The assimilation of AMSU-B radiances in the CMC global data assimilation system: Difficulties and impact relative to AMSU-A radiances

C. Chouinard and J. Hallé

Meteorological Service of Canada / Service Météorologique du Canada
Dorval, Québec, Canada

Abstract

The Canadian Meteorological Centre's (CMC) three Dimensional Variational (3D-Var) is an incremental analysis system that is currently used by both our global and regional models with very little modifications. During the last few years, it has undergone a series of upgrades from isobaric to a terrain-following coordinate, and most importantly to the direct assimilation of satellite radiances. The quality control (QC) of observations was also upgraded to a variational quality control whereby the data rejection/acceptance decisions are taken consistently during the minimization problem.

In terms of radiance data, the system currently uses so-called raw level-1b AMSU-A that are quality-controlled (QC), and bias controlled by the data user and not the producer. The QC and thinning algorithms of the radiance data are more complex and system dependent. Because of QC and bias correction algorithms, the impact of satellite data on CMC's analyses and forecasts are now very large and comparable to that of radiosonde data in the SH.

The resolution of NWP forecast/analysis systems is forever increasing and so is the volume of data from various instruments. The volume of satellite data has become quite a challenge even at the level of preparation and QC prior to the analysis step. One aspect of NWP systems which definitely can benefit from this additional data is the moisture analysis. In that context we have started to use the water sensitive radiances from the AMSU-B instruments onboard NOAA-15, NOAA-16, and NOAA-17. As will be shown, the quality of both the temperature and moisture analyses are significantly improved when using these additional radiance data. Preliminary evaluations indicate marked improvements in 5-10 day temperature forecasts and significant improvements in Quantitative Precipitation Forecast (QPF) skill scores in the first 5 days of 10-day forecasts.

Introduction

One of the advantages of variational data assimilation is its ability to assimilate indirect observations such as satellite radiances. With the help of a fast radiative transfer model (RTM), most NWP Centres are now able to directly assimilate radiance data and these have produced significant gains in the quality of operational analyses and forecasts. The quality of measurements from an instrument dictates how much influence this type of data will receive in an analysis system, but when it comes to indirect radiance measurements the quality of the RTM

which maps out the influence of radiance data in physical space, such as temperature and moisture, is also an issue.

The effective sensitivity of a satellite radiance measurement to an atmospheric state variable such as water vapor i.e. the so-called Jacobian is indicative of the impact of the radiance on atmospheric variables. The radiance data from AMSU-A instrument has the advantage of being sensitive almost exclusively to temperature, moreover, its Jacobian is very homogeneous varying very little from Tropical to mid-latitude atmospheric air-masses. On the other hand, the Jacobian of AMSU-B data is primarily sensitive to water vapor, but in drier atmospheres, it is also sensitive to temperature. The Jacobian also varies significantly from Equator to Pole. Because of this dual sensitivity, the assimilation of AMSU-B data is a more delicate problem requiring very accurate temperature and moisture trial fields and prior knowledge of their corresponding background error statistics.

Because of the difficulties inherent to the assimilation of moisture sensitive radiances, their current use at most NWP Centres is limited to the use of a few infrared channels from either the GOES or NOAA/HIRS instruments also onboard the NOAA platforms. NCEP and UKMET have been assimilating AMSU-B data since their availability i.e. NOAA-15 and more recently they have added NOAA-16 and NOAA-17 data. In Canada, we have just started to use AMSU-B in replacement of our current use of statistically derived humidity profiles obtained from the GOES sensors (Garand and Hallé, 1997). In this paper there will be a brief description of the steps involved in the preparation and QC of AMSU-B data prior to assimilation, followed by basic experimental test results, and finally results from their recent implementation in the full 3D-Var global data assimilation system at CMC.

Brief description of the revised 3D-Var analysis system and recent revisions

The basic analysis system used in this study is the one that was described in Gauthier et al. 1999, and more recent improvements have been described in three papers presented at the ITSC-11 and ITSC-12 (Chouinard and Hallé, 2000, Chouinard et al. 2000), and ITSC-13 meetings in Lorne, Australia (Chouinard et al. 2002). It is a global 28 level terrain following co-ordinate analysis/forecast system producing analyses directly on the model's vertical and horizontal grids. The most recent improvements to the system pertain to the preparation, QC, and use of conventional data, and most importantly, the introduction of new sources of satellite data. The combined impact of the new satellite data and the revision of the analysis procedure have contributed to major improvements in the reliability and quality of the CMC forecast/analysis system as described in Chouinard et al. 2002.

The peak sensitivity of some AMSU-B radiances is as high as 200 hPa in Tropical atmospheres and somewhat lower in Extra-Tropical cases. In the previous AMSU-A analysis system, the moisture analysis was limited to 300 hPa because most of the conventional moisture data above that were generally not very reliable. Because the peak sensitivity of some AMSU-B radiances to

moisture is around 200 hPa with tail effects extending up to70 hPa, the moisture analysis top had to be raised so as to retain most of their response. This is graphically illustrated in Fig.1.

Satellite data used in this study

The core satellite data used in this study are the AMSU-A and AMSU-B radiances from the NOAA-15, NOAA-16, and NOAA-17 satellites that are received at CMC via a public FTP link. These data are in level-1b format and originate from an operational NESDIS server in Washington. Further processing of the level-1b radiances is done at CMC using the AAPP software package (http://www.metoffice.com/research/interproj/nwpsaf/atovs/index.html). The main functions of this software package are the navigation and calibration of the level-1b radiance data. Finally, the radiances are coded in BUFR format and stored in a database at CMC.

The AMSU-A instrument has 15 microwave channels with a NADIR resolution of approximately 45km. Because of difficulties in specifying surface emissivities over land and ice, certain channels that are sensitive to skin surface temperature, are not used. Similarly, some stratospheric channels are not used because their peak contribution is above our NWP model top level currently at 10hPa, and consequently, we do not assimilate channels 11 to 14.

The AMSU-B instrument has 5 microwave channels with a higher resolution than the AMSU-A instrument, i.e. 16km (AMSU-B) compared to 45km (AMSU-A). Fig. 2 shows a typical composite coverage map of AMSU-B from the three NOAA satellites in a 6-hour time window. All AMSU-B radiances are sensitive to atmospheric column moisture, temperature, skin surface temperature and, surface emissivity. Over water, all 4 AMSU-B channels are assimilated because the fast surface emissivity model of S. English (FASTEM2) is used. However, over land and over different types of ice surfaces, because the emissivity is not well known, low peaking AMSU-B channels are either restricted or not used.

AMSU-B radiance processing for assimilation

Following the navigation/calibration validation, the AMSU-B data is subject to a passive monitoring check whereby it is systematically compared to simulated radiances over an extended period of a few months. From this comparison a first estimate of systematic and random error is obtained. The random error contains both the noise directly related to the instrument and an added component of noise due to RTM errors. This combined estimate will be used to specify the effective observational error used by the analysis procedure. For more details on the monitoring step, please refer to Chouinard et al. 2002 where this same procedure is described in the context of AMSU-A.

The systematic component of the error, or so-called radiance bias, has to be removed before the data assimilation step. The same procedure developed to remove AMSU-A biases was adapted to the AMSU-B data stream (Chouinard et al., 2002). There was reason to believe that some of the biases in AMSU-B could be related to RTM deficiencies in moisture treatment. However, attempts to relate AMSU-B biases to column-integrated moisture predictors have failed to show improvements over a simpler two-predictor approach. Similarly, attempts to use surface parameters as predictors in the AMSU-B also failed as they did with AMSU-A. Finally, the same type of algorithm is now used for AMSU-A and AMSU-B data, which is the 2 predictor algorithm, namely the geopotential thickness of layer 1000hPa-300hPa and, the geopotential thickness of layer 200hPa-50hPa.

Quality Control

Once the AMSU-B radiance data has been unbiased, it is then subjected to a series of quality control checks before it makes its way to the assimilation. In all, each AMSU-B radiance observation undergoes 14 checks; these are listed in Annex 1. Note that these tests are applied to the bias-corrected radiance rather than the original non-corrected radiance.

Besides checking the radiance itself, we also verify the quality of the complementary information which accompanies each observation, e.g. surface type; scan position, satellite zenith angle, etc. Some tests consist of checking for coding errors. Others check the internal consistency of the report, or the consistency between the type of surface reported and the model surface type, or for gross errors.

Some AMSU-B channels are sensitive to precipitation. These channels are not used since the 3Dvar system does not have a cloud liquid water variable as part of the model state and is incapable of correctly assimilating these radiances. To determine the precipitation contamination for AMSU-B radiances, we make use of a scattering index algorithm developed by Bennartz (1999). As with AMSU-A, some lower-peaking channels are also flagged over high terrain, where the surface contribution is non-negligible. The topography thresholds used are listed in Annex 1. Similarly, in very dry atmospheric conditions mostly in the Polar Regions, we do not assimilate some AMSU-B channels because of a significant surface contribution. These points are easily depicted as the innovation statistics become very large. To eliminate these data, a so-called dryness index was developed. This index is the difference between the observed AMSU-B radiances of channels 3 and 5. By relating the index to areas where innovations were notably larger because of a large surface contribution, a set of threshold values was determined for three of the four AMSU-B channels assimilated. The threshold values of the dryness index are listed in Annex 1.

As for AMSU-A, a Rogue check is performed on the innovations or difference between observed

and simulated radiance *(O –P)*. This is similar to what is referred to as a background check in the context of conventional data. Depending on the channel and its inherent difficulties, innovations greater than 2-4 times the total channel error standard deviation are rejected. The exact multiple of standard deviation used for each channel for the Rogue check are listed in Annex 1.

Rejects are of three different types:

<u>Single</u>: a test rejects each channel individually,

<u>Partial</u>: a test rejects more than one channel, but not all,

<u>Full</u>: a test rejects all channels at an observation point.

Finally, it is also possible for the operational meteorologist to specify the rejection of a complete orbit, in the case of major problems with satellite operations.

Channel selection and horizontal thinning

Following bias correction and quality control, the final data selection process begins. This can be divided into two steps, channel selection and horizontal thinning.

Due to difficulties in specifying surface emissivity and because of uncertainties in the trial field skin surface temperature over land and sea-ice, we make restricted use of lower-peaking channels over these surfaces.   Channel selection over water and over land or sea-ice surfaces is summarized in Table 1.

Ocean	Land or Sea-ice
AMSU-B 2 to 5	AMSU-B 3 to 5

Table 1. AMSU-B channels selected for assimilation.

In order not to overwhelm the 3D-Var with satellite data and to provide a volume of data compatible with the resolution of the global analysis system grid (240x120), the AMSU-B data are thinned to a separation of about 250km. This separation seems to be optimal at the current system resolution, given the fact that the 3D-Var assumes that observational errors are not correlated horizontally. Effectively at 250 km spacing, the horizontal correlation of the error in the radiance data is negligible.

The thinning process can be summarized as follows:

i) A pre-thinned (75km) AMSU-B data are grouped together in 250km square boxes.

ii) Within a box, a priority scheme determines which pixel will be retained. Priority goes to the pixel which has the lowest percentage of channels rejected; in the case where more than one pixel has the same low percentage; the pixel which is closest to the box center will be chosen.

iii) Radiances measured at the extreme left and right edges of the satellite swath are not used in the analysis because their errors are generally larger. More precisely, fields of view numbered 1-7 and 84-90 are excluded for AMSU-B.

Basic experimental results with AMSU-B radiance data

The first tests with a radiance data pertain to the sensitivity of the channel to atmospheric variables, it is nothing but a verification that the RTM is producing the proper response in the analysis. One observation from each of the channels considered are isolated as well as the atmospheric variables needed for the RTM, and the sensitivity or Jacobian of individual channels are calculated and plotted against each other and compared to other satellite data. The vertical response of the data can then be plotted and inspected to insure that most if not all of the response is within the NWP model vertical domain. Such plots are indicated in the right panel of Fig. 1 and were used to effectively raise the moisture analysis top level. Similarly the sensitivity to surface variables can be looked at and judged whether acceptable for assimilation or not.

The next series of tests pertain to the full 3D-Var system and the evaluation of the response of one channel at one location (not shown), and as shown in Fig. 3, the cumulative contribution of all channels at one location. Again this is to verify that all the operators such as interpolation of the trial field for the RTM are responding as expected, and more specifically to measure the impact of radiances on the temperature and moisture retrievals. Note the difficulty with AMSU-B data in that the response in the Tropics is very large on the moisture retrieval and relatively small on temperature, whereas the response in the Extra-Tropics is large on temperature and relatively small on moisture.

Results from OSE and from the recent implementation of AMSU-B in 3D-Var

In order to evaluate the impact of new data sources, such as AMSU-B in this study, most NWP Centres prepare Observing System Experiments (OSE) with and without these new data to measure their impact in a full forecast/analysis system. It is generally accepted that to get a clear signal, the OSE should cover a period of at least 1 month and preferably two months as was done in this study. We have prepared many such OSEs and present here the latest which produces

acceptable results for both a summer and winter periods.

In Fig. 4, the 2-month averaged verification against the North Hemisphere (NH) radiosonde dataset for the control (operational, blue) and the AMSU-B system (red) are presented. As indicated, the short term 6-h results are very positive particularly on the moisture variables. In Fig. 5, the verification in the Southern Hemisphere (SH) shows a very large positive impact of AMSU-B data on the moisture forecast at 6h, 48h, and somewhat smaller beyond 96h (not shown).

Evaluating against radiosonde data is very valuable because of the high quality of this dataset, however, it does not give a very good evaluation of the system over oceanic areas and other areas such as the SH which are basically void of radiosonde data. NWP Centres also prepare verifications against analyses which has the advantage of evaluating continental and oceanic areas. In Fig. 6, the 500 hPa geopotential anomaly correlation scores for the month of September 2003 are presented. This is 3 months after the June implementation of AMSU-B data in our operational system. As can be seen, the scores of the Canadian model are very competitive with other leading Centres both in the short (day1-4) and the longer term forecasts.

Finally, another measure of performance for verifying the impact of moisture sensitive data such as AMSU-B is by verifying the QPF forecasts issued from the operational (blue) and AMSU-B systems (red). As indicated in Fig. 7, the QPF THREAT scores against the surface synoptic network measurements are significantly improved particularly in the 20mm/24h and above categories with a somewhat more neutral result in the in the less than 20mm/24h categories.

Conclusions

We have successfully implemented the use of moisture sensitive AMSU-B radiances in CMC's 3D-Var data assimilation system. The impact of this additional source of moisture data is very positive on the moisture analyses and, as expected, the precipitation forecasts issued from the new analyses are also improved. The direct impact on moisture fades out with time and beyond 72 hours is not measurable on the moisture forecasts. However, the impact on the other analysis variables such as temperature, geopotential, and wind field, however small initially, becomes increasingly larger in the 4-6 day range contributing to significant improvements in the long term forecasts.

References

Bennartz, R., A. Thoss, A. Dybbroe and D. B. Michelson, 1999: Precipitation Analysis from AMSU, Nowcasting SAF, Swedish Meteorological and Hydrological Institute, Visiting Scientist Report, November 1999.

Chouinard C. and J. Hallé: The impact of TOVS radiances in the CMC 3D-Var analysis system. ITSC-X proceedings, Boulder, Colorado, February 1999, p92-98.

Chouinard C., J. Hallé, and R. Sarrazin: Recent results with TOVS data in the new CMC 3D-Var-analysis system: the combined and separate impact of microwave radiance observations with aircraft wind data. ITSC-XI proceedings, Hungary, Budapest, September 2000, p53-57.

Chouinard C., C. Charette, J. Hallé, P. Gauthier, J. Morneau, and R. Sarrazin: The Canadian 3D-Var analysis scheme on model vertical coordinate. 18th Conference on Weather Analysis and Forecasting, 30 July-2 August 2001, Fort Lauderdale, Florida.

Chouinard C., J. Hallé, C. Charette, and R. Sarrazin: Recent improvements in the use of TOVS satellite radiances in the Unified 3D-Var system of the Canadian Meteorological Centre. ITSC XII proceedings, Lorne, Australia, 27 February-March 5, 2002 (to be published).

Garand L, and J. Hallé: Assimilation of Clear and cloudy-sky Upper -Tropospheric Humidity Estimates Using Goes 8 and Goes 9 Data. *J. Atm. Science*, **14**, pp. 1036-1054.

Gauthier, P., C. Charette, L. Fillion, P. Koclas and S. Laroche, 1999: Implementation of a 3D variational data assimilation system at the Canadian Meteorological Center. Part I: The global analysis, Atmosphere-Ocean, No.2, pp 103-156.

Grody N., F. Weng, and R. Ferraro: Application of AMSU for obtaining hydrological parameters. Microwave and Remote Sensing of the Earth's surface and atmosphere, 2000, pp.339-351.

Annex 1; Quality control tests for AMSU-B channels.

| #	Test	Rejected if:	Type of reject
1	topography reject	topography > 2500m for AMSU-B 3, 2000m for AMSU-B 4, 1000m for AMSU-B 5	partial (AMSU-B 3-5)
2	invalid land/sea qualifier	qualifier differs from {0, 1, 2}	full
3	invalid terrain type	terrain type differs from {-1, 0,1}	full
4	invalid field of view number (fov)	fov outside valid range [1,90]	full
5	satellite zenith angle out of range	satellite zenith angle outside valid range [1,60]	full
6	inconsistent field of view and satellite zenith angle	$ABS(((fov-45.5)*1.31)-angle) > 1.8$	full
7	inconsistent land/sea qualifier and model mask	other than: qualifier=1 (sea observation) and model mask <0.20 (model sea) or qualifier=0 (land observation) and model mask>0.50 (model land)	full
8	inconsistent terrain type and model ice	terrain type=0 (sea ice) and model ice<0.01 (no model ice)	full
9	uncorrected radiance	correction flag is off	single
10	rejected by RTTOV	3Dvar quality control flag is on	single
11	radiance gross check failure	Tb < channel varying Tb min, or Tb > channel varying Tb max.	single
12	Dryness index reject	Dryness index = Tb(AMSUB3) – Tb(AMSUB5) Reject if (dryness index) > 0 for AMSU-B 3, -10 for AMSU-B 4, -20 for AMSU-B 5	partial (AMSU-B 3-5)
13	Bennartz scattering index reject	Bennartz scattering index> 40 over sea-ice, or 15 over sea, or 0 over land.	full
14	innovation rogue check failure	$(y-H(x))>\alpha*(total\ error)$, where α=2 for AMSU-B 1, =3 for AMSU-B 2 =4 for AMSU-B 3-5	single
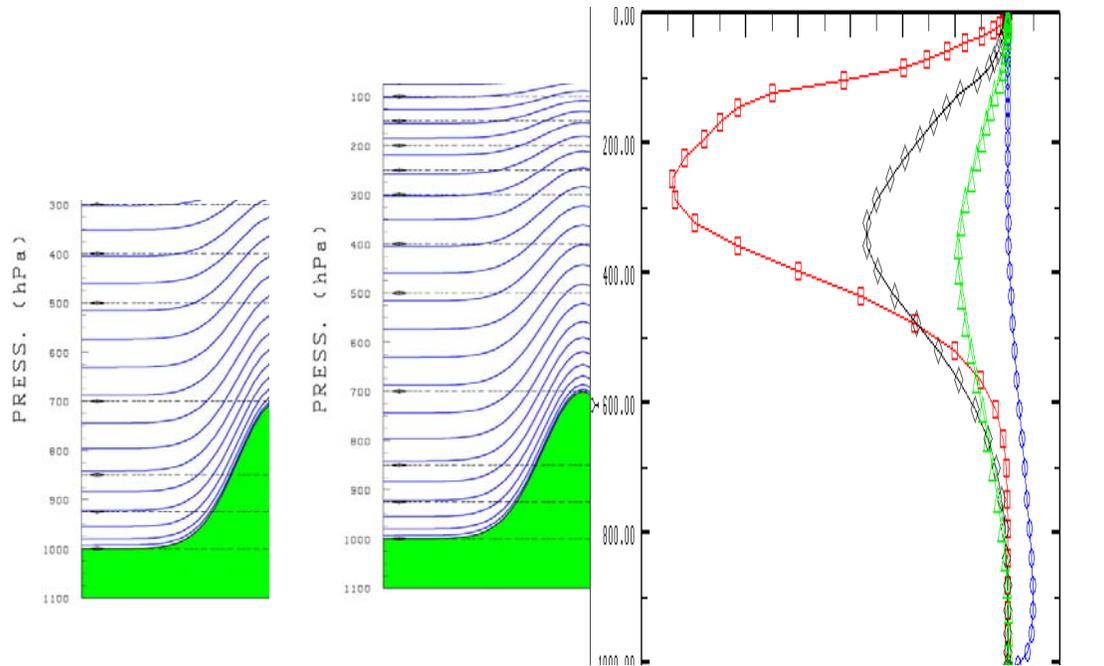
Fig. 1 Schematic view of the model top level of moisture analysis (left panel) prior to AMSU-B in comparison to the current raised top (central panel) to accommodate the sensitivity of AMSU-B radiances (right panel)
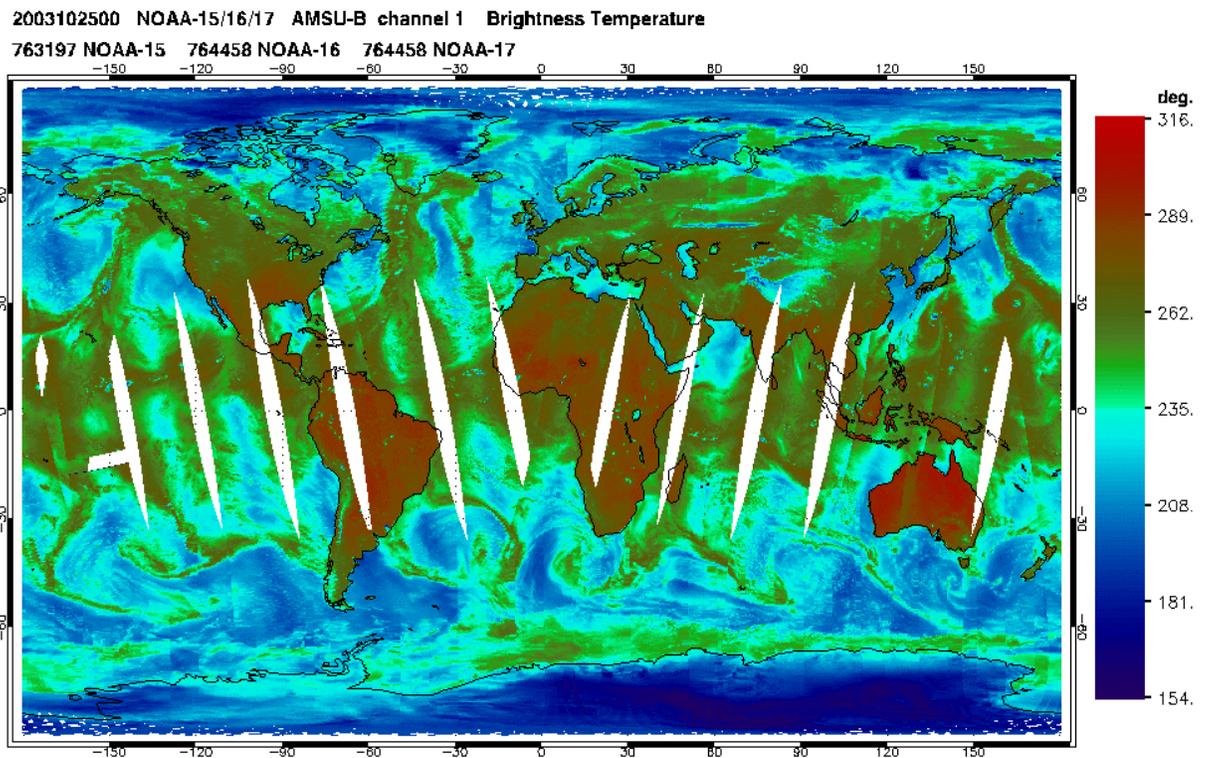

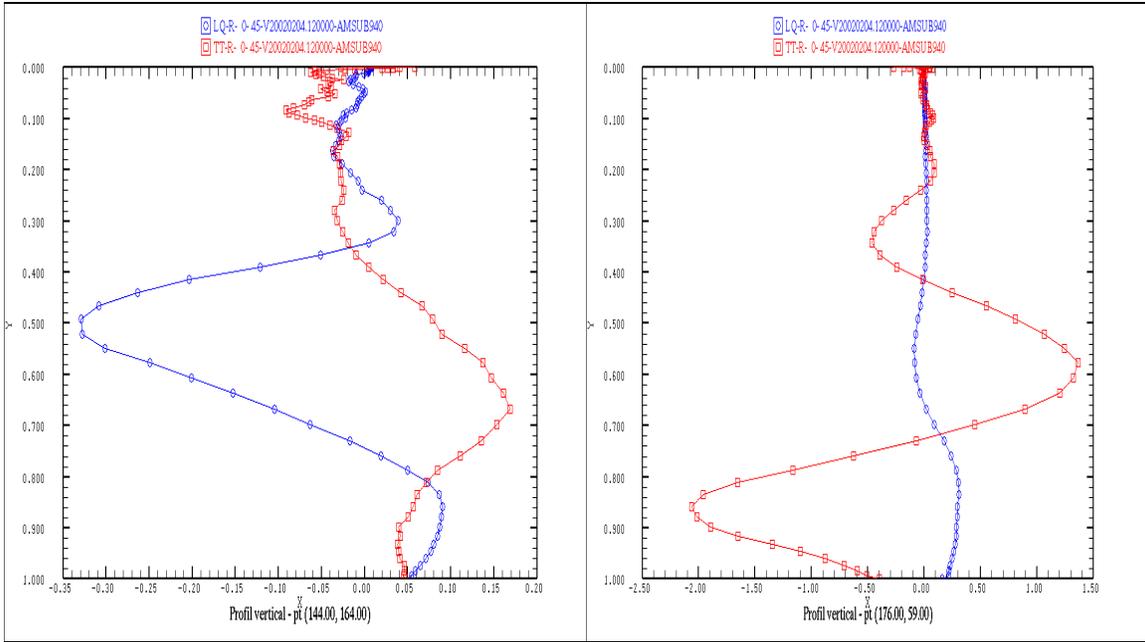Figure 2. Typical coverage of AMSU-B radiances for a 6-hour time window (16 km footprint)

Fig. 3 First analysis tests; impact of the 4 AMSU-B channels at one pixel location. Vertical profile of temperature (red) and lnq moisture variable (blue) analysis increments in the Tropics (left panel) and Extra-Tropics (right panel).
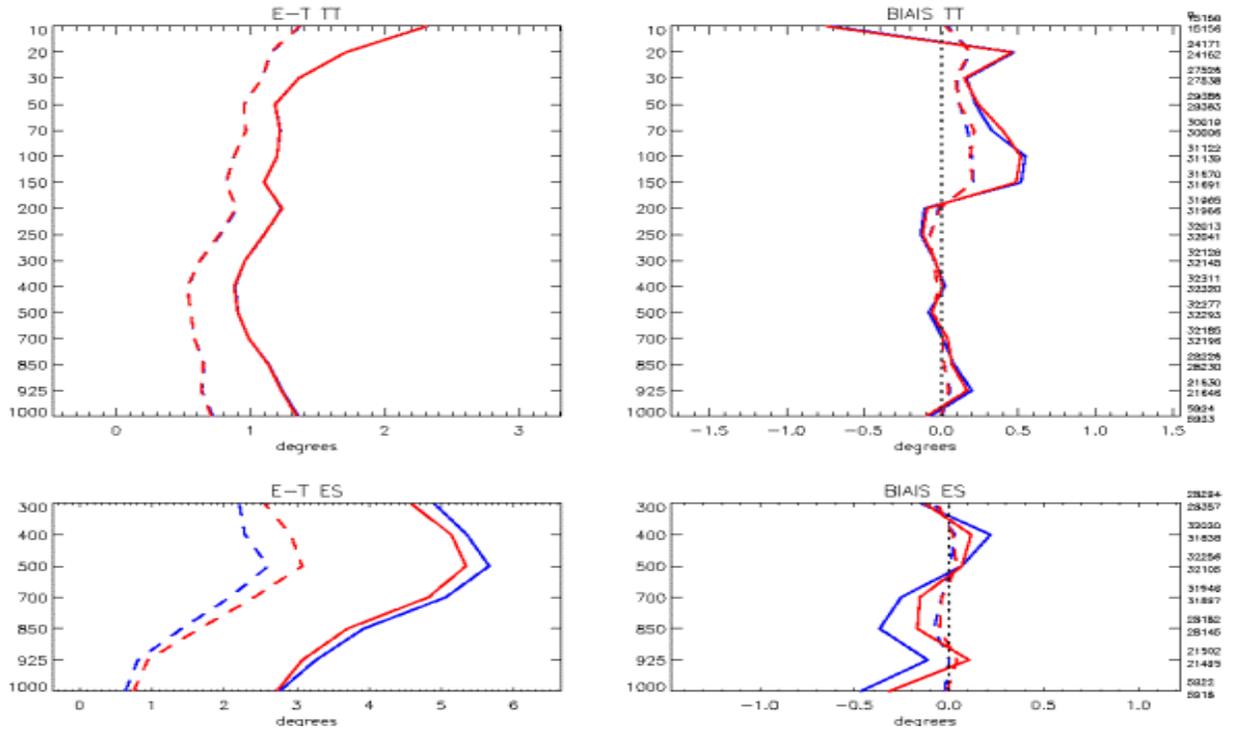
Fig. 4 Verification against NH radiosondes for the August-September 2002 period. Top panels are for temperature and bottom panels for dewpoint depression. Units are degrees.
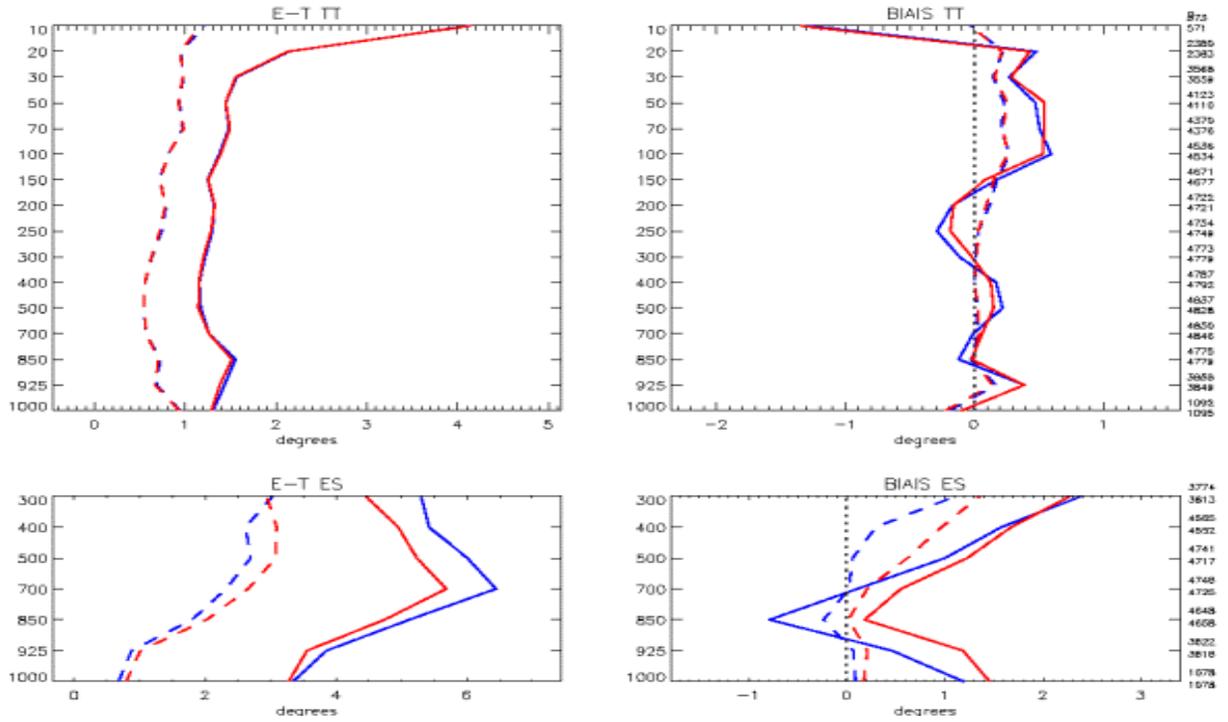
Fig.5 Verification against SH radiosondes for the August-September 2002 period. Top panels are for temperature and bottom panels for dewpoint depression. Units are degrees.
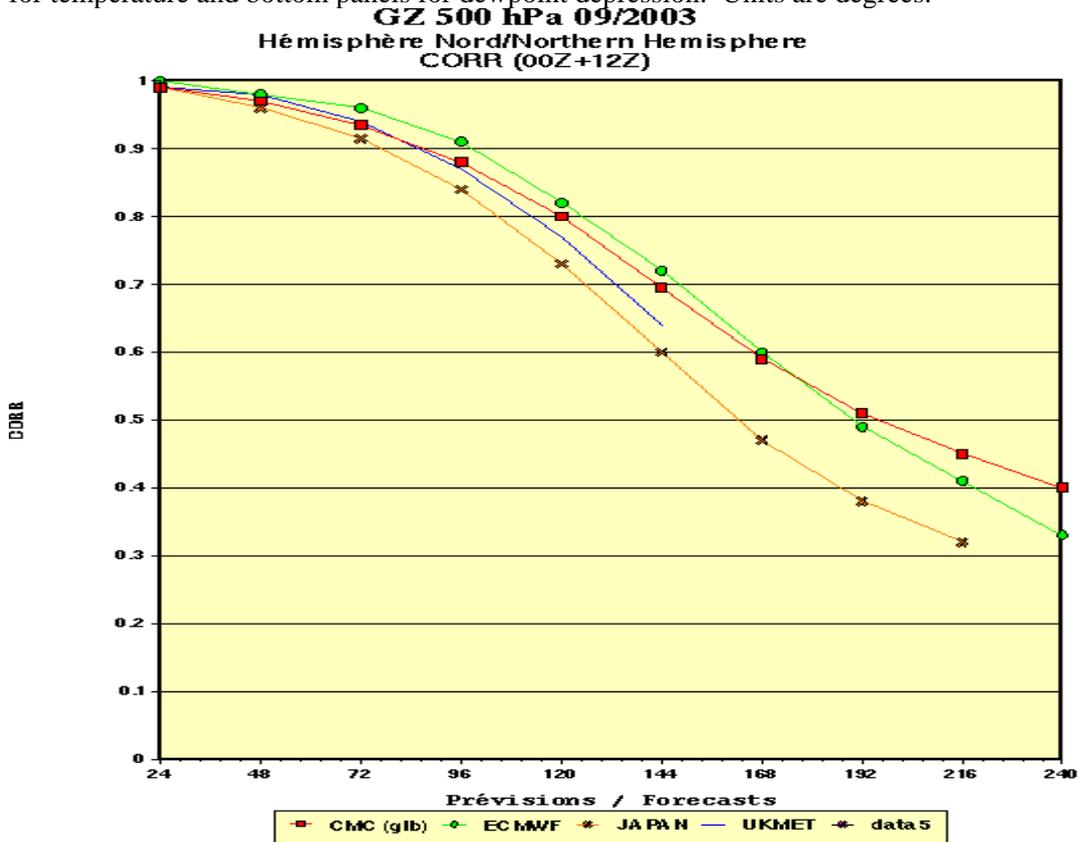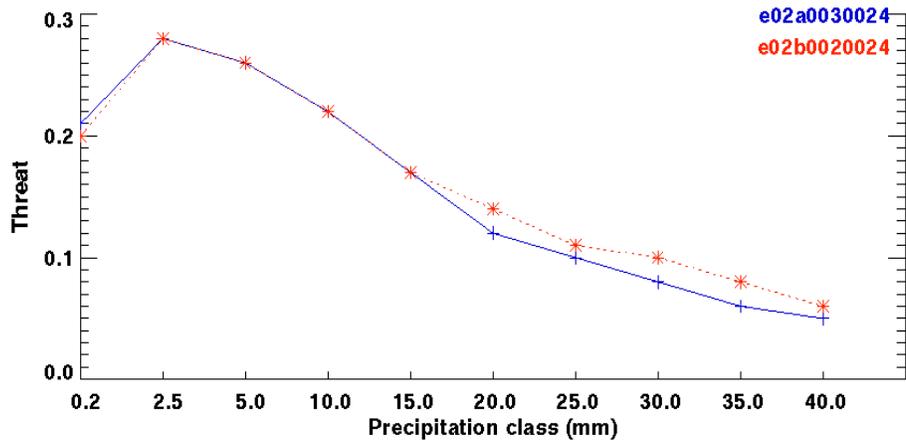
Fig. 6 NH Anomaly correlation scores of the new AMSU-B system (red line) compared to scores from other leading NWP Centres for the month of September 2003.

Fig. 7. THREAT scores of the 0-24h QPF forecasts issued from the OPERATIONAL (full blue lines) and the AMSU-B system (red dashed lines) against the NA surface synoptic network measurements. The number of observations in each category and the categories are indicated at the bottom.