Land surface emissivity at microwave frequencies: operational implementation in the French global 4DVar system and impact of using surface sensitive channels on the African Monsoon during AMMA

Élisabeth Gérard, Fatima Karbou, Florence Rabier, Jean-Philippe Lafore, Jean-Luc Redelsperger

CNRM / GAME, Météo-France / CNRS, 42 Av. Coriolis, 31057 Toulouse Cedex, France

Olivier Bock

LRG / IGN, Aile Cassini 4e étage, 6-8 av Blaise Pascal, Cité Descartes - Champs-sur-Marne, 77455 Marne la Vallée Cedex 2, France

Abstract

Satellite microwave measurements have large atmospheric and surface information contents and are known to be very useful for numerical weather prediction. However these observations are still not fully used over land because of non negligeable uncertainties about land surface temperature and emissivity. The emissivity retrieval and assignment to the AMSUB/MHS and SSM/I channels are the baseline of a method implemented in the Météo-France global analysis system; it allows to assimilate surface sensitive channels over land. Research experiments using these data over land appear to have a strong impact on the hydrological cycle both in analysis/first guess and short to medium range forecast. Focusing in this study on North Africa in the framework of the AMMA project, the addition of these surface sensitive channels over land appears to be globally beneficial to the analysis and forecast skills.

1. INTRODUCTION

Satellite microwave observations are expected to have a great potential in the estimation of meteorological variables such as temperature and humidity profiles, but one of the challenges is to use them over all surfaces. So far, the assimilation of satellite microwave observations such as AMSU or SSM/I has been preferentially limited to channels that are weakly sensitive to the surface. For sounding channels the sensitivity to the surface is non-existent or weak compared to the signal associated to the atmosphere, whereas surface sensitive sounding channels or imaging channels are more difficult to use over land because of large uncertainties on surface properties like surface temperature and emissivity. In particular, emissivity modelling is more complex over land because of its variation in time and space, with surface types, roughness and soil moisture. Moreover, unlike oceans, land surfaces are associated with high emissivities, i.e. almost 1 to be compared to about 0.5 over the ocean. This is why assimilating microwave observations over land is a challenge.

Developments have been undertaken at Météo-France a few years ago to assimilate surface sensitive satellite channels over land (Karbou *et al.*, 2006; Karbou *et al.*, 2007; Karbou *et al.*, 2009a/b). The use of a dynamically retrieved emissivity to better assimilate AMSUA and AMSU-B sounding channels over land became operational at Météo-France in July 2008. Since then, research experiments with AMSUB/MHS (surface sensitive channels) and SSM/I over land have been run within the ARPEGE global 4DVar assimilation and forecast systems, developed in a collaboration between Météo-France and ECMWF. Beyond the expected improvement of operational numerical weather forecasts, one of the motivations is the AMMA (African Monsoon Multidisciplinary Analysis) project (Redelsperger *et al.*, 2006); to which extent is it possible to improve the hydrological cycle over the Tropics ?

After a short recall of the method for dynamically retrieving emissivity over land (Section 2), this paper describes the impact on the ARPEGE global assimilation and forecast systems during the 2006 AMMA campaign (from July to September) of using this retrieved emissivity to assimilate surface sensitive AMSUB/MHS channels (Karbou *et al*., 2009b) and SSM/I observations (Section 3). In particular the impact on the hydrological cycle over North Africa is looked at in more detail, in the analysis as well as in the forecast. Section 4 concludes this study.

2. LAND EMISSIVITY DYNAMIC RETRIEVAL FROM SATELLITE OBSERVATIONS

At the root of this work, emissivity is dynamically retrieved given satellite observations, a radiative transfer model and meteorological fields from short-range forecasts. This method is fully described in Karbou *et al.* (2006).

With hypotheses such as a flat and specular surface, and a non-scattering plane-parallel atmosphere, the brightness temperature T_b at polarization p and frequency ν, as observed by a sensor in space, is expressed as the sum of atmospheric contributions in its upwelling and downwelling components and of a surface contribution, as follows:

$$T_b(p, \nu) = T_b^{up}(p,\nu) + (1-\varepsilon(p,\nu))\, \Gamma\, T_b^{down}(p,\nu) + \varepsilon(p,\nu)\, T_s\, \Gamma \qquad (1)$$

where $T_b^{up}(p,\nu)$ and $T_b^{down}(p,\nu)$ are the atmospheric upwelling and downwelling brightness temperatures respectively, $\varepsilon(p,\nu)$ the surface emissivity, T_s the skin temperature and Γ the net atmospheric transmissivity.

With temperature and specific humidity profiles given by a short-range forecast (or radiosonde or reanalysis), the 6-hour forecast so-called first-guess in this study, as inputs to the radiative transfer model RTTOV (Eyre, 1991; Saunders *et al.*, 1999; Matricardi *et al*., 2004), it is possible to derive the microwave land emissivity from:

$$\varepsilon(p,\nu) = [\, T_b(p, \nu) - T_b^{up}(p,\nu) - T_b^{down}(p,\nu)\, \Gamma\,] \, / \, [\, (\, T_s - T_b^{down}(p,\nu)\,)\, \Gamma\,] \qquad (2)$$

For land emissivity retrieval from satellite observations, using sounding channels is not recommended as transmission is too small. Emissivities retrieved at window channels can be used as a good approximation to simulate brightness temperatures at sounding channels (Karbou *et al.*, 2005). As a direct application of this property, emissivity is retrieved from the first AMSUB/MHS channel (89 GHZ) and the first two SSM/I channels (19 GHZ, vertical and horizontal polarizations) and is assigned to the remaining channels.

3. IMPACT STUDIES: AMSUB/MHS AND SSM/I OVER LAND

Experimental framework

Experiments have been run in the ARPEGE global model at Météo-France to assess the performance of assimilating AMSUB/MHS radiances over land. The so-called “Experiments” consist in

- when focusing on AMSUB/MHS observations, assimilating surface sensitive channels over land (except the first channel, i.e. 89 GHz);
- when focusing on SSM/I observations, assimilating the SSM/I channels over land (except the first two channels 19V and 19H, i.e. vertical and horizontal polarizations at 19 GHz).

These so-called “discarded channels” from any further use (analysis or validation) are those used for retrieving the emissivity to be assigned to the other channels.

The impact of using surface sensitive AMSUB/MHS and SSM/I channels over land has been evaluated separately using a “control” run which was representative of the operational system in July 2006. In the so-called “Control” run experiment and with respect to AMSUB and SSM/I data use,

- Only AMSU-B channels with no contribution from the surface were assimilated, the land surface emissivity was taken from an empirical version of Grody, 1988 model;
- SSMI observations are only assimilated over sea.

In this paper the period of test has been chosen during the AMMA 2006 monsoon period (15 July – 14 September 2006).

In the following plots “CTR” refers to “Control” and “EXP” to “Experiment”. Comments, if not explicitly stated, focus on North Africa.

Assimilation of AMSUB/MHS radiances over land

Only channels 3 and 4 (183+/-1 GHz and 183 +/-3 GHz respectively) are assimilated over land in the Control run, with a condition on orography (lower than a threshold, i.e. 1500 m for channel 3 and 1000 m for channel 4). In the Experiment, surface sensitive channels 2 (150 GHz) and 5 (183+/-7 GHz) are also used in the assimilation, where orography is lower than 1000 m. Emissivity is dynamically derived from the 1st channel (89 GHz) and assigned to all AMSU-B sounding channels. As already done for channels 3 and 4, cloud contaminated data are rejected, i.e. where observation departure from first guess in window channel 2 is greater than 5 K in absolute value.

On average over a 45-day period the Total Column Water Vapour (TCVW) analysis difference between the Experiment and the Control shows a global moistening over central and western parts of Africa together with a drying in the eastern part of North Africa (see Figure 1).

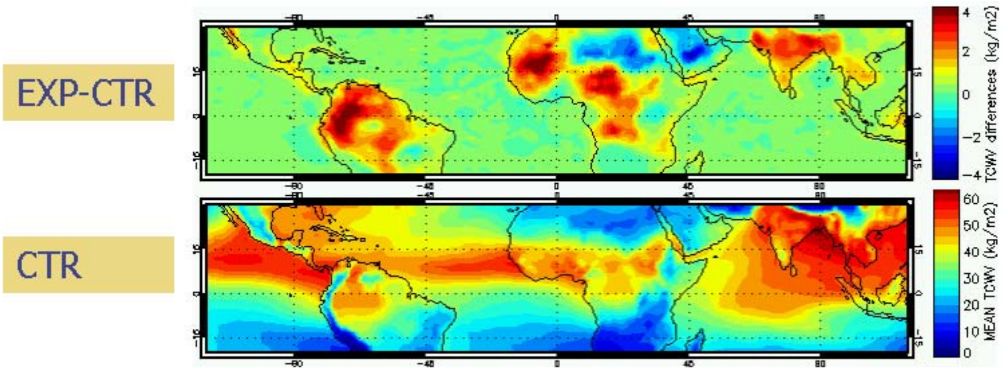

***Figure 1*: Total Column Water Vapour (TCWV) (top) analysis difference between the Experiment using additional AMSUB/MHS channels over land and the Control, (bottom) analysis field in the Control, on average over a 45-day period (1 Aug – 14 Sep 2006).**

When comparing the model humidity time series to GPS TCWV observations, the Experiment is closer to the observations than the Control, and the diurnal cycle is much better represented as shown in Figure 2.

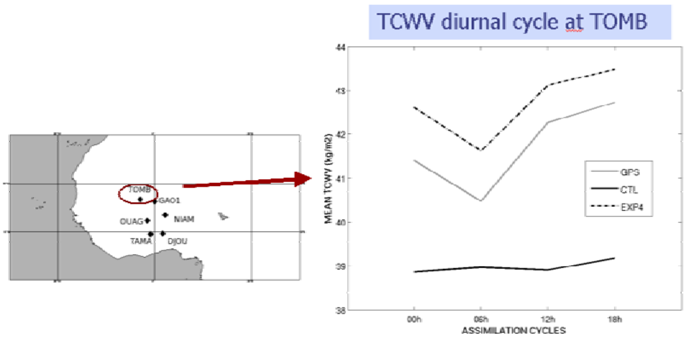

Figure 2**: Mean estimates of Total Column Water Vapour (TCWV) obtained from measurements at Tombouctou GPS station and from analysis near Tombouctou for the Control (black dashed curve) and for the Experiment using additional AMSUB/MHS channels over land (black solid curve), at 0h, 6h, 12h and 18h. At each cycle the TCWV mean values have been averaged over a 45-day period (1 Aug – 14 Sep 2006). Extracted from Karbou et al., 2009b.**

The difference in 24-hour cumulated precipitation between the Experiment and the Control shows an increase of precipitation over equatorial Africa and a decrease over the ocean off the western part of the African continent (see Figure 3). It is a good feature over the ocean where the model usually suffers from an excess of precipitation. As a first evaluation, the tendency over land seems to be in agreement with GPCP precipitation products. But part of the extra moisture is rapidly eliminated through precipitation during the first forecast steps, as shown by the enhancement of the model precipitation spin-down. The Experiment has 0.3 $mm.day^{-1}$ more precipitation than the Control at 6h forecast range (4.3 $mm.day^{-1}$ in Experiment; 4.0 $mm.day^{-1}$ in Control), 0.2 $mm.day^{-1}$ more precipitation at 18h (4.7 $mm.day^{-1}$ in Experiment; 4.5 $mm.day^{-1}$ in Control), 0.1 $mm.day^{-1}$ more precipitation at 30h (3.9 $mm.day^{-1}$ in Experiment; 3.8 $mm.day^{-1}$ in Control) and from 42h forecast range, both experiments have the same precipitation rate.

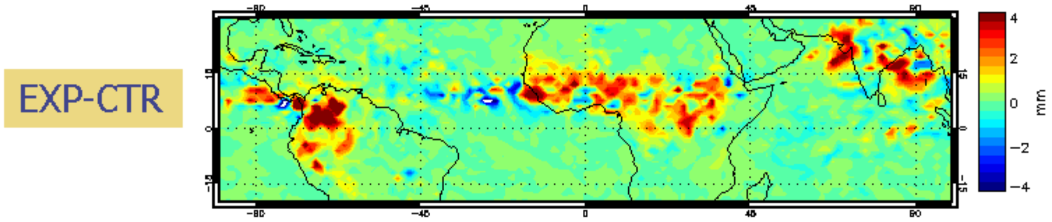

Figure 3**: Average of 24-hour forecast cumulated rain rate difference over 45 days (1 Aug – 14 Sep 2006) between the Experiment using additional AMSUB/MHS channels over land and the Control. Positive (negative) values indicate that the Experiment has increased (decreased) precipitation. Extracted from Karbou et al., 2009b.**

Figure 4 shows maps of difference between the Control and the Experiment of geopotential forecast rms error at 200 hPa with respect to ECMWF analysis, at 24h, 48h and 72h forecast range. The impact of assimilating additional AMSUB/MHS channels over land on geopotential scores is impressive, up to a reduction of 8 metres in the Experiment over Africa at day 1 and day 2, and to a lesser extent at day 3.

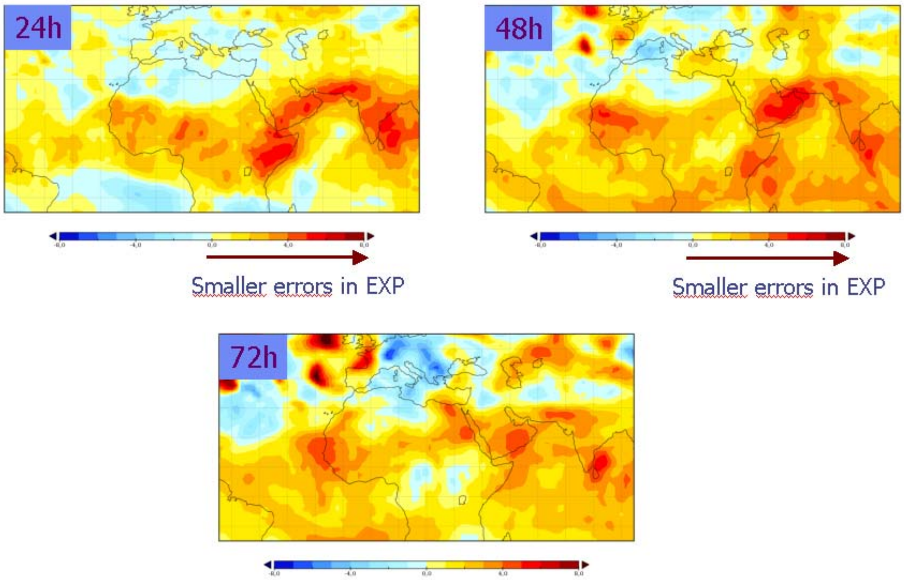

***Figure 4*: Difference in RMS error between the Control and the Experiment (using additional AMSUB/MHS channels over land) forecast at (upper left) 24h, (upper right) 48h and (bottom) 72h forecast range. Errors are computed for August for geopotential at 200 hPa with respect to ECMWF analysis. Extracted from Karbou et al., 2009b.**

Assimilation of SSM/I radiances over land

Emissivity retrieved from both polarizations at 19 GHZ is assigned to the other SSM/I channels of same polarization but with a frequency parameterization (offset). Coastal points are rejected as well as high latitude regions, i.e. where | latitude | > 60°.

Observation biases are corrected through the variational satellite radiance bias correction called "VarBC", as developed at ECMWF (Auligné *et al*., 2007)). Bias parameters associated to predictors are part of the 4DVar control variable. Surface temperature, total column water vapour and surface wind speed are the air mass related predictors for bias correcting SSM/I radiances over sea. Expecting a different behaviour of the radiative transfer model over land than over sea, 19V channel dynamically retrieved emissivity, acting as a sort of land sea mask, is introduced in VarBC as a modulation of one of the predictors, i.e. surface temperature; predictor "T_s" is replaced by "$\varepsilon(V,19)\ T_s$".

When using SSM/I data over land there is a global moistening in the model, particularly over North Africa, and drying spots in the vicinity of Central Africa and Angola, if focus is only made on Africa (see Figure 5, top). The global moistening affects the mid and lowest part of the troposphere, below 500 hPa, with a maximum intensity at 20°N latitude (see Figure 5, bottom).

The moistening happens from the very beginning of the Experiment run, as shown on the time series of TCWV from the first guess and from the analysis, in the Northern Extratropics and Tropics (see Figure 6, left). The influence of assimilating SSM/I channels over land remains in the forecasts for up to at least 4 days in these regions, as the Experiment is still characterised by higher amounts of water vapour than the Control at this forecast range (see Figure 6, right).

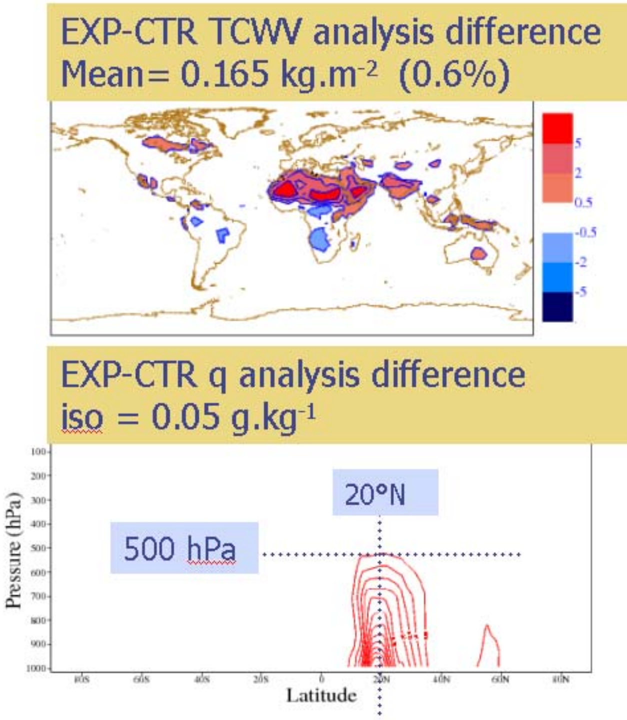

***Figure 5*: Difference between the Experiment with SSM/I over land and the Control for (top) Total Column Water Vapour (TCWV) and (bottom) zonal mean of specific humidity vertical distribution (q). On average over a 2 month period (15 July – 14 Sep 2006).**

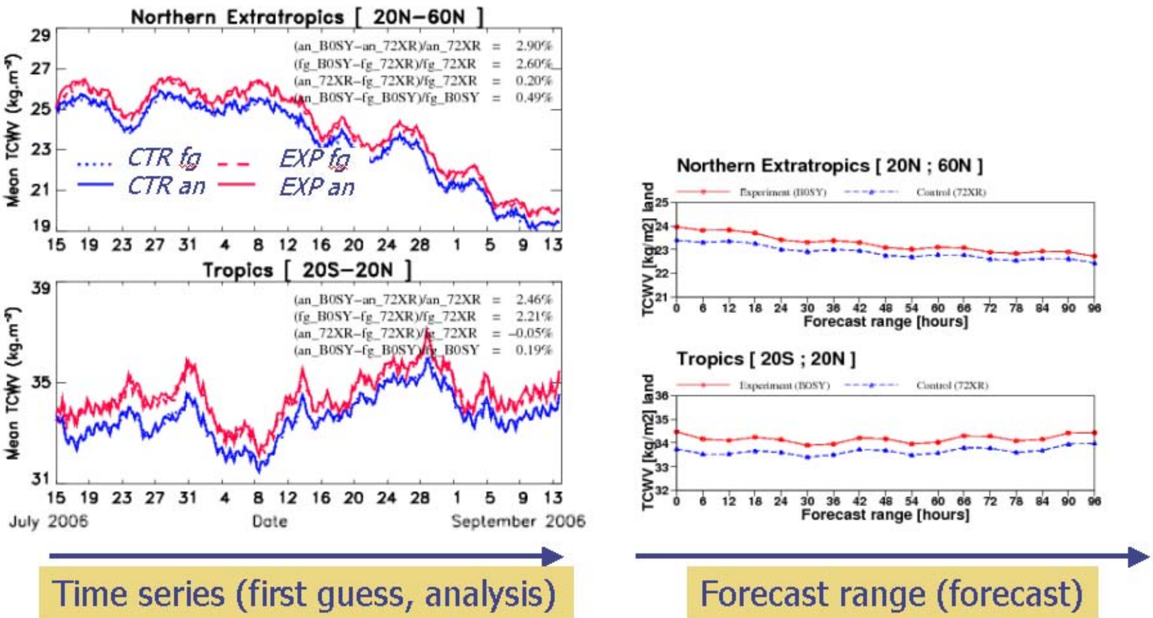

***Figure 6:* Time evolution of Total Column Water Vapour (TCWV): (left) as derived from first guess (dotted and dashed lines) and analysis (solid lines) for the Control (blue lines) and the Experiment using SSM/I over land (red lines); (right) as a function of forecast range for the Control (blue line) and the Experiment (red line). Both kinds of plots represent (top) Northern Extratropics and (bottom) Tropics.**

As a consequence of additional moisture available used in the analysis over North Africa, larger amounts of precipitation, decreasing with forecast range, are available, as illustrated in Figure 7. The spin-down problem, already present in the Control, is reinforced in this region in the Experiment under the effect of additional moisture in the model. This refers to an enhancement of the imbalance between the assimilation and the forecast systems.

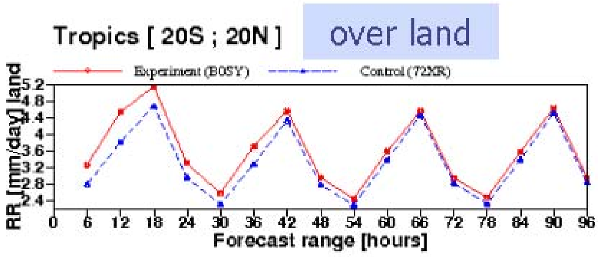

***Figure 7*: Mean rain rate forecast as a function of forecast range and as provided by the Control (blue line) and the Experiment using SSM/I over land (red line), obtained on average over a 2-month period, 15 July – 14 Sep 2006, over land in the Tropics.**

The forecast scores with respect to SYNOP data, in terms of rms error and bias, as a function of forecast range, are given for temperature, humidity and cloudiness over North Africa in Figure 8. The use of SSM/I radiances over land in the analysis is accompanied with a large reduction of the bias for these parameters associated with a reduction of rms error for cloudiness but not for temperature and humidity. This unwanted feature needs to be looked at in more details, but as a first explanation, it might be due to small scale features slightly misplaced when surface sensitive channels are introduced over regions usually poorly covered by observations.

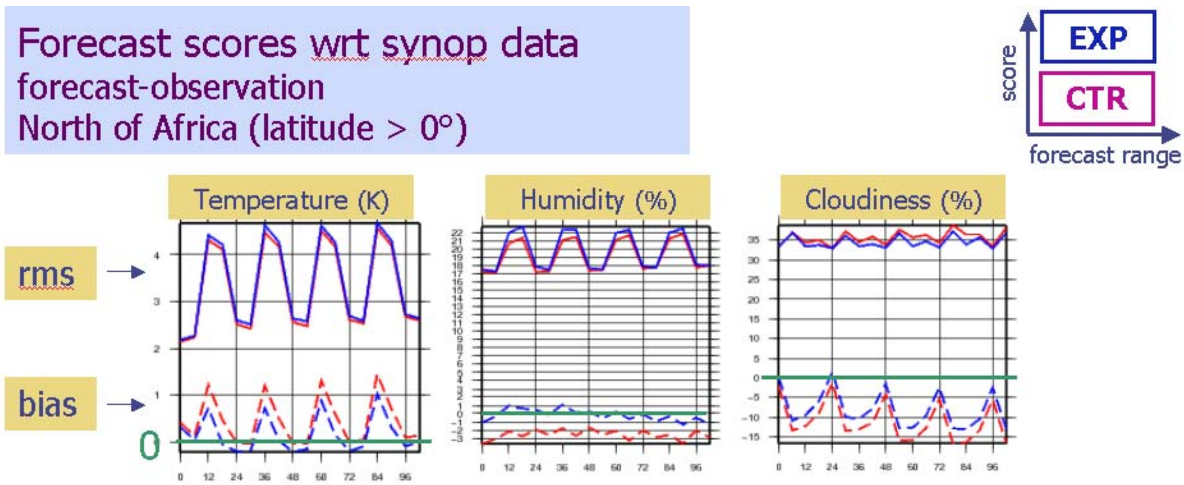

***Figure 8*: RMS error and bias of the model forecast when compared to SYNOP data, for temperature (left), humidity (middle), cloudiness (right) for the Control (red) and the Experiment using SSM/I over land (blue). Errors are computed over a 2-month period (15 July – 14 September 2006) over North of Africa.**

The geopotential forecast scores over the Tropics with respect to radiosondes are shown in Figure 9 as a function of pressure from 1000 to 10 hPa (y-axis) and forecast range up to day 4 (x-axis). The impact of SSM/I over land is positive above 500 hPa, with a reduction of 1 metre in rms error at about 200 hPa at any range, and of 3 metres in bias at day 3 - day 4 at the same level.

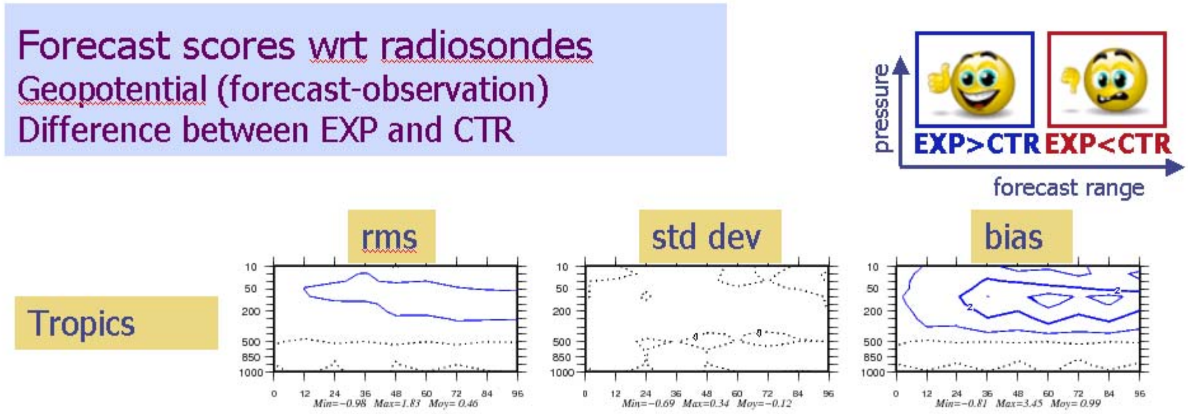

***Figure 9*: Difference of RMS error, standard deviation and bias (from left to right) between the Control and the Experiment using SSM/I over land, where forecasts are compared to radiosondes, as a function of forecast range (x-axis) and vertical pressure (y-axis). Errors are computed over a 2-month period (15 July – 14 September 2006) for geopotential over the Tropics. Positive (negative) impact of using SSM/I data over land is shown in blue (red).**

When looking at the maps of forecast rms error for geopotential at 200 hPa (see Figure 10), a large reduction of the rms error is noticeable when the forecast is compared to ECMWF analysis, but there is also an increase of error over North Africa at day 1, day 2 and still, but to a lesser extent, at day 3. This negative effect is partly corrected when a rain flag criterion is applied to reject rain flagged observations over land. This last version is the one that is currently under investigation. Note that the ECMWF analysis has the advantage of being an independent source of validation and is expected to be of relevant quality, although not an absolute reference.

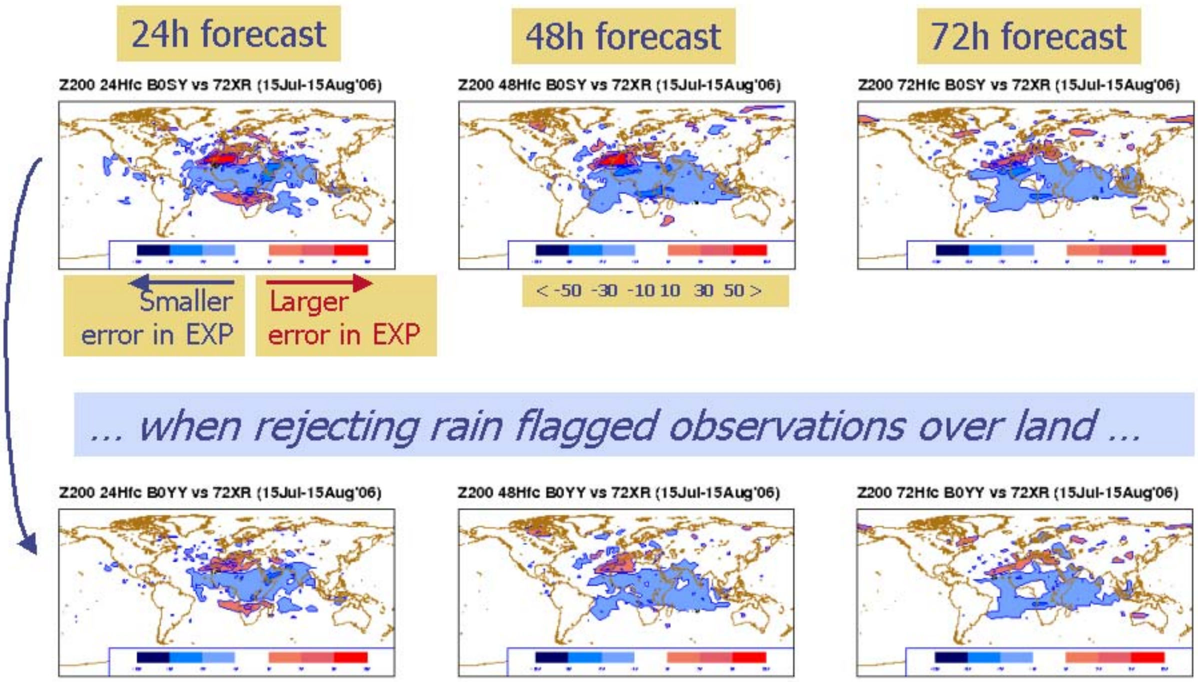

***Figure 10*: Difference in RMS error between the Experiment (using SSM/I over land) and the Control forecast at (left) 24h, (middle) 48h and (right) 72h forecast range, (top panels) before and (bottom panels) after rejecting rain flagged observations over land. Errors are computed over a 2-month period (15 July – 14 September 2006) for geopotential at 200 hPa with respect to ECMWF analysis. Positive (negative) impact of using SSM/I data over land is shown in blue (red).**

4. CONCLUSION AND FUTURE WORK

A method for dynamically retrieving emissivity over land and assigning it to the AMSUB/MHS and SSM/I surface sensitive channels has been implemented in the Météo-France assimilation system to assimilate these channels over land. The operational model already benefits since July 2008 from these developments, in the sense that a better description of land emissivity improves the assimilation of AMSU sounding channels over land. The assimilation of surface sensitive AMSUB/MHS channels, within the current pre-operational suite at Météo-France, is mature enough to be operationally implemented in the nearby future. As for the use of SSM/I channels over land, this subject is still under investigation, improvements are expected with rejection of rain flagged observations and need to be assessed with GPS TCWV observations, CPC/GPCP precipitation products, … Further studies with AMSUA/B concern feasibility studies to assimilate AMSUA/B data also in cloudy conditions. Once SSM/I data can be used over land, the expected role of SSMI/S over land will also be investigated and exploited.

The largest impact of using AMSUB/MHS and SSM/I data over land has been found to be in the hydrological cycle over the AMMA region: global increase of moisture in the first guess and analysis and, consequently, of precipitation. Similar overall effect of both instruments has been found, but discrepancies are to be noticed over North Africa, the region of interest of this study: the dipole with AMSUB/MHS (moistening of the model in the western part, drying in the eastern part) does not exist with SSM/I (moistening over the whole area). Do these instruments sound the same features ? Both effects need to be compared more tightly, also to the effect obtained with MERIS data (Bauer, 2009). Indeed, in a collaboration with ECMWF, it appears that AMSUB and MERIS instruments have the same signature on the humidity field in this region, even though elsewhere differences are to be noticed. So there are still a lot of exciting things to do to better understand the potential and the role of each instrument to improve the hydrological cycle over the Tropics.

REFERENCES

Auligné, T., McNAlly, A.P. and Dee, D., 2007: Adaptive bias correction for satellite data in numerical weather prediction system. *Q. J. R. Meteorol. Soc*., **133**, 631-642

Bauer, P., 2009, 4D-Var assimilation of MERIS total column water-vapour retrievals over land, *Q. J. R. Meteorol. Soc*., **135**, 1852-1862

Eyre, J.R., 1991: 'A fast radiative transfer model for satellite sounding systems'. *Tech. Memo*. **176**, ECMWF, Reading, UK

Grody, N.C., 1988: Surface identification using satellite microwave radiometers. *IEEE Trans. Geosci. Remote Sensing*, **26**, 850-859

Karbou, F., Aires, F., Prigent, C. and Eymard, L., 2005 : Potential of Advanced Sounding Unit-A (AMSU-A) and AMSU-B measurements for temperature and humidity sounding over land. *J. Geophys. Res.*, **110**, D07109, doi:10.1029/2004JD005318

Karbou, F., Gérard, E. and Rabier, F., 2007: On the use of microwave observations over land at Météo-France, in Proceedings of the Joint 2007 EUMETSAT Meteorological Satellite Conference and the 15th American Meteorological Sociely Satellite Meteorology and Oceanography Conference, 24-28 Sept 2007, Amsterdam, The Netherlands

Karbou, F., Gérard, É. and Rabier, F., 2006: Microwave land emissivity and skin temperature for AMSU-A and –B assimilation over land. *Q. J. R. Meteorol. Soc*., **132**, 2333-2355

Karbou, F., Gérard, É. and Rabier, F., 2009a: Global 4d-var assimilation and forecast experiments using land surface emissivities from AMSU-A and AMSU-B. Part-I: Impact on sounding channels. *Weather and Forecasting*, in press

Karbou, F., Rabier, F., Lafore, J.-Ph., Redelsperger, J.-L. and Bock, O., 2009b: Global 4D-Var assimilation and forecast experiments using AMSU observations over land. Part II: Impact of assimilating surface sensitive channels on the African Monsoon during AMMA, *Weather and Forecasting*, in press

Matricardi, M., Chevallier, F., Kelly, G. and Thépaut, J.-N., 2004 : An improved general fast radiative transfer model for the assimilation if radiance observations. *Q. J. R. Meteorol. Soc*., **130**, 153-173

Redelsperger, J-L., Thorncroft, C. D., Diedhiou, A., Lebel, T. , Parker, D. J. and Polcher, J., 2006: African Monsoon Multidisciplinary Analysis: An International Research Project and Field Campaign. *Bull. Am. Met. Soc.*, **87**, 1739-1746

Saunders, R.W., Matricardi, M. and Brunel, P., 1999: An improved fast radiative transfer model for assimilation of satellite radiance observations. *Q. J. R. Meteorol. Soc*., **125**, 1407-1425