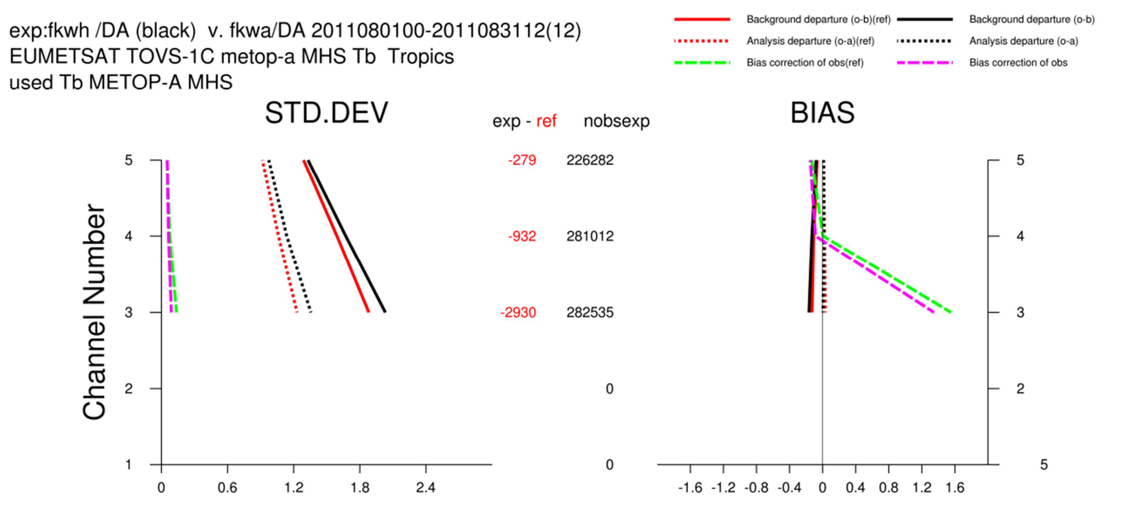

Figure 4: As Figure 3, but for the Control experiment (Exp 0), red, and the experiment when IRSs are withheld (Exp 3), black.

Total column water vapour forecast impact

Figure 5 shows the mean analysis difference for the Total Column Water Vapour (TCWV) for the Control experiment (Exp 0) and each of the humidity OSEs (Exp1, Exp2, Exp3 and Exp 4) where a single (MWIs, MWSs, IRSs) or the combined satellite data type (MWIs + MWSs + IRSs) has been removed. It is quite evident that the bias, positive or negative, introduced by the denial of microwave imager observations (top left panel) are, in terms of location and intensity, comparable to those generated when the full set of satellite observations is denied (right bottom panel). The TCWV analysis is clearly dominated by the all-sky MWIs assimilation.

In order to investigate in more detail the impact of MWIs on the global medium-range TCWV forecasts produce by the ECMWF system, 10 days forecast, with 1 hour step, have been generated from the analysis at 00 UTC for both the Control experiment and the experiment where MWIs have been withheld by the Control. The TCWV forecasts obtained from each experiment have been subsequently verified against independent TCWV observations derived by the Envisat MicroWave Radiometer (MWR) (Obligis et all. 2006).

The MWIs forecast impact has been therefore evaluated in terms of RMS of the differences between observed and forecasted TCWV. Figure 6 shows the beneficial impact of assimilating all-sky microwave radiances on the global medium-range TCWV forecasts. When MWIs are removed by the assimilation system, deterioration in RMS is significant over the entire 4-day (T+96) and 2-day (T+48) forecast range in the Tropics and in the Northern hemisphere respectively. In the Southern Hemisphere, instead, a very slight deterioration is only observed over 1-day (T+24), while globally the RMS estimation becomes worse over the entire 3-day forecast range (T+72).

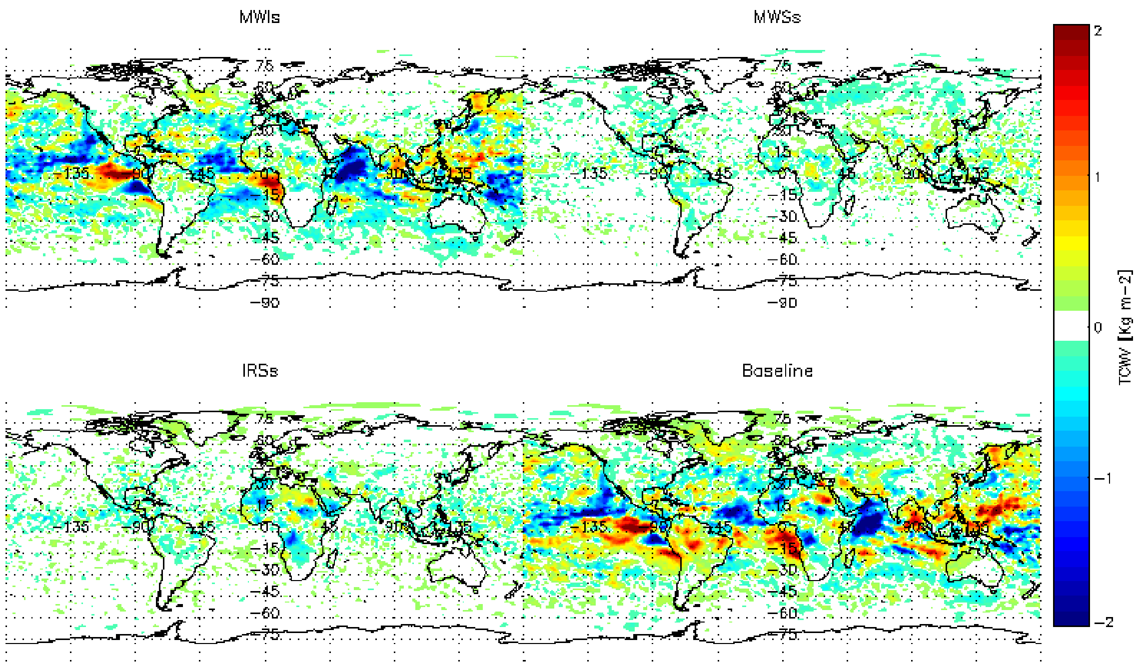

Figure 5: Mean analysis difference for TCWV for Control assimilation (Exp 0) and each of the humidity OSEs investigated: Exp 0 - Exp 1 (MWIs denied), top left, Exp 0 - Exp 2 (MWSs denied), top right, Exp 0 - Exp 3 (IRSs denied), bottom left, Exp 0 - Exp 4 (baseline), bottom right.

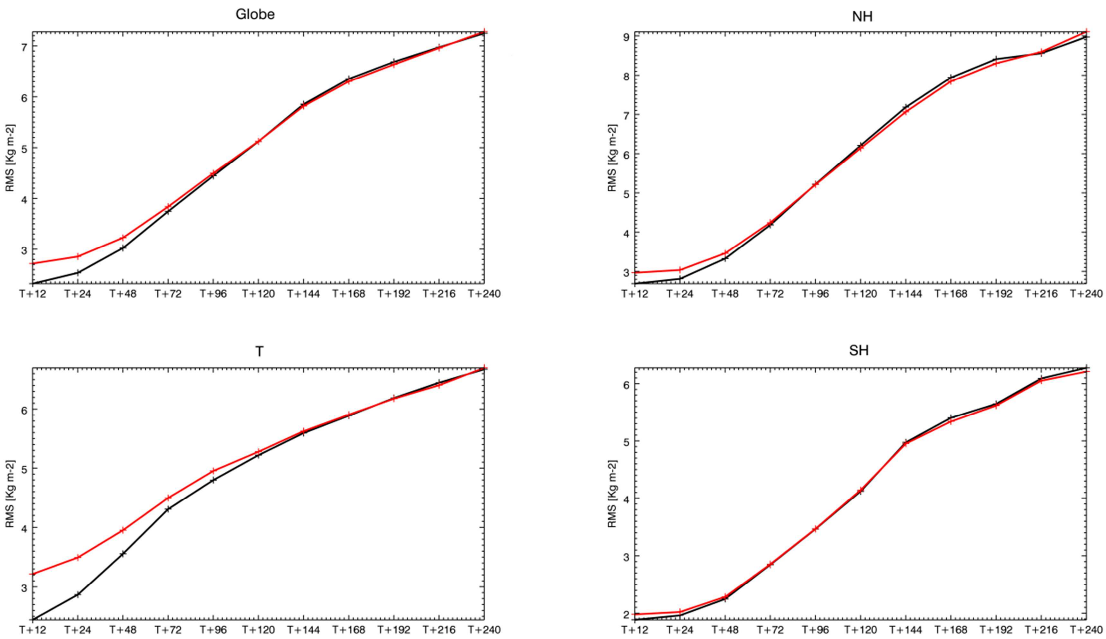

Figure 6: RMS of the differences between independent TCWV observations from Envisat Microwave Radiometer (MWR) and 10 days TCWV forecast from the analysis at 00 UTC: Control experiment, black, and experiment where MWIs have been withheld by the Control, red. Four geographical regions are displayed: the whole Globe, top left, North Hemisphere (20°, 90°), top right, Tropics (20°, -20°), bottom left, South Hemisphere (-20°, -90°), both right.

Conclusion

The analysis and forecast impact of satellite humidity observations has been investigated by means of one-month observing system experiments (OSEs) using the ECMWF's 4D-Var data assimilation system. The separate and the combined impact of three main types of satellite humidity observations (Microwave Imagers, MWIs, Microwave Sounders, MWSs, Infrared Sounders, IRSs) has been evaluated in terms of root mean square (RMS) of analysis differences with respect to a reference experiment (Control), which used all the data assimilated operationally. Additionally, in order to estimate and take into account the analysis uncertainty of the full assimilation system itself, another Control experiment was run with slight different initial conditions.

Our results show good agreement with OSEs obtained using a previous cycle of the ECMWF assimilation system (Andersson et all. 2007), but they also demonstrate the impact introduced by the assimilation of microwave imagers observation in the all-sky approach, where clear, cloudy and precipitating scenes are treated in the same stream and assimilated directly in 4D-Var (Bauer et al. 2010, Geer et al. 2010). The baseline experiment, where the combined satellite observing system (MWIs + MWSs + IRSs) has been removed by the Control experiment, shows clearly the impact of satellite observations on the moisture estimation with both height and latitude dependencies. The loss of the full set of satellite data brings to high RMS values globally and conventional observations, not removed by the baseline experiment, are able to compensate the absence of satellite observations only in the lower and middle troposphere from 30 to 60 degrees latitude in the Northern Hemisphere, where radiosonde coverage is generally good.

MWIs completely control the moisture analysis in the lower troposphere, 1000-600 hPa, with an additional peak of sensitivity to the humidity estimation at about 200 hPa in the deep tropical convection area. Geostationary and Infrared Sounders, instead, have impact on the middle-upper tropospheric humidity at middle and high latitude in both the Hemispheres. MWSs show a similar impact like the IRSs, but not as significant. The MHS brightness temperature departure statistics are also in agreement with the results obtained by RMS analysis differences.

The Total Colum Water Vapour (TCWV) analysis, compared to other satellite observations, has been also found clearly dominated by the all-sky assimilation and, in order to investigate in more detail the impact of MWIs on the global medium-range TCWV forecasts produced by the ECMWF system, independent TCWV observations derived by the Envisat MicroWave Radiometer (MWR) have been taken into account. The results show the beneficial impact of assimilating all-sky microwave radiances on the global medium-range TCWV forecasts. RMS of the differences between observed and forecasted TCWV, when MWIs are removed by the assimilation system, are deteriorated over the entire 4-day and 2-day forecast range in the Tropics and in the Northern hemisphere respectively. In the Southern Hemisphere, instead, a very slight deterioration is only observed over 1-day.

The important information content of satellite radiances in cloudy and precipitating areas encourages further studies in order to explore the assimilation of microwave observations in all-sky conditions. The assimilation of SSMIS humidity channels over land in the all-sky approach is a potential additional development that is being currently under investigation.

Acknowledgements

Fabrizio Baordo is funded by the EUMETSAT Fellowship Programme.

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