Environnement Canada
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Processing of ATOVS radiances at the

Canadian Meteorological Centre

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Revision history			
Version	Date	Author/modifications	Remarks
1.0	1999/07/30	J. Hallé	First version, TOVS level 1D
2.0	2002/03/27	J. Hallé	Modified to reflect ATOVS level 1B system
3.0	2003/10/16	J. Hallé	Includes RTTOV-7 , NOAA-17 and AMSU-B
3.1	2004/09/27	J. Hallé	Include AQUA satellite
3.2	2004/12/24	J. Hallé	Modified to reflect 4dVar changes
3.3	2005/12/07	J. Hallé	Include NOAA-18
3.4	2007/05/14	J. Hallé	RTTOV-8, dynamic bias correction, vertical interpolator, include additional data at extreme scan positions.
3.5	2009/09/10	C. Côté	Include METOP-2 and NOAA19. Eliminate option to reject a full orbit by operational meteorologist.
3.6	2013/02/13	C. Côté	Include RARS data.
3.7	2013/05/07	C. Côté	Include METOP-1, remove NOAA17
3.8	2014/05/21	A. Beaulne	Some updates/corrections to the text
3.9	2015/06/04	A. Beaulne	Update for the GDPS4.0.0 implementation of November 18, 2014.

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1. Introduction.

This document is a description of the operational processing of ATOVS radiances at the Canadian Meteorological Centre (CMC). The technical aspects of ATOVS processing are discussed, including quality control, bias correction, channel selection, data thinning and operational monitoring.

Preceding versions of this document described the three previous implementations of TOVS radiances which occurred at CMC during a period of 15 months, from September 2000 to December 2001. The first operational one was on September 27th, 2000 and it assimilated MSU/AMSU-A level 1D radiances from NOAA-14 and NOAA-15 satellites. The first version of this document (version 1.0) described this system. Subsequent major improvements included replacing the level 1D radiances by level 1B radiances, changing from observation to model predictors in the bias correction scheme and only assimilating AMSU-A channels from NOAA-15 and NOAA-16. This work resulted in the second implementation on June 7th, 2001, while a third one followed on December 11th, 2001. On that occasion, an improved quality control allowed lower-peaking AMSU-A channels to be added to the analysis..

This document (version 3.9) incorporates the modifications made to the operational system after December 11th, 2001.

1) on December 12th, 2002, the radiation model was upgraded from RTTOV-6 to RTTOV-7 and NOAA-17 AMSU-A radiances were added;

2) on June 19th, 2003, AMSU-B radiances from NOAA-15 16 and 17 were added;

3) on September 21st 2004, AMSU-A radiances from AQUA were added;

4) on December 7th, 2005, AMSU-A and MHS radiances from NOAA-18 were added;

5) on May 28th, 2008, the radiation model was upgraded from RTTOV-7 to RTTOV-8, a dynamic bias correction scheme and a new vertical interpolation scheme were implemented. The thinning algorithm was also modified to include previously excluded data at extreme scan positions.

6) on June 22nd, 2009, the channel 11 to 14 of AMSU were added for assimilation in the analysis system with the raise of model lid from 10 to 0.1 hPa. The forecast model levels went from 58 eta levels to 80 hybrid levels. A static bias correction was preferred for these channels.

7) on December 3rd, 2009, AMSU-A and MHS radiances from METOP-2 and NOAA19 were added. The quality control scheme was modified so that it is no longer possible for the operational meteorologist to reject a full orbit.

8) on November 16th 2011, the horizontal resolution of the sampling (thinning) of all the satellite radiances was reduced from 250 km to 150 km. Also, the bias correction "averaging period", over which channel-specific biases are evaluated from stored innovation data, was decreased from 15 days to 7 days. Finally, there has been an update to the RTTOV radiative transfer model spectroscopic files (no-zeeman) for AMSUA.

9) on February 13th 2013, RARS (Regional Atovs Retransmission Service) data were added to the global and regional systems (except for AQUA & METOP-2).

10) on April 2013, NOAA17 was decommissioned.

11) on November 7th 2013, AMSU-A (channels 11 to 14 not assimilated) and MHS radiances from METOP-1 were added, including RARS.

12) on June 2014, NOAA16 was decommissioned.

13) on November 18th 2014, AMSU-A (channels 11 to 14) radiances from METOP-1 were added. The RTTOV radiative transfer model was upgraded from version 8.7 to 10.2.

Table 1 summarizes all implementations related to ATOVS radiances.

Date	Description	Satellites
2000/09/27	First implementation. MSU/AMSU-A level 1d radiances.	NOAA14-15
2001/07/07	-Level 1b radiances; -bias correction based on model predictors.	NOAA15-16
2001/12/11	Addition of lower-peaking channels	NOAA15-16
2002/12/12	-Upgrade to RTTOV-7; -added NOAA-17 satellite.	NOAA15-16-17
2003/06/09	Added AMSU-B.	NOAA-15-16-17
2004/09/21	Added AMSU-A from AQUA.	NOAA15-16-17, AQUA
2005/12/07	Added AMSU-A and MHS from NOAA-18.	NOAA15-16-17-18, AQUA
2008/05/28	-Upgrade to RTTOV-8; -introduced a dynamic bias correction scheme; -new vertical interpolation scheme; -additional data at extreme scan positions.	NOAA15-16-17-18, AQUA
2009/06/22	Add channels 11,12,13 and 14 of AMSUA instrument with implementation 80 level version of NWP model (lid at 0.1 hPa)	NOAA15-16-17-18, AQUA
2009/12/03	Added AMSU-A and MHS from METOP-2 and NOAA19 - Eliminate option to reject a full orbit by operational meteorologist.	NOAA15-16-17-18-19, AQUA, METOP-2
2011/11/16	Increase in thinning resolution (150km). Bias correction based on 7 days history. Correction to RTTOV spectroscopic files.	NOAA15-16-17-18-19, AQUA, METOP-2
2013/02/13	Inclusion of RARS data	NOAA15-16-17-18-19
2013/04	Decommission of NOAA17	
2013/11/07	Added AMSU-A (no channel 11-14) and MHS from METOP-1, including RARS.	NOAA15-16-18-19, AQUA, METOP-1, METOP-2
2014/06	Decommission of NOAA16	
2014/11/18	Added AMSU-A channels 11-14 from METOP-1. Upgrade to RTTOV10.2.	NOAA15-18-19,AQUA, METOP-1,METOP-2

Table 1. Summary of implementation of ATOVS at CMC.

More details on these implementations are available on the CMC operations web site:

http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/docs/changes_e.html

From outside, it requires a username and password for access that are easily available by sending a request via e-mail to simon.pellerin@ec.gc.ca.

This document gives a description of the operational system and is organized in the following way. First, a flowchart in section 2 gives a summary of the different steps in the processing of ATOVS radiances. In sections 3 through 8, each process is described individually. In the final section, a description of the operational ATOVS monitoring is presented and monitoring products are shown.

2. Flowchart of ATOVS radiance processing.

The flowchart, in Figure 1, illustrates the different steps leading to the assimilation of radiances. The grey oval represents a BURP file, while a green rectangle is a process. The variables in the ovals are the observed radiance (O), the corrected radiance (O'), the simulated radiance (P) and the analyzed radiance (A). The processes are:

1) computing the innovation using the variational analysis operator;
2) computing the correction to the bias of the radiance;
3) quality control;
4) RARS redundancy removal, channel selection and thinning;
5) assimilation in the 4Dvar analysis.

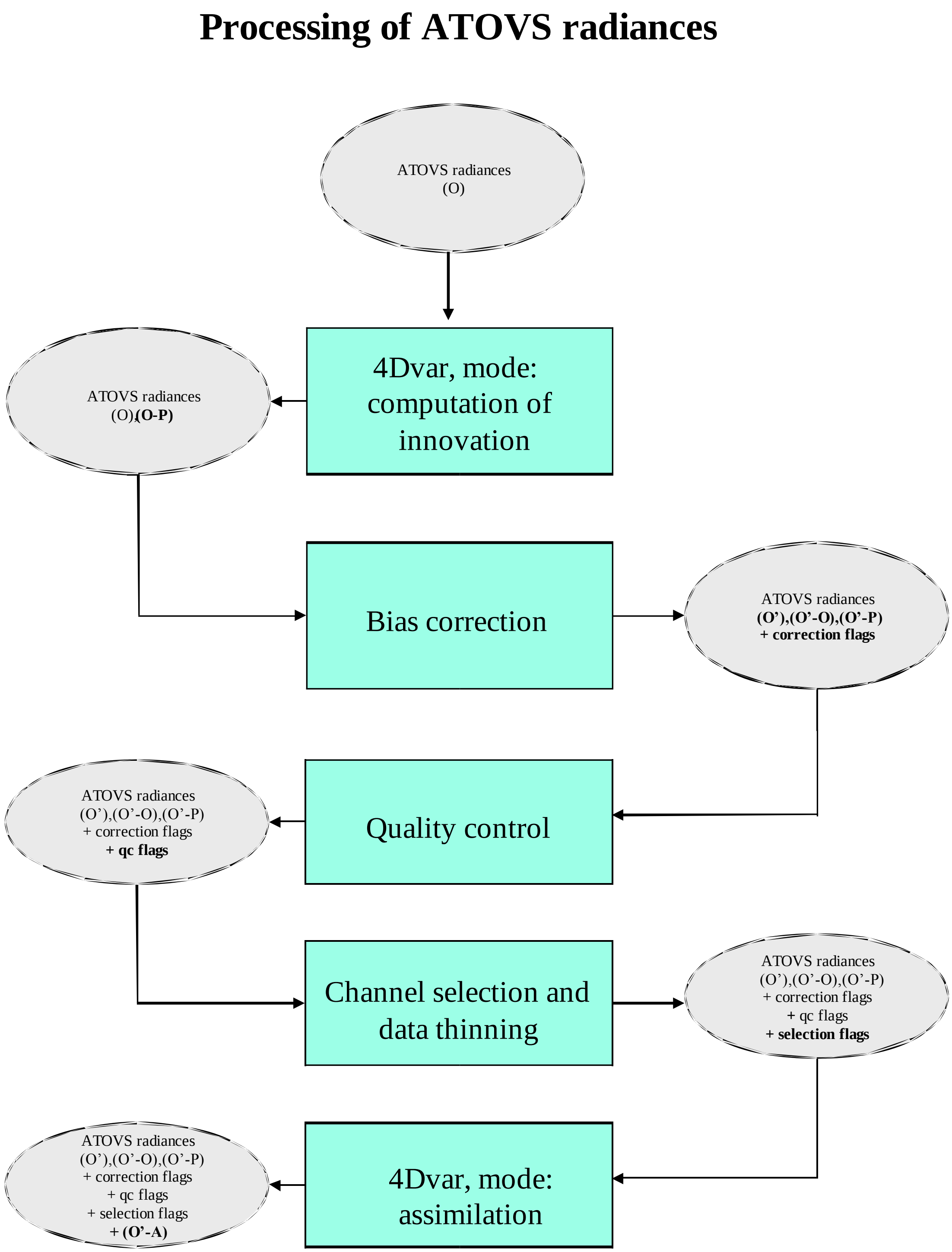


Figure 1. Processing of ATOVS radiances.

3. Observed radiance.

Observed AMSU-A and AMSU-B/MHS radiances from the several NOAA, the AQUA, and two METOP satellites are received at CMC from two sources. These data are in level 1B format. The global coverage data come via a public FTP link from an operational NESDIS server in Washington. Regional coverage, or RARS, data come from GTS (Global Telecommunication System) bulletins received mainly from Washington but also from UKMet Office. All data are processed in the same way, except in the thinning section where a selection between global and RARS is performed and some RARS data are removed (see Section 7).

Although METOP-2 RARS data are received, they are not used at the time of implementation due to a calibration difference in AAPP package.

Further processing of the level 1B radiances at CMC uses the AAPP (ATOVS and AVHRR Pre-processing Package) software package: (https://nwpsaf.eu/deliverables/aapp/); its main functions are quality control, navigation and calibration. Finally, the radiances are stored in a database at CMC in BURP format, which is a local one similar to BUFR.

The AMSU-A instrument has 15 microwave channels, with a resolution of approximately 45km, and although CMC receives them all, we only assimilate a subset of them. For instance, we exclude certain channels, which are sensitive to the underlying surface and cause inherent difficulties in their assimilation over land and ice, and one stratospheric channel because its peak contribution is above our NWP model's top level of 0.1hPa.

Meanwhile, we only exclude AMSU-B and MHS channel 1 because it is also significantly sensitive to the underlying surface. This is one of five microwave channels from the AMSU-B and MHS instruments, each having a resolution of approximately 15km or three times higher than that of AMSU-A (45km). Thus, in order to reduce the processing time, the AMSU-B and MHS radiances are pre-thinned at a resolution of 75km, i.e. sampled every 5th field of view (fov) and every 5th scan line, reducing the volume of data by a factor of 9.

4. Simulated radiance.

In order to assimilate ATOVS radiances, we need to calculate the so-called (O-P) innovation $y - H(x)$, where:

y: observed radiance,
x: model state (temperature TT,
ln specific humidity LQ,
surface pressure PS,
surface temperature TS,
surface winds UU and VV),
H: non-linear observation operator.

The operator *H* includes the following:

- horizontal interpolation of the FGAT (First Guess at Appropriate Time) model state to ATOVS observation points;
- vertical interpolation of TT and LQ from the background eta levels to the RTTOV-10 radiation model's 43 pressure levels; a piecewise log-linearly weighted averaging interpolator is used (Rochon et al., 2007);
- vertical extrapolation of TT and LQ to levels above the NWP model's top, i.e. up to 0.1 hPa;
- computation of the simulated radiances using the RTTOV-10 fast radiative transfer model.

Currently, we use the RTTOV-10 radiative transfer model, which is maintained and distributed by the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF). The RTTOV web site can be found at: https://nwpsaf.eu/deliverables/rtm/.

5. *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.

If the ensemble mean of A is <A>, (< > indicates a time average), the innovation bias, *<y-H(x)>*, manifests itself principally in two different ways, one of which depends on scan position and the second of which is air-mass dependent. This led to a two-step approach at CMC, the first of which is to remove a global bias at each scan position, followed by a second step that removes the remaining bias, using a linear regression between the innovation bias, *<y-H(x)>* , and the following model predictors:

- geopotential thickness of the layer 1000hPa-300hPa;
- geopotential thickness of the layer 200hPa-50hPa.
- geopotential thickness of the layer 50hPa -5hPa
- geopotential thickness of the layer 10hPa -1hPa (only for AMSU-A ch. 13-14)

It should be noted that a different set of regression coefficients are computed for each satellite, each instrument and each channel. Up until May 2008, the coefficients were updated operationally, typically every two or three months or when deemed necessary. This updating method, based on manual intervention, was later automated. The current system GDPS4.0.0 re-computes the regression coefficients every 12 hours (previously every 6 hours and as planned to return with the future GDPS5.0.0) based on the innovation/predictor statistics of the previous 7 days for AMSU-A channels 3-12 (previously channels 3-10) and AMSU-B / MHS. Coefficients for AMSU-A channels 13-14 (previously channels 11-14) are not computed dynamically but are updated when necessary.

For its first implementation, it has been decided that METOP-1 AMSU-A channels 11-14 would not be assimilated. They were included in the current GDPS4.0.0.

The implementation of this correction to the bias at the level of the BURP observation file proceeds in the following way:

1) a flag indicates that a radiance has been corrected;
2) the bias correction itself appears as a separate element in the BURP file.

Therefore, it is always possible to re-construct the original observed radiance by using the corrected radiance and its correction. Appendix A has a summary of the main BURP descriptors associated with ATOVS data.

6. Quality control.

After having had its bias corrected, each ATOVS radiance which will eventually make its way to the assimilation system passes a series of 15 quality control checks, which are listed in Tables 3 and 4. 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 check for coding errors, while others check the internal consistency of the report or the consistency between the type of surface reported and the model surface type or they check for gross errors.

Some AMSU-A channels and all AMSU-B and MHS channels are sensitive to precipitation. These channels are flagged, since the 4Dvar system does not include cloud liquid water as part of the model state and it is incapable of correctly assimilating these radiances. For AMSU-A, in order to determine contamination due to precipitation, we use the algorithms for cloud liquid water (CLW) and scattering index (SI), developed by Grody et al. (2000), while we use the algorithm for scattering index developed by Bennartz et al. (1999) to detect precipitation, associated with AMSU-B and MHS radiances.

Over high terrain we flag some channels, for which the surface contribution may be non-zero due to their peak response at low levels. The thresholds are listed in Tables 3 and 4. For AMSU-B and MHS, the sensitivity to the surface is slightly more complicated to determine; this is due to the highly non-linear response of AMSU-B and MHS channels with respect to atmospheric moisture. Moreover, in very dry conditions mostly in Polar regions, we do not assimilate most AMSU-B and MHS channels, because there is a significant surface contribution. We use the difference between the observed radiances of channels AMSU-B/MHS 3 and 5 as an indicator of air-mass dryness; the thresholds for this so-called dryness index are listed in Table 4.

Furthermore, the quality control will reject innovations *(y-H(x))* greater than 2-4 times the standard deviation of the total error depending on the channel.

New test 15 was previously done in the thinning program but is now done in the quality control program: Due to the difficulty in determining the surface emissivity and skin temperature over land and sea-ice, we make more restricted use of channels particularly sensitive to these surfaces. Furthermore, we exclude channel AMSU-A 15 because it senses the lower stratosphere, which is above the current model’s top of 0.1 hPa. Channel selection is summarized in Table 2.

Ocean	Land or Sea-ice
AMSU-A 3 to 14	AMSU-A 6 to 14
AMSU-B/MHS 2 to 5	AMSU-B/MHS 3 to 4

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

Finally, there are then three different types of rejects:

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.

#	Test	Rejected if:	Type of reject
1	model topography	> 250m for AMSU-A 6, 2000m for AMSU-A 7	partial (AMSU-A 6-7)
2	invalid land/sea qualifier	differs from {-1, 0, 1, 2}	full
3	invalid terrain type	differs from {-1, 0,1}	full
4	invalid field of view number (fov)	outside valid range [1,30]	full
5	invalid satellite zenith angle	outside valid range [0.,60.]	full
6	inconsistent field of view and satellite zenith angle	ABS(((fov-15.5)*3.92)-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	unphysical atmospheric state (as determined by RTTOV)	4Dvar quality control flag is on	single
11	gross radiance	Tb minimum physical limit <Tb < Tb maximum physical limit	single
12	cloud liquid water	Grody cloud liquid water>0.3 mm	partial (AMSU-A 1-5, 15)
13	scattering index	Grody scattering index>9	partial (AMSU-A 1-6, 15)
14	innovation rogue	$(y\text{-}H(x))>\alpha*(total\ error)$, where α=2 for AMSU-A 1-3, 15 =3 for AMSU-A 4 =4 for AMSU-A 5-14	single except partial (AMSU-A 1-5, 15), if AMSU-A 1 or 2 or 3 is rejected
15	channel selection and surface channel filtering over land and sea-ice	Iutilst = 0 (set bit 11) Iutilst = 2 (set bit 7 and 9 if not over water)	single

Table 3. Quality control tests for ATOVS AMSU-A.

#	Test	Rejected if:	Type of reject
1	model topography	> 2500m for AMSU-B/MHS 3, 2000m for AMSU-B/MHS 4, 1000m for AMSU-B/MHS 5	partial (AMSU-B/MHS 3-5)
2	invalid land/sea qualifier	differs from {0, 1, 2}	full
3	invalid terrain type	differs from {-1, 0,1}	full
4	invalid field of view number (fov)	outside valid range [1,90]	full
5	invalid satellite zenith angle	outside valid range [0.,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	unphysical atmospheric state (RTTOV errcode)	4Dvar quality control flag is on	single
11	gross radiance	minimum physical limit <Tb < maximum physical limit	single
12	Dryness index	Dryness index = Tb(AMSUB/MHS3) – Tb(AMSUB/MHS5). (dryness index) > 0 for AMSU-B/MHS 3, -10 for AMSU-B/MHS 4, -20 for AMSU-B/MHS 5	partial (AMSU-B/MHS 3-5)
13	Bennartz scattering index	> 40 over sea-ice, or 15 over sea, or 0 over land.	full
14	innovation rogue	(y-H(x))>α*(total error), where α=2 for AMSU-B/MHS 1-2, =4 for AMSU-B/MHS 3-5	single, except partial (AMSU-B/MHS 1-2) if AMSU-B/MHS 1 or 2 is rejected
15	channel selection and surface channel filtering over land and sea-ice	Iutilst=0 (set bit 11) Iutilst=2 (set bit 7 and 9 if not over water)	single

Table 4. Quality control tests for ATOVS AMSU-B/MHS.

7. *Further selection processes*

Following quality control, the sensitivity of channels with their peak response relatively close to the underlying surface, others with their peak response in the upper stratosphere and the overall abundance of radiances require further selection processes. These comprise the coverage selection (RARS redundancy removal), channel selection and horizontal thinning.

- 7.1 RARS redundancy removal

Because we receive data from two different sources (RARS and global coverage), a specific pixel can be found more than once in the database. Due to differences in treatment by local centers, these data are not exactly identical. Slight differences are found in position, time and brightness temperature. In order to choose the pixel to be used in the analysis, we give priority to global coverage data. Three originating centers (element 001033 in BURF table) are considered as global: 53 - Montreal, 74 - UKMet Office, 160 - US NOAA/NESDIS (satellite Aqua only). A RARS pixel will be eliminated if a pixel originating from a global center exists within a 10km radius and with a difference in reception time (element 004197 in burp files) of less than 6 minutes.

- 7.2 Horizontal thinning

In order not to overwhelm the 4Dvar assimilation system and to provide an appropriate volume of data for the analysis grid (0,45deg x 0,45deg since GDPS4.0.0), the density of ATOVS data from all satellites are reduced to a separation of about 150 km. Since the analysis grid has been reduced in this last implementation, this separation is fine with the current system (tests with a finer separation are under way), due to the fact that it assumes no correlation of the observational error for radiances and given the rather broad horizontal correlation functions of the background error.

The thinning process can be summarized as follows.

1) ATOVS data are separated into time slots, corresponding to each time step of the model background field. Currently, the time slot in the thinning process is 15 minutes.
2) For each time slot, each square box (150 x 150 km) groups AMSU-A data at their full resolution of 45km and AMSU-B/MHS data at their already reduced resolution of 75km.
3) Within each box, for a given family, a priority scheme retains the observation profile closest to the center of the box which satisfy the following condition: its number of rejected channels among the assimilable channels (that is bit 9 'on' and bit 11 'off') should be less than 80% of its number of assimilable channels (defined as bit 11 'off'). Also, the distance from the center of the box to the chosen observation profile shall not exceed 75km. ‡ (next page)
4) Previously excluded radiances measured at the extreme left and right edges of the satellite swath (FOV 1-3, 28-30 AMSU-A; FOV 1-7, 84-90 AMSU-B/MHS) are now included.

‡ As it is done right now this scheme, using fractional numbers, will give similar priorities to all satellites during overlaps. Looking at Fig. 3 (lower panel), we can observe lows in the number of observation profiles assimilated for Metop-2 satellite around April 26th, May 7th and May 19th, and the same behavior for Metop-1 satellite around May 2nd and May 14th. These lows correlate with the lows for NOAA16 satellite, which indicate some superposition of orbits between the Metop and NOAA satellites in the different temporal/spatial bins on these dates. When this occurs, priority for the thinning is split in nearly equal parts between the two overlapping satellites. However, older satellites having tendency to have a fewer total number of channels remaining assimilable (bit 11 off), it could be more optimal to look instead at the number of good assimilable channels (bit 9 and 11 off) as the main criterion for priority. Using such scheme would give results similar to what can be seen on the ECMWF monitoring site for AMSUA, where the number of assimilated observation profiles for NOAA16 falls near zero during its lows while the Metop satellites don't show any low behavior. At CMC, with hyperspectral instruments (AIRS or IASI), the priority is given to the profile which contain the most good assimilable channels inside a given radius around the box center. Work is currently under way to look at the feasibility of using a similar priority scheme for ATOVS data.

Moreover, the radius distance from the center of the box of 75km is a parameter that was forgotten when thinning went down from 250km to 150km since it is an hardcoded value and so easy to miss. The program will be updated in the future to make this an input value, as it is done with hyperspectral thinning programs. Also, tests are currently done to evaluate the impact of reducing this parameter to a value similar with other radiances (45km). However, this would reduce the amount of data assimilated and we would not wish degradation in the results.

8 .   Monitoring.

The operational monitoring of ATOVS radiances is part of the CMC on-line monitoring system, developed for all observations used in the 4Dvar assimilation. The address of this web site is the following:

http://collaboration.cmc.ec.gc.ca/cmc/data_monitoring/

It requires a username and password for access that are easily available, by sending a request via e-mail to simon.pellerin@ec.gc.ca

The ATOVS monitoring is divided in four parts:

- data reception;
- data quality monitoring;
- data included in the analysis;
- monthly means.

Information is available on the number of ATOVS and their geographical distribution, both on reception and following data thinning. Time series of innovations are also available and their use is mainly to detect any drift in the satellite measurements and/or in the bias correction of the radiances. Maps of 6-hour innovations are available for each satellite, channel and synoptic hour, while monthly means of these are useful in detecting systematic errors in the system, if any should exist.

A few examples are given in Figures 2 through 7. Figure 2 shows an example of the geographical distribution of ATOVS AMSU-A received at CMC and the distribution of those actually used in the analysis (global run G2) of May 20th, 2014 at 00 UTC. Time series of the volume of data, received and assimilated, appear in Figure 3, with those for April-May 2014 as an example. Figure 4 shows the innovations (O-P) for channels AMSU-A 3-14 of the NOAA-18 satellite for a one-month period in April-May 2014. It also shows the residuals of the observed radiances from the analysis (O-A). Figure 5 shows the geographical distribution of the monthly mean number of ATOVS AMSU-A received at CMC and that of the monthly mean number actually used in the analysis (global run G2) for April 2014. Finally, two examples of monthly means of innovations for ATOVS AMSU-A and AMSU-B/MHS appear in Figure 6 for April 2014.

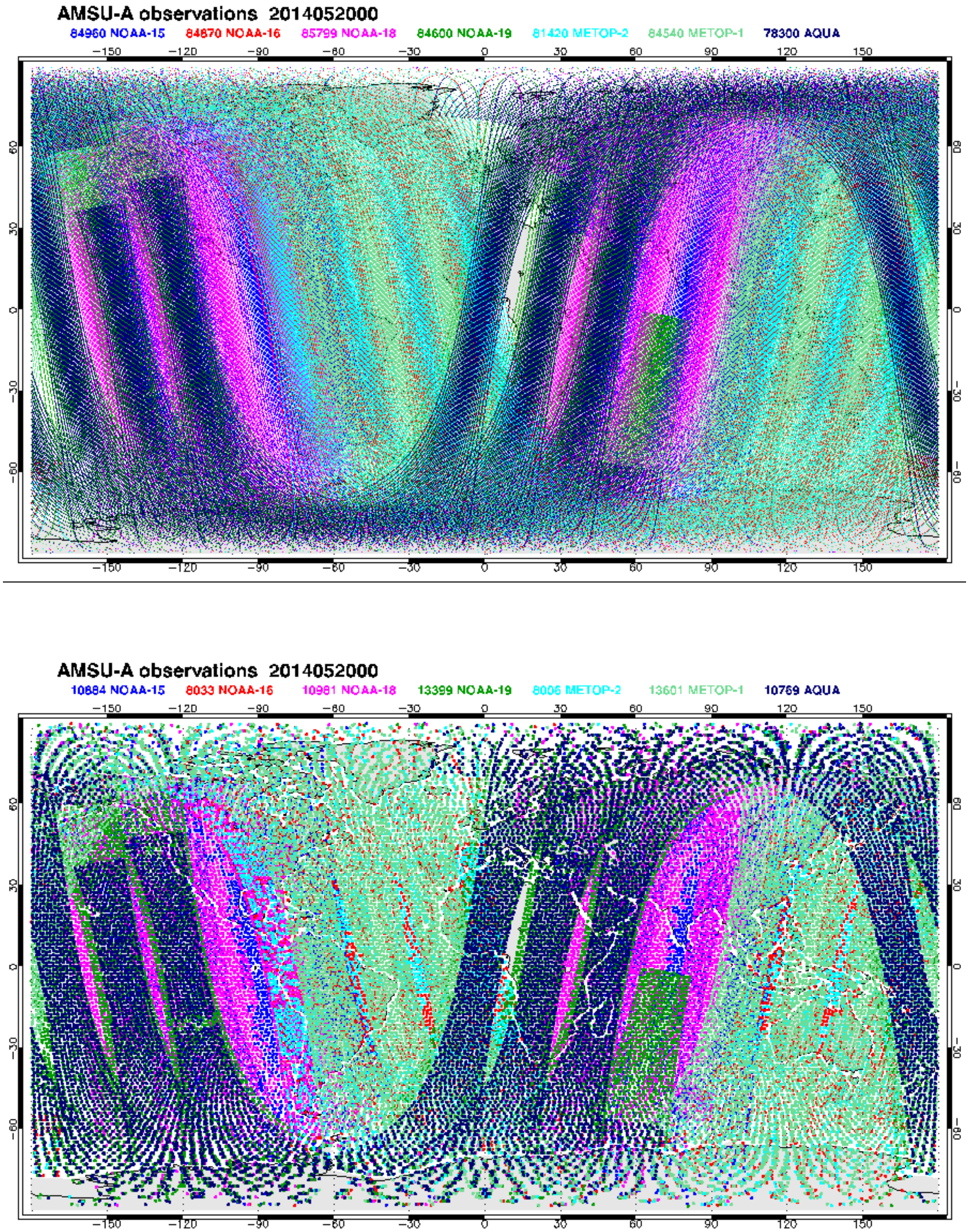


Figure 2. Distribution of ATOVS AMSU-A observation profiles received (upper panel) and after thinning (lower panel) for the operational 4dvar global run G2 analysis of May 20th, 2014 at 00 UTC.

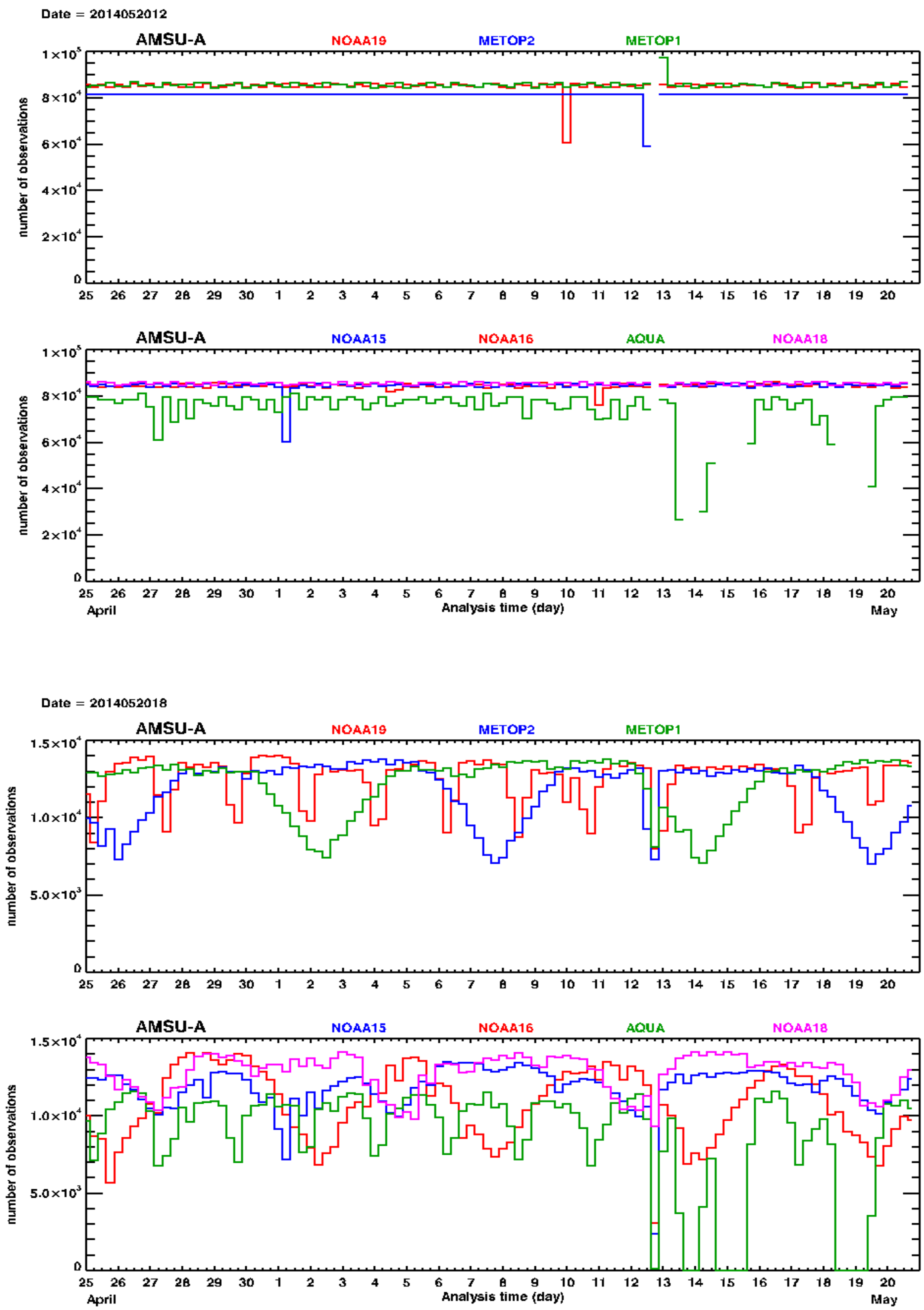


Figure 3. Time series of the number of ATOVS AMSU-A observation profiles received (upper panel) and assimilated (lower panel) for the operational 4dvar global run G2 analyses of a 25-day period during April-May 2014.

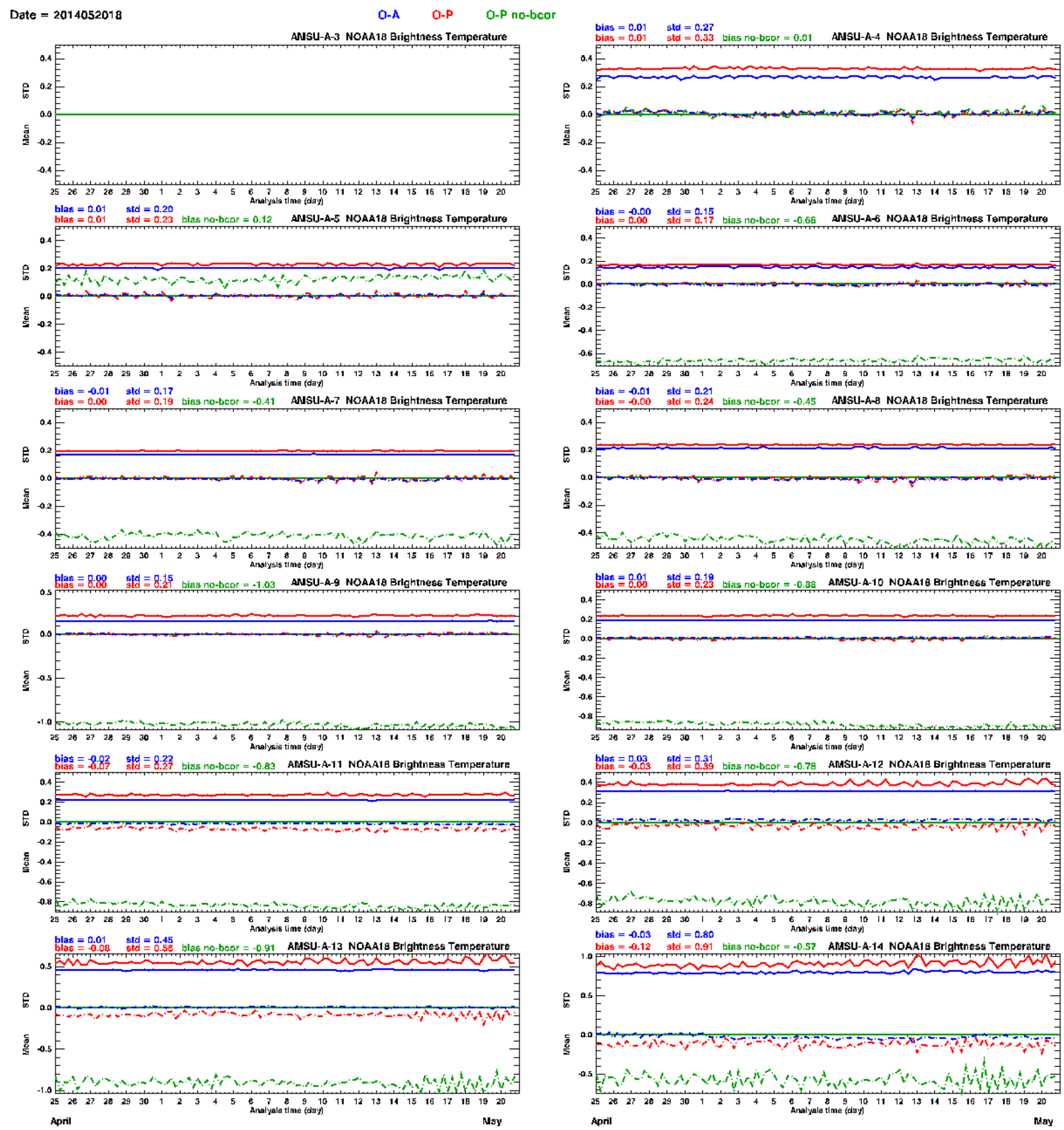
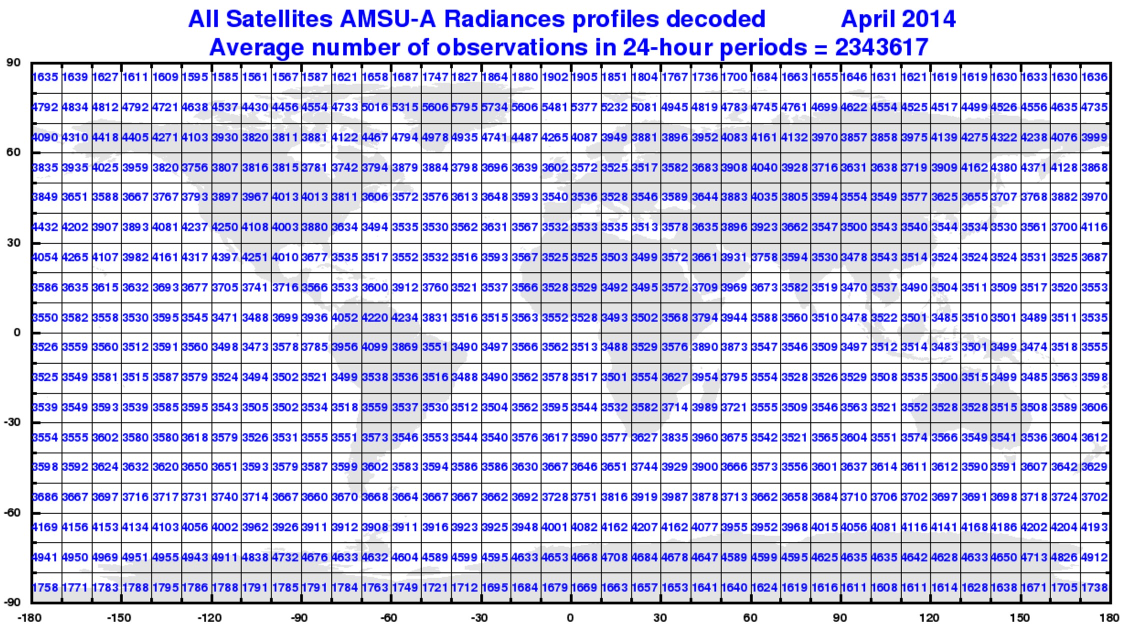


Figure 4. Time series for the innovations (O-P) in red, the analysis residuals (O-A) in blue and the bias correction in green for NOAA-18 ATOVS AMSU-A during a 25-day period during April-May 2014. The solid and dashed curves represent, respectively, the standard deviation and the bias.



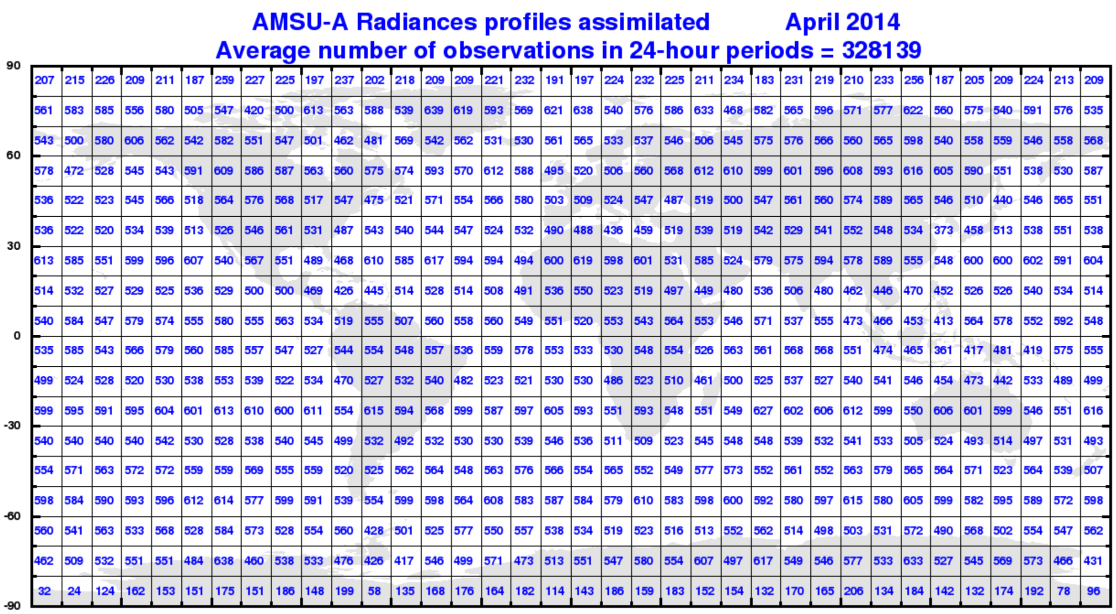
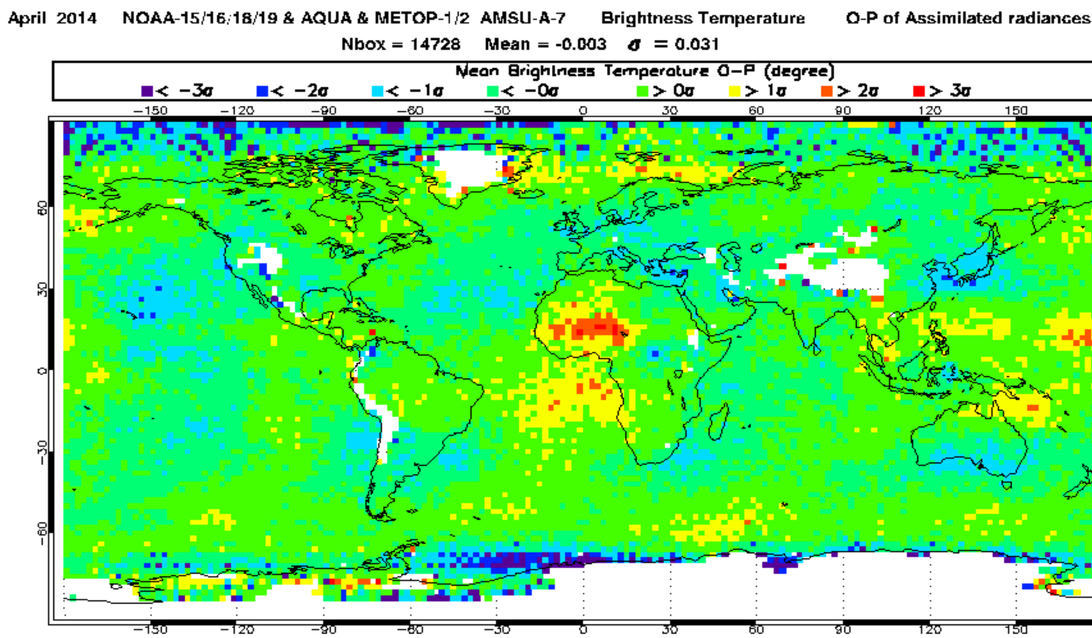


Figure 5. Monthly average of ATOVS AMSU-A number of observation profiles received (upper panel) and assimilated (lower panel) for April 2014. In each 10° x 10° box, the plotted number indicates the average number within a 24-hour period.



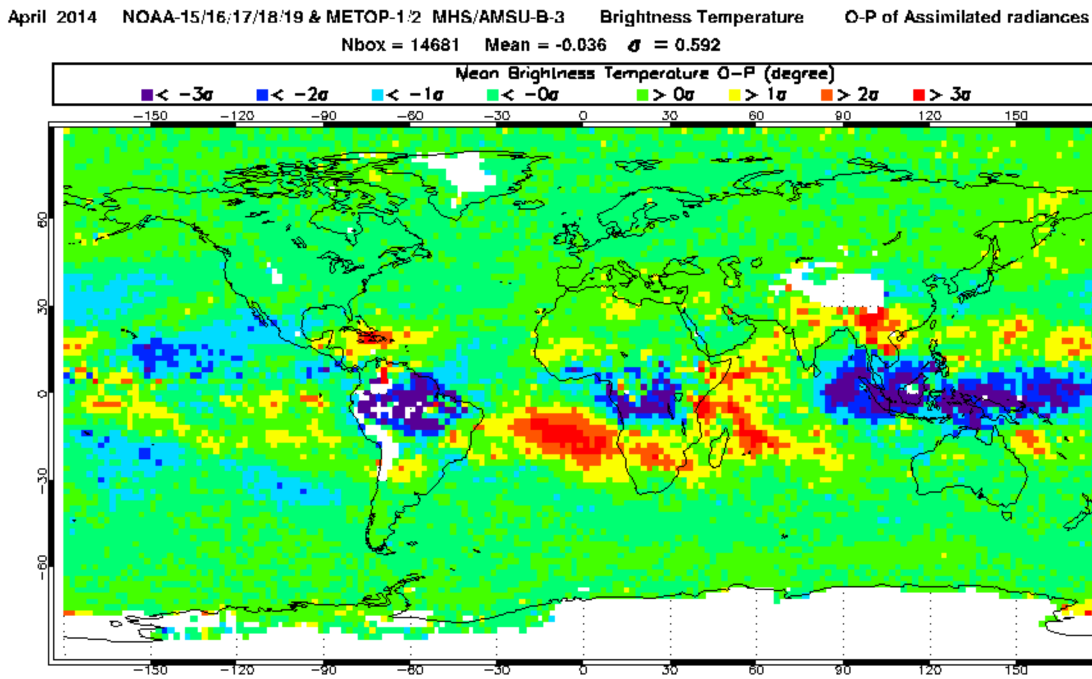


Figure 6. Monthly mean of innovations (observed Tb minus simulated Tb) for April 2014, consolidated from channel AMSU-A 7 (upper panel) and channel AMSU-B 3 (lower panel) for all satellites available.

9 . 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**.

Ferraro, R.R, F. Weng, N.C. Grody and L. Zhao, 2000: Precipitation characteristics over land from the NOAA-15 AMSU Sensor. *Geophysical Research Letters*, **27, No. 17**, 2669-2672.

Rochon, Y., L. Garand, D. S. Turner, and S. Polavaparu, 2007: Jacobian mapping between vertical coordinate systems in data assimilation, To appear in *Quart. J. Royal Meteor. Soc*.

10 . Glossary.

AAPP	AVHRR and ATOVS Processing Package
AMSU	Advanced Microwave Sounding Unit
ATOVS	Advanced TIROS Operational Vertical Sounder
AVHRR	Advanced Very High-Resolution Radiometer
BUFR	Binary Universal Format for Representation [of data]
BURP	Binary Universal Report Protocol
CMC	Canadian Meteorological Centre
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FGAT	First Guess at Appropriate Time
FOV	Field of view (scan position)
FTP	File Transfer Protocol
HIRS	High-Resolution Infrared Radiation Sounder
MHS	Microwave Humidity Sounder
MSU	Microwave Sounding Unit
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
RTTOV	Radiative Transfer for TOVS
SAF	Satellite Application Facility
TIROS	Television Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
4DVAR	4-Dimensional Variational analysis

Appendix A. BURP descriptors for ATOVS (based on BUFR).

Descriptor number	Descriptor
002150	TOVS/ATOVS/AVHRR instrument channel number
012163	Brightness temperature
012233	Brightness temperature correction
001007	Satellite identifier
005040	Orbit number
005043	Field of view number
007024	Satellite zenith angle
008012	Land/sea qualifier (0: land; 1:sea; 2:coast)
013039	Terrain type (0:sea ice; 1:snow on land)

Note that the missing value for burp is -1.