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USE OF AMSU-B RADIANCES IN THE CANADIAN METEOROLOGICAL CENTRE 3D-VAR SYSTEM

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1. INTRODUCTION

The Canadian Meteorological Centre (CMC) 3D-var is an incremental analysis system that is currently used by both our global and regional models. During the last few years, it has undergone a series of upgrades from isobaric to a terrain-following coordinate, and most importantly the assimilation allows for direct assimilation of satellite radiances.

In terms of radiance data, the operational system currently uses so-called raw level-1b AMSU-A whose quality and bias are controlled by the data user and not the producer. The quality control (QC) and thinning algorithms of the radiance data are more complex and air-mass dependent, but their impact on analyses and forecasts are very large, most noticeably in the Southern Hemisphere.

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 ingest and QC. One aspect of NWP systems, which definitely can benefit from this additional data, is the moisture analysis. In that context we have started to experiment with the ingest of water sensitive radiances from the AMSU-B instruments onboard NOAA-15 and NOAA-16 (and soon NOAA-17) . As will be shown, the quality of both the temperature and moisture analyses are significantly improved when using these additional satellite data. Improvements in the analyses and forecasts are greatest in the Tropics. Preliminary evaluations of the impact of AMSU-B radiances on quantitative precipitation forecasts (QPF) are encouraging.

One of the advantages of variational data assimilation systems is their ability to assimilate indirect observations such as satellite radiances. With the help of a fast radiative transfer model, most NWP Centres have been able to directly assimilate radiance data and show significant gains in the quality of their analyses and forecasts. The quality of an instrument and its measurements dictate how much influence a type of data will receive in an analysis system, but when it comes to indirect radiance measurements the quality of the radiative transfer model which maps out the radiance data in physical space such as temperature and moisture will also be an issue. Depending on the perceived sensitivity of a radiance to say water vapour i.e. the Jacobian, the response/impact on the moisture analysis will be larger/smaller.

The radiance data from AMSU-A instrument has the advantage of being sensitive to temperature only and its sensitivity or Jacobian is very homogeneous and varies little whether in a Tropical or mid-latitude atmospheric air-mass. On the other hand, the data from the AMSU-B instrument is very sensitive to water vapour and also to temperature. The Jacobian of the AMSU-B channels varies significantly from pole to Equator. This makes the assimilation of AMSU-B data a more delicate operation requiring a very good knowledge of the temperature and moisture background error statistics.

The current use of moisture sensitive radiances at many NWP Centres is still limited to the use of infrared channels from either the GOES or NOAA/HIRS instruments. However, NCEP and UKMET have been assimilating AMSU-B data since their availability i.e. NOAA-15 and more recently NOAA_16. In Canada, we have just started to experiment with AMSU-B in view of replacing the current use of statistically derived humidity profiles derived from the GOES sensors (Garand and Hallé, 1997). In this paper there will be a brief description of the steps involved in preparing AMSU-B data for assimilation followed by some preliminary experimental results from tests done with the full 3D-Var assimilation global data assimilation system.

2. BRIEF DESCRIPTION OF THE REVISED 3D-VAR SYSTEM

The basic system used in this study is the one that was described in Gauthier et. Al. 1999, and more recently in two papers at the ITSC-11 meeting (Chouinard and Hallé, 2000 and Chouinard et al. 2000). 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 and use of conventional data, the introduction of new sources of data, and the QC as described in Chouinard et al. 2002. The combined impact of 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.

3. SATELLITE DATA USED IN THIS STUDY

Observed AMSU-A and AMSU-B radiances from the NOAA-15 and NOAA-16 satellites 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) whose main functions are navigation and calibration. Finally, the radiances are stored in a database at CMC in a local format similar to BUFR.

The AMSU-A instrument has 15 microwave channels with a resolution of approximately 45km. All 15 channels are received at CMC, although only a subset of these is actually assimilated. Certain channels, which are sensitive to the underlying surface, are not used because of the inherent difficulties of assimilating surface channels over land and ice. Many stratospheric channels are not used because their peak contribution is above our NWP model top level currently at 10hPa.

The AMSU-B instrument has 5 microwave channels with a higher resolution than the AMSU-A instrument, i.e. 15km (AMSU-B) compared to 45km (AMSU-A). AMSU-B radiances are very sensitive to moisture in the atmosphere but are also sensitive to temperature. The objective of the experiments presented here is to assess the usefulness of AMSU-B radiances, when added to our operational global assimilation system. Radiances from the HIRS instrument are also received via the same link but were not used in the series of experiments presented here.

4. SATELLITE FLOWCHART OF ATOVS RADIANCE PROCESSING FOR ASSIMILATION

Before the satellite data can be assimilated it has to be monitored to obtain a prior estimate of the level of noise and biases in the data. Following this passive monitoring step, there is an elaborate bias correction procedure that is made of three steps; the first to remove a global bias, the second to remove the scan dependent bias, and the last to remove what residual bias is left and relate it to air-mass predictors. To remove the air-mass bias, the algorithm now uses only 2 predictors, a tropospheric, and a lower stratospheric measure of temperature. Because the channels we have chosen to assimilate have little surface sensitivity, these predictors seem to work very well as indicated by our monitoring system. For more details the reader is referred to (Chouinard et al., 2002)

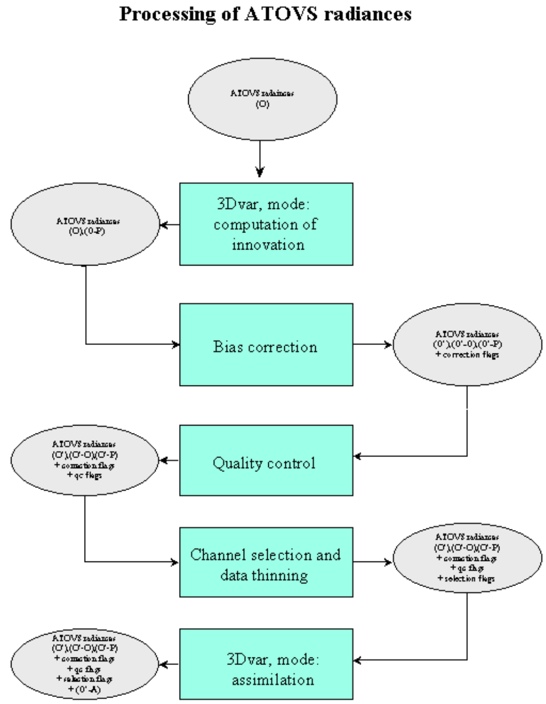

Fig. 1. Processing of ATOVS radiances.

The different steps leading to radiance data assimilation are illustrated in the flowchart of Fig. 1. The grey oval represents a BURP file, while the green rectangle represents a process. Variables shown are the observed radiance (O), the corrected radiance (O'), the simulated first guess radiance (P) and the analyzed radiance (A). The processes shown are:

1) computing the innovation using the 3Dvar,
2) computing the radiance bias correction,
3) quality control,
4) channel selection and thinning,
5) assimilation in the 3Dvar.

5. PREPARATION OF THE SIMULATED RADIANCES

In order to assimilate a radiance in 3D-Var, we need to first calculate the so-called innovations or (O-P) from the atmospheric state variables. At each location where a radiance is observed, the radiative transfer model needs a vector of temperatures, specific humidity at 43 pressure levels, and the pressure, temperature and wind components at the surface. These state variables have to be horizontally interpolated to the actual location of the radiance and vertically interpolated from the model coordinate to the 43 pressure levels including extrapolation at the top if needed. The simulated radiance P, can then be computed with the help of a radiative transfer model. Currently, we use the RTTOV-7 radiative transfer model, which is maintained and distributed by the EUMETSAT Satellite Application

Facility on Numerical Weather Prediction (NWPSAF). The RTTOV web site can be found at: http://www.metoffice.com/research/interproj/nwpsaf/rtm/index.html.

6. BIAS CORRECTION

It is a well-known fact that radiance observations, as well as radiative transfer models, contain important errors. It is essential to remove the radiance biases in order to properly extract the information content for data assimilation. Denoting the ensemble mean of A as <A>, (time average), the innovation bias, <(O -P)>, manifests itself principally in two different ways, one which depends on scan position and the second which is air-mass dependent.

The bias correction scheme developed at CMC uses a two-step approach. The first step is to remove a global bias at each scan position. The second step consists of removing the remaining bias using a linear regression between the innovation bias, <(O -P)>, and the following model predictors:

- geopotential thickness of layer 1000hPa-300hPa,
- geopotential thickness of layer 200hPa-50hPa.

Operationally, the bias correction coefficients are updated when deemed necessary, typically every two or three months. This bias correction method is applied to both AMSU-A and AMSU-B radiances.

7. QUALITY CONTROL

Each ATOVS radiance which will eventually make its way to the assimilation system passes a series of quality control checks. In all, each radiance observation undergoes 14 tests. These are listed in Table 1 for AMSU-B. Note that these tests are applied to the bias-corrected radiance rather than the original non-corrected radiance.

#	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))>α*(total error), where α=2 for AMSU-B 1, =3 for AMSU-B 2 =4 for AMSU-B 3-5	single

Table 1. Quality control tests for ATOVS AMSU-B channels

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 flagged since the 3Dvar system does not have the cloud liquid water variable as part of the model state and is incapable of correctly assimilating these radiances. To determine precipitation contamination for AMSU-B radiances, we make use of scattering index algorithm developed by Bennartz (1999). Some lower-peaking channels are also flagged over high terrain, where the surface contribution is non-zero. The thresholds used are listed in Table 1. Moreover, in very dry conditions mostly in the Polar Regions, we do not assimilate AMSU-B channels because of a significant surface contribution. The difference between the observed radiances of channels 3 and 5 was found to be reasonable indicator of air-mass dryness; the thresholds for the dryness index are also listed in Table 1.

Furthermore, the innovation (O -P) is used in the quality control procedure. Innovations greater than 2-4 times the total channel error standard deviation are rejected.

Rejects are of three different types:

1) single: a test rejects each channel individually,
2) partial: a test rejects more than one channel, but not all,
3) full: a test rejects all channels at an observation point.

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.

8. CHANNEL SELECTION AND HORIZONTAL THINNING

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

8.1 *Channel selection*

Due to the difficulty in determining the surface emissivity and skin temperature over land and sea-ice, we make more restricted use of lower-peaking channels over these surfaces. Channel selection is summarized in Table 2.

8.2 *Horizontal thinning*

In order not to overwhelm the 3Dvar assimilation system and to provide a proper volume of data as supported by the analysis grid (240x120), the ATOVS data are thinned at a separation of about 250km. This separation seems to be optimal with the current system, given the fact that the 3Dvar assumes no observation error correlation for radiances and given the rather broad horizontal correlation functions used for the background error.

The thinning process can be summarized as follows.
A pre-thinned (75km) AMSU-B ATOVS data are grouped together in 250km square boxes. Within a box, a priority scheme determines which observation point will be retained. Priority goes to the point which has the lowest percentage of channels rejected; in the case where more than one point has the same low percentage, the point which is closest to the box centre will be chosen.
Radiances measured at the extreme left and right edges of the satellite swath are not used in the analysis because of their larger errors. More precisely, fields of view numbered 1-7 and 84-90 are excluded for AMSU-B.

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

Table 2. ATOVS AMSU-B channels selected for assimilation.

9. EXPERIMENTAL RESULTS FROM 3D-VAR ASSIMILATION TESTS

In order to demonstrate the impact of new data sources, such as AMSU-B in this study, most NWP centres prepare parallel suites of their full forecast/analysis system and monitor the performance of this system with and without these new data. The

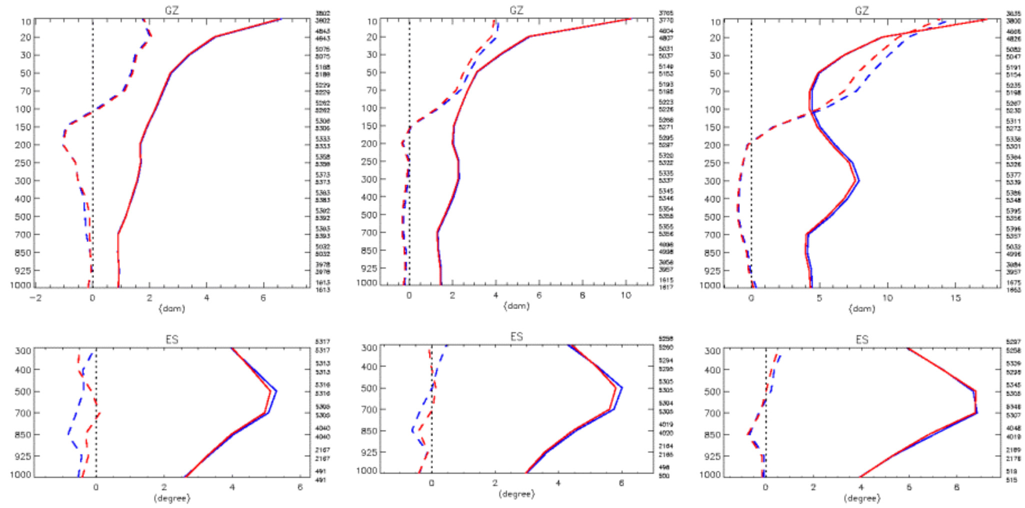

Fig. 2a The 2-month (January and February 2002) averaged verification against the North American (NA) radiosonde dataset for the control (blue lines) and the suite with AMSU-B (red lines). The full lines are the std of the error whereas the dashed lines are the biases. The upper panel is the geopotential (in dam)and the bottom panel the dewpoint depression (in deg.). The left panel is the 6-h forecast, the middle the 48-h, and the right the 96-h forecast.

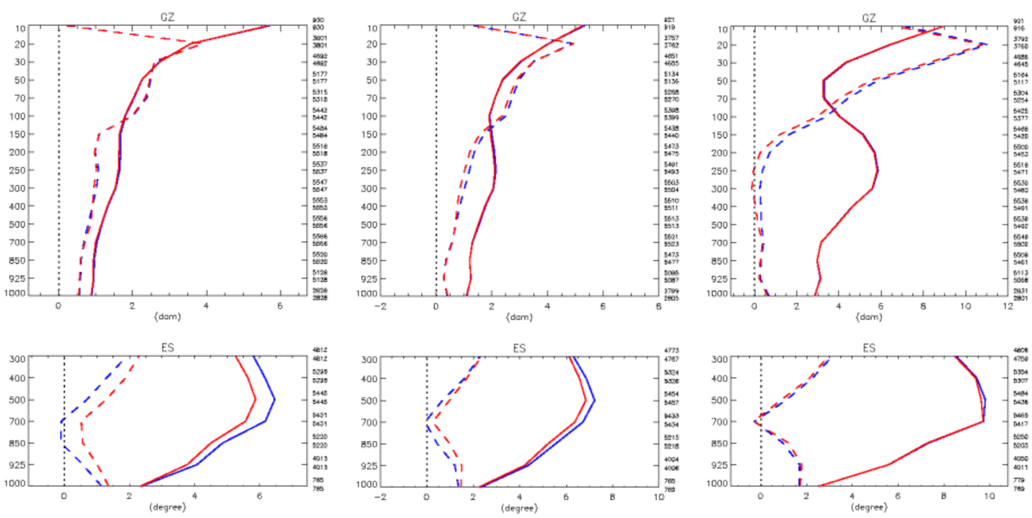

Fig. 2b Same as Fig. 2a but verified against the Southern Hemisphere radiosonde dataset.

period of tests should be at least 1 month and preferably a few months so as to get a clear signal. In this study we have prepared many such parallel runs and present here the latest which produces acceptable results for both a summer and winter periods.

One type of verification consists of comparing the new and control analyses and their respective trial or 6-h forecasts against radiosonde data. The same type of verifications can also be done for 5-10 day forecasts issued from the parallel and control suite of analyses. The radiosonde data covers most of the troposphere and is generally regarded as a good quality dataset, however, with the exception of island data, it covers only continental areas To complement this type of verifications, we have compared the forecasts from each analysis suite to their respective analyses. Over land where the analyses have fitted the radiosonde data very closely, the verifications from analyses or radiosonde are very similar. Over the oceans, the verification of forecasts against analyses complement the radiosonde data and give us a better indication of the performance of the system. In what follows, both type of verifications are presented.

In Fig. 2a, the 2-month averaged verification against the North American (NA) radiosonde dataset for the control and the suite with to the same with AMSU-B data. As indicated the short term 6-h results are very positive and remain so until 96h. In Fig. 2b, the verification in the Southern Hemisphere (SH) shows a very large positive impact of AMSU-B data on the moisture forecast at 6h and 48h and somewhat smaller beyond 96h.

In Fig.3 the verifications against analyses over NA and the SH extra tropics are compared for the forecasts issued from each parallel suite. These results confirm that the improvements of the AMSU-B data over land are even larger over the oceans particularly in the and remain positive up to 96 h. Note that the AMSU-B system consistently outperforms the Control run on almost every forecast of the 2-month period.

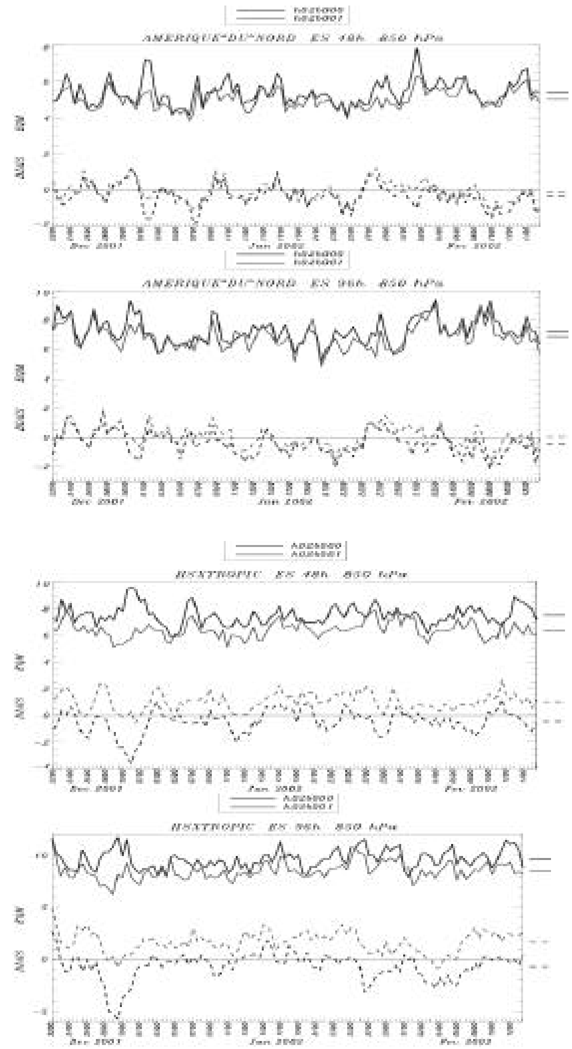

Fig.3 The verification against analyses over NA (upper two panels) and the SH extra tropics (bottom two panels) for the 48-h (left) and 96-h (right) forecasts of moisture at 850 hPa. The black lines are for the CONTROL and the grey lines for the AMSU-B forecasts. The RMS (full lines) and BIAS (dashed lines) are the individual scores for the full 2-month period as indicated in the bottom axis. The2-month mean appear on the right hand side of the panels. Units are degrees C.

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 control and parallel suite. The QPF measurements from the surface synoptic network are used for this. As indicated in Fig. 4, the bias and Threat scores of the AMSU-B forecasts are significantly improved in the 20mm/24h and above with a somewhat more neutral result in the in the less than 20mm/24h categories.

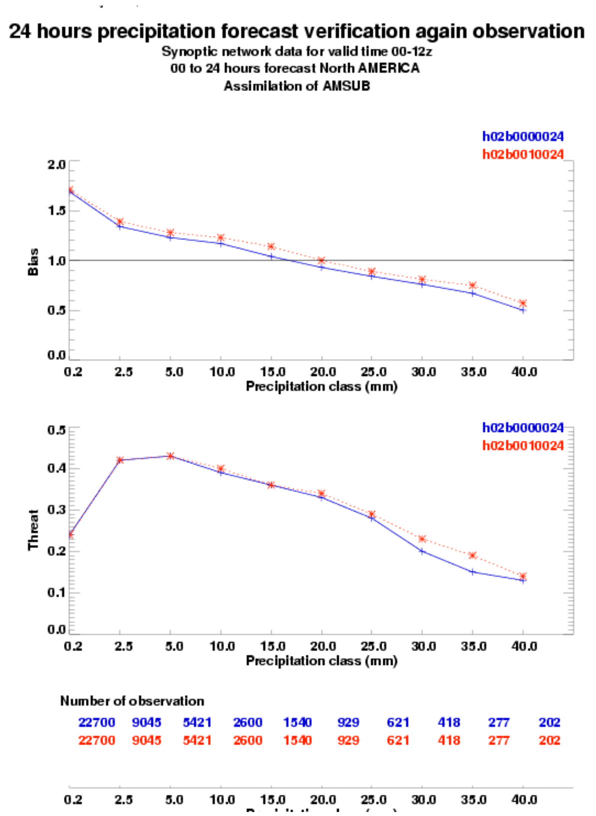

Fig. 4. Verification of the 0-24h QPF forecasts issued from the CONTROL (blue line) and the AMSU-B suite (red line) against the NA surface synoptic network measurements. The number of observations in each category and the categories are indicated at the bottom, and the top panel shows the BIAS, and the bottom panel the traditional THREAT score

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