TECHNICAL MEMORANDUM

523

The evaluation of the HIRS/4 instrument on Metop A by using the ECMWF data assimilation system to provide a reference to compare with other sensors

Graeme Kelly

Research Department

May 2007

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/publications/

Contact: library@ecmwf.int

Abstract

The HIRS instrument was first flown onboard NIMBUS-6 in (June 1975 to May 1976). Since Oct 1978 there have been one or more of these instruments providing operational good quality inferred measurements on the NOAA operational satellites and now onboard Metop A. Although this instrument is inferior to the new multi-spectral instruments, such as AIRS and IASI, it is of sufficient accuracy to provide a 30 year global climate record of temperature and moisture. The current operational version of the ECMWF data assimilation was considered unsuitable for this study because of the use of Variational satellite bias correction that slowly evolves the satellite radiance biases with the time varying forecast error. A version of the operational system was run using non-evolving satellite bias coefficients. An additional study was undertaken to estimate the bias corrections for HIRS channel 8 (atmospheric window) on Metop A and NOAA17. The HIRS window check and the cloud detection scheme are required to produce the HIRS clear radiances. Using the data assimilation as the reference, a comparison of the HIRS clear radiances was made between HIRS/4 onboard Metop A and HIRS/3 on board NOAA17. These two instruments have very similar departure statistics (with the exception of channel 1 on HIRS NOAA17). These departure statistics are also similar for equivalent microwave channels from AMSUA and MHS on Metop A and NOAA18. There is also evidence that the smaller field of view for HIRS on Metop A produces about 20 % more clear spots. Finally a comparison is made with the current operational HIRS cloud detection and there is a need to retune the operational HIRS cloud detection.

1. Introduction

The HIRS instrument is ideal to monitor short term climate change and has been used to study changes of cloud and upper level moisture (Wylie et all 2005, Chevallier at all 2005, and Soden and Bertherton 1996). The first HIRS was carried onboard NIMBUS-6 in 1975 and then it has been on-board operational NOAA satellites since Oct 1978 and now on the Metop series.

Using the first NIMBUS 6 HIRS it was possible to derive atmospheric soundings of significant quality to greatly improve Numerical Weather Prediction (Kelly et al. 1978). These early forecast impact experiments helped HIRS to become a core instrument on the operational NOAA polar spacecraft series. The basic design for the Nimbus HIRS was modified becoming (HIRS/2) on TIROS N until NOAA 14. Further small modifications lead to HIRS/3 (NOAA 15, 16 and 17) and the latest HIRS/4 design, on Metop A, includes further improvements including a smaller field of view (FOV) of 10 km (ITT 1998).

The direct comparison of individual HIRS channels is sometimes difficult due to the spacecraft having different equatorial crossing times. The development of the simultaneous nadir overpass (SNO) observations (Cao et al. 2005) is a method used for instrument comparison. At high latitudes collations occur about ever nine days and direct comparison can be made. A limitation of SNO is time to collect the sample and is only available at high latitudes.

The use of the ECMWF Four Dimensional Variational Data Assimilation (4DVAR) for the inter-comparison of satellite instruments has many advantages. There is always an on time vertical profile reaching .01 hPa available coincident with all measurements. A measure of the accuracy of the data assimilation can be found from the fit to other data sources (e. g. radiosonde and aircraft temperature, wind and humidity measurements). This study uses the 4DVAR as a reference to inter-compare the Metop A HIRS/4 with other instruments and including HIRS/3 on NOAA17 whose orbital crossing times are within two hours.

2. Data assimilation setup

The main objective of an operational data assimilation system is to produce an accurate forecast. The accuracy of the assimilation is dependent on the observations used together with the forecast guess and varies spacially depending on observation type, density and the accuracy of the model background. By far the major data source in the assimilation is satellite measured radiances, and the treatment of their biases relative to the model guess is important and if not correctly estimated will seriously affect the skill of the forecast. In the past at ECMWF radiance biases were estimated offline (Harris and Kelly) and generally remained fixed in time for each satellite instrument unless there was a significant forecast or radiative transfer model change. An alternate method of calculating these satellite biases has been introduced into the ECMWF system based on the method used at NCEP (Derber et al.) that allows these biases to evolve in time with changes to the data assimilation state variables. Radiances biases calculated using this method are influenced by forecast model errors and can vary in space and time. Hence this method of bias correction was considered unsuitable for this study and the offline method of bias correction was used.

This study uses the current operational version a 4DVAR (cycle 31r2) at a horizontal resolution of TL511 and 60 Levels. In addition to the current operational observation set the new Metop A instruments HIRS/4, AMSUA and MHS were also used in an active mode. This data assimilation was started from 15 Dec 2006 and the radiosonde temperatures and moisture assimilation statistics (9 day average) are shown in Figs 1 and 2. Radiosonde temperature errors are usually less than a degree but their accuracy and bias can vary with altitude, day or night and radiosonde type. There appears reasonable agreement between the three latitude bands with biases, less than .2 deg K in the troposphere, and the assimilation system becomes colder in the stratosphere. In an assimilation cycle the fit to the observations improves in terms of standard deviation (sigma) but the assimilation does not remove the cold bias. The moisture statistics are different than temperature. In the Northern Hemisphere the assimilation shows a slightly smaller sigma, possibility due to the cold dry winter conditions with many inland stations compared with the warmer Tropics and Southern Hemisphere. In comparison with the radiosonde temperatures, radiosonde moisture errors are larger relative to the background and only a small amount of moisture information is extracted during the analysis.

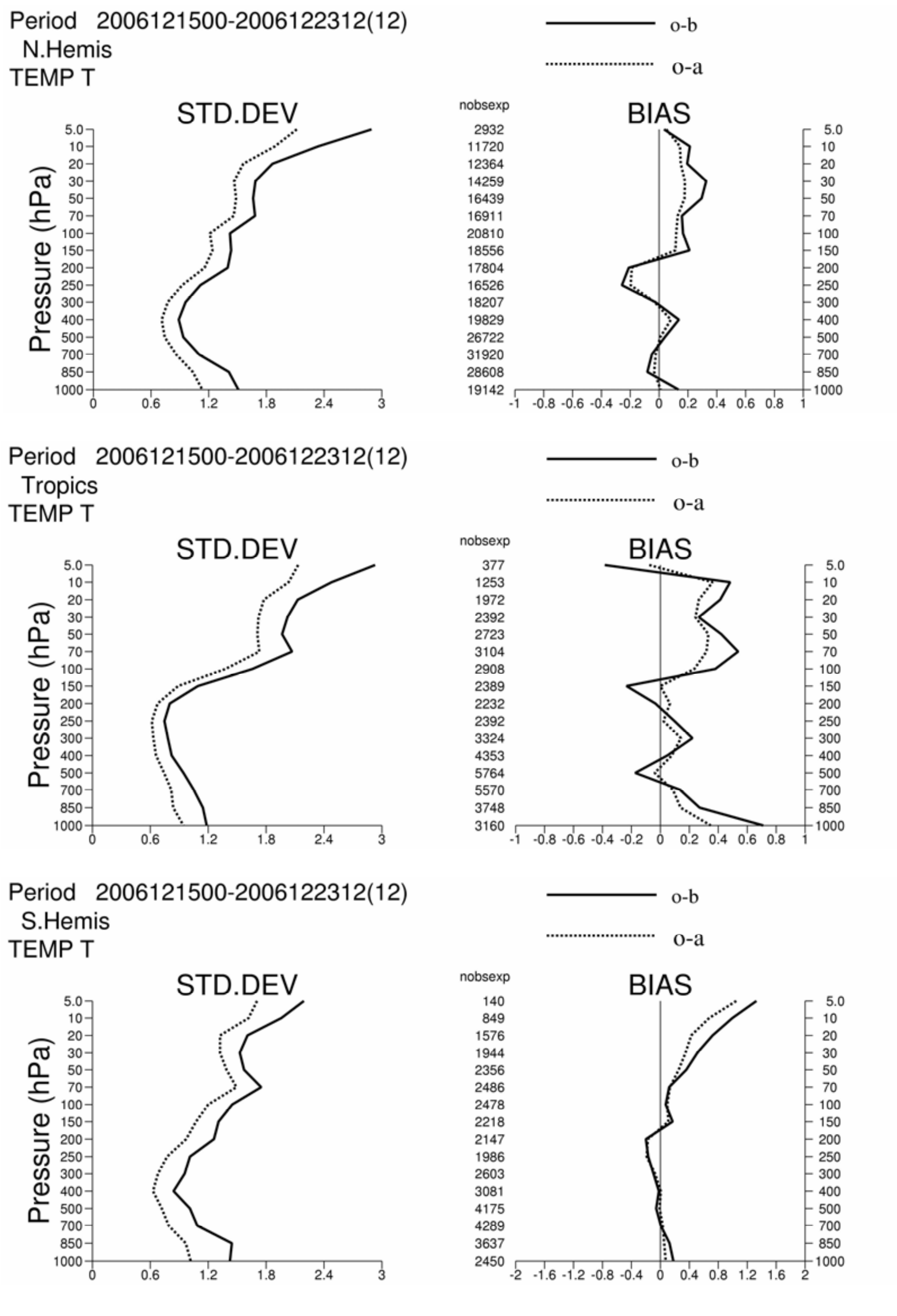

Figure 1: Radiosondes statistics: solid background forecast - dotted analysis. Top panel Northern Hemisphere (20n-90n), middle panel Tropics (20n-20s) and lower panel Southern Hemisphere (20s-90s)

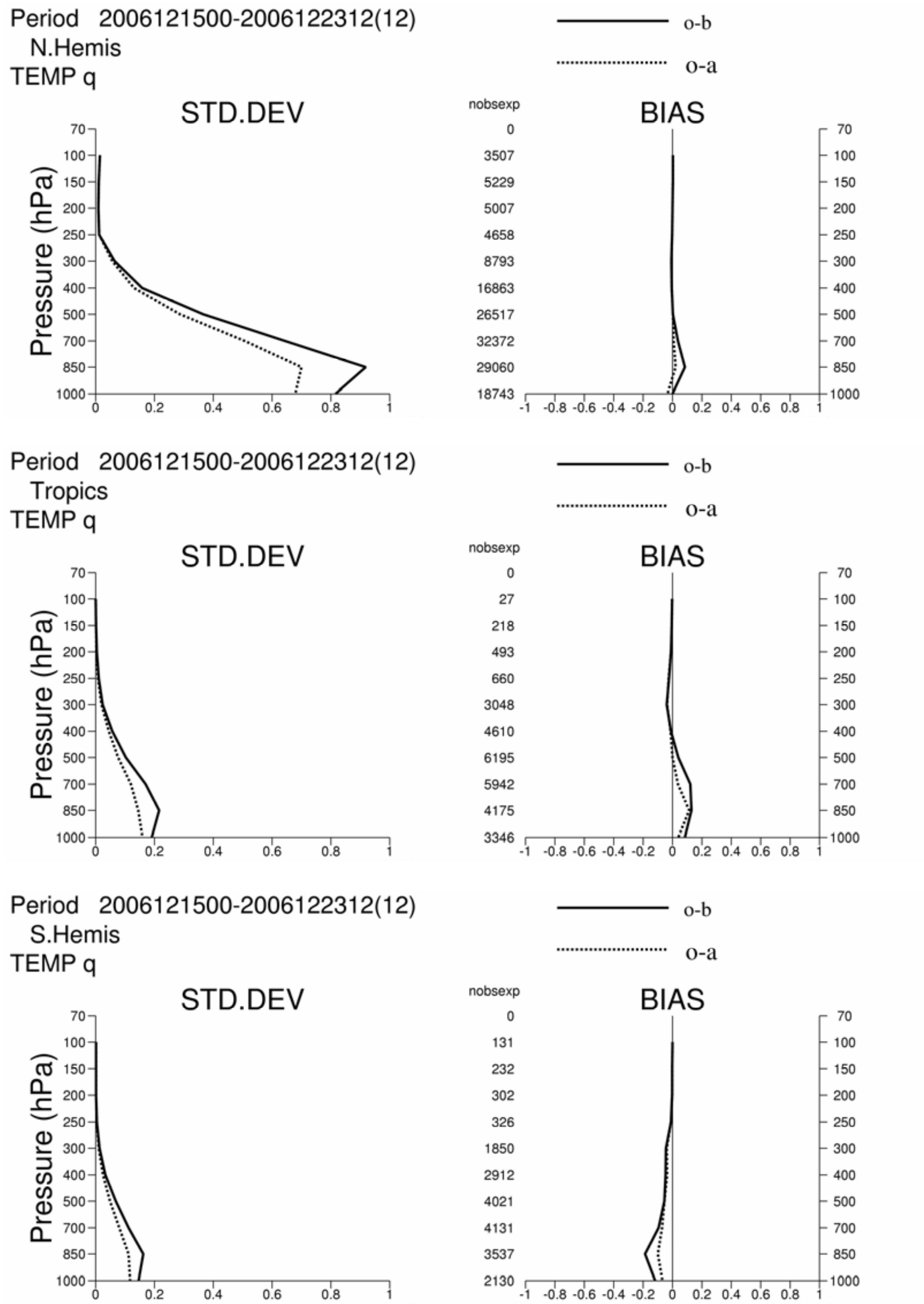

Figure 2: Radiosonde statistics:solid background forecast dotted analysis Top panel Northern Hemisphere (20n-90n), middle panel Tropics (20n-20s) and lower panel Southern Hemisphere (20s-90s). All units are gm/gm.01 except for the top left STD which is gm/gm*.001*

3. Determination of the bias in the HIRS (channel 8) Window

In the ECMWF 4DVAR system estimates of all HIRS radiances at each all HIRS spot locations are calculated using RTTOV. The surface temperature over the ice free ocean is taken from the NECP SST analysis and the ECMWF first guess provides the vertical profile temperature and moisture.

To estimate the HIRS (channel 8) window bias a 12 hour global set of 4DVAR unbiased radiances departures were selected. This sample was reduced by removing very cloudy data and outliers if the departure is outside the range of -19 deg k to +3 deg k. Next all observations colder than 280 deg k are removed to avoid cases where cloud temperatures are warmer than the SST. This situation often occurs with status cloud over frozen or partly frozen surfaces. In addition data is not used over land where background forecast temperature errors are larger than the over the sea.

Fig. 3 shows observed minus background forecast departures of HIRS channel 8 from Metop A and NOAA 17. These two plots are very comparable suggesting both instruments have a similar window channel biases. These two geographical plots are coloured by temperature, the warmer being red-yellow and cooler green-blue. The histograms below show the distribution of these departures, the colours correspond to the data plotted above. By removing departures greater than -19 deg k most of the high cloud regions are identified by the missing sections of the orbital swabs.

It is not possible to estimate the window channel bias better than about 0.3 deg k given the errors in the radiative transfer model, background forecast and SST. In future field experiments combining HIRS/4, IASI and surface and aircraft measurements it may be possible to improve the METOP HIRS window bias. With reference to both histograms in figure 3 it is a reasonable assumption that the warm side or leading edge is part of the normal distribution and near the top and cold tail are affected by the cloud. By choosing about 8% of the warm departures gives a window channels bias of zero. This zero bias represents the warmer two thirds of both histograms and corresponds to about 3 % of the full sample which is reasonable for the number of clear spots. Fig. 4 shows two ‘xy’ scatter plots of the data in Fig. 3 for Metop A and NOAA 17 and the choice of zero give a reasonable sample of clear HIRS radiances with window channel estimate between 280 and 297 deg k. Several other 12 hour periods were examined and it was found that zero bias for the window channel was reasonable for both satellites. The value of zero for the bias could be a little on the warm side but still allows a reasonable sample for clear spots and allows good estimates of the biases of colder channels.

Using 9 days of data assimilation with the static bias version of 4DVAR, a clear sky HIRS radiance (CSHR) data set containing background forecast departures was created for both satellites using a HIRS (channel 8) window selection of -0.5 to +1.0 deg k. By restricting the sample with this tight departure check there is good agreement between the variances of the simulated clear radiances and the observed radiances for those channels whose contribution is mostly atmospheric. These variances were used as a first estimate in the HIRS cloud detection scheme.

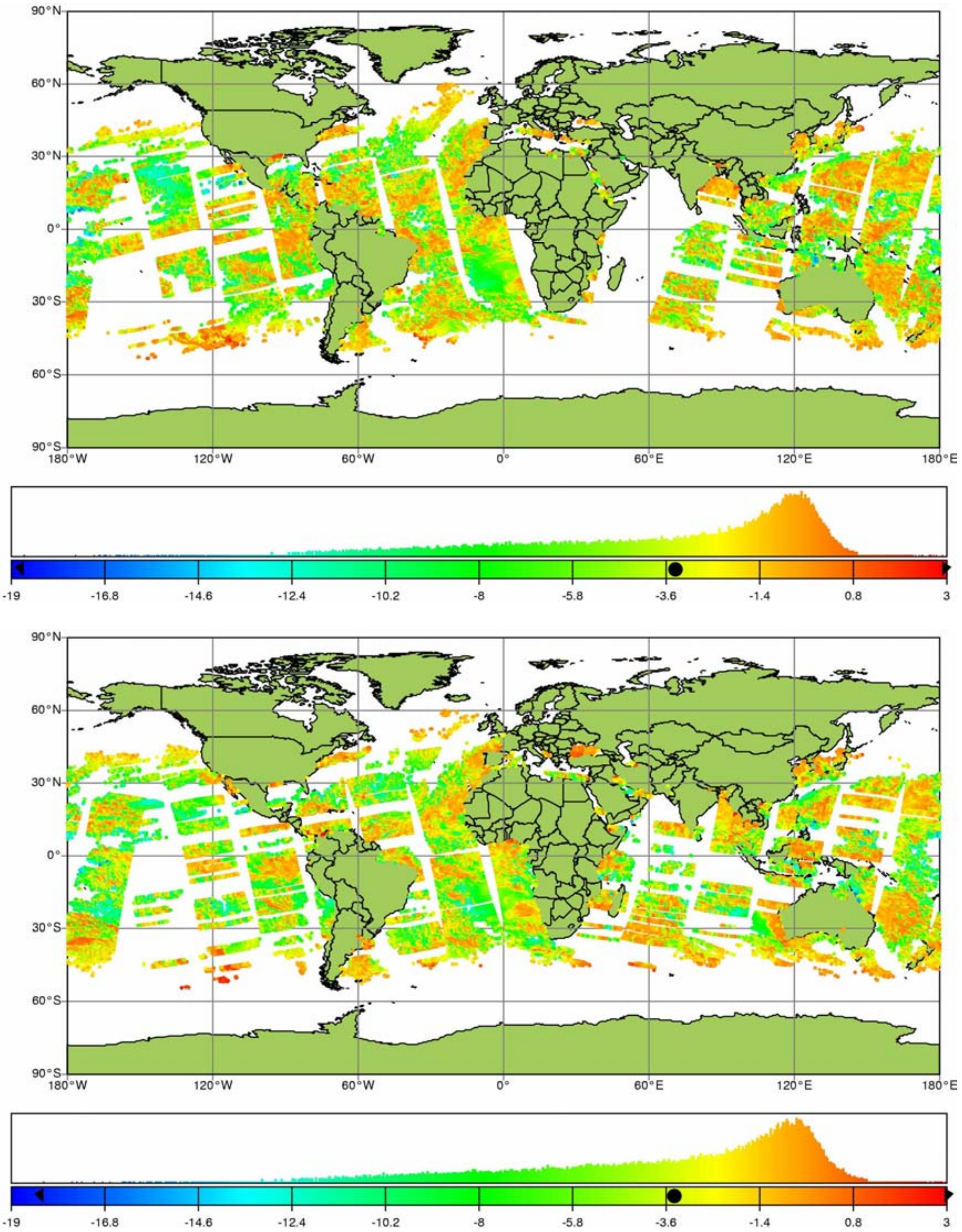

Figure 3: All HIRS spots for +-6hrs at 00z 15/12/2006 over sea with channel 8 brightness temperature greater than 280 deg K and background forecast departures in the range -19deg k to +3deg K .Top HIRS Metop and bottom HIRS NOAA17. The colour in the plot corresponds to the same colour in the histogram below.

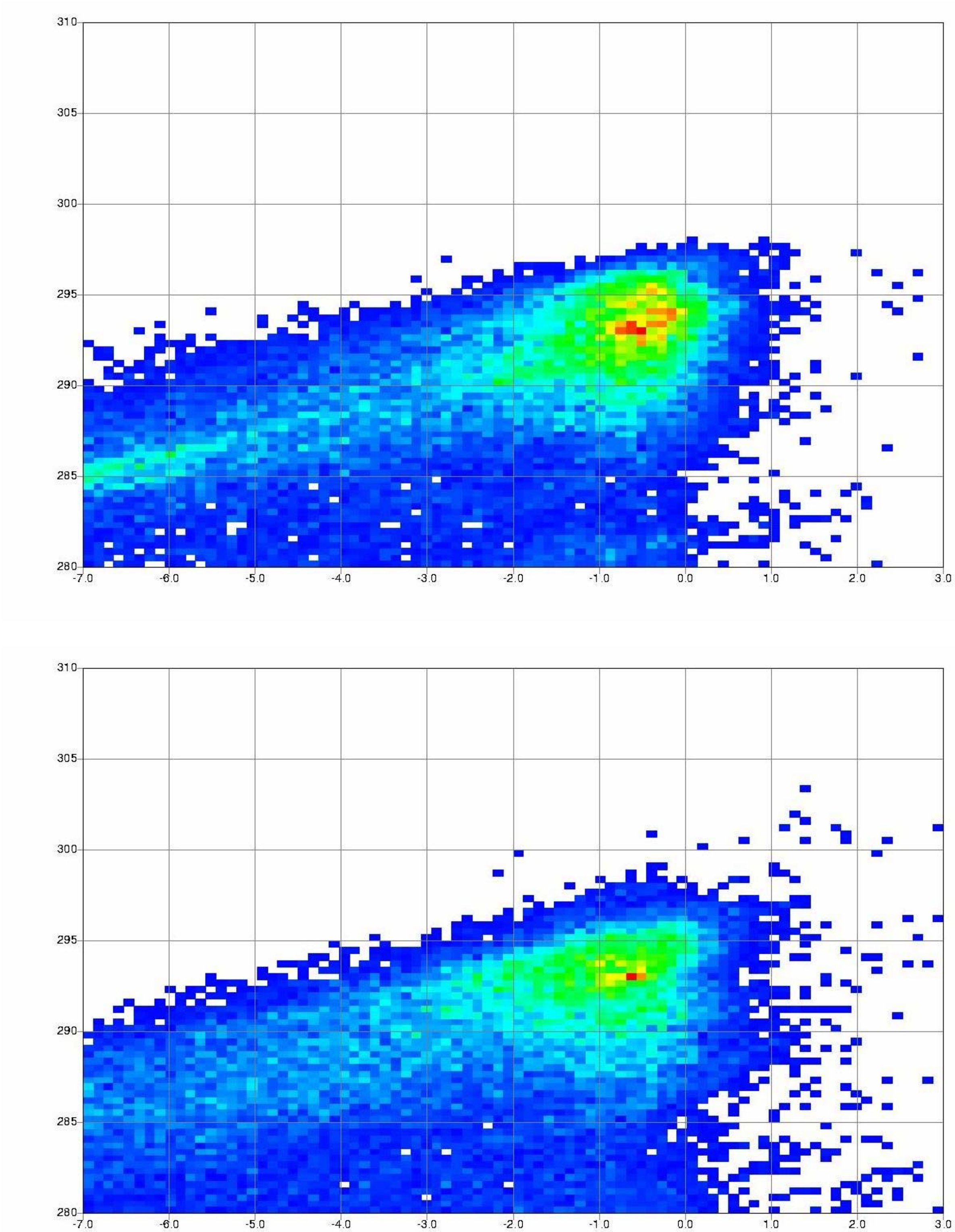

Figure 4 Scatterplots showing all HIRS channel 8 data shown in Figure 3. The x-axis is the background forecast departures and the y-axis the observed channel 8 brightness temperature. Top Metop HIRS and bottom NOAA 17 HIRS.

4. HIRS cloud detection.

In the past HIRS radiances have been used to estimate cloud properties (height and amount) by making use of channels 1-7 in the 15 micron band (Wylie et all 2005, Chevallier at all (2001,2005). The method is called 'CO2 slicing' and is used in 4DVAR to detect cloud affected radiances and remove them from the assimilation. In the future cloudy HIRS radiances may be used in data assimilation.

4.1 The HIRS cloud detection scheme

The HIRS channels used for the cloud detection are 2 to 8. Channel 2 peaks highest (about 50hPa) and the others gradually peak lower into the atmosphere and become more cloud and surface sensitive. The cloud detection is done at the screening step of 4DVAR. Firstly outliers are removed with a 3 sigma check on the background forecast departures and then normalized bias corrected background forecast departures are calculated.

A second check is based on the idea of 'CO2 slicing'. A sample of the difference of the normalized background departures between the pairs of adjacent channels is made and statistics calculated. If the standard deviation of this difference sample (channel 2 minus 3) exceeds 1.5 sigma then Channel 3 is considered to be cloud affected and a cloud flag is set to 3.

These two tests are then applied in sequence to channel pairs (3/4, 4/5, 5/6 and 7 /8) and setting the cloud flag to (4, 5, 6, 7, 8 and 9). The cloud flag is also set to all channels below the first channel to be cloud affected. If the cloud flag is set to 9 the HIRS spot is considered clear with respect to the cloud detection.

Based on the channel where the cloud flag is set then the other channels 9-15 are assigned to be cloudy. Table 1. shows the channel linkage.

HIRS 15 micron channel set cloudy	Set other HIRS channel cloudy
8	9 (ozone)
8	10 (low level water vapour)
7	11 (mid level water vapour)
5	12 (mid level water vapour)
8	13 (low level temperature)
7	14 (low level tropospheric temperature
6	15 (middle level tropospheric temperature)

Table 1: Correspondent between 15 micron HIRS chanel cloudy flag and other HIRS channels.

4.2 Case studies to demonstrate the performance of the HIRS cloud detection.

The first case chosen is a very cloudy scene for the application of the HIRS cloud detection (Fig. 5). The value plotted at each HIRS spot on MTSAT infrared imagery is the first HIRS channel to detect cloud starting from channel 2 until channel 8. If the value 9 is plotted then the spot is considered not cloudy. In the image there is an active cold front, depicted by the white cloud, covering most of the left portion of the image with infrared brightness temperatures generally colder then 220 deg k. and in this region cloud is first detected in channel 3 or 4. On the right of the image, just north of New Zealand there is large grey status cloud with infrared temperatures of about 275 deg k. Over this cloud deck, the HIRS cloud detection begins with channels 4 or 5.

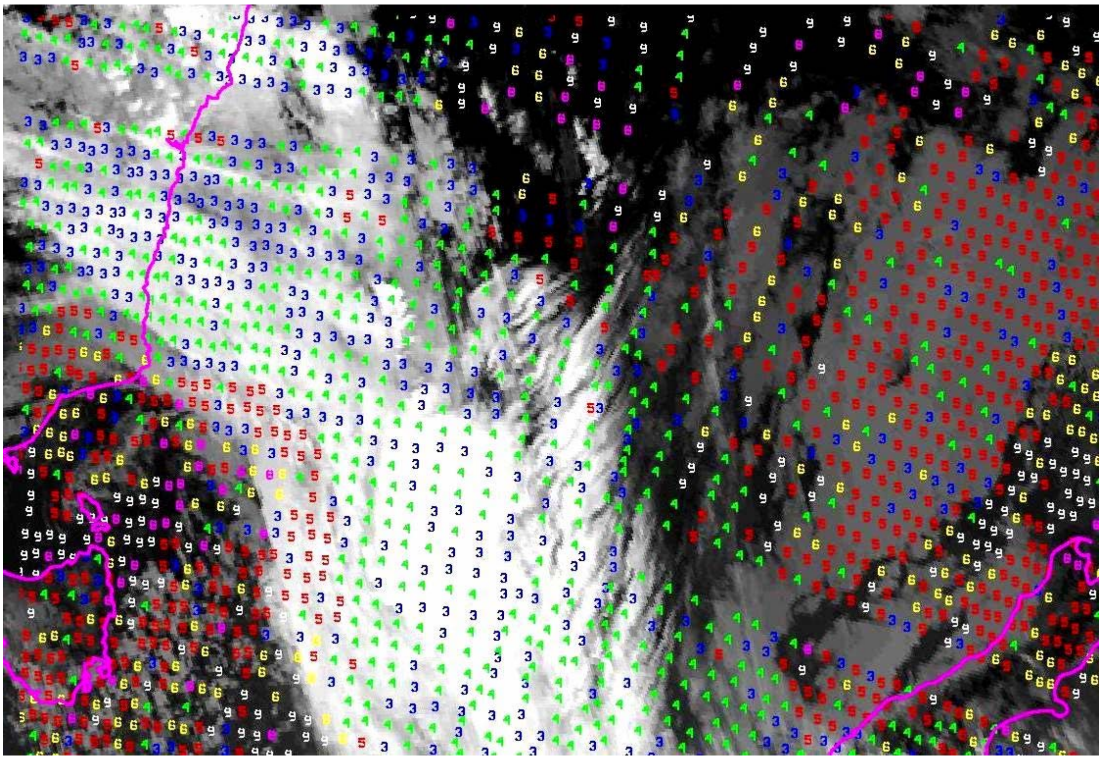

Figure 5: Example of the HIRS cloud detection plotted on the MTSAT IR imagery for 2039z on 14/12/2006. The number plotted is the first HIRS channel found to fail the cloud test. If the values are 9 then the HIRS spot is considered clear.

A second example of the HIRS cloud detection was chosen from the same 12 hour period as the previous example but over an area of more broken cloud north of New Zealand. HIRS clear spots are plotted on three channels of MTSAT imagery, visual, infrared and water vapour. In Figs 6 and 7 both satellites HIRS channel 8 departures within the range (-0.5 to 1.0) deg k are plotted in blue and the spot becomes yellow if the cloud flag is set to 9. For a reference Australia is located in the bottom left and New Calodonia bottom right. There is good correspondence between clear areas and these clear HIRS locations given that there is a small time difference between the geostationary imagery and the HIRS measurements. In the future the AVHRR imagery will be used for this comparison. Finally the clear HIRS (passing both the cloud and window checks) are plotted for both Metop A and NOAA 17 on top of the 6.7 micron water vapour imagery, Fig. 8. All spots appear to be in the clear area not affected by cloud.

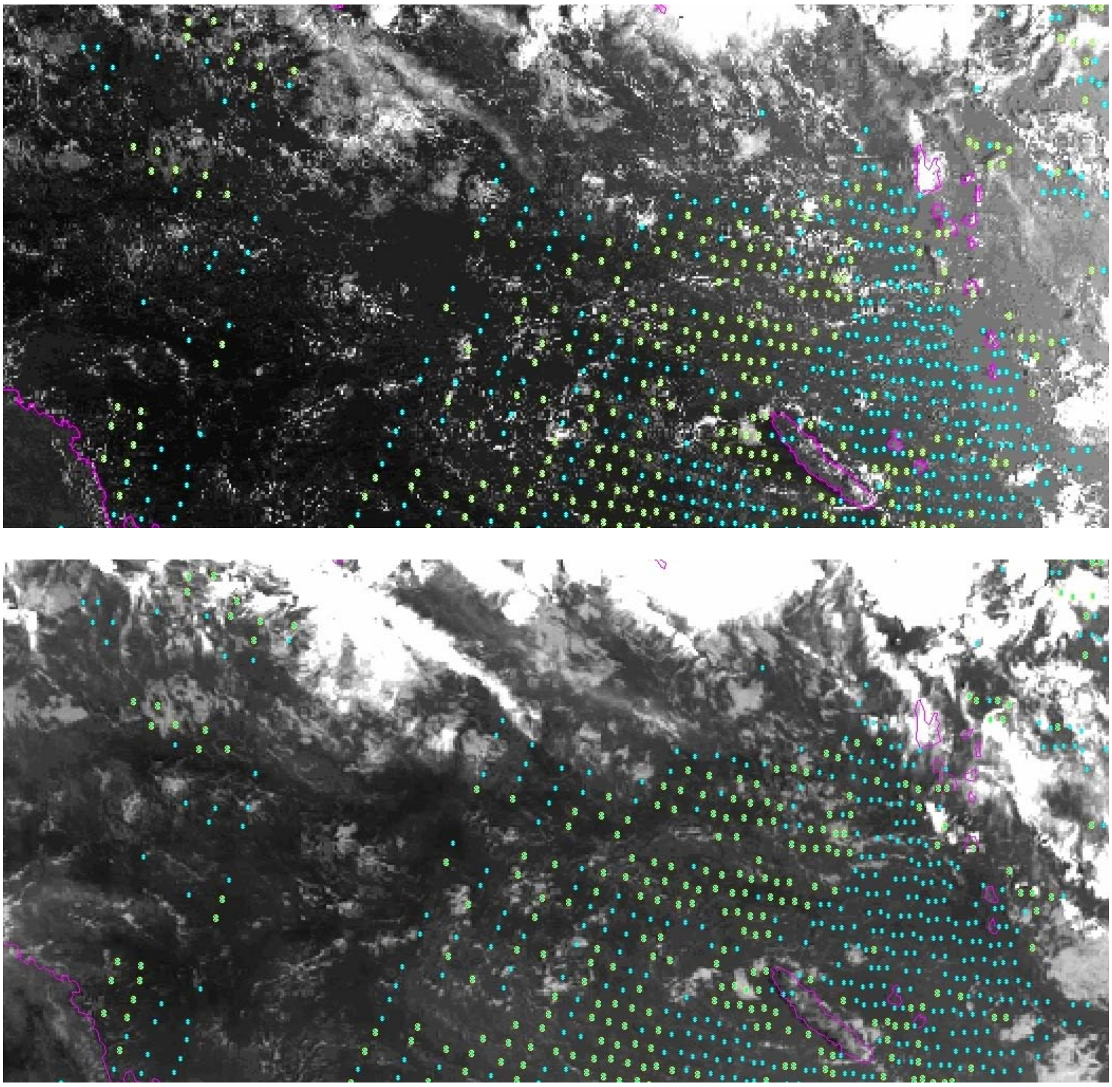

Figure 6: Metop HIRS spots ch 8 f g departures between-.5 to 1 deg k in yellow also blue spots include an additional no fail test of the cloud detection. The underlying imagery is MTSAT for 2039z on 14/12/2006, top VIS and bottom IR

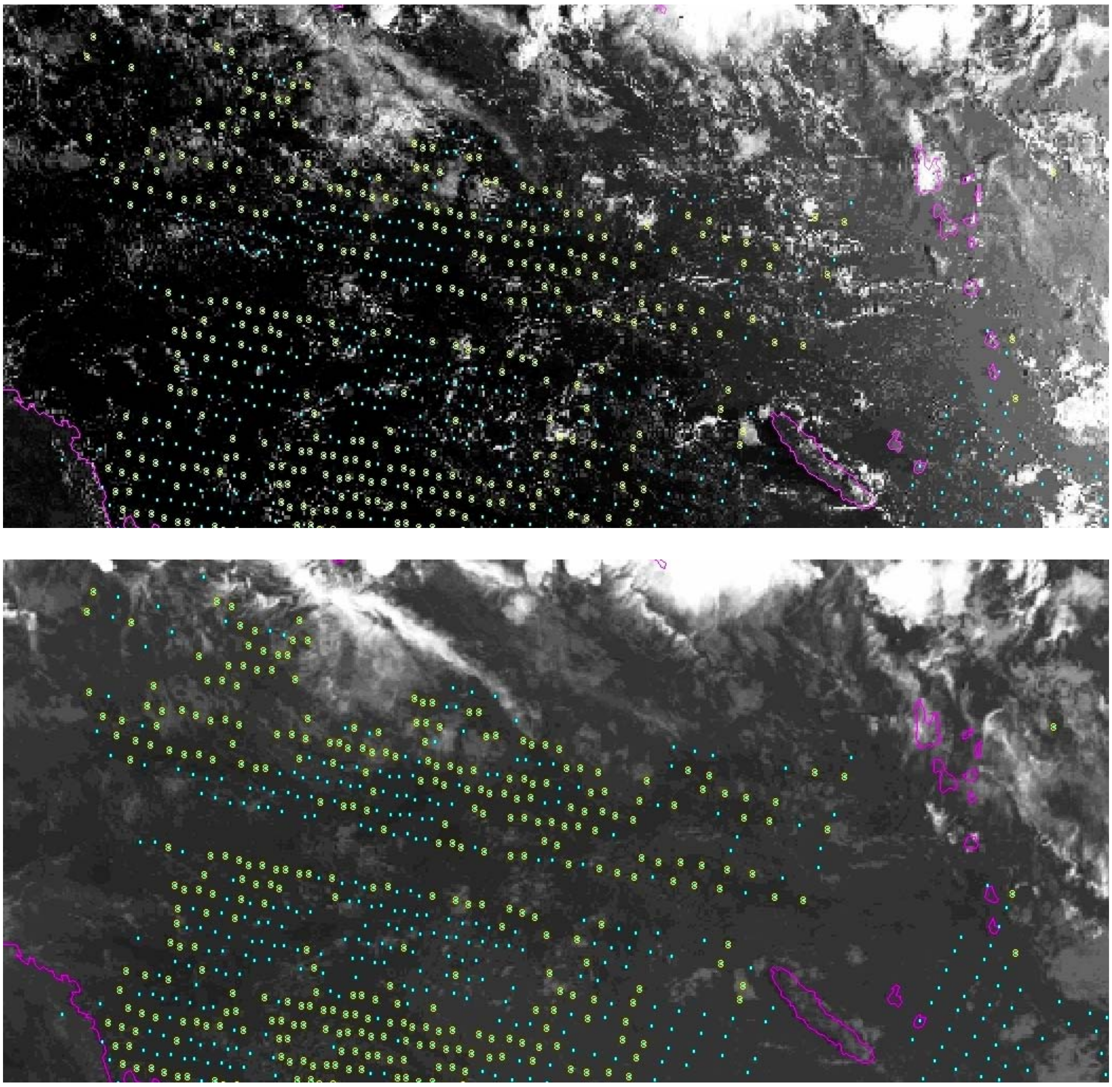

Figure 7: NOAA 17 HIRS spots ch 8 f g departures between-.5 to 1 deg k in yellow also blue spots include an additional no fail test of the cloud detection. The underlying imagery is MTSAT for 2039z on 14/12/2006, top VIS and bottom IR

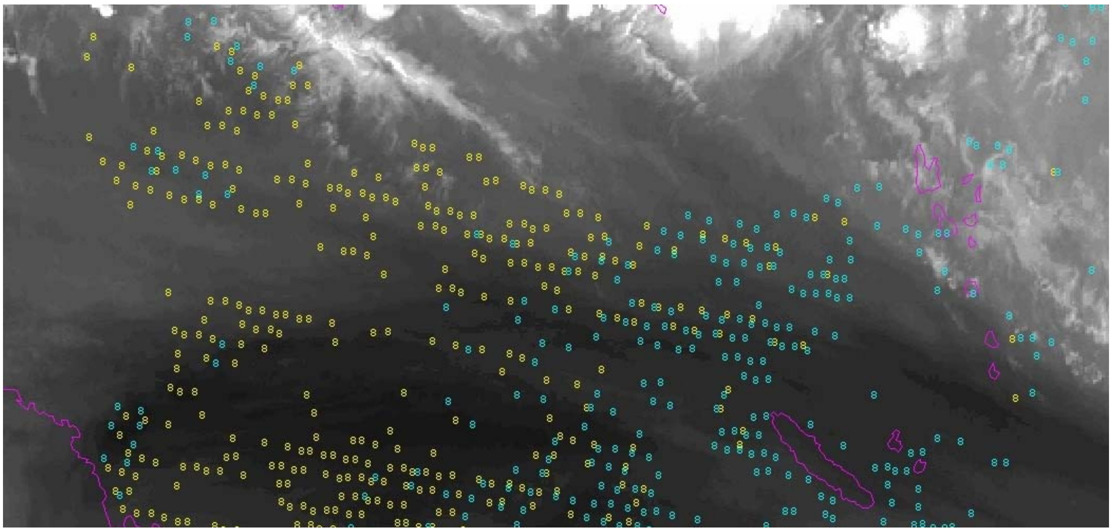

Figure 8: HIRS ch 8 passing both background forecast and cloud checks from Figure 6, Blue Metop and yellow NOAA 17. The underlying imagery is the water vapour channel from MTSAT for 2039z on 14/12/2006.

5. Comparison of Metop A and NOAA HIRS CSHR data

The logical sequence of retuning both the HIRS cloud detection and the static radiance bias corrections (all sensors) in the assimilation could be difficult if the HIRS observations have a strong impact in 4DVAR. In recent impact experiments the influence of HIRS in the current operational system is now small, sensors like AIRS and the four AMSUA instruments provide most of the impact. The initial HIRS bias corrections were calculated from CSHR radiance departures based on an operational run and using the new HIRS window check. 4DVAR was run (as described above) for two weeks with the retuned static radiance bias corrections and retuned HIRS cloud check. In order to check if further retuning was required and the radiance bias correction and HIRS cloud detection was further retuned from this assimilation and 4DVAR experiment rerun. There were only small differences in this rerun.

Fig. 9 shows the comparison of statistics for Metop A and NOAA17 of CSHR data (sea only) which was obtained using both the HIRS channel 8 window check and the HIRS cloud check. The departures are with respect to the 4DVAR analysis and the sample is from the second 4DVAR experiment (described above) and covers a 6 day period. The number of CSHRs were 74433 for Metop A and 59875 for NOAA17. The increase in the number of clear spots for Metop A suggests it is due to the smaller FOV of Metop (~10 km) compared to NOAA17 (~20 km).

The RMS statistics of both Metop A and NOAA 17 compared with the 4DVAR analysis are comparable except for channel 1 and 2, Fig 9 top panel. The magnitude of the RMS errors for the temperature channels, 1-7 13-15, are of order of 0.2 to 0.3 deg. k and the water vapour channels 11 and 12, less than 1.2 deg k. It will be discussed in the next section that low RMS values are real and caused by the use some HIRS channels in the analysis. The analysis is dominated by other data sources including AIRS and AMSU. The purpose of this CSHR dataset is to provide statistics for tuning the HIRS cloud detection scheme and setting the analysis HIRS observational errors.

Bias plots, with reference to the 4DVAR analysis, are shown in Fig, 9. There is generally agreement between both HIRS instruments, most channel biases are negative and similar to radiosondes biases suggesting the analysis is cold. The two channels in which the biases do not agree are channels 4 and 13 and suggests the reason may be in specification of their filter functions. In particular for NOAA 17 channel 4 and both HIRS instruments for channel 13.

An additional CSHR dataset for Metop A was produced only with the window check being applied and the dataset has 106685 clear spots with an increase of about 30% .The variance of the sample is larger but not significantly different except for the surface sensing channels. The biases of both samples are very similar which suggests the initial CSHR set was OK for tuning of the HIRS cloud detection. The main purpose of the cloud detection is to be able to make use of uncontaminated radiances above the clouds but also provides an additional check to ensure the CSHR data set is cloud free.

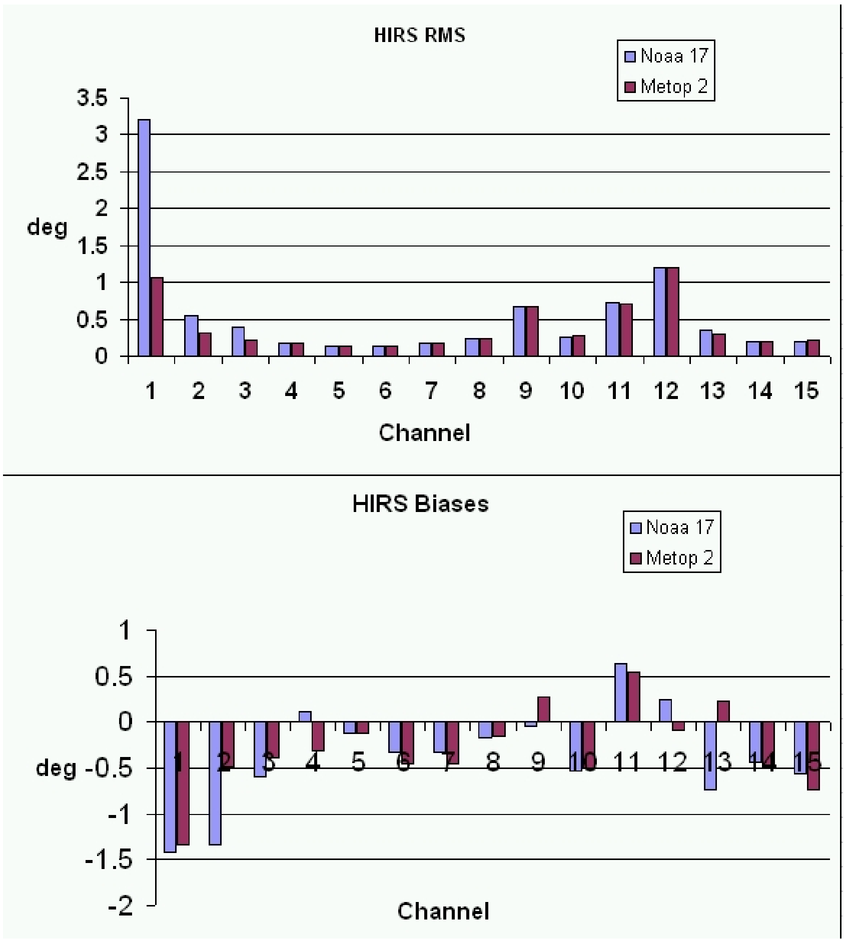

Figure 9: Comparison of HIRS/4 from Metop A (74413 spots) and HIRS/3 NOAA 17 (59875) spots) for global clear sea only data for the period 15/12/2006 to 20/12/2006 Top is RMS errors form the background forecast and bottom the Biases.

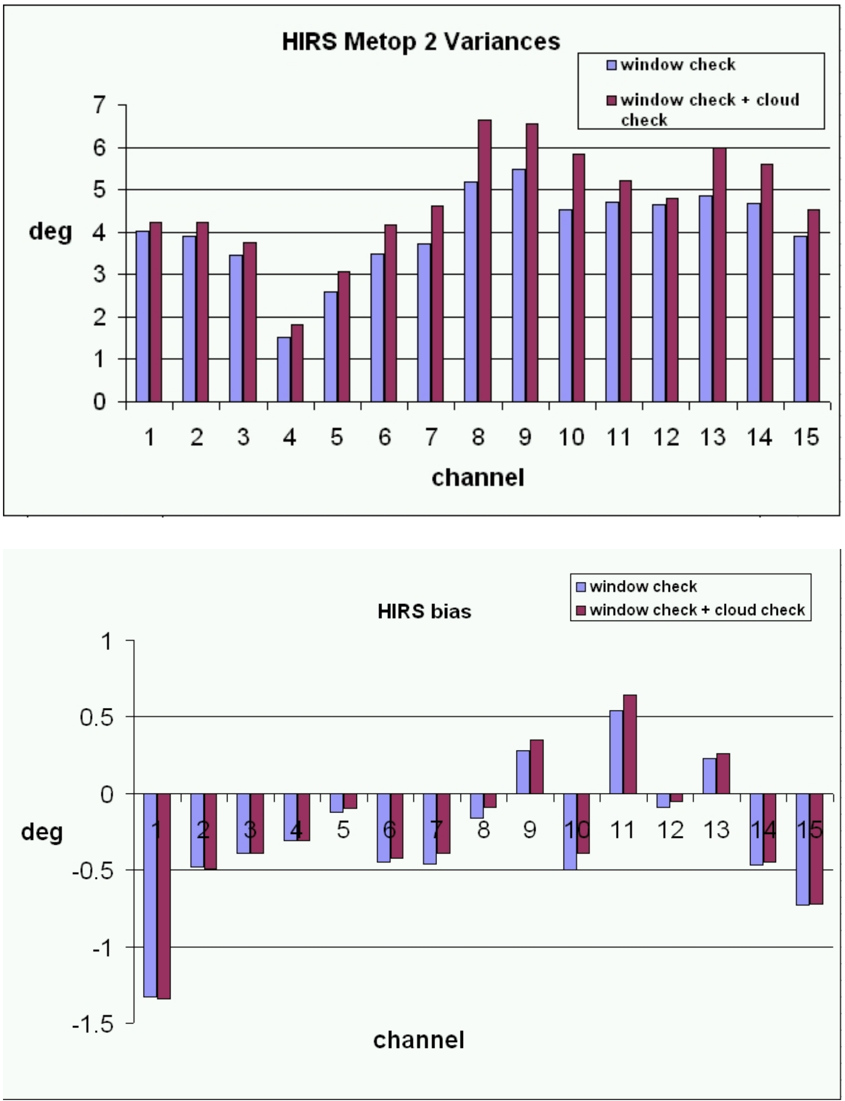

Figure 10: Variances (top) and biases (bottom) with and without cloud checks for Metop HIRS.

6. Data assimilation statistics

6.1 HIRS

At present only eleven of the HIRS channels are assimilated, however background forecast departures are calculated for channels 1 to 19. The 4DVAR averaged statistics from 15/12/2006 for nine days shown in Fig. 11 for three latitude bands (20n to 90n), (20s to 20n), and (20s to 90s). All three panels have standard deviation to the right and bias to left. The statistics plotted are:

i) Observed radiances (bias corrected) - Background forecast (solid line red (Metop A) and black (NOAA17))

ii) Observed radiance (bias corrected) - Analysis (small dotted red (Metop A) and black (NOAA17))

iii) Bias correction (small dashed green (Metop A) and magenta (NOAA17))

The standard deviations of the bias corrected HIRS radiances background forecast departures both HIRS instruments are almost identical. After the 4DVAR analysis the departures are only a little smaller due to the accuracy of the background forecast. These background forecast departures are less than 0.3 deg k for the short wave and long wave channels. The water vapour channel background forecast departures are larger than for temperature channels, about 1.9 deg k. for channel 12 but after analysis change only slightly.

Both HIRS instruments on Metop A (green) and NOAA17 (magenta) have similar air mass bias corrections across the three latitude bands for most channels with respect to the 4DVAR. The channels with largest differences are channels 11 and 12 (water vapour) and channels 14 and 15 (short wave).After applying the air-mass bias correction the background forecast and analysis departure biases are small for both HIRS instruments, generally less than 0.1 deg k. These statistics suggest that more weight should be given to these data but, as will be shown below, the AMSUA and MHS departure statistics are very similar to HIRS.

6.2 AMSUA

In the data assimilation there were five active AMSUA instruments and statistics for two of these instruments, Metop A and NOAA 18, are shown in Fig. 12. The standard deviations on all channels of both instruments are similar but there are different biases in channels 5 to 8 due to an antenna correction not being applied to Metop A. In the stratosphere, channels 9 to 14, the biases are more similar but increases as the channel peak higher in the stratosphere. The other three AMSUA instrument biases have similar patterns. This upper level cold bias has recently increased in operational system with the introduction of VARBC. Unfortunately the fixed bias 4DVAR used in this study starts and is tuned using the operational analysis. It is fortunate that most of the HIRS channels peak lower into the atmosphere to be affected by this cold bias.

In the troposphere a comparison can be made with the AMSUA NOAA18 channels 5, 6, 7 and 8 and the two HIRS channels 7, 6, 5 and 4. These two channel sets, microwave and infrared, peak in similar regions of the atmosphere. The standard deviations of the departures are similar and there is only a small improvement after the analysis. All the biases are small and do not change in the three latitude bands indicating weak air-mass dependence in all instruments.

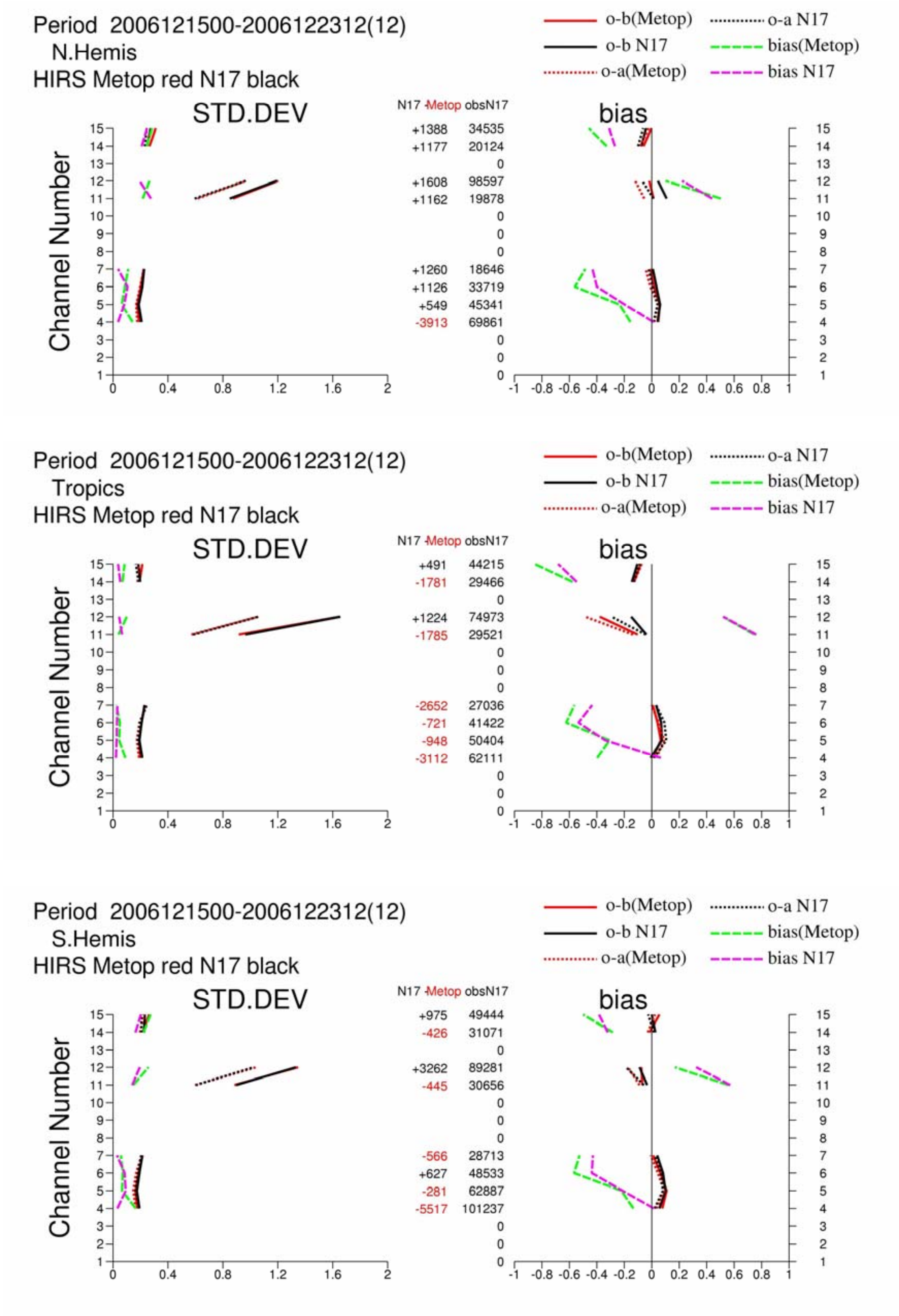

Figure 11 Analysis and background forecast statistics for HIRS on Metop and Noaa 17. Top panel N H 90n- 20n, middle 20n-20s and bottom 20s to 90s.

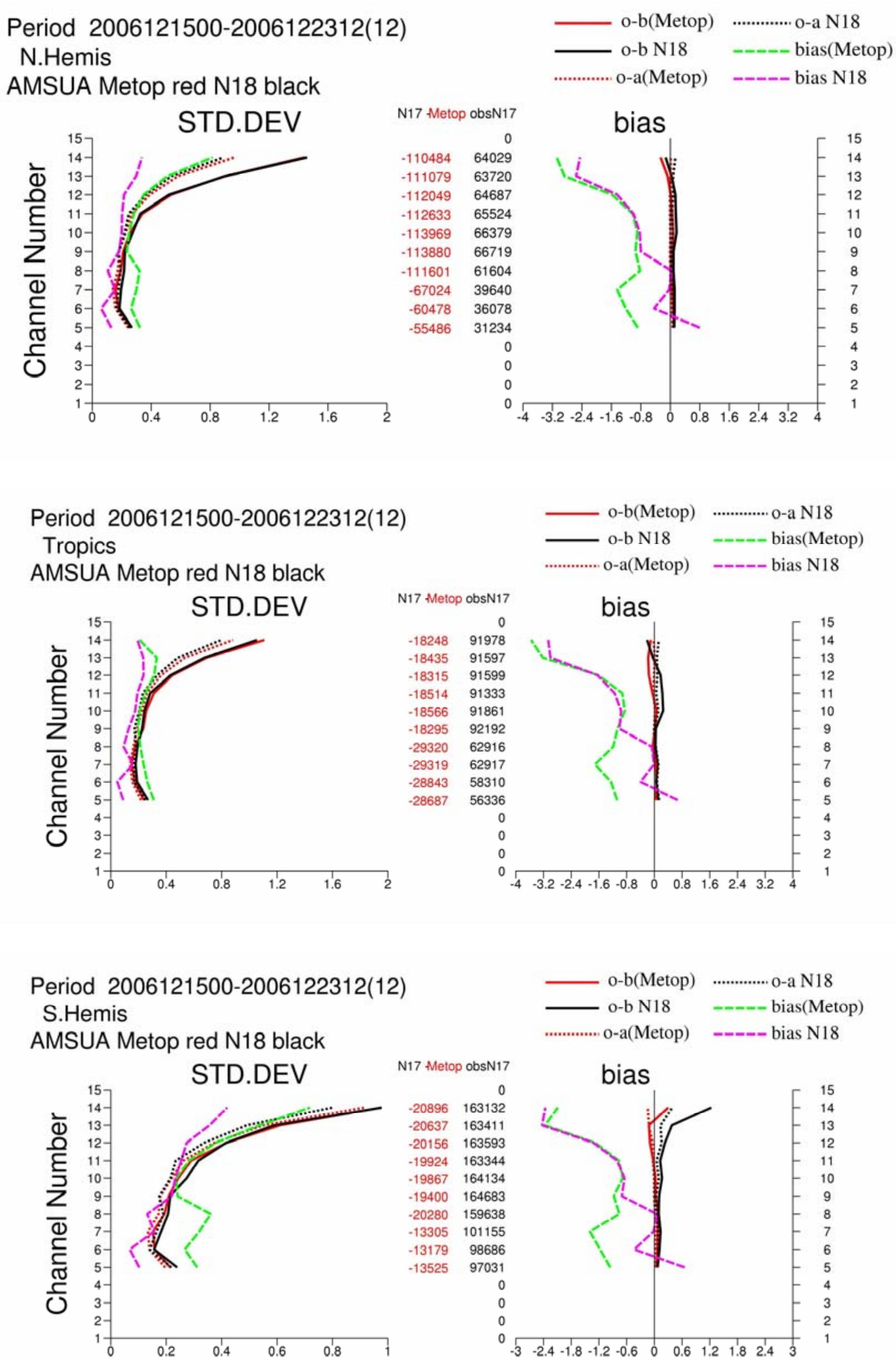

Figure 12: Analysis and background forecast statistics for AMSUA on Metop and NOAA 18. Top panel N H 90n- 20n, middle 20n-20s and bottom 20s to 90s.

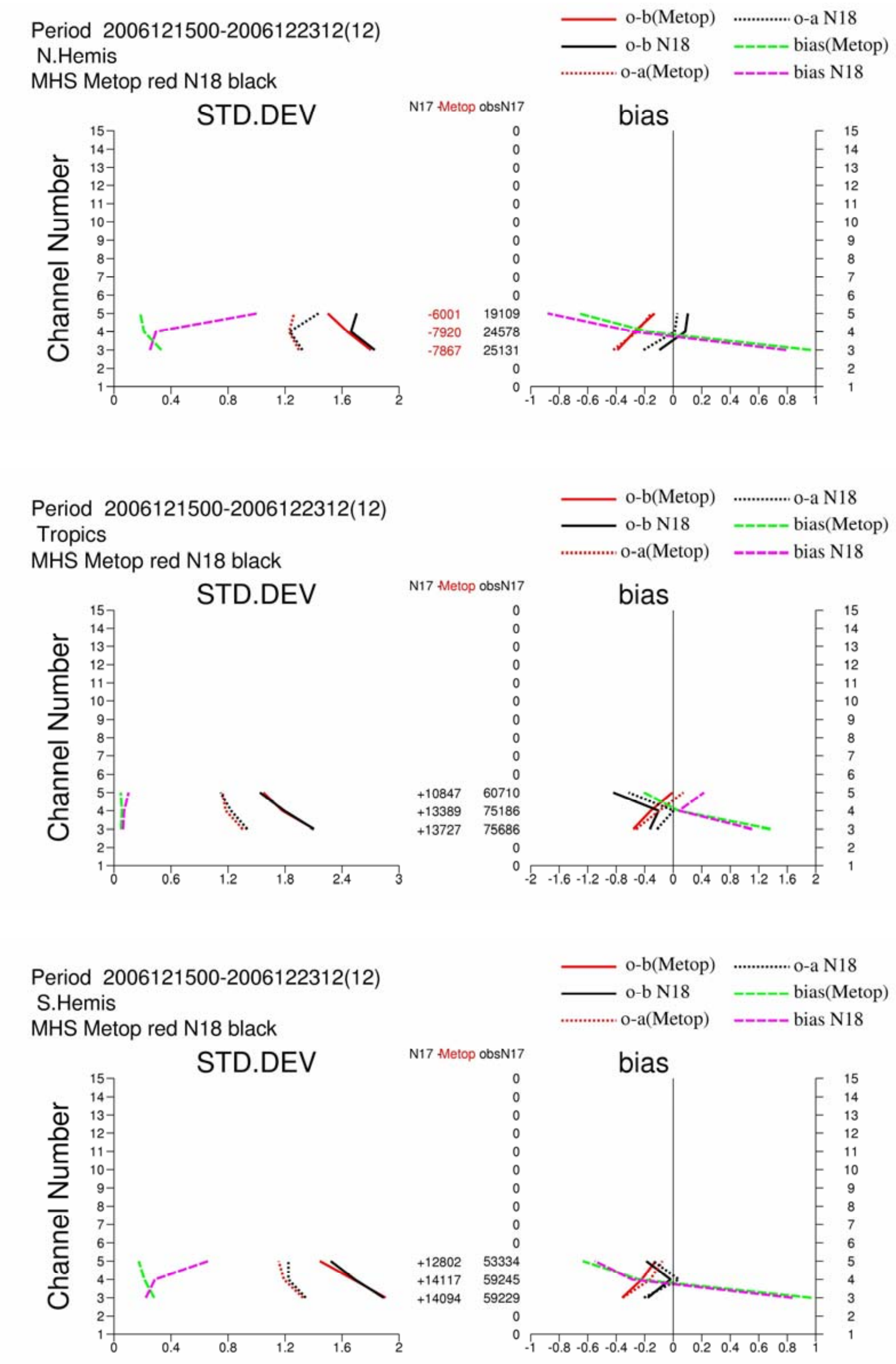

Figure 13: Analysis and background forecast statistics for AMSUA on Metop and NOAA 18. Top panel N H 90n- 20n, middle 20n-20s and bottom 20s to 90s.

6.3 AMSUB/MHS

The data assimilation also includes two AMSUB instruments and two MHS instruments which measure tropospheric water vapour. The departure statistics for MHS on Metop A and NOAA 18 are shown in Fig. 13 and are very similar. In both instruments there is an increase in standard deviation in the tropics, particularly in channel 2 which measures the upper tropospheric water vapour. It is interesting that the microwave bias does not show the air-mass dependency as seen in similar HIRS channels 11, 12 (Fig. 11)

7. Comparison with the operational HIRS clouding statistics

In the current operational ECMWF data assimilation (cycle 31R2) the values used in the HIRS cloud detection are shown in Fig. 13 and were based on a much earlier assimilation cycle. The RMS values of the lower peaking HIRS channels are much larger than those estimated in the current study (see Fig. 9). In fact the HIRS window channel 8 is almost three times larger that the new estimate thus allowing many more lower HIRS channels radiances to be used in the data assimilation.

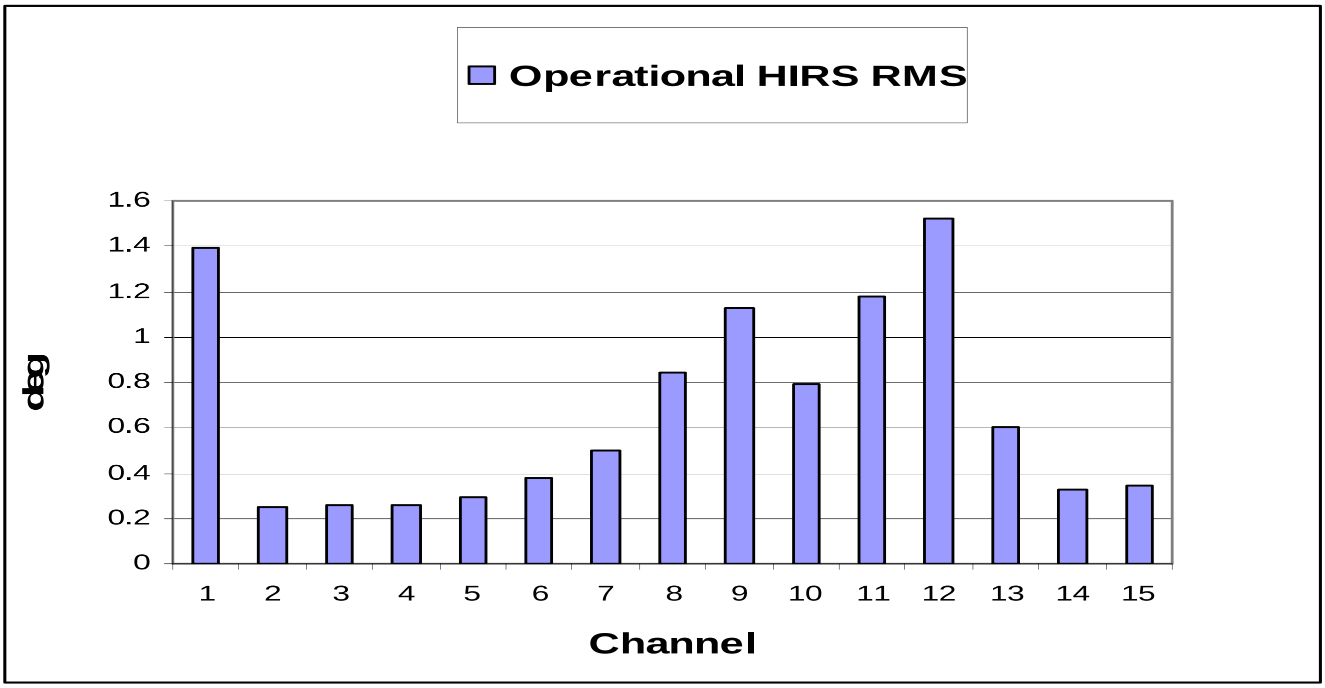

Figure 14 Variances used in the operational HIRS cloud detection.

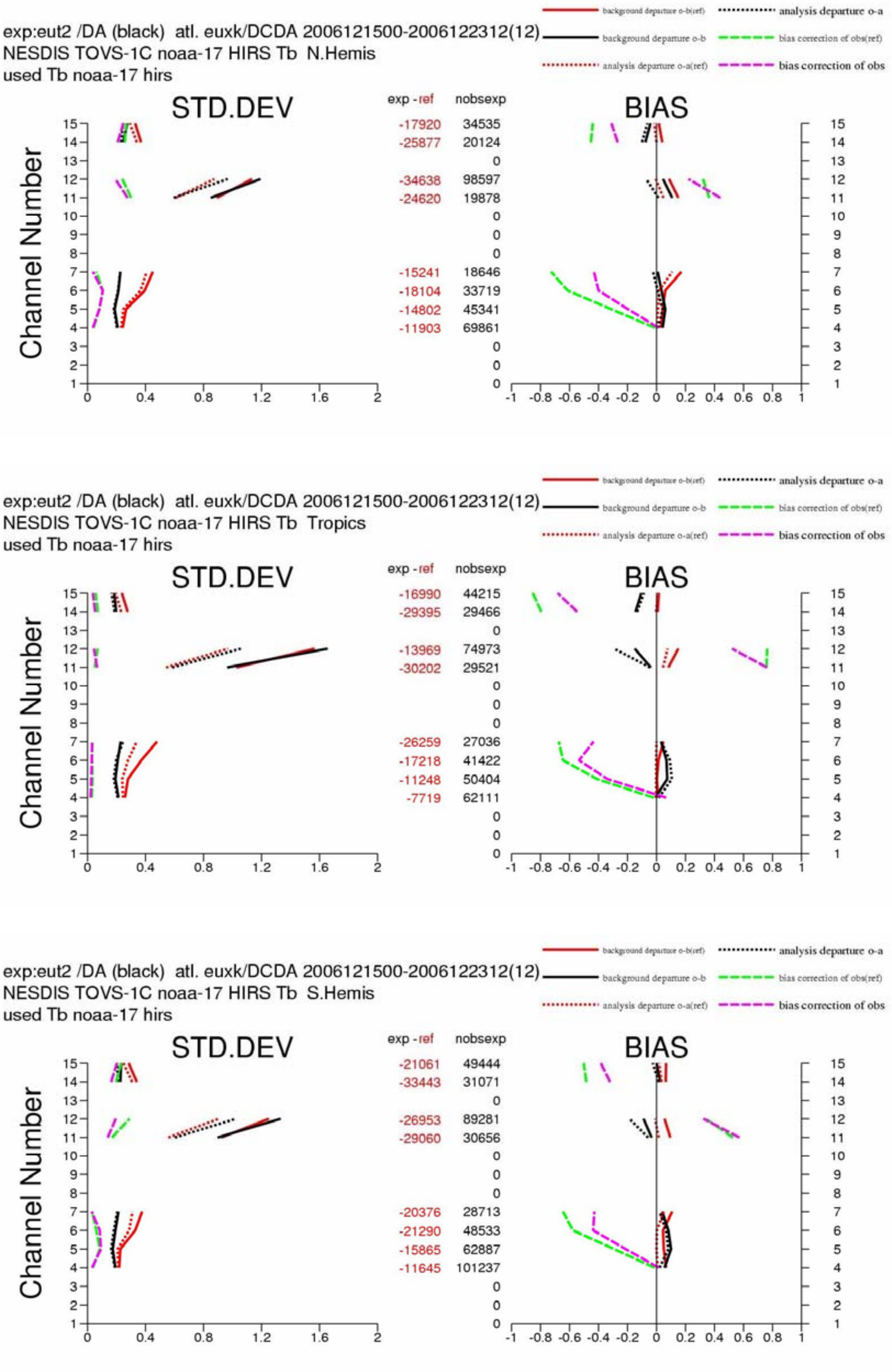

Figure 15: Comparsion with the operational cloud detection statistics

Fig. 15 shows a comparison of an experiment ‘euxk’ run as the operational system at TL799 and 91 levels but including Metop A AMSUA, HIRS and MHS. It is similar to the experiment used in this study ‘eut2’ the differences between experiments are the model resolution, bias correction method and different statistics for the HIRS cloud clearing. The differences are in the standard deviations of the fit to the background and analysis. The retuned experiment has reduced this fit considerably. The biases are also warmer in the retuned experiment but there is still a cold bias with respect to the background and analysis. The number of observations used by the retuned experiment is reduced almost by half in the lowest channel 7, reducing to 10% in channel 4. Generally the reduced HIRS observation set leads to a warmer analysis.

8. Conclusions

With the use of the 4DVAR data assimilation it was possible to compare the biases of HIRS/4 on Metop A and HIRS/3 onboard NOAA 17. A comparison was also made with the microwave sensors AMSUA and MHS. The HIRS biases relative to the 4DVAR analysis are generally less than 0.5 deg k cold except for channels 1,2 13 (temperature) and 11 (humidity).

Using the HIRS cloud detection it is possible to get good quality clear radiances above clouds, and increase the amount of usable cloud free HIRS radiances.

To develop a good climate record from HIRS it would be useful to have an unbiased reference HIRS instrument and adjust radiances of all other HIRS instruments to this reference. IASI and HIRS are both on Metop A with similar FOVs and the use of IASI spectra, within each HIRS channel could used adjust HIRS spectral response to agree with the relevant IASI spectra.. Simulated measurements would be obtained using RTTOV and the data assimilation profiles. Next the SNO method could be to collect pairs of HIRS observations from Metop A and NOAA 17 and compare their biases in observation and simulation space. Again the use of the data assimilation profiles and RTTOV could calculate simulated radiances. Finally a readjustment of spectral response for each channel of NOAA 17 could be made to agree with Metop A.

Finally a revision of the HIRS cloud detection statistics should be considered for a future update of the ECMWF system.

9. References

Changyong Cao, Hui Xu, Jerry Sullivan, Larry McMillin, Pubu Ciren, and Yu-Tai Hou, 2005: Intersatellite Radiance Biases for the High-Resolution Infrared Radiation Sounders (HIRS) on board NOAA-15, -16, and -17 from Simultaneous Nadir Observations. Journal of Atmospheric and Oceanic Technology, 22, 381-395

Chevallier F., G. Kelly, A. J. Simmons, S. Uppala, and A. Hernandez, 2005: High Clouds over Oceans in the ECMWF 15- and 45-Yr Reanalyses. Journal of Climate, 18, 2647-2661

Chevallier F., P. Bauer, G. Kelly, C. Jakob, and T. McNally, 2001: Model Clouds over Oceans as Seen from Space: Comparison with HIRS/2 and MSU Radiances. Journal of Climate, 14, 4216-4229

Derber, J. C. and Wu, W. S., 1998: The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system. Mon. Wea. Rev., 126, 2287-2299

ITT, 1996: Technical description for the high resolution infrared radiation sounder, HIRS/4. ITT Aerospace/Communications Division, 175 pp.

——, 1998: Instruction manual and alignment/calibration handbook and optical data for the High Resolution Infrared Radiation Sounder HIRS/3. ITT Aerospace/Communications Division, 355 pp.

Kelly, G.A.M., G.A. Mills and W.L. Smith, 1978: Impact of Nimbus-6 temperature soundings on Australian region forecasts. Bull. Amer. Mereor. Soc., 59: 393-405

Soden, B. J., and F. P. Bretherton, 1996: Interpretation of TOVS water vapor radiances in terms of layer-average relative humidities: Method and climatology for the upper, middle, and lower troposphere. J. Geophys. Res., 101 (D5), 9333–9343.

Wylie, Donald; Jackson, Darren L.; Menzel, W. Paul and Bates, John J, 2005: Trends in global cloud cover in two decades of HIRS observations. Journal of Climate, 18, 3021-3031