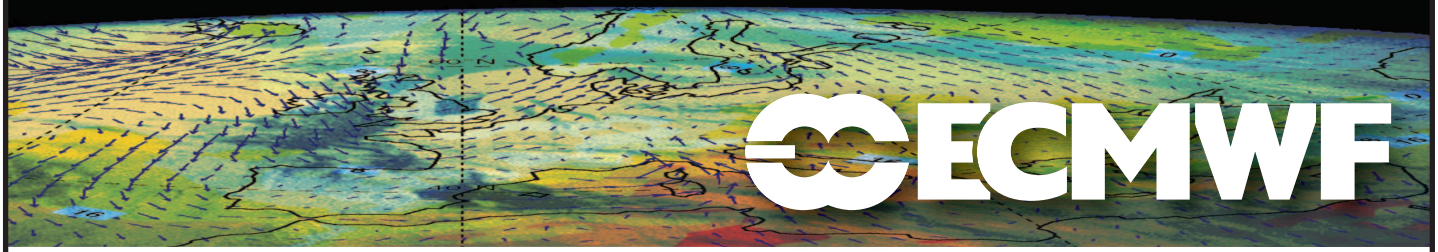

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Assimilation of ATOVS radiances at ECMWF: first year EUMETSAT fellowship report

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1 Executive summary

Clear-sky ATOVS observations from AMSU-A, ASMU-B/MHS and HIRS are assimilated directly as radiances in the ECMWF assimilation system, and have a significant impact on temperature, wind and humidity. Here we report on research towards improving further the assimilation of ATOVS data at different stages of their usage in the ECMWF 4D-Var system: the data coverage, the correction of systematic errors in the observations relative to the forecast model, and of errors in the observation operator (i.e. the mapping of the forecast model state to the observations).

In the first part of the report we evaluate the impact of ATOVS data on the performance of global numerical weather prediction (NWP) through observing system experiments. This work aims to provide some references for planning future observing systems that involve ATOVS-like instruments, according to the CGMS' objectives (WMO 2011) to harmonise meteorological satellite mission parameters such as orbits. A large number of ATOVS instruments are currently assimilated into the ECMWF system and contribute substantially to the correct assessment of the atmosphere. Future changes in the constellation of ATOVS (or equivalent) instruments might affect the skill of NWP forecasts. Here we report on the impact of ATOVS data from three evenly-spaced orbits (MetOp-A, NOAA-18 and NOAA-15) versus a less optimal coverage (MetOp-A, NOAA-18 and NOAA-19), and from more than three satellites. The main findings of the observing system experiments are the following:

- ATOVS microwave sounder data from three satellites providing a greater temporal sampling (i.e. MetOp-A, NOAA-18 and NOAA-15) have a slightly larger positive forecast impact in the Southern Hemisphere than data from three satellites having a less optimal coverage (i.e. MetOp-A, NOAA-18 and NOAA-19);
- Departures of MetOp-A AMSU-A observations from the NWP model estimates of the atmospheric state show some benefits from assimilating observations from NOAA-15 rather than NOAA-19 in addition to the a.m. and p.m. satellites (MetOp-A and NOAA-18), providing a further indication of an improved short-term forecast in the constellation of more evenly-spaced orbits;
- The assimilations of AMSU-A observations from a thrird satellite has a positive forecast impact in the Southern Hemisphere in comparison to the use of just two AMSU-A instruments, and there is a clear advantage in assimilating all available ATOVS data. The latter shows that the benefit of ATOVS data is not saturated yet with a three-satellite configuration.

The above results are obtained examining the impact of ATOVS data on global NWP. While the benefit of evenly-spaced orbits appears relatively small in a global system, it is expected to be stronger in limited area systems where the coverage plays a more crucial role.

Due to the global coverage of satellite observations, systematics errors in radiance observations assimilated into NWP systems can quickly damage the quality of the analysis and the forecast. In the second part of the report we review the bias correction of AMSU-A high stratospheric channels motivated by the interaction between forecast model errors and the bias correction scheme, VarBC (Dee 2004), currently used at ECMWF. VarBC adaptively corrects radiance biases for errors relative to the forecast model: the correction terms are estimated together with the optimal state of the atmosphere during the variational analysis. In such a scheme systematic model errors can erroneously be attributed to observation bias. AMSU-A high stratospheric channels peak where the forecast model error is particularly significant and they are therefore prone to be corrected for model error. To counteract this effect, the highest-peaking AMSU-A channel (channel 14) is currently assimilated without being bias corrected (McNally 2007).

We review the bias correction of both channel 12 and channel 14, respectively peaking around 10 hPa and 2 hPa: we consider the assimilation of channel 12 and 14 uncorrected or corrected only for scan bias and for a flat global bias. The assimilation experiments show that:

- Assimilating channel 12 and 14 with zero bias correction reduces significantly the bias in the temperature analysis in the upper part of the atmosphere, but has a slightly negative forecast impact in the troposphere in the winter Pole. This suggest that there are biases associated with these channels that need to be corrected prior to the assimilation;
- Inter-satellite biases can be aliased into an erroneous scan-bias correction when correcting AMSU-A channel 12 and channel 14 only for scan bias;
- Assimilating channel 12 and 14 with both an offset and a scan bias correction (with one of the AMSU-A instrument having channel 12 and 14 corrected only for scan bias) reduces the bias in the temperature analysis in the upper part of the atmosphere, improves the forecast in the winter Pole compared to the assimilation of these channels with zero bias correction, but in some cases has a slightly negative forecast impact compared to the operation configuration. The offset term allows for inter-satellite biases to be adequately corrected.

Since the results of the reviewed bias correction are mixed compared to the operation configuration, we do not suggest an operational change to the current correction of AMSU-A channel 12 and 14.

VarBC corrects on-line also for biases resulting from errors in the observation operator. In the third part of the report we tackle off-line specifically errors in the radiative transfer modelling which, together with spatial interpolation, constitutes the observation operator for satellite radiances. The radiative transfer model plays a crucial role in radiance assimilation as it is used in the estimation of the optimal state of the atmosphere to fit the analysis to the measured radiances. The radiative transfer absorption coefficients for AMSU-A channels 5 to 8 on NOAA-15, NOAA-18 and AQUA are currently scaled at ECMWF by a factor, termed γ, of the order of a few percentages, while the radiative transfer calculations for the same instrument on NOAA-18 and on METOP-A do not have such a correction factor applied. Here we aim to harmonise the treatment of radiance data over the different platforms. We have estimated the value of an absorption coefficient correction γ for all the AMSU-A instruments currently assimilated, following the work of Watts and McNally (2004). The new or updated values of γ were tested in the ECMWF system, with the following results:

- Scaling the absorption coefficient by a factor smaller than 1.05 reduces significantly the air-mass dependent component of the bias in AMSU-A channel 5 to 8 first guess departures;
- VarBC is however able to compensate for the absence of the above correction and efficiently correct the air-mass dependent component of the bias in the variational analysis;
- The forecast impact of the experiments with or without a γ correction for all the AMSU-A instruments is comparable. This result is coherent with the small differences in departure statistics of the first-guess and analysis in the two experiments after the bias correction.

We plan to harmonise in operations the use of the γ correction over the different platforms when new absorption coefficients will be calculated after the introduction of RTTOV-10.

The structure of the report is as follows. First we present the ATOVS observing system experiments and discuss the forecast impact of different orbit constellations. We then review the bias correction of high-peaking AMSU-A channels, subsequently estimate the γ correction for the simulation of AMSU-A radiances and provide the results of our assimilation experiments followed by some final remarks.

2 Observing system experiments on orbit constellations

2.1 Assimilation experiment setup

In this section we investigate the use of AMSU-A and AMSU-B/MHS from existing polar-orbiting satellites to evaluate the benefit for NWP of having microwave sounding data from three evenly-spaced orbits and from more than three satellites. At the time of writing, there are seven polar-orbiting satellites currently present in the ECMWF system carrying at least some of the ATOVS instruments: the NOAA series, NASA's Aqua satellite and the European MetOp-A satellite. Table 1 shows their orbit equatorial crossing times. We have run a set of experiments where ATOVS Microwave (MW) Sounders (AMSU-A and AMSU-B/MHS) data from already-deployed instruments were added or denied as shown in Table 2. Only AMSU-A has been tested as an additional instrument in the "three-satellite experiments", as there are not three satellites in the desired orbits carrying all functioning ATOVS instruments. AMSU-A has been shown to be the instrument with the largest forecast impact (Cardinali 2009).

In the "two-satellite experiment" AMSU-A and AMSU-B/MHS from just two satellites were assimilated in the system, namely MetOp-A and NOAA-18, respectively orbiting in the morning (a.m.) and afternoon (p.m.) orbit. The "NOAA-15 experiment" included AMSU-A data from an additional third satellite NOAA-15 in an orbit that is near-optimal to provide additional coverage to MetOp-A and NOAA-18. In contrast, the "NOAA-19 experiment" considered as an additional third satellite NOAA-19 flying close to NOAA-18's orbit. Fig 1 shows a sample coverage for used AMSU-A data in the "two-satellite experiment", the "NOAA-15 experiment", and the "NOAA-19 experiment". Due to thinning, a greater number (circa 6%) of NOAA-18 AMSU-A observations were used in the "NOAA-15 experiment" than in the "NOAA-19 experiment", while the number of used AMSU-A observations from other platforms was comparable between the two experiments. The impact on global NWP of a third satellite additional to the a.m. and p.m. orbiting satellites is the central focus of these experiments. While the "NOAA-15 experiment" ensures a better sampling of the atmosphere compared to the "NOAA-19 experiment", the constellation in the "NOAA-19 experiment" may provide a better coverage of short-term dynamic events. In order to see a greater impact of the ATOVS data on the system, we have run the same set of experiments also in the case in which the advanced sounder instruments IASI and AIRS are denied.

Table 1: ATOVS satellite equatorial crossing times in April 2009

Satellite	Local time of the ascending node
NOAA-15	16:50
NOAA-16	17:31
NOAA-17	21:34
NOAA-18	13:41
NOAA-19	13:58
Aqua	13:37
MetOp-A	9:30

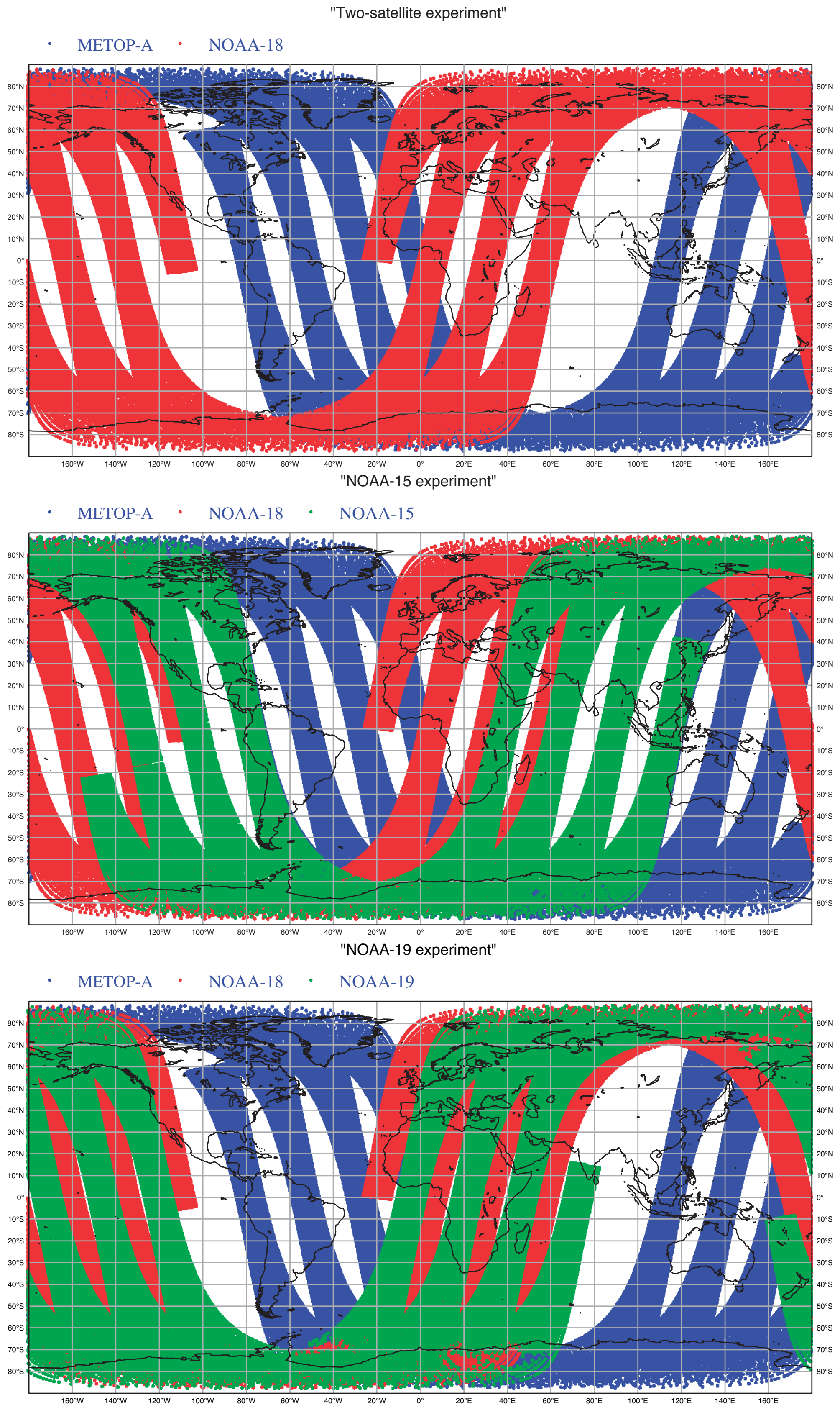


Figure 1: Sample coverage from the 6-hour period around 15 April 2009 0Z for the "two-satellite experiment" (top), the "NOAA-15 experiment" (middle), and the "NOAA-19 experiment" (bottom).

Table 2: ATOVS MW sounders sensors available to the experiments

Experiment name and id	Satellite	MW sounders	
”no-MW sounder experiment” fbhv			
”two-satellite experiment”	NOAA-18	AMSU-A	MHS
fbio	MetOp-A	AMSU-A	MHS
”NOAA-15 experiment”	NOAA-15	AMSU-A	
fbis	NOAA-18	AMSU-A	MHS
	MetOp-A	AMSU-A	MHS
”NOAA-19 experiment”	NOAA-18	AMSU-A	MHS
fbit	NOAA-19	AMSU-A	
	MetOp-A	AMSU-A	MHS
”all-satellite experiment”	NOAA-15	AMSU-A	
fbiu	NOAA-16	AMSU-A	(till 22June09)
	NOAA-17		AMSU-B
	NOAA-18	AMSU-A	MHS
	NOAA-19	AMSU-A	MHS
	Aqua	AMSU-A	
	MetOp-A	AMSU-A	MHS

The ECMWF 4D-Var assimilation system used for the experiments was Cy36r1 at a T511 resolution, with analysis increments at a T159 resolution. Experiments were run from 14 April 2009 to 4 August 2009. The dates were chosen taking into account both new satellite launches and instrument failures involving ATOVS instruments. The experimental system was identical to the operational system except for the thinning. Half thinning of AMSU-A data has been applied compared to the operational system, following recent experiments that show forecast improvements from using AMSU-A more densely (Bormann 2010). Additional experiments have been run where AMSU-A data were used even more densely: no-thinning was applied and an extra measurement was assimilated at each edge of the instrument scan that otherwise gets excluded in the operational system. Furthermore for a fair comparison between the two “three-satellite experiments”, channel 6, 11 and 14 of AMSU-A on NOAA-19 were not assimilated in the “NOAA-19 experiment” as these channels are malfunctioning in AMSU-A on the NOAA-15 satellite.

2.2 Results

2.2.1 Departure statistics of the first guess and analysis

A first way to assess the experiments is to measure the impact of the AMSU-A and AMSU-B/MHS data on the quality of the analysis and of the first guess. This is done by studying the fit to conventional observations like radiosonde and aircraft temperature and humidity measurements. Departure statistics (biases or mean departures and standard deviations) for the radiosonde and aircraft temperature and humidity measurements are computed over the period 20 April 2009 to 4 August 2009 for the Northern Hemisphere (extra Tropics), Tropics, and Southern Hemisphere (extra Tropics). Both background (first guess) departure statistics and analysis departure statistics are calculated after the bias correction of satellite radiances.

When comparing the “NOAA-15 experiment” and the “NOAA-19 experiment”, there are no relevant differences in the departure statistics of the radiosonde temperatures in favour of one experiment or the other, and the differences are marginal also for the aircraft temperatures and for radiosonde humidity observations (not shown). Both NOAA-15 (fbis) and NOAA-19 (fbit) bring some small improvement to the fit to temperature observations (especially between 100 hPa and 20 hPa and with the exception of the upper stratosphere, see Fig 2), as well as to the fit to AMSU-A data already present in the system (onboard of NOAA-18 and MetOp-A) compared to the assimilation of data from just two satellites. The latter improvement is slightly greater in the "NOAA-15 experiment" than in the "NOAA-19 experiment" (see Fig 3).

As expected, a major improvement of the fit to temperature and humidity observations results from assimilating the data from two satellites (fbio) compared to no AMSU-A and AMSU-B/MHS being assimilated (fbhv), e.g. see Fig 4. In comparison, the assimilation of observations from an additional third satellite (fbis or fbit) can only provide smaller reductions of the biases or standard deviation. The improvements in the standard deviation of the first guess departures in Fig 4 (especially in the Southern Hemisphere and in the tropical stratosphere) though small suggest a better quality of the temperature first guess in the data assimilation procedure. The strong biases present in the stratosphere are due to NWP model biases in this region of the atmosphere. In the ECMWF system these are compensated for by assimilating AMSU-A channel 14 without a bias correction so as to anchor the stratospheric analysis (Dee 2004). Note in Fig 5 also how wind information can be gained through the assimilation of ATOVS MW sounders data in 4DVar.

The above considerations on the departure statistics are valid in both cases when the advanced sounder instruments are denied and added.

2.2.2 Forecast impact

The experiments' impact on the forecast is studied for different variables, regions and forecast ranges. Forecast results are computed for 107 days of assimilation experiments over the period 20 April 2009 to 4 August 2009. When averaged over the extra-Tropics the impact for the forecast of the geopotential of "NOAA-15 experiment" versus "NOAA-19 experiment" is neutral to slightly positive (see Fig 6).

For the forecast of the temperature the impact of the "NOAA-15 experiment" (fbis) versus "NOAA-19 experiment" (fbit) is also quite neutral, with a slightly positive impact in the Southern Hemisphere that appears statistically significant at the 95% level about the 5 day forecast at 1000 hPa and 850 hPa (see Fig 7), while for the forecast of the relative humidity the impact of the same experiments is neutral or slightly not uniform (not shown).

Both the assimilations of NOAA-15 and NOAA-19 data have a clearly positive forecast impact in the Southern Hemisphere compared to the use of two satellites only (fbio). The improvement for the forecast of the geopotential in the troposphere is statistically significant at the 95% level typically up to 60 hours for the "NOAA-15 experiment" (see Fig 8). A mostly neutral impact is found in the Northern Hemisphere. Similar results are obtained also in the forecast of the temperature, the winds and the humidity.

Despite the assimilation of AMSU-A and AMSU-B/MHS data from two satellites having a very strong positive impact on the forecast, the presence in the system of all satellites (fbiu) has, as expected, an even more positive impact especially in the Southern Hemisphere (see Fig 9 for the forecast of the geopotential in the "two-satellite experiment" (fbio) and the "all-satellite experiment" (fbiu), with an improvement statistically significant at the 95% level in the Southern Hemisphere). This provides a reassuring confirmation of the benefit of having ATOVS data from seven satellites assimilated at the moment in the ECMWF system. It also suggests that the benefit of ATOVS-like data is not saturated yet with a three-satellite configuration.

The above results refer to the case in which the advanced sounder instruments IASI and AIRS are added into the

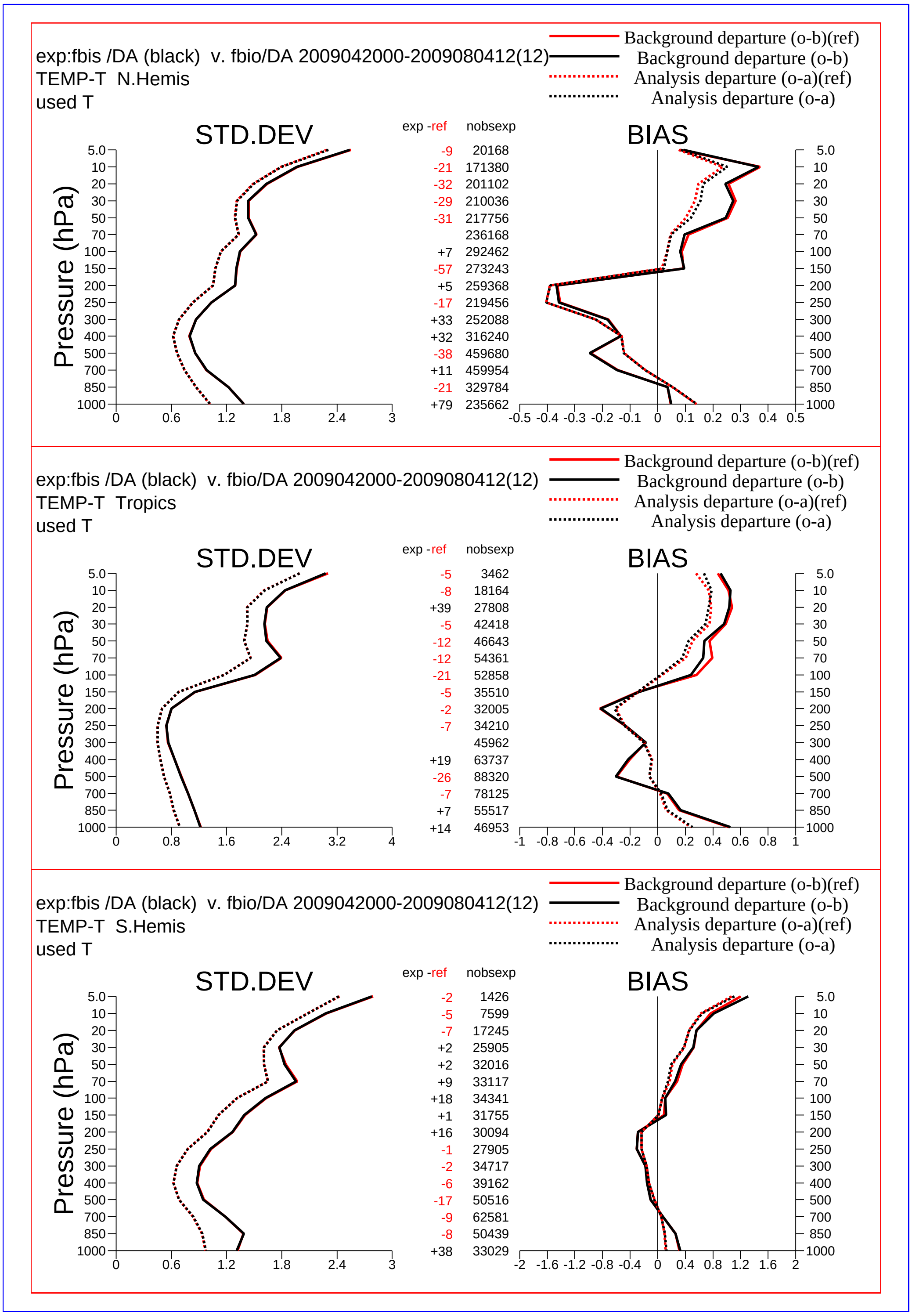


Figure 2: Radiosonde temperature departure statistics for the ”NOAA-15 experiment” (fbis) (black) and the ”two-satellite experiment” (fbio) (red) for the Northern Hemisphere (top), Tropics (centre) and Southern Hemisphere (bottom). Data counts are printed along the vertical axes in the centre.

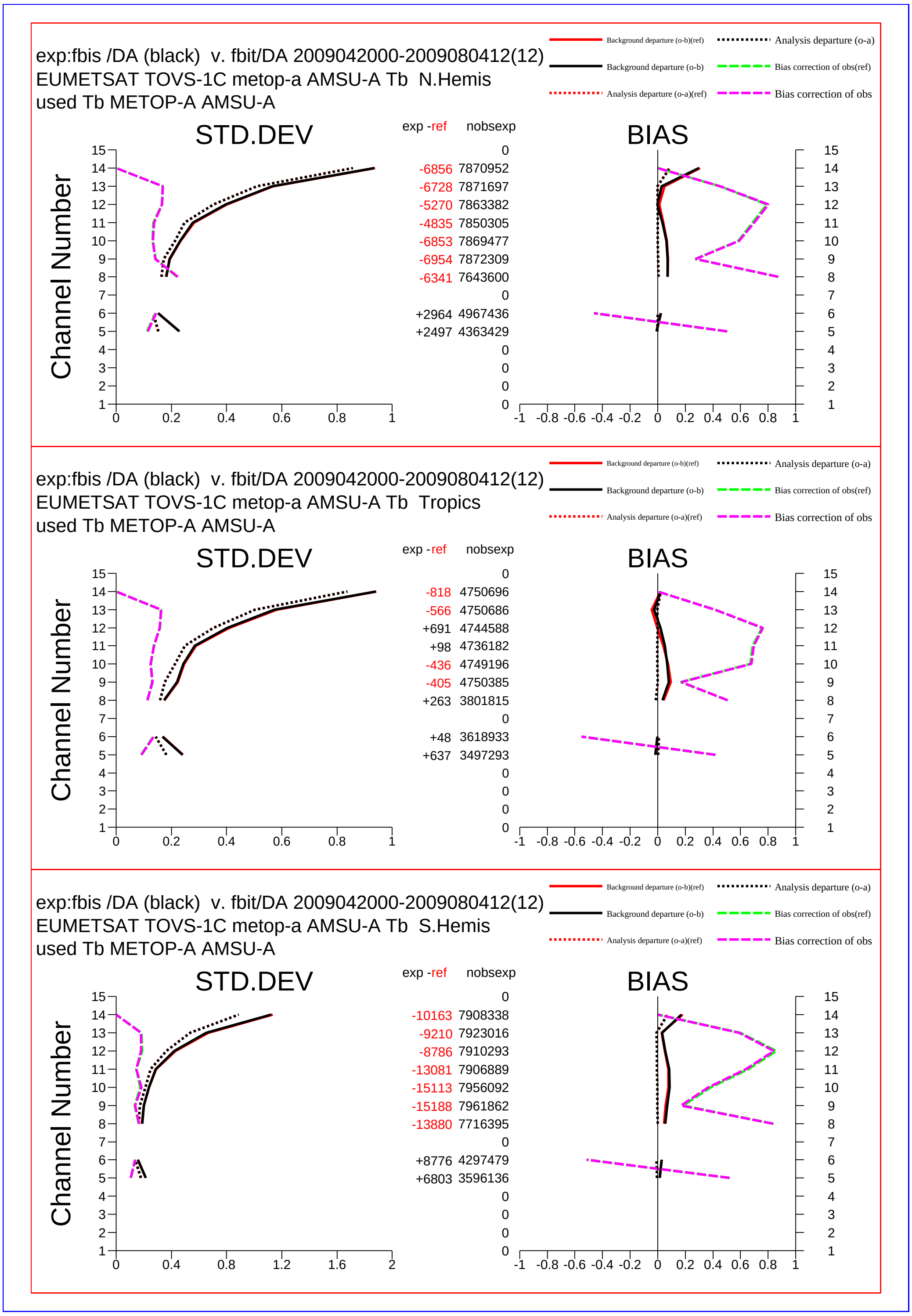


Figure 3: MetOp-A brightness temperature departure statistics for the "NOAA-15 experiment" (fbis) (black) and the "NOAA-19 experiment" (fbit) (red) for the Northern Hemisphere (top), Tropics (centre) and Southern Hemisphere (bottom). Data counts show a small reduction in the number of used data in the extra-tropics; this is due to the combined thinning of all AMSU-A instruments over the polar regions.

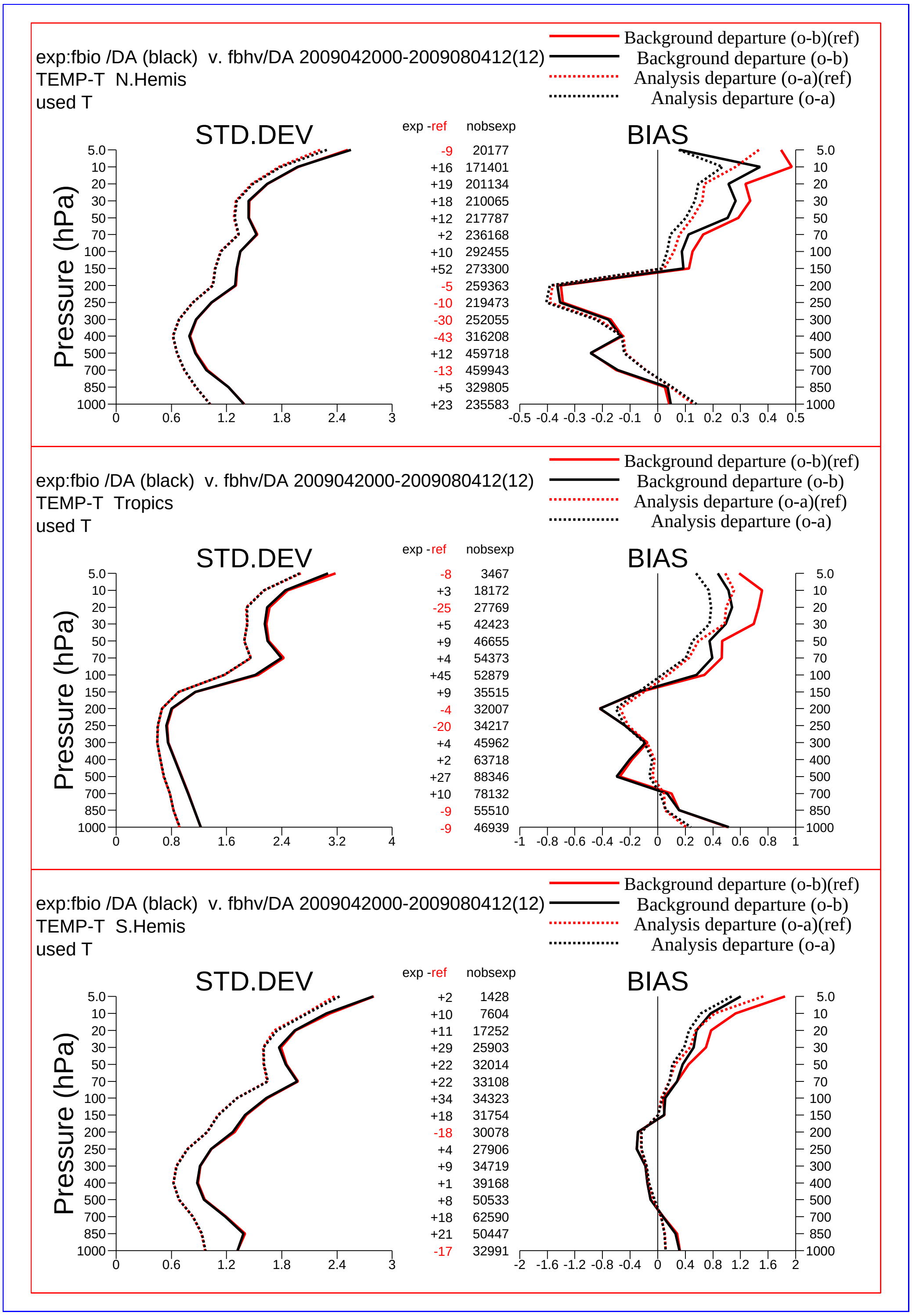


Figure 4: Radiosonde temperature departure statistics for the "two-satellite experiment" (fbio) (black) and the "no-MW sounder experiment" (fbhv) (red) for the Northern Hemisphere (top), Tropics (centre) and Southern Hemisphere (bottom).

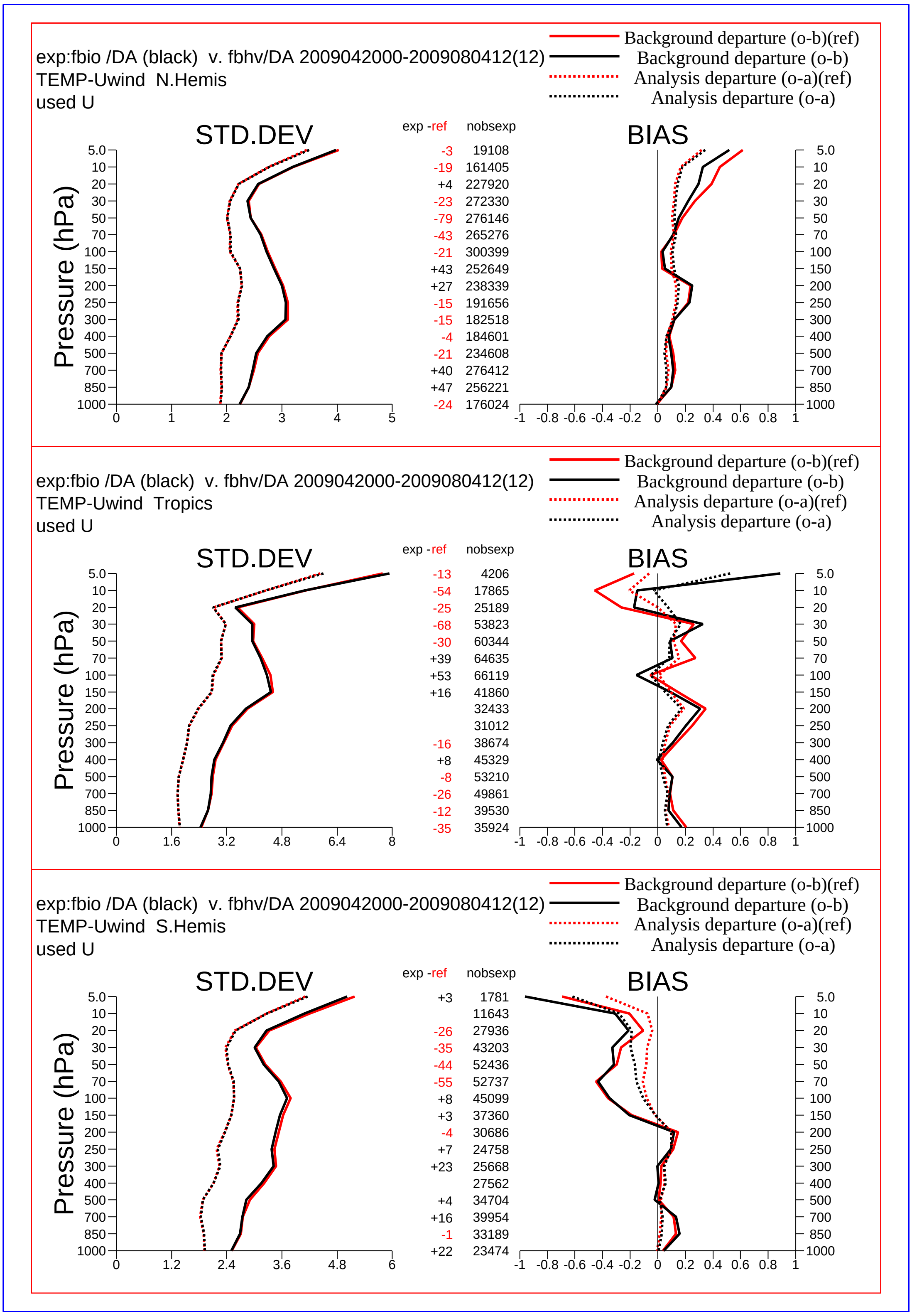


Figure 5: Radiosonde wind departure statistics for the "two-satellite experiment" (fbio) (black) and the "no-MW sounder experiment" (fbhv) (red) for the Northern Hemisphere (top), Tropics (centre) and Southern Hemisphere (bottom).

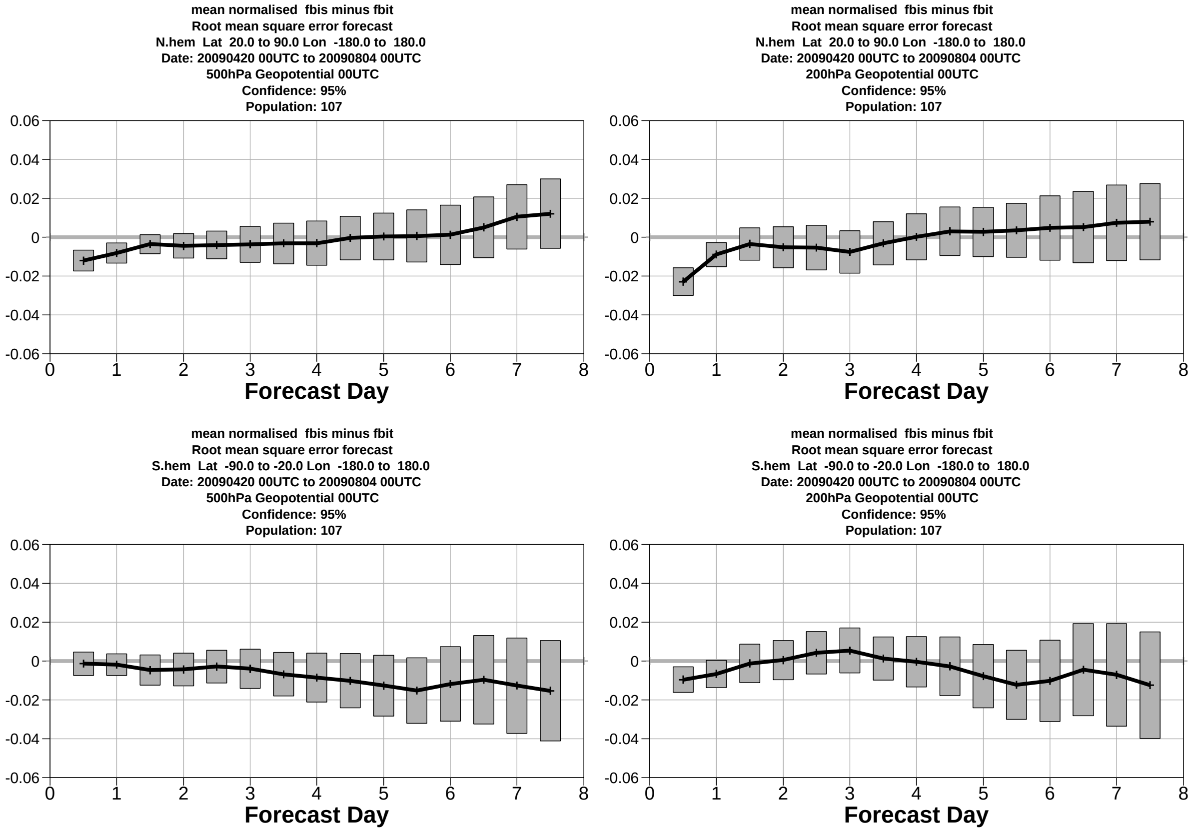


Figure 6: Normalised differences in the root mean squared forecast error between the "NOAA-15 experiment" (fbis) and the "NOAA-19 experiment" (fbit) for the 0Z forecast of the 500 hPa and 200 hPa geopotential for the Northern Hemisphere (top) and the Southern Hemisphere (bottom). Verification is against the operational analysis. Negative values indicate a better performance for the "NOAA-15 experiment".

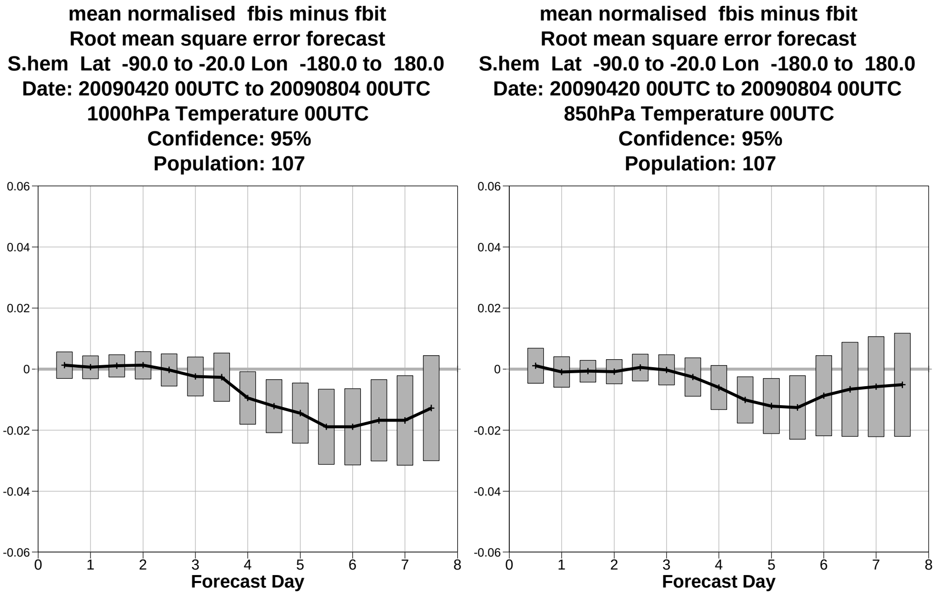


Figure 7: Normalised differences in the root mean squared forecast error between the "NOAA-15 experiment" (fbis) and the "NOAA-19 experiment" (fbit) for the 0Z forecast of the 1000 hPa and 850 hPa temperature for the Southern Hemisphere. Verification is against the operational analysis.

system. When IASI and AIRS are denied, the results show in general a stronger positive impact when additional ATOVS data are assimilated into the NWP system (e.g. see Fig 10), while the results of the comparison between the "NOAA-15 experiment" and the "NOAA-19 experiment" are not uniformly in favour of one or the other experiment (not shown).

When comparing the "three-satellite experiments" with the "two-satellite experiment" where data are used even more densely, there is still some advantage in using measurements from three AMSU-A rather than two (e.g. see Fig 11 for the forecast of the 1000 hPa and 850 hPa temperature in the Southern Hemisphere).

2.2.3 Conclusions

In conclusion, when comparing microwave sounder data from two different sets of three satellites, the constellation of more evenly-spaced orbits (MetOp-A, NOAA-18 and NOAA-15) performs slightly better than the constellation with a less optimal coverage (MetOp-A, NOAA-18 and NOAA-19): there is a small improvement to the fit of radiance observations and a slightly more positive forecast impact in the Southern Hemisphere. The assimilation of data from an additional third AMSU-A (in both the above constellations) has a clear benefit in the Southern Hemisphere when compared to the assimilation of only two AMSU-A, flying in the morning and afternoon orbits. Experiments show however that the benefit of microwave sounder data is not saturated yet with a three-satellite configuration: the current configuration of six AMSU-A and four AMSU-B/MHS instruments outperforms the other constellations where less sensors are being assimilated.

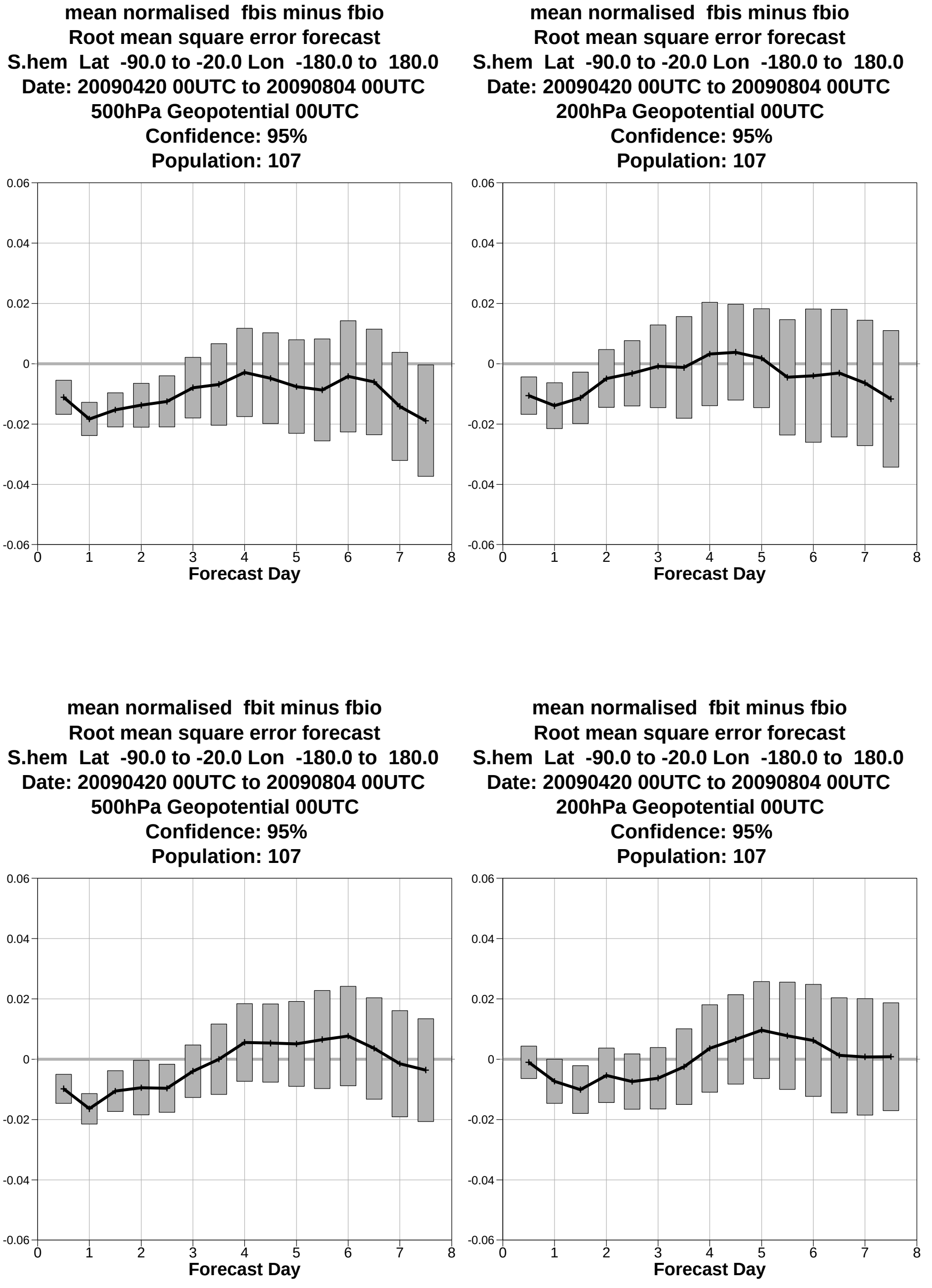


Figure 8: Normalised differences in the root mean squared forecast error for the 0 Z forecast of the 500 hPa and 200 hPa geopotential for the Southern Hemisphere between the "NOAA-15 experiment" (fbis) and the "two-satellite experiment" (fbio) (top half) and between the "NOAA-19 experiment" (fbit) and the "two-satellite experiment" (fbio) (bottom half). Verification is against the operational analysis.

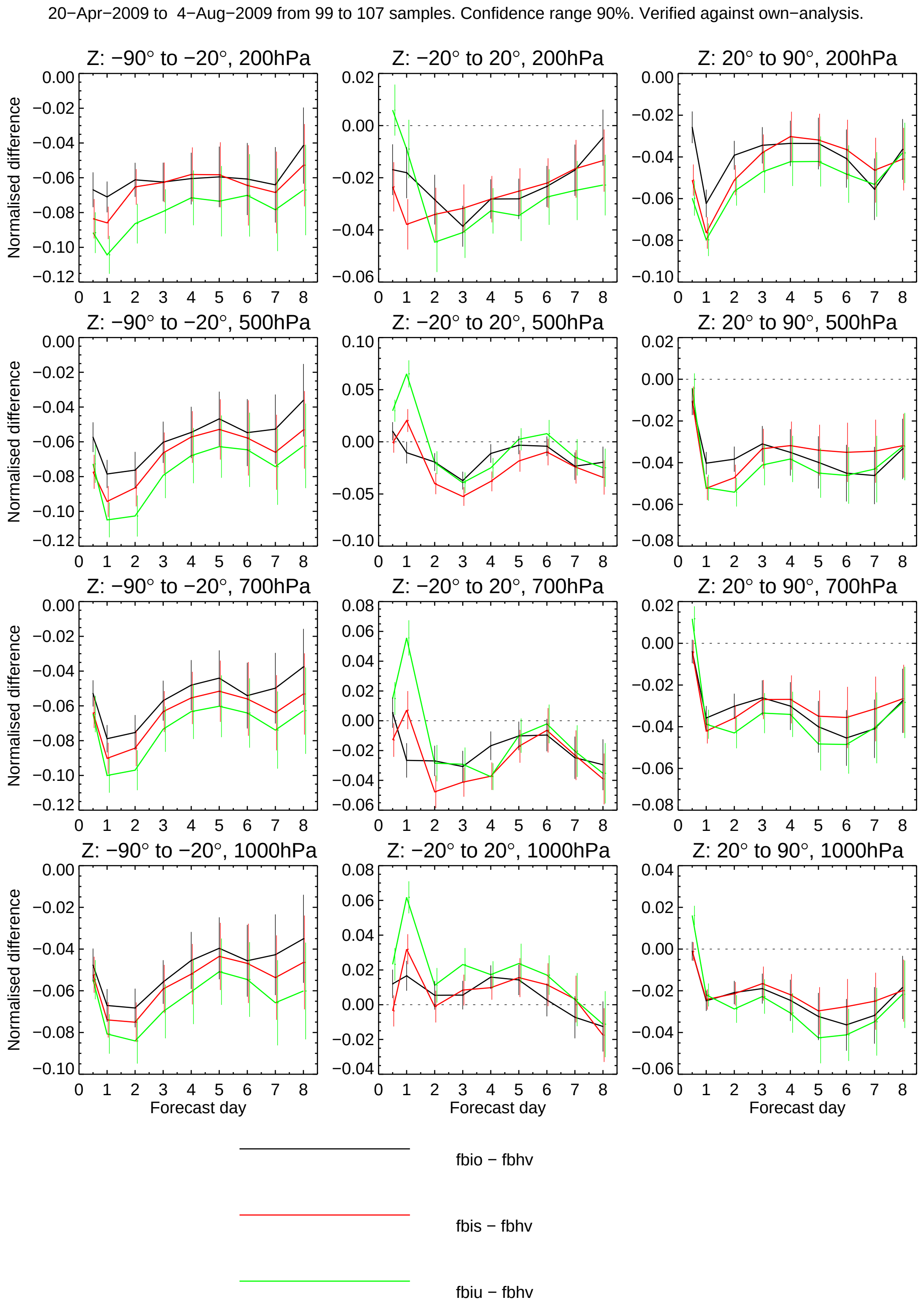
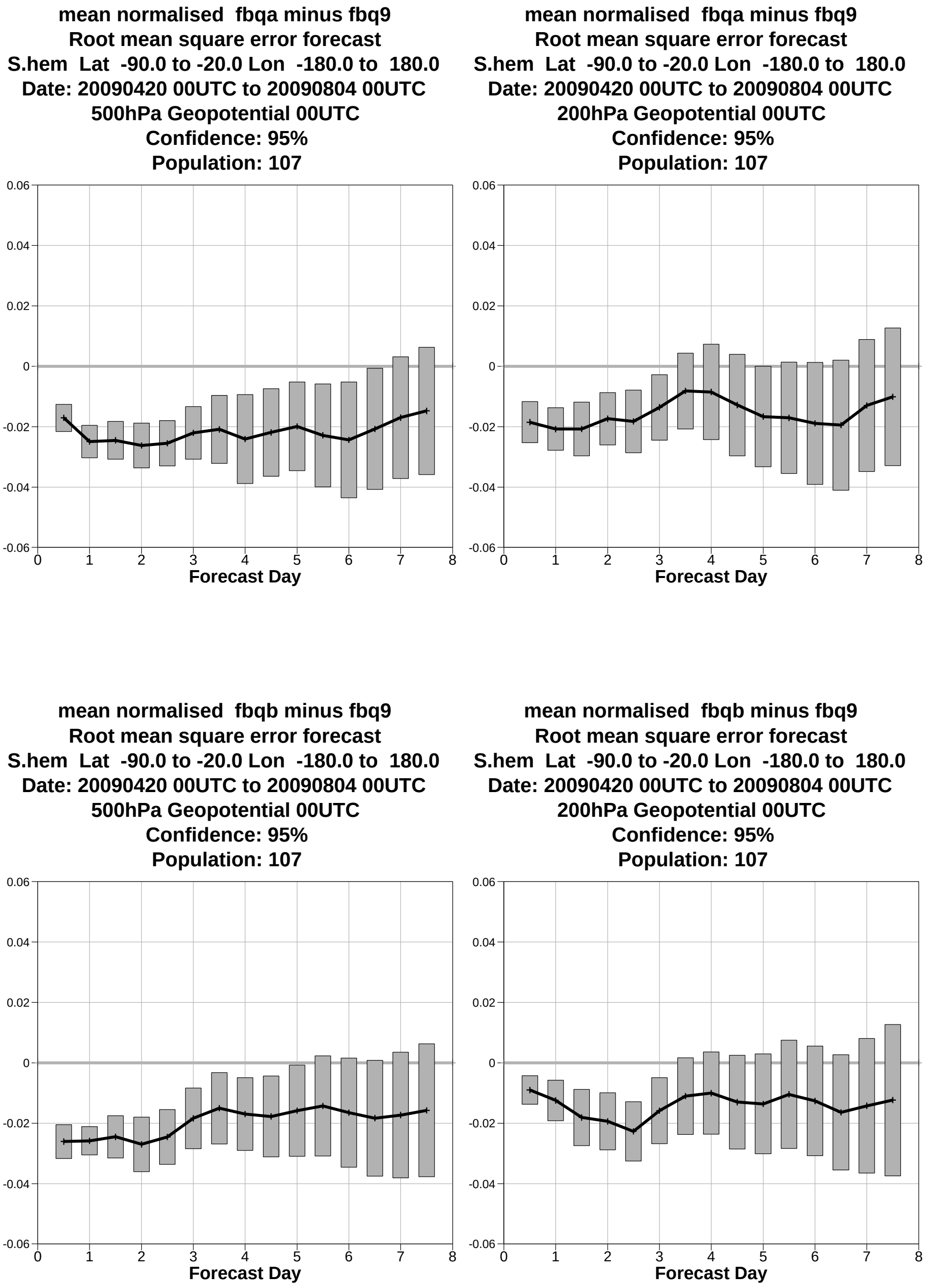


Figure 9: Normalised differences in the root mean squared forecast error between the "two-satellite experiment" (fbio) and the "no-MWsounder experiment" (fbhv) (black), between the "NOAA-15 experiment" (fbis) and the "no-MWsounder experiment" (fbhv) (red), and between the "all-satellite experiment" (fbiu) and the "no-MWsounder experiment"(fbhv) (green) for the 0Z forecast of the 200 hPa, 500 hPa, 700 hPa and 1000 hPa geopotential. Verification is against the experiment own-analysis.



mean normalised fbqa minus fbq9
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20090420 00UTC to 20090804 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 107

mean normalised fbqa minus fbq9
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20090420 00UTC to 20090804 00UTC
200hPa Geopotential 00UTC
Confidence: 95%
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mean normalised fbqb minus fbq9
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
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mean normalised fbqb minus fbq9
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20090420 00UTC to 20090804 00UTC
200hPa Geopotential 00UTC
Confidence: 95%
Population: 107

Figure 10: Same as Fig 8 but when IASI and AIRS are denied: normalised differences in the root mean squared forecast error for the 0Z forecast of the 500 hPa and 200 hPa geopotential for the Southern Hemisphere between the "NOAA-15 experiment" (fbqa) and the "two-satellite experiment" (fbq9) (top half) and between the "NOAA-19 experiment" (fbqb) and the "two-satellite experiment" (fbq9) (bottom half). Verification is against the operational analysis.

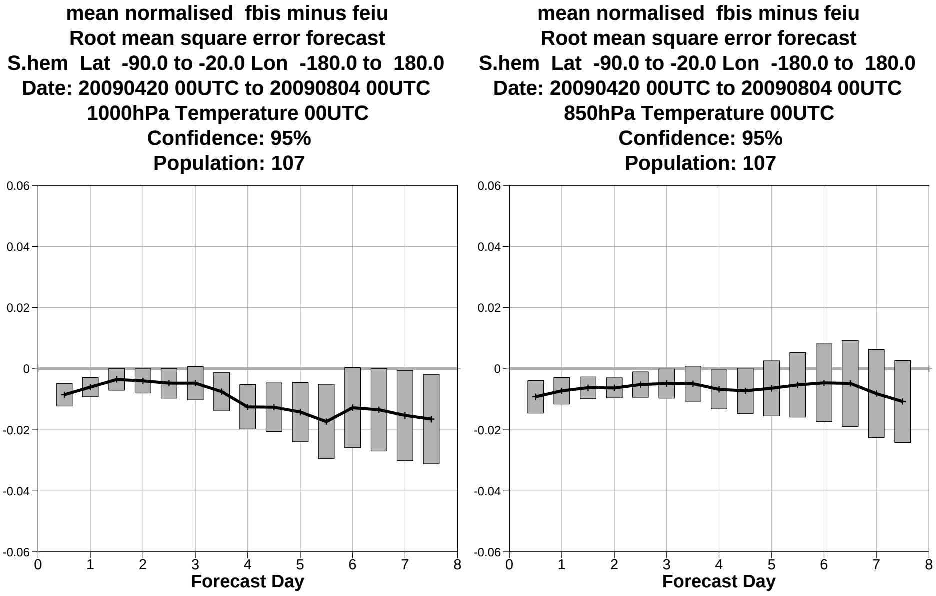


Figure 11: Normalised differences in the root mean squared forecast error between the "NOAA-15 experiment" (fbis) and the "two-satellite experiment" where data are used more densely (feiu) for the 0Z forecast of the 1000 hPa and 850 hPa temperature for the Southern Hemisphere. Verification is against the operational analysis.

3 Bias correction of AMSU-A high stratospheric channels

3.1 Assimilation experiment setup

In this section we review the bias correction of AMSU-A high stratospheric channels 12 and 14 in an attempt to avoid correcting these observations towards a biased model. These channels peak in a region where the forecast model error is particularly significant and they are therefore prone to be erroneously corrected for model error by the variational bias correction (VarBC) scheme. The recent change at ECMWF to high spatial model resolution has amplified the issue: radiosondes in fact show resolution-dependent temperature biases in the stratosphere (see Fig 12). These biases occur even though channel 14 of AMSU-A (peaking at 2 hPa) is assimilated without a bias correction to "anchor" the stratospheric analysis. In the following, we investigate a revision of this anchoring and an extension of the concept to channel 12 (peaking at 10 hPa).

AMSU-A channel 12 is currently corrected in operations for a global offset bias, a bias that varies depending on the location or air-mass, and a bias that varies depending on the instrument scan position. The correction is performed by estimating in the variational analysis eight parameters b_i of a linear bias model, for the following bias correction:

$$BC = \sum_{i=1}^{8} b_i p_i, \tag{1}$$

where the predictors p_i include, beside the constant 1 (offset correction), functions of the state of the atmosphere (air-mass bias correction) and functions of the instrument scan angle (scan bias correction).

We have run a set of experiments where no bias correction or only a scan bias correction is applied to AMSU-

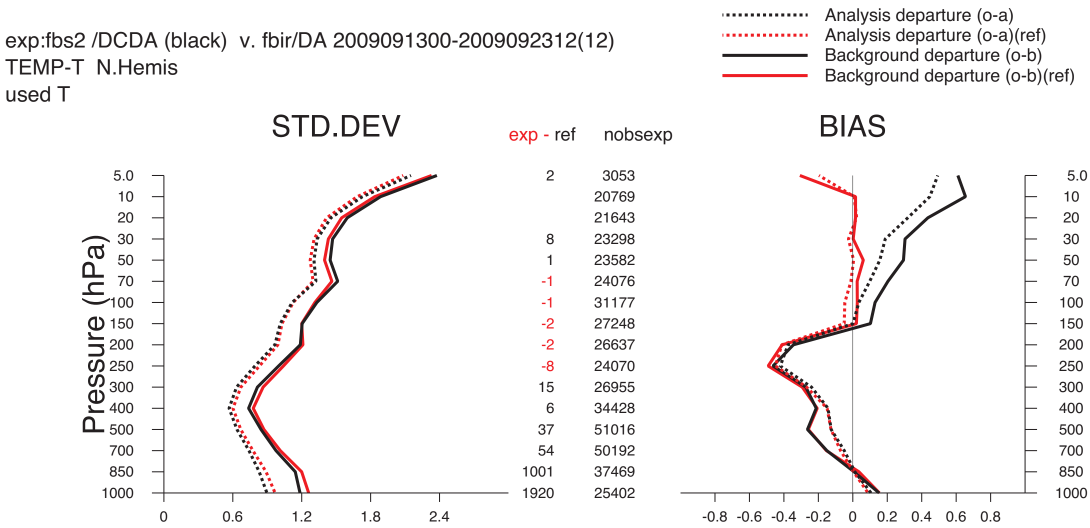


Figure 12: Radiosonde temperature departure statistics for a high resolution (T1279, ˜16 Km) experiment (fbs2) (black) and a low resolution (T255, ˜80 Km) experiment (fbir) (red) for the Northern Hemisphere.

A channel 12 and channel 14 (respectively called hereafter “no-BC experiment” and “scan-BC experiment”). The scan bias correction is polynomial in the scan angle and with no constant term. Channel 12 has been chosen versus channel 13 because its weighting function has a smaller overlap with the one of channel 14. Assimilating uncorrected channel 13 observations (additionally to channel 14) can cause oscillation problems in the temperature field as the significant overlap between the two channels and residual inter-channel biases can lead to erroneous increments in the analysis (McNally 2010, personal communication).

We have also tested the case in which an offset correction is applied additionally to the scan bias correction of channel 12 and channel 14 for all but one AMSU-A, on NOAA-19 (we refer to this experiment as the “NOAA-19 anchoring experiment”). The aim of the latter experiment is to allow VarBC to correct for inter-satellite biases. The observations that are corrected only for scan bias play the role of an ’anchor’ for all the other observations. As stated earlier, in the current operational setup (“ctl experiment”) channel 12 is corrected with the eight predictors in equation 1, and channel 14 is assimilated uncorrected. The ECMWF 4D-Var assimilation system used for the experiments was Cy36r3 at a T511 resolution. The experiments are described in Table 3. They were run in two different seasons: the period from 20 July 2009 to 31 October 2009 (’summer’), and from 6 December 2009 to 31 March 2010 (’winter’). The first few days of the experiments were discarded to allow the spin-up of the VarBC predictor parameters.

3.2 Results

3.2.1 Departure statistics of the first guess and analysis

Departure statistics for the observing system are computed over the two seasons (from 1 August 2009 to 31 October 2009, and from 1 January 2010 to 31 March 2010): mean and standard deviation of the differences between observations and NWP first guess are computed after the bias correction of satellite radiances. The assimilation of uncorrected AMSU-A channel 12 and channel 14 radiances in the “no-BC experiment” improves to a great extent the fit of the NWP first guess (or background) to temperature observations in the stratosphere (see Fig 13 for the fit to radiosonde temperatures in the Northern Hemisphere). The improvement in the bias of

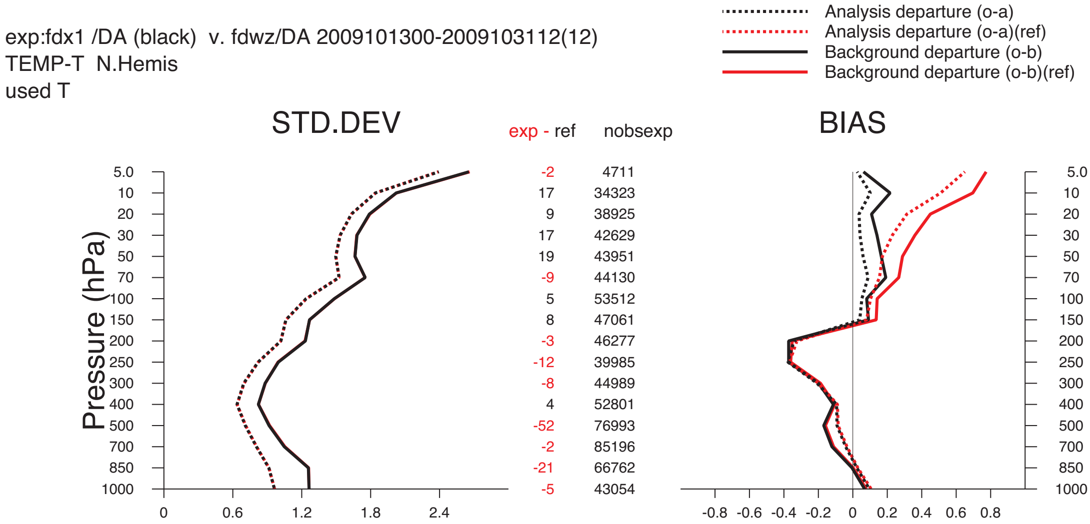


Figure 13: Radiosonde temperature departure statistics for the "no-BC experiment" (fdx1) (black) and the "ctl experiment" (fdwz) (red) for the Northern Hemisphere.

the first guess departures occurs in both seasons and it is present also in the GPS radio occultation measurements (not shown).

Climatology data suggest that also the analysis in the upper stratosphere and mesosphere is changed in the right direction. Close to the top of the model, where no conventional observations are available, the temperature field for the same experiment is in good agreement with data from the SPARC climatology (WCRP 2011) (see Fig 14). The mean temperature differences between the "no-BC experiment" and the "ctl experiment" are either small or they bring the "no-BC experiment" closer to the climatological data than the "ctl experiment".

The bias correction of the other high-peaking AMSU-A channels is reduced by a large amount by the 'anchoring' provided by channel 12 and 14. The mean bias correction of channel 13 and channel 11 is reduced by a few tenths of Kelvin in the "no-BC experiment" compared to the "ctl experiment", and also the corrections of the tropospheric channels down to channel 8 are marginally affected (see how in Fig 15 the mean bias correction in the "no-BC experiment" (pink line) compares to the mean bias correction in the "ctl experiment" (green line) for channels 8 to 13). This reduction in the bias correction suggests that the analysis is in better agreement with

Table 3: Experiment description

Experiment name	Experiment id in summer (winter)	Type of bias correction for AMSU-A ch12 and 14
"no-BC experiment"	fdx1 (fdto)	zero bias correction
"scanBC experiment"	fdx0 (fdtk)	scan bias correction
"NOAA-19 anchoring experiment"	ffm2 (ffly)	scan bias correction on NOAA-19, scan bias and offset correction on other satellites
"ctl experiment"	fdwz (fe3k)	full bias correction for ch 12, zero bias correction for ch 14

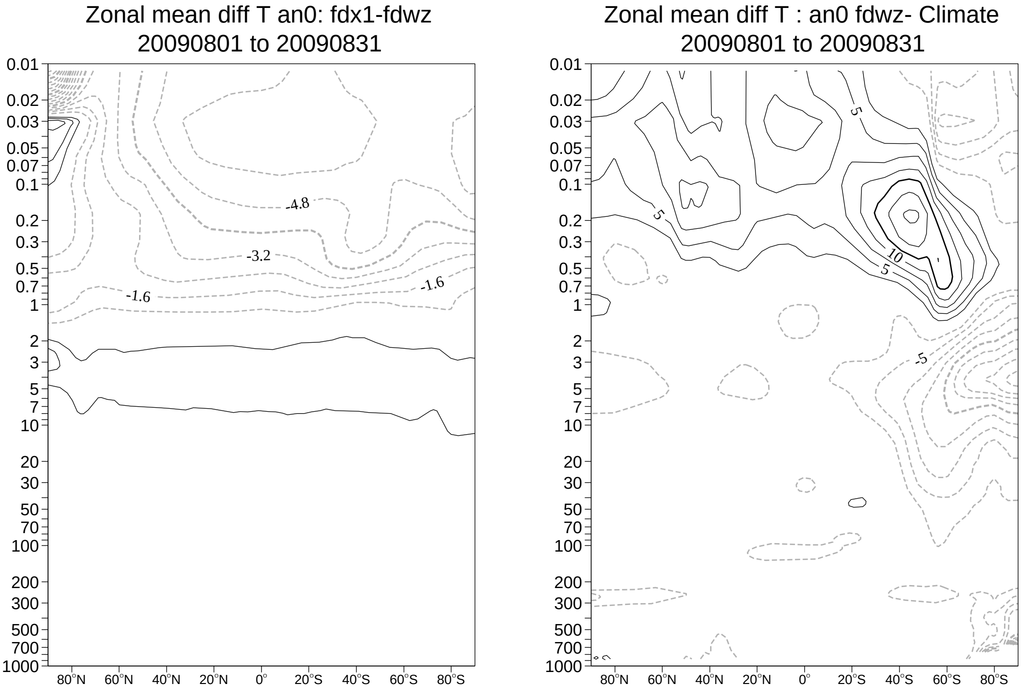


Figure 14: Zonal mean temperature analysis differences between the "no-BC experiment" (fdx1) and the "ctl experiment" (fdwz) (left) and between the "ctl experiment" (fdwz) and the climate temperature (right).

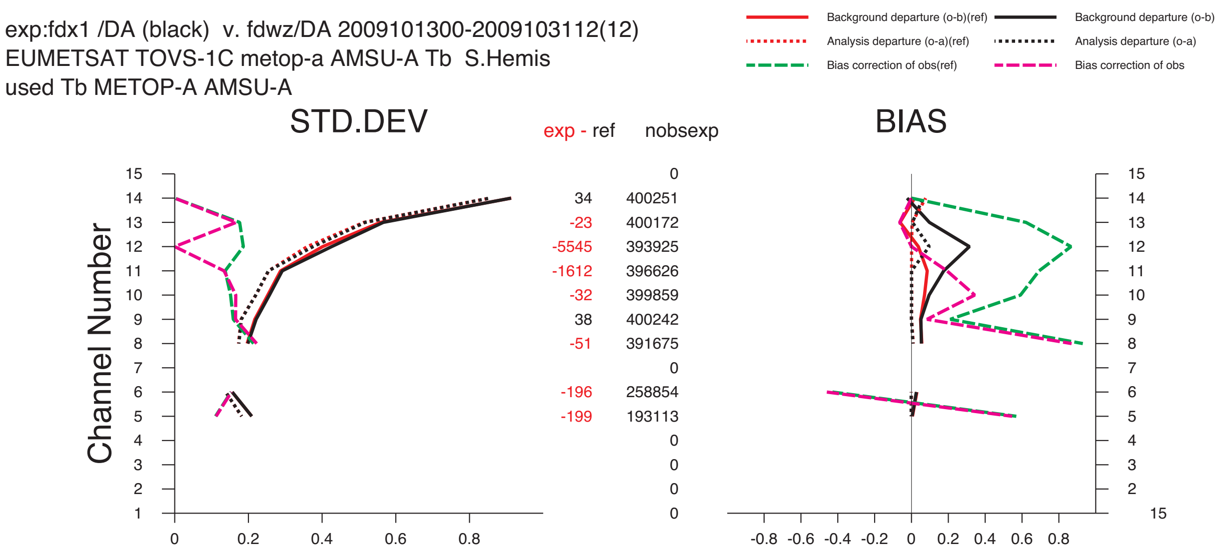


Figure 15: MetOp-A brightness temperature departure statistics and bias correction for the "no-BC experiment" (fdx1) (black and pink) and the "ctl experiment" (fdwz) (red and green) for the Southern Hemisphere.

AMSUA observations before bias correction when channel 12 and 14 are assimilated uncorrected.

Departure statistics for the "scan-BC experiment" and for the "NOAA-19 anchoring experiment" show also an improved first-guess of observations such as radiosonde and GPS radio occultation measurements, as well as a reduction in the mean bias correction of stratospheric channels below channel 14.

Departure statistics as function of the instrument field of view show that in the "scan-BC experiment" VarBC does not correct adequately the scan bias of AMSU-A channel 12 and 14 on-board NOAA-18 (see Fig 16 top): VarBC estimates the scan bias parameters so that they attempt to correct also for differences in bias between different satellites, and AMSU-A on NOAA-18 is the only AMSU-A instrument with a warm bias in the stratosphere (Bormann 2009, Fig 2). Such a correction is normally performed by the offset term. In the "NOAA-19 anchoring experiment" VarBC adequately corrects the scan biases of AMSU-A on NOAA-18 (Fig 16 bottom) (as it does it for the other satellites) thanks to the offset correction applied to most of the channels 12 and 14.

3.2.2 Forecast impact

Forecast results are computed for different variables and regions for 92 and 90 days of assimilation experiments in the two seasons. The forecast impact of the "no-BC experiment" is positive in the stratosphere in both seasons (see for example Fig 17 for the forecast of the 50 hPa geopotential in the winter experiments). The positive impact in the stratosphere is due mainly to a reduction of the mean error than of the standard deviation of the error (Fig 18), consistent with what has been observed in the observation departure statistics. However, the impact is neutral to slightly negative in lower regions of the atmosphere over the winter Pole (see Fig 19 for the forecast of the 500 hPa geopotential). The degradation of the tropospheric scores for the winter Pole can be improved by allowing for some aspects of the bias to be corrected. Both the "scan-BC experiment" and "NOAA-19 anchoring experiment" improve the forecast of the geopotential in the winter Pole compared to the "no-BC experiment" (see for example how Fig 20 compares to Fig 19). It appears that neglecting the scan-bias when assimilating channel 12 has a detrimental effect. Scan-biases for the stratospheric AMSU-

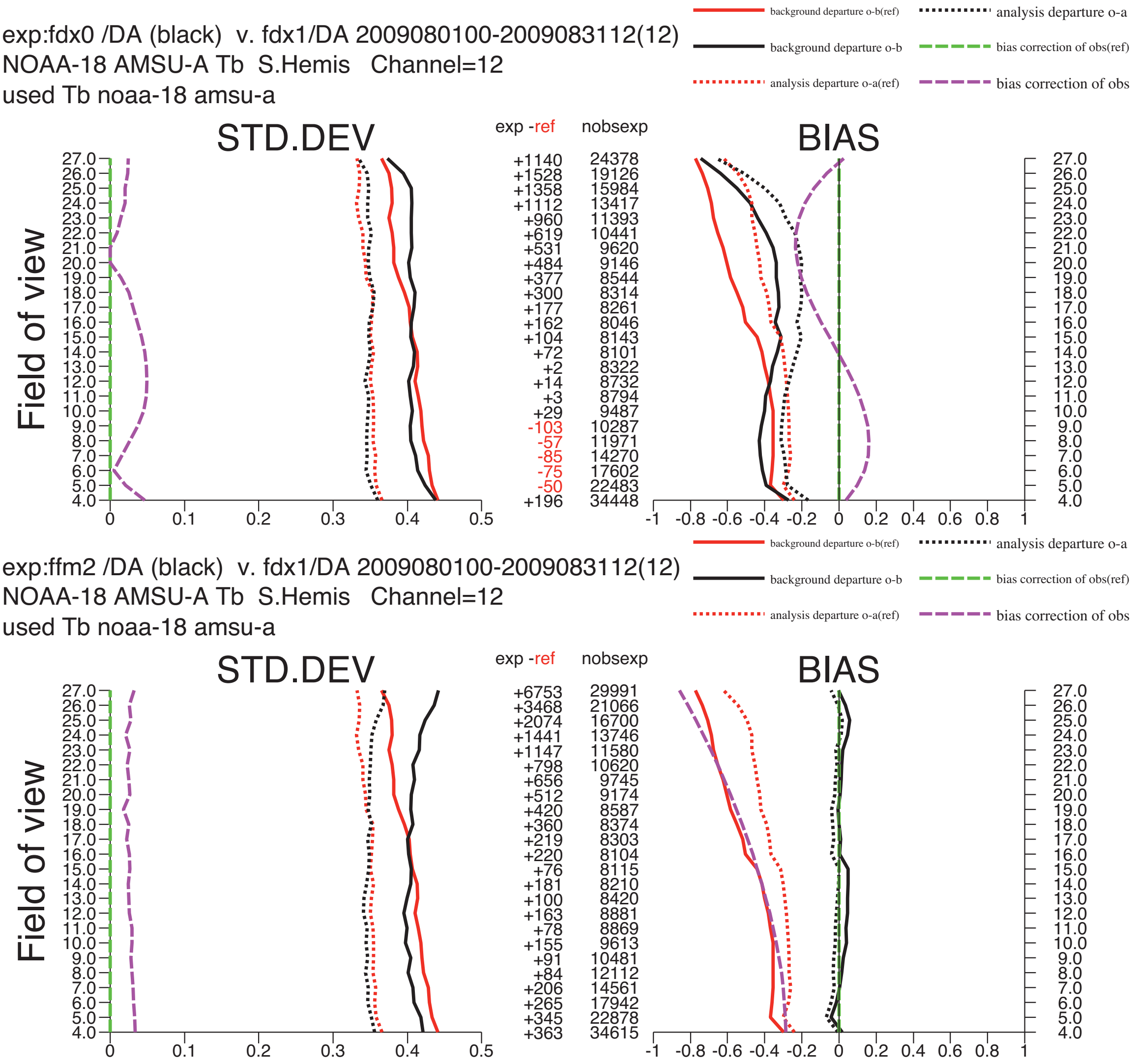


Figure 16: NOAA-18 brightness temperature statistics as function of the field of view for the "scan-BC experiment" (fdx0) (black) and the "no-BC experiment" (fdx1) (red) (top), and for the "NOAA-19 anchoring experiment" (ffm2) (black) and the "no-BC experiment" (fdx1) (red) (bottom) for the Southern Hemisphere.

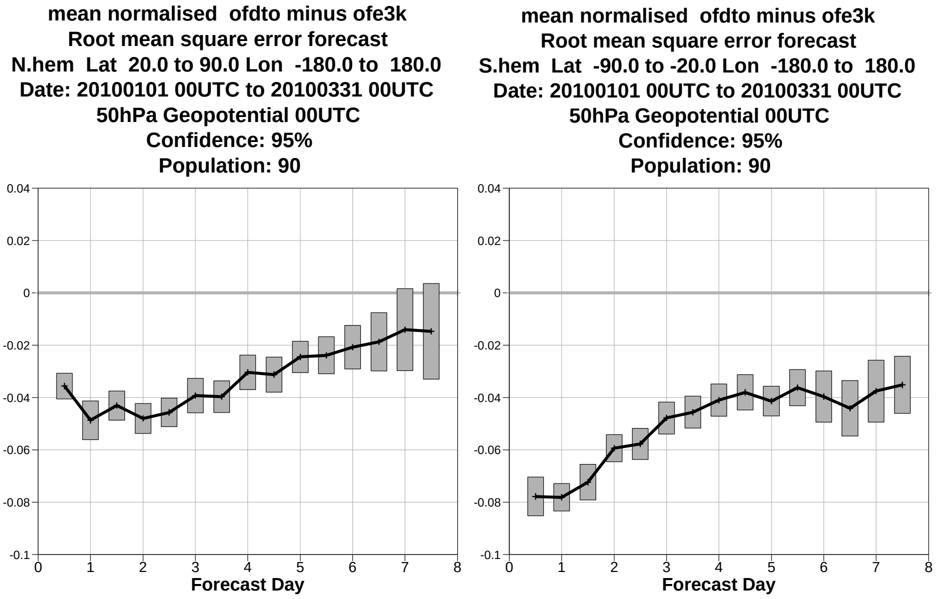


Figure 17: Normalised differences in the root mean squared forecast error for the 0 Z forecast of the 50 hPa geopotential between the "no-BC experiment" (fdto) and the "ctl experiment" (fe3k) in the Northern (left) and Southern(right) Hemisphere with verification against a set of radiosonde observations.

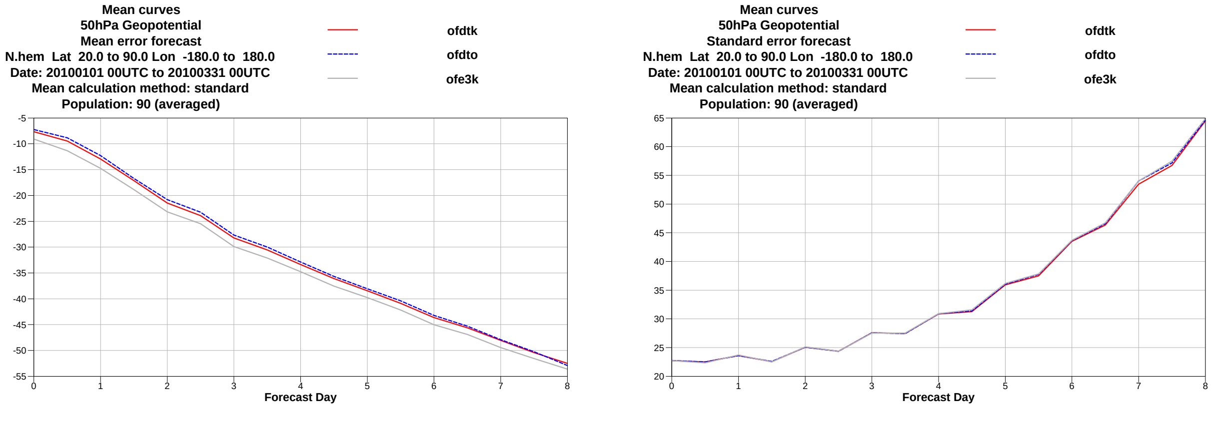


Figure 18: Mean (left) and standard deviation (right) of the error for the 0 Z forecast of the 50 hPa geopotential in the "scan-BC experiment" (fdtk) (red), in the "no-BC experiment" (fdto) (blue) and in the "ctl experiment" (fe3k) (gray) in the winter with verification against a set of radiosonde observations.

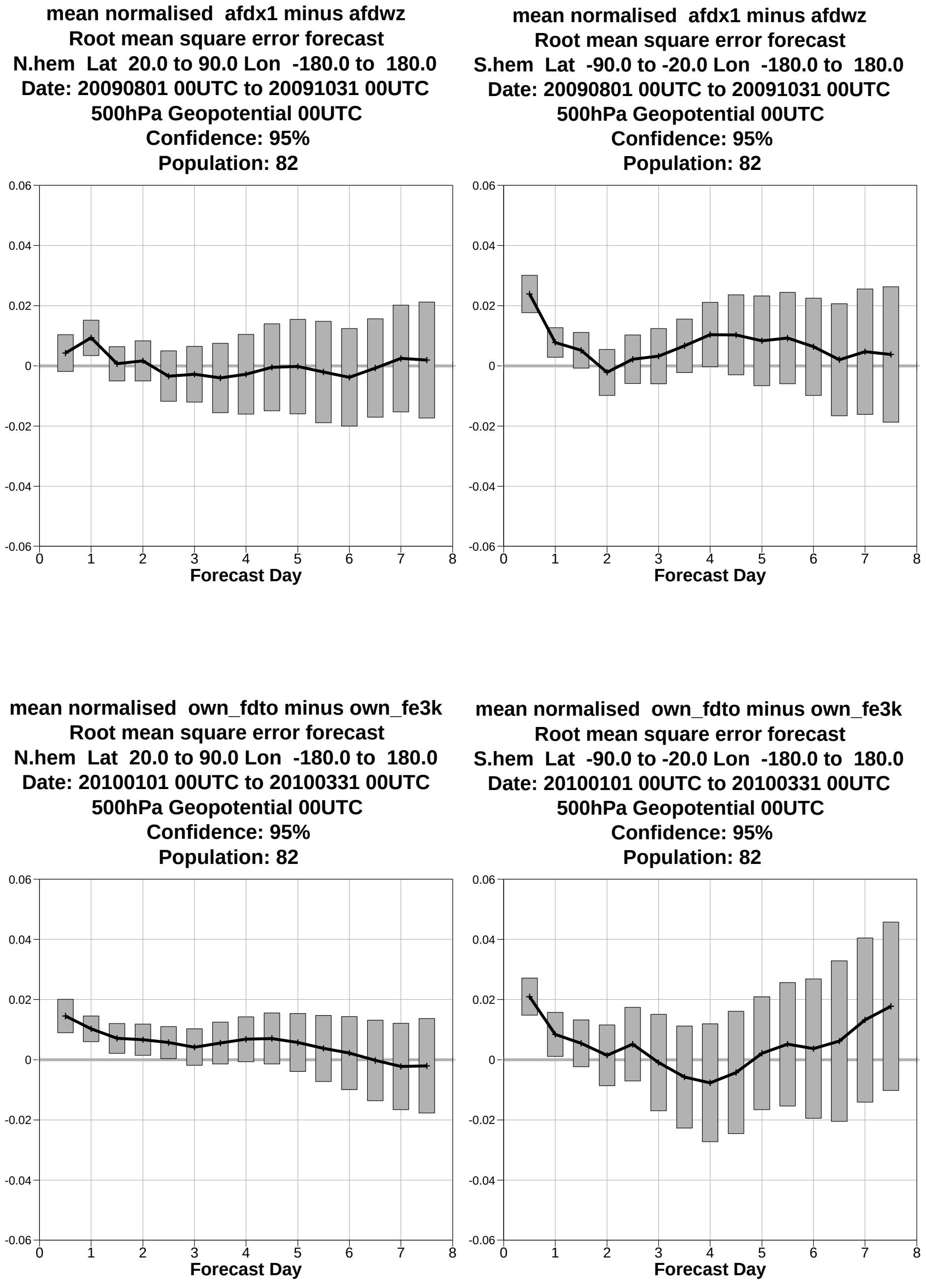
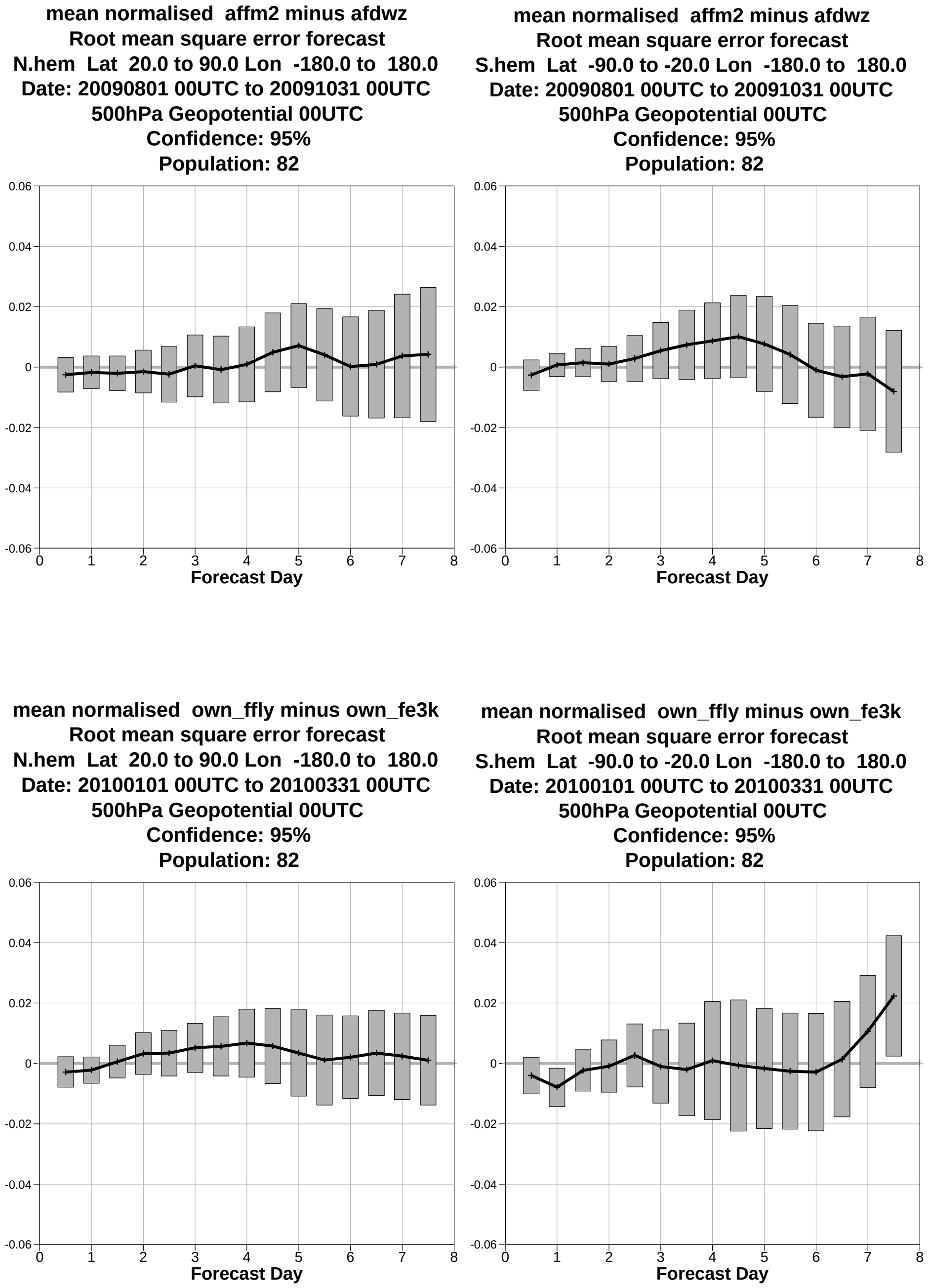


Figure 19: Normalised differences in the root mean squared forecast error for the 0 Z forecast of the 500 hPa geopotential between the "no-BC experiment" in the summer (fdx1) (top) and in the winter (fdto) (bottom) and the "ctl experiment" (fdwz and fe3k) in the Northern Hemisphere (left) and in the Southern Hemisphere (right) with verification against the experiment own-analysis.



mean normalised affm2 minus afdwz
Root mean square error forecast
N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
Date: 20090801 00UTC to 20091031 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 82

mean normalised affm2 minus afdwz
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20090801 00UTC to 20091031 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 82

mean normalised own_ffly minus own_fe3k
Root mean square error forecast
N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
Date: 20100101 00UTC to 20100331 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 82

mean normalised own_ffly minus own_fe3k
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20100101 00UTC to 20100331 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 82

Figure 20: Normalised differences in the root mean squared forecast error for the 0 Z forecast of the 500 hPa geopotential between the "NOAA-19 anchoring experiment" in the summer (ffm2) (top) and in the winter (ffly) (bottom) and the "ctl experiment" (fdwz and fe3k) in the Northern Hemisphere (left) and in the Southern Hemisphere (right) with verification against the experiment own-analysis.

A channels are primarily due to instrument-related biases, and if uncorrected lead to erroneous increments. However the forecast impact of the above two experiments is mixed: the forecast of the low-level geopotential in the Southern Hemisphere in “NOAA-19 anchoring experiment” in the summer, and of the geopotential in the Northern Hemisphere in the “scan-BC experiment” in both seasons shows some slightly negative scores compared to the “ctl experiment”.

3.2.3 Conclusions

The assimilation of channel 12, together with channel 14, with zero bias correction provides the system with a better first guess in the upper part of the atmosphere compared to operations. When channel 12 is assimilated uncorrected, VarBC has less degrees of freedom to drift the corrected observations (and subsequently the analysis) towards significant model errors in the higher part of the atmosphere. This reduction in bias is retained throughout the forecast. Forecast scores though show that this change in VarBC predictors has a slightly negative impact in the troposphere in the winter Pole, and suggest that there are biases associated with these channels that need to be corrected prior to the assimilation.

The correction of the offset and scan dependent bias of channel 12 and 14 (with one of the AMSU-A instrument having channel 12 and 14 corrected only for scan bias) improves the forecast compared to the assimilation of these channels with zero bias correction, though has in some cases a slightly negative impact when compared to the operation configuration. The channel 12 and 14 corrected only for scan bias ’anchor’ the channels of the other AMSU-A instruments so that their offset correction does not drift the analysis towards the model error. This ’anchoring’ reduces significantly the systematic differences between the analysis and radiosonde temperatures in the stratosphere compared to operations. The offset term allows for inter-satellite biases to be corrected as inter-satellite biases can be aliased into an erroneous scan-bias correction when correcting AMSU-A channel 12 and channel 14 only for scan bias.

4 Absorption coefficient correction in the radiative transfer for AMSU-A

4.1 Correction factor calculation

In this section we deal with systematic errors in the radiative transfer simulation of AMSU-A radiances. Watts and McNally (2004) have shown that biases commonly observed between observed and FG-simulated radiances for some channels can be modelled through a scaling factor γ for the optical depth. We estimate the values of the correction γ to the the optical depth $\sigma(p)$ in the AMSU-A channel transmittance $\tau(p)$ from pressure level p to space, such that

$$\tau(p) = e^{-\gamma\sigma(p)}. \tag{2}$$

The γ-correction provides a more physically-based approach than VarBC to correcting some commonly observed air-mass dependent biases. The γ-correction accounts for constant errors in the optical depth calculations, that is errors in the absorption coefficient due for example to inaccurate channel response function or line strength. Calibration errors or variable errors in the assumed gas concentrations have to be corrected differently.

Let us suppose that AMSU-A radiance systematic errors can be modelled by a global constant offset δ plus the bias due to an incorrect absorption coefficient in the radiative transfer as follows:

$$mean[Obs - FG] = \delta + mean[FG_\gamma - FG], \tag{3}$$

where *Obs* is the radiance measurement, FG is the corresponding model first guess (the simulated radiance from the model state; FG used without subscript implies that no γ-correction is applied in the radiative transfer, i.e. $\gamma = 1$), and γ is the absorption coefficient correction used in the calculation of FG_{γ}. The constant offset in this case corrects for global average values of all biases not attributable to an absorption coefficient error. Then, under a linear assumption for γ (see Watts and McNally 2004), equation 3 can be written as

$$mean[Obs - FG] = \delta + \beta(\gamma) mean[FG_{\gamma^*} - FG], \tag{4}$$

where γ^* is a given fixed value and β is a linear function of γ.

We have run experiments, both in the summer and winter season, with a 5% increment in the absorption coefficient ($\gamma^* = 1.05$) of the AMSU-A channels in order to calculate FG_{γ^*}. We have used an equivalent increment for the sensors which had already a correction γ_0 applied, so that equation 4 becomes:

$$mean[Obs - FG_{\gamma_0}] = \delta + \beta(\gamma) mean[FG_{\gamma_0+.05} - FG_{\gamma_0}]. \tag{5}$$

The experiments were run in a ’monitoring mode’ (i.e. without the assimilation of the observations) with the short-term forecast taken from a control experiment: the first-guess FG_{γ^*} (or $FG_{\gamma_0+.05}$) and FG in equation 4 (or 5) were calculated from the same short-term forecast, respectively with and without the 5% increment in the absorption coefficient. The control experiment used the same γ corrections as in operations: $\gamma \neq 1$ for NOAA-15, NOAA-18, Aqua, and $\gamma = 1$ for NOAA-19 and MetOp-A. The ECMWF 4D-Var assimilation system used for the experiments was Cy36r3 at a T255 resolution and with version 9 of the fast radiative transfer model RTTOV (Saunders et al. 1999).

We have estimated β (and hence a new value of γ) from equation 4 (and 5) for all AMSU-A channels. The updated values of γ are in Table 4, together with the values used currently in operations for the tropospheric channels 5 to 8. For the higher peaking channels the γ-correction model performs poorly in correcting air-mass biases due to larger model biases in the higher part of the atmosphere, as also stated in Watts and McNally (2004).

The new values of γ compare well with the old ones for the AMSU-A sensors that had already a correction applied (NOAA-15, NOAA-18 and Aqua), suggesting that they are modelling radiative transfer errors rather than model errors (as the forecast model went through numerous changes since the previous γ calculations in 2004). Only channel 5 shows slightly bigger differences consistently for the three above sensors. This is likely due to the recent change in the emissivity calculations (Krzeminski 2008) which has modified the bias of channel 5 since the previous γ calculations were performed.

4.2 Assimilation experiment setup

We have tested the updated values of the γ-correction (the fourth column of Table 4) in the ECMWF 4D-Var assimilation system. We have run an experiment (“gamma experiment”) with a γ correction for all AMSU-A tropospheric channels 5 to 8: updated values were used for the satellites that had already a correction. The current setting for VarBC were left unchanged. Additionally we have run an experiment with no γ-correction (“no-gamma experiment”) for any AMSU-A instruments. The current operational setup (“ctl experiment”) is a mixture of the two above experiments with a γ correction applied only to some of the satellites. The ECMWF 4D-Var assimilation system used for the experiments was Cy36r3 at a T255 resolution, and experiments were run from 20 July 2009 to 31 October 2009. A description of the three experiments is in Table 5.

Table 4: Values of γ used in operations and new estimates

Satellite	Channel	Operational γ	New γ
NOAA-15	5	1.0500	1.0419
	6	1.0500	NA
	7	1.0339	1.0321
	8	1.0400	1.0386
NOAA-18	5	1.0420	1.0344
	6	1.0180	1.0204
	7	1.0390	1.0370
	8	1.0350	1.0414
NOAA-19	5	1.0000	1.0348
	6	1.0000	1.0199
	7	1.0000	1.0309
	8	1.0000	1.0430
Aqua	5	1.0500	1.0305
	6	1.0390	1.0297
	7	1.0450	NA
	8	1.0460	1.0438
MetOp-A	5	1.0000	1.0322
	6	1.0000	1.0165
	7	1.0000	NA
	8	1.0000	1.0436

Table 5: Experiment description

Experiment name	Experiment id	γ-correction for AMSU-A ch 5 to 8
"gamma experiment"	fgkh	new $\gamma \neq 1$ for all AMSU-A
"no-gamma experiment"	ffv3	$\gamma = 1$ for all AMSU-A
"ctl experiment"	ffwz	old $\gamma \neq 1$ for NOAA-15, NOAA-18, Aqua, $\gamma = 1$ for NOAA-19, MetOp-A

4.3 Results

4.3.1 Departure statistics of the first guess and analysis

Mean and standard deviation of the FG-departures (i.e. the differences between the observations and the model first guess) are computed for the observing system over the period 1 August 2009 to 31 October 2009. Correcting the absorption coefficient errors removes to a great extent the air-mass dependent biases for AMSU-A channels 5 to 8. As an example we show in Fig 21 the mean first guess departures before (VarBC) bias correction of AMSU-A channels 5 and 8 on NOAA-19, in the "gamma experiment" (where a γ-correction equal to 1.035 and 1.043 is used respectively for channel 5 and 8) and in the "ctl experiment" (where no γ-correction is applied to AMSU-A on this satellite). In the "gamma experiment" location-dependent biases are significantly removed and channel 5 to 8 radiances are fed into the assimilation system with a much more flat bias. This is a positive aspect, as it means that VarBC has to do less work to correct the residual biases. Note that in the case of channel 5 the γ-correction produces different biases over land and sea in the first guess departures before the VarBC bias correction is applied. This is likely a result of different methods being used to estimate the surface emissivity over land and sea, leading to different biases in the emissivity. For this reason VarBC uses different scan bias predictors over land and over sea for the correction of channel 5 which is the lowest-peaking among the assimilated AMSU-A observations. Without a γ-correction the air-mass dependent bias appear to compensate for the difference in bias over different surfaces.

Departure statistics after the VarBC bias correction show that VarBC is able to correct well for the air-mass dependent component of the bias and compensate for the correction of the absorption coefficient performed by γ for the channels that do not have a γ-correction applied. Fig 22 shows the mean first guess departures after bias correction for the same channels and experiments of Fig 21. The mean first-guess departures are comparable with or without a γ-correction, with the exception of channel 5 where the γ-correction produces slightly higher biases over land. For this reason, we are currently investigating further the γ-correction of channel 5 and the impact that the higher biases and standard deviations over land have on the forecast.

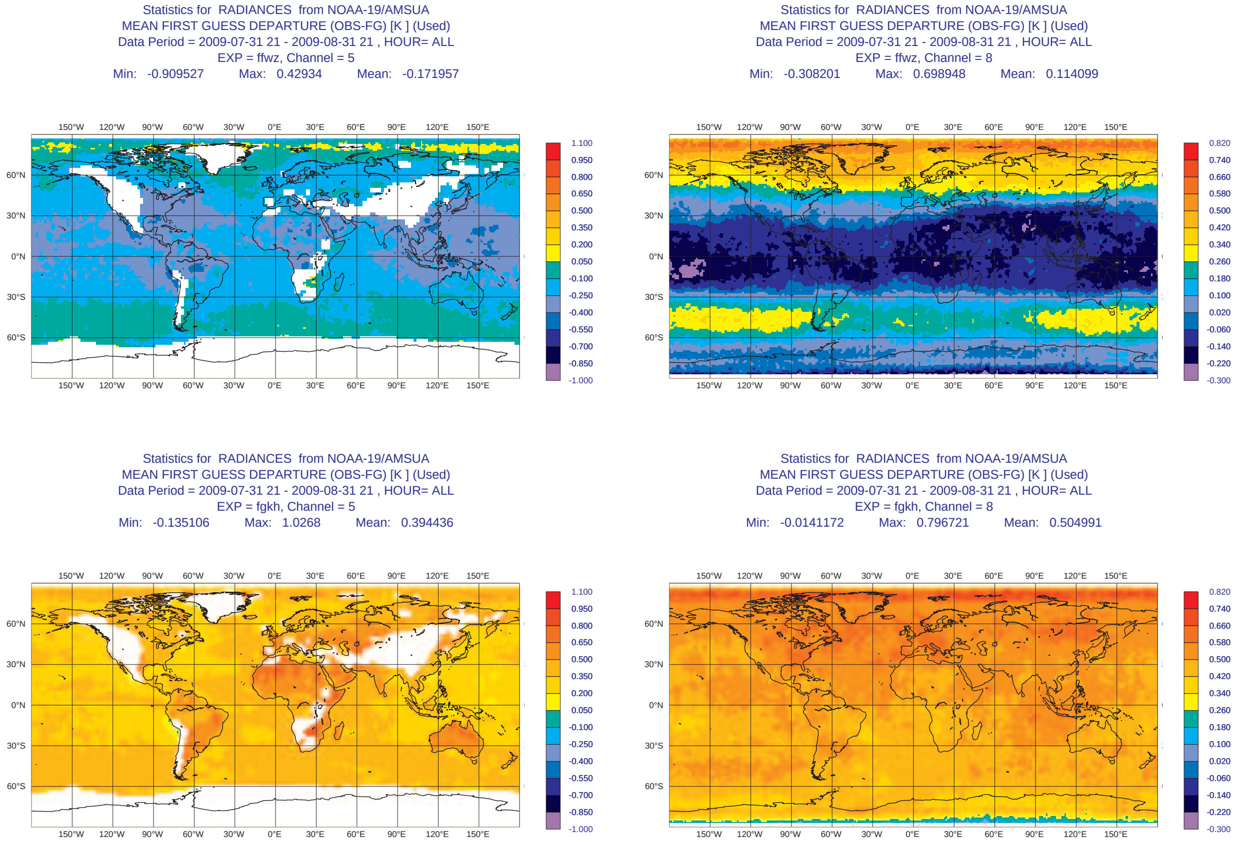
The fit to other observations like radiosonde temperature and GPS radio occultation measurements suggest that the γ-correction produces a better first-guess in the higher part of the atmosphere. Fig 23 shows for example the improvement in the stratospheric bias of the first-guess and analysis for the "gamma experiment" versus the "no-gamma experiment". The improvement is less obvious when the "gamma experiment" is compared to the "ctl experiment" as there three out of five AMSU-A have a γ-correction applied in both experiments.

4.3.2 Forecast impact

The impact of the γ correction on the forecast is studied for different variables and regions. Forecast results are computed for 92 days of assimilation experiments. The forecast impact of the "gamma experiment" versus the "no-gamma experiment" is not uniformally in favour of one or the other experiment (see for example Fig 24 for the forecast of the geopotential). This result is coherent with the small differences in departure statistics of the first guess and analysis after the bias correction. As shown earlier, the VarBC air-mass predictors are able to correct location-dependent biases as efficiently as the off-line γ-correction.

4.3.3 Conclusions

We have calculated a correction for the absorption coefficient of AMSU-A channels 5 to 8 of NOAA-19 and MetOp-A (and updated the correction factors for the other AMSU-A instruments) using a physically-based



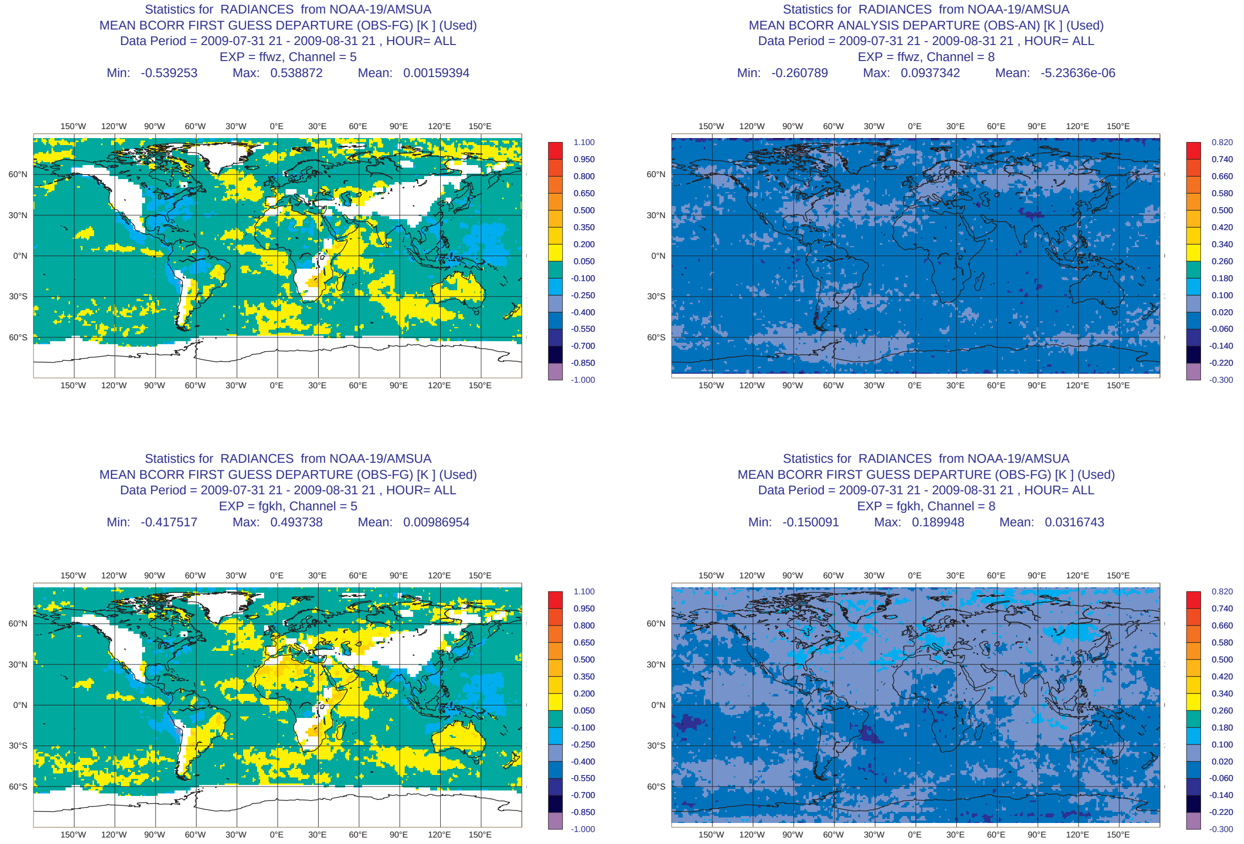
Statistics for RADIANCES from NOAA-19/AMSUA
MEAN FIRST GUESS DEPARTURE (OBS-FG) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = ffwz, Channel = 5
Min: -0.909527 Max: 0.42934 Mean: -0.171957

Statistics for RADIANCES from NOAA-19/AMSUA
MEAN FIRST GUESS DEPARTURE (OBS-FG) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = ffwz, Channel = 8
Min: -0.308201 Max: 0.698948 Mean: 0.114099

Statistics for RADIANCES from NOAA-19/AMSUA
MEAN FIRST GUESS DEPARTURE (OBS-FG) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = fgkh, Channel = 5
Min: -0.135106 Max: 1.0268 Mean: 0.394436

Statistics for RADIANCES from NOAA-19/AMSUA
MEAN FIRST GUESS DEPARTURE (OBS-FG) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = fgkh, Channel = 8
Min: -0.0141172 Max: 0.796721 Mean: 0.504991

Figure 21: Mean first guess departures for AMSU-A channel 5 (left) and channel 8 (right) on NOAA-19 before bias correction for the "ctl experiment" (ffwz) (top) and for the "gamma experiment" (fgkh) (bottom). Note that in the"ctl experiment" AMSU-A on NOAA-19 has no γ-correction applied, while in the "gamma experiment" a correction equal to 1.035 and 1.043 is used respectively for channel 5 and 8.



Statistics for RADIANCES from NOAA-19/AMSUA
MEAN BCORR FIRST GUESS DEPARTURE (OBS-FG) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = ffwz, Channel = 5
Min: -0.539253 Max: 0.538872 Mean: 0.00159394

Statistics for RADIANCES from NOAA-19/AMSUA
MEAN BCORR ANALYSIS DEPARTURE (OBS-AN) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = ffwz, Channel = 8
Min: -0.260789 Max: 0.0937342 Mean: -5.23636e-06

Statistics for RADIANCES from NOAA-19/AMSUA
MEAN BCORR FIRST GUESS DEPARTURE (OBS-FG) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = fgkh, Channel = 5
Min: -0.417517 Max: 0.493738 Mean: 0.00986954

Statistics for RADIANCES from NOAA-19/AMSUA
MEAN BCORR FIRST GUESS DEPARTURE (OBS-FG) [K] (Used)
Data Period = 2009-07-31 21 - 2009-08-31 21 , HOUR= ALL
EXP = fgkh, Channel = 8
Min: -0.150091 Max: 0.189948 Mean: 0.0316743

Figure 22: Mean first guess departures for AMSU-A channel 5 (left) and channel 8 (right) on NOAA-19 after bias correction for the "ctl experiment" (ffwz) (top) and for the"gamma experiment" (fgkh) (bottom). Note that in the"ctl experiment" AMSU-A on NOAA-19 has no γ-correction applied.

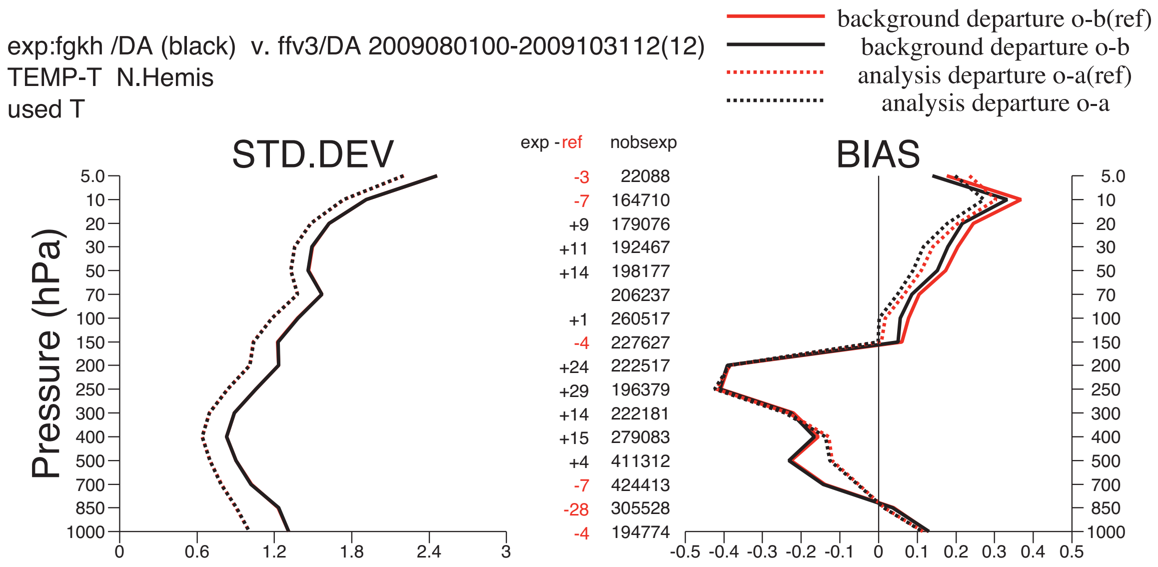


Figure 23: Radiosonde temperature departure statistics for the "gamma experiment" (fgkh) (black) and the "no-gamma experiment" (ffv3) (red) for the Northern Hemisphere.

model which followed the work of Watts and McNally (2004). Assimilation experiments show that the γ-correction reduces significantly the air-mass dependent component of the bias and leaves VarBC with an easier (more flat) bias to correct. The new values of gamma for channels 5 to 8 do not differ much from the values computed in 2004, suggesting that the biases they correct are likely due to radiative transfer errors. When no γ-correction is applied, VarBC is however able to correct the systematic differences between the observations and the model. Correcting systematic errors off-line prior to the application of VarBC is however preferable as the γ-correction is less likely to correct effects which are not radiative transfer biases.

We are currently investigating further the correction of AMSU-A channel 5 because of the higher biases and standard deviations over land caused by the applying a γ-correction to this surface-sensitive channel.

5 Conclusions

This study investigates three aspects of the use of ATOVS data at ECMWF: (1) the impact of different constellations of MW-sounders, (2) a review of the variational bias correction of stratospheric observations, (3) the correction of the absorption coefficient in the AMSU-A observation operator. The main findings of this work are explained in the executive summary at the beginning of the report. Here we briefly summarise them.

We have investigated the use of AMSU-A and AMSU-B/MHS from existing polar-orbiting satellites. Observing system experiments show some benefit from having an evenly-spaced orbit constellation of AMSU-A sensors and a clear advantage from assimilating all available ATOVS data. These results can provide some references for planning future orbit constellations that involve ATOVS-like instruments.

We have reviewed the bias correction of high-peaking AMSU-A channels and showed that correcting to a lesser extent AMSU-A channel 12, additionally to channel 14, reduces the bias in the temperature analysis in the upper part of the atmosphere, this reduction in bias is retained throughout the forecast. However, we do not suggest an operational change to the current correction of AMSU-A channel 12 and 14 as the results of the forecast impact are, in some cases, slightly negative compared to operations.

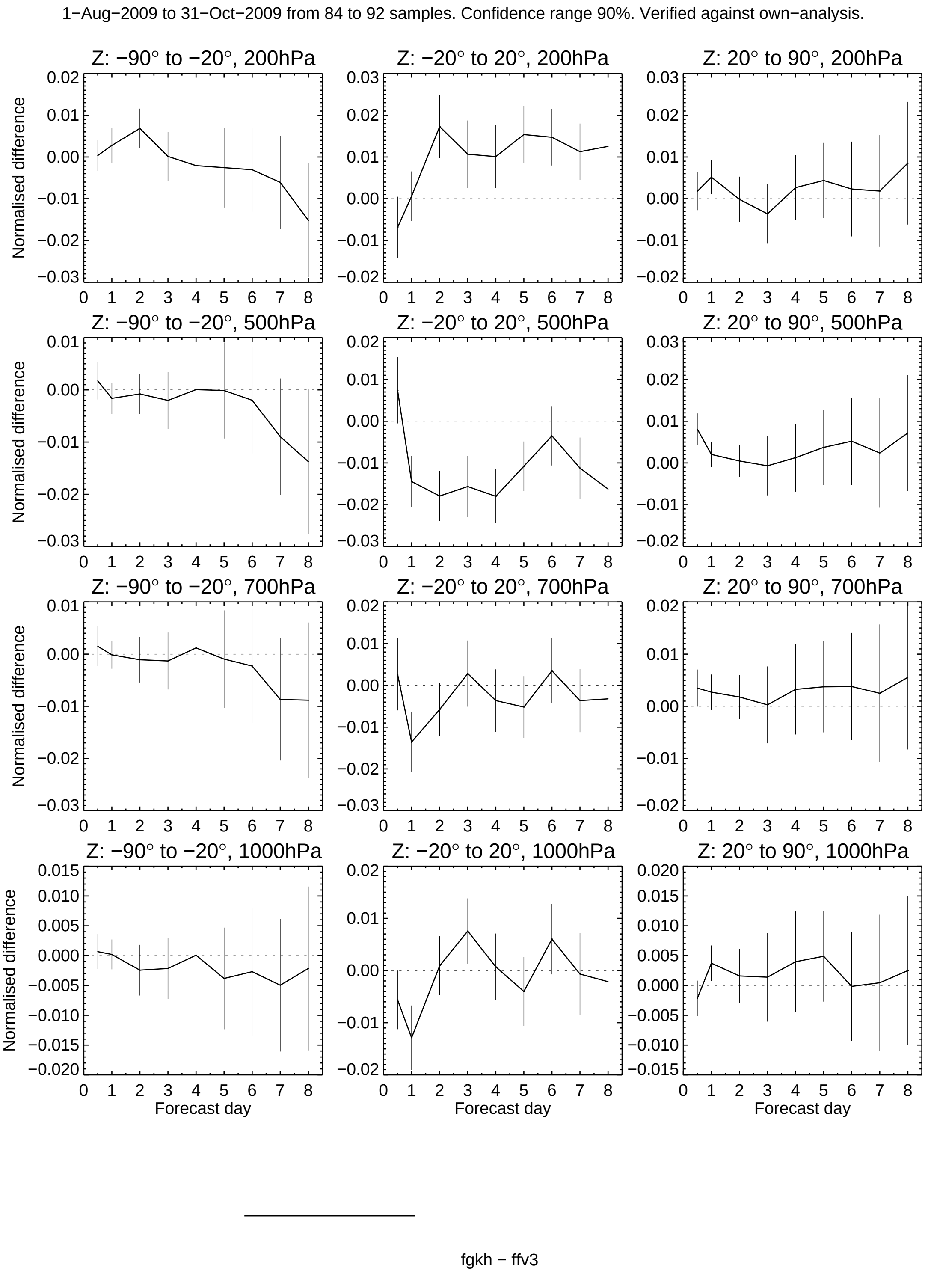


Figure 24: Normalised differences in the root mean squared forecast error between the "gamma experiment" (fgkh) and the "no-gamma experiment" (ffv3) for the 0Z forecast of the 200 hPa, 500 hPa, 700 hPa and 1000 hPa geopotential. Verification is against the experiment own-analysis.

We have calculated a correction γ for the absorption coefficient of all the AMSU-A instruments to harmonise the treatment of radiance data over the different platforms. The results of assimilation experiments show that a γ factor smaller than 1.05 reduces significantly air-mass dependent biases in channels 5 to 8. We plan to harmonise in operations the use of the γ-correction over the different platforms when new absorption coefficients will be calculated after the introduction of RTTOV-10.

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