A GLOBAL COMPARISON OF HIRS AND AVHRR RADIANCES

Roger Saunders
Met Office, Bracknell, U.K.

1. INTRODUCTION

Radiances measured by the High-resolution Infra-red Radiation Sounder (HIRS) on the NOAA spacecraft are now assimilated directly into NWP forecast models using the new variational techniques (e.g. McNally et. al., 2000; English et. al., 2000). These radiances directly influence the model-analysed temperature and humidity fields and indirectly (with 4D-Var) the model wind field. At present only cloud-free infrared radiances are assimilated as the corresponding simulated radiances (using a fast radiative transfer model) can only be reliably modelled for clear sky conditions. If HIRS radiances, assumed to be cloud-free, are in reality affected by cloud the radiances of the tropospheric sounding channels will normally be reduced and often observed as a 'cold tail' in the histogram of observed-simulated HIRS radiances for these channels. The effect of this cloud contamination is to incorrectly cool and/or moisten the model analysed fields. Hence cloud effects on the infra-red radiances should be reduced at least to below the assumed observation and forward model errors. Recent experience at the European Centre for Medium Range Weather Forecasts (ECMWF) has shown that careful quality control is needed before assimilating the HIRS radiances within 4D-Var to ensure the analyses and forecasts are not degraded.

The cloud detection algorithm for HIRS, currently in use at the Met Office, is described by English et. al. (1999). It is based on Bayesian probability theory and is included as part of the 1D-Var pre-processor in the Met Office 3D-Var assimilation system where the first iteration of the 1D-Var minimisation uses all radiances and if the cost function exceeds a certain value the instantaneous field of view (ifov) is assumed to be cloudy. If the ifov is cloudy then only the microwave and stratospheric HIRS channels are subsequently used in the 3D-Var assimilation. At the National Centre for Environmental Prediction a cloud detection scheme for HIRS described by McNally et. al. (2000) is used which examines the difference between the measured and simulated HIRS channel 8 and 12 radiances. The former is a very stringent test to try and trap all low cloud, the latter detects thin cirrus not detected by channel 8. Both methods rely on the HIRS radiances themselves to detect the cloud. Other methods are being developed (e.g. Joiner and Rokke, 2000) to cloud-clear the HIRS radiances so that the tropospheric channel cloudy radiances are not discarded but clear radiance values are inferred from them.

In order to improve the detection of HIRS cloud contaminated ifovs NESDIS, in collaboration with the Met Office, have developed a product using the coincident Advanced Very High Resolution Radiometer (AVHRR) global area coverage (GAC) radiances within the HIRS ifov. This product has been made available to the Met Office in near real time since March 2000 in addition to the level 1b ATOVS (Advanced TIROS Operational Vertical Sounder) datasets. In addition, for this study local area coverage (LAC) AVHRR data have also been used to validate the global dataset.

This paper describes initial results comparing the new AVHRR dataset with the corresponding HIRS window channel data as an initial assessment to ascertain if using the coincident AVHRR data can improve the assimilation of HIRS radiances in the Met Office model.

2. DESCRIPTION OF AVHRR DATASETS

2.1 Global dataset from NESDIS

NESDIS currently use AVHRR radiances to improve the cloud detection in their operational ATOVS pre-processing (see Reale et. al. 2001 for more details). They co-locate 17 AVHRR (global area coverage) GAC radiances within each HIRS ifov and use these to compute cloud-free AVHRR radiances for each HIRS ifov (if possible) and a fractional cloud coverage. Each GAC radiance is a mean of 4 AVHRR original ifovs (i.e. 1.1km at nadir) across a scan line and so at nadir it has a footprint of 4.4 km across track and 1.1km along track with samples from every third scan line used. This compares with the HIRS/3 ifov which is about 20km diameter at nadir. The AVHRR data are therefore representative of strips of the Earth's surface within the elliptical HIRS ifov. The higher spatial resolution of the AVHRR radiances is the key to detecting cloud within the HIRS ifov. Included in this dataset are the mean and cloud-free mean albedo or brightness temperatures for all 6 channels of the AVHRR, the standard deviation of the AVHRR channel 4 brightness temperature and an estimate of the fraction of cloud affected AVHRR ifovs. The complete description of the file contents is at:
http://www.metoffice.com/sec5/NWP/SRAG/ATOVS_product_file_contents.html.
The AVHRR and HIRS channels used in this report are hereafter assigned numbers for ease of reference and are defined in Table 1.

HIRS channel #	Centre Wavelength	AVHRR channel #	Centre Wavelength
8	11.14μm	4	10.80μm
		5	11.91μm
		45	Mean of 4 & 5
19	3.76μm	3b	3.71μm
		3a (not used)	1.61μm
20	0.69μm	1	0.63μm
		2	0.86μm

Table 1. Definition of AVHRR and HIRS channels for NOAA-15

The 5 AVHRR channel radiances (the 1.6μm channel is not used at present) from the 17 GAC ifovs have a series of tests applied to them in the NESDIS processing to detect cloud. Only those ifovs which pass *all* the tests, listed in Table 2, are classified as clear. These tests are based on the APOLLO scheme originally developed by Saunders and Kriebel (1988) for application to 1.1km resolution AVHRR radiances over Europe and the N. Atlantic. It must be emphasised these tests were developed for mid-latitude conditions and still need to be optimised for global use. NESDIS have implemented them as a first step and it is hoped they may be optimised for global use through experience.

Test	**When applied**	**Formulation; cloudy if true**
1. Surface temperature	Day/Night/Twilight	$a_0 + a_1.T_4 + a_2.T_5 < T_{ST}$
2. Thin cirrus	Day/Night/Twilight	$T_4 - T_5 > \Delta T_{45}(T_4, secz)$
3. Fog/low stratus	Night, T_{3b} 270-290K	$T_4 - T_{3b} > 1.0K$
4. Medium/high cloud	Night, T_{3b} >240K	$T_{3b} - T_5 > 1.5K$
5. Nir/Vis ratio	Day	$R_2/R_1 < 1.6$ over land $R_2/R_1 > 0.75$ over sea
6. Visible reflectance	Day	$R_1 > 0.44$ over land $R_2 > 0.20$ over sea

Table 2. Cloud tests applied to AVHRR data in a HIRS ifov (subscripts refer to channel numbers defined in Table 1)

After application of these tests the mean and cloud-free albedo or brightness temperatures for all 6 channels and fraction of cloud affected AVHRR ifovs is computed together with the standard deviation of all 17 and only the clear AVHRR channel 4 brightness temperatures in the HIRS ifov. These values for each HIRS ifov together with their location and solar zenith angle make up each record of the AVHRR dataset.

For this study, after some investigations, the following criteria were used to assign a HIRS ifov as clear according to the GAC data:

- If fraction of cloud affected AVHRR ifovs (hereafter referred to as fractional cloud cover) within the HIRS ifov < 5%
- If standard deviation of AVHRR channel 4 brightness temperature in HIRS ifov < 1K

The HIRS ifov was flagged as clear only if both the above criteria were met. The fractional cloud coverage product could be improved by refining the tests described above. The above criteria could also be refined in the future to give a better indication of the effect of the cloud on the clear sky radiance.

This dataset is sent orbit-by-orbit in near real time to the Met Office and is then processed to co-locate with the HIRS 1b data by adding the corresponding HIRS line and scan position to the AVHRR dataset, BUFR encoded and output for onward transmission to other centres and for local use. The data volumes for the AVHRR files are 1.5Mbytes per orbit. These AVHRR BUFR files are available typically 45-90 minutes after the corresponding ATOVS level 1d files. This means for real time operational use the processing has to be designed so that it can use the AVHRR data if they are available but otherwise run without it using existing cloud detection tests.

2.2 Local area coverage AVHRR data

The GAC dataset described above would be used for an operational cloud detection scheme but as there are gaps in its spatial sampling within a HIRS ifov comparisons were made with the full resolution AVHRR (1.1km at nadir) LAC data obtained from MétéoFrance at Lannion. This dataset covered the area 30-80N; 50W-30E which is the reception area for the Lannion station. These data are not spatially sampled allowing more accurate mean AVHRR radiances and standard deviations over the HIRS ifov to be computed. This dataset was obtained for 23 May 2000 to correspond with the global data. In addition to mean AVHRR radiances averaged over the HIRS ifov the results of the AVHRR cloud mask derived at Lannion (Derrien and LeGleau, 1999) were used to compute cloud-free AVHRR radiances and a fractional cloud cover for the HIRS ifov. The AVHRR cloud tests applied for this dataset should be more robust than for the global dataset as they are only for a limited area. The LAC clear flag was defined as for the GAC flag when the fractional cloud cover was <5% and the standard deviation less then 1K.

3. RADIANCE SIMULATIONS

As a first step to investigate the relationship between the HIRS and corresponding AVHRR channels, simulations were performed for a diverse set of 117 atmospheres selected from a subset of a larger profile dataset from the ECMWF 50 level forecast model (Chevallier et. al., 2000). The RTTOV-6 fast radiative transfer model (Saunders et. al. 1999) was used to simulate both HIRS and AVHRR radiances for the 117 profiles and 5 satellite zenith angles. The two HIRS channels, which cover a similar part of the spectrum to the AVHRR channels, are HIRS channels 8 and 19 (see Table 1). The radiative transfer simulations showed that the mean of the AVHRR channel 4 and 5 brightness temperatures (denoted as AVHRR(45)) gave a close match to the HIRS channel 8 values. A linear combination of the two AVHRR channels would give a better fit to HIRS-8 but for this study a simple mean was employed. HIRS channel 19 and AVHRR channel 3b simulated brightness temperatures were in close agreement as their filter responses are similar. Figure 1 shows for these channel combinations the simulated HIRS minus AVHRR simulated brightness temperature differences as a function of underlying surface temperature, which in this case is the lowest profile level temperature.

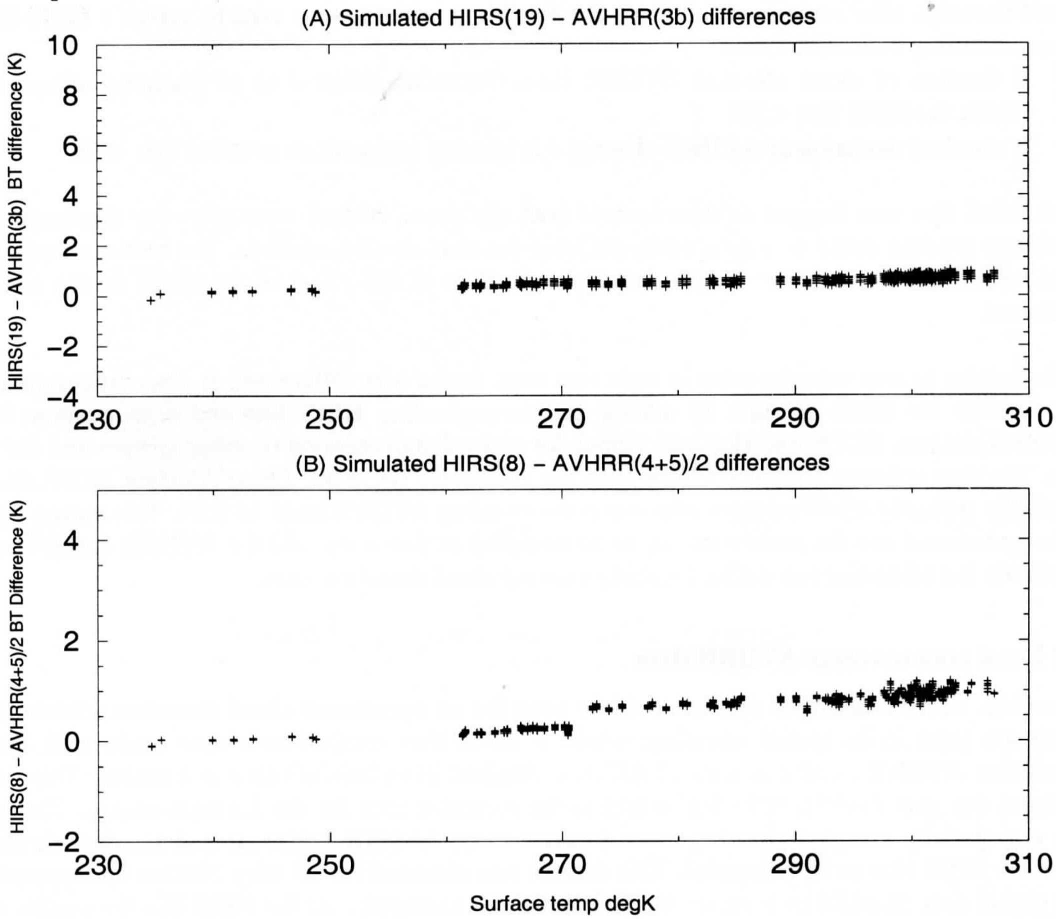

Figure 1. Simulated HIRS and AVHRR window channel brightness temperature differences.

The jump in the HIRS(8) minus AVHRR(45) brightness temperature differences at 271K is due to the surface emissivity changing from sea-ice to water, which for AVHRR(5) is significantly different from the HIRS(8) emissivity change. The brightness temperature differences all lie in the range -0.2K to +1.2K assuming the AVHRR ifovs are representative of the same part of the atmosphere/surface as seen by HIRS and the instruments are perfectly calibrated.

4. COMPARISON OF MEASURED HIRS AND AVHRR RADIANCES

Measured HIRS and AVHRR radiance data from NOAA-15 for 23 May 2000 from 0Z to 18Z were used to investigate the relationship between the HIRS and AVHRR window channel radiances. All instruments were operating normally during this period, although the HIRS was subject to anomalous behaviour before and after this date and the AVHRR failed in early July 2000. In addition one orbit of data was also processed for 22 March 2000 to check any biases seen were stable with time and not influenced by the deterioration of the HIRS instrument. The results presented are all for 23 May

2000. The AVHRR data were first co-located with the ATOVS level 1d data, which included the 1D-Var cloud flag and observation minus background differences from the Met Office unified model 6hr forecasts.

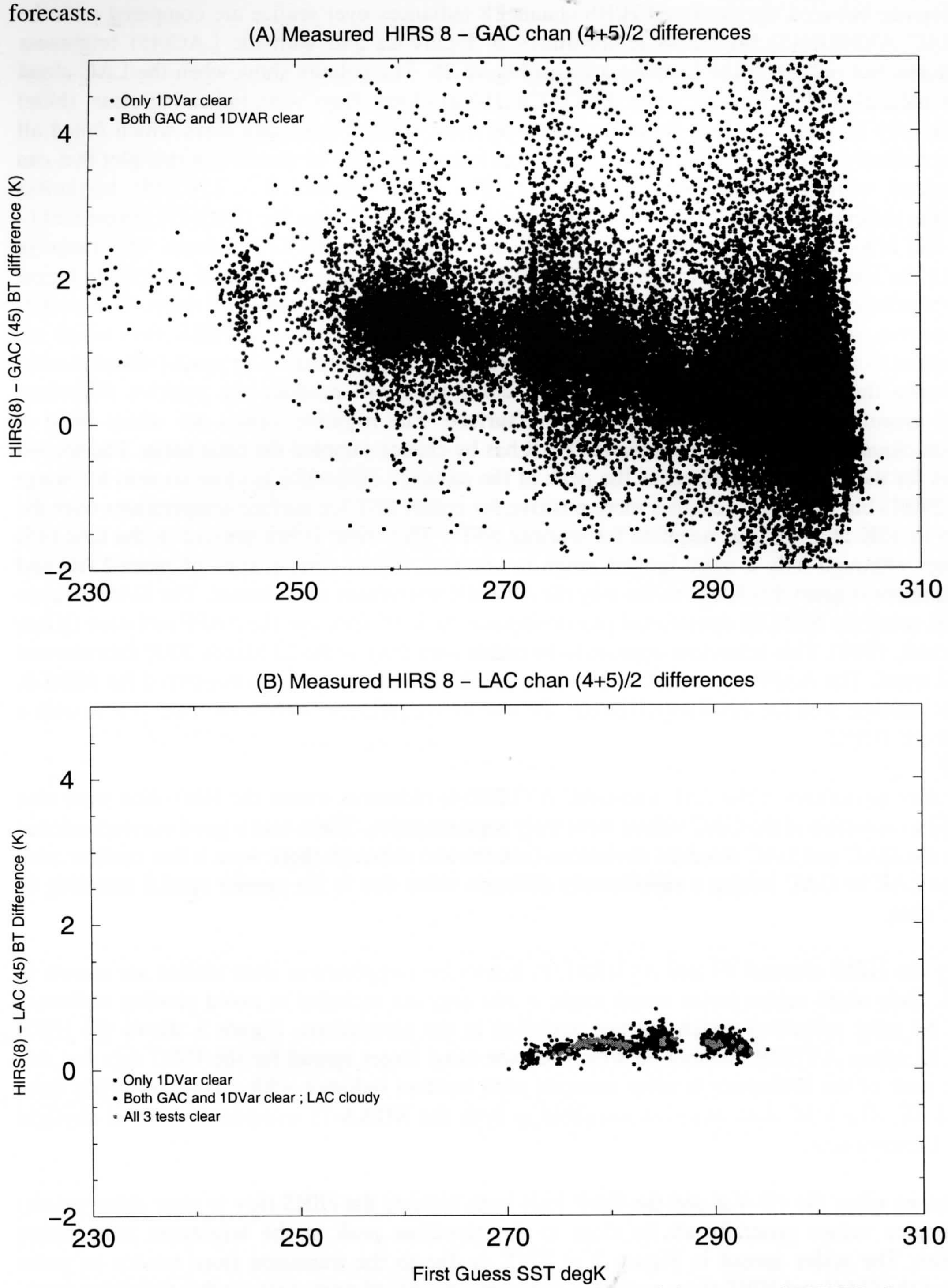

Figure 2. The difference of measured `clear' HIRS channel 8 and the mean of AVHRR channels 4 and 5 plotted as a function of the model SST over sea and ice. The top panel (A) is for the global GAC data and the lower panel (B) for the LAC data. The colours indicate which tests identified the HIRS ifov as clear.

5

The difference between the measured HIRS channel 8 radiances over sea/ice are compared with the mean GAC AVHRR(45) brightness temperatures in Figure 2a and with the LAC(45) brightness temperatures, but only over the Lannion area, in Figure 2b. The colours show when the LAC cloud flag was indicating clear (green), when the GAC+1D-Var cloud flags were indicating clear (blue) and when only the 1D-Var cloud flag was indicating clear (red). The cloudy ifovs which failed all tests (the majority) are not plotted. There are several features worthy of mention in this plot that can be compared with the simulations in Figure 1. The HIRS channel 8 – LAC(45) brightness temperature differences (Fig. 2b) show a much smaller spread (<1K) than the GAC(45) differences (–2K to +5K) at least over the limited range of radiances sampled by the LAC dataset. This range of values for the HIRS(8)–GAC(45) brightness temperature differences is an order of magnitude bigger than the simulations predict whereas the LAC(45) differences are consistent with them. The outliers on the positive side of the mean are likely to be due to undetected cloud in the HIRS ifovs which are less sensitive to small amounts of cloud but the AVHRR can still be sensitive to small (~1km) clouds. If by chance the AVHRR GAC strips are over cloud they will produce the positive difference observed assuming the cloud is colder than the surface. The negative values are where there is significant cloud in the HIRS ifov but the AVHRR has by chance sampled the clear areas. The second feature is for the GAC(45) differences the peak of the radiance difference is close to zero for warm SSTs (~290K) but gradually becomes more positive for colder SST/ice surface temperatures over the poles up to +2K at 250K and negative for warmer SSTs. This trend is not present in the LAC(45) differences although only a more limited range is sampled. Direct comparisons of mean LAC and GAC radiances suggest this is due to the way the AVHRR instrument is calibrated. The GAC data are calibrated using the NESDIS operational processing and the LAC data use the AAPP software (Klaes and Schraidt, 1999). This behaviour appears to be stable with time as the 22 March 2000 data showed the same trend. The AAPP and NESDIS provided HIRS radiances were also compared for HIRS-8. Over the Lannion area for this limited dataset the maximum differences were of order 0.12K with a mean bias of 0.05K.

The standard deviations of the LAC and GAC AVHRR(4) radiances within the HIRS ifov were also compared to ascertain if the GAC values were truly representative. There was a good correspondence between the GAC and LAC standard deviations (not shown) although there were a few outliers with either the LAC or GAC having a significantly different value due to the sparser spatial sampling of the GAC data.

Similarly the HIRS channel 19 and AVHRR(3b) brightness temperatures over sea/ice are shown in Figure 3. Only night values (solar zenith angle > 100 deg) are included to avoid plotting radiances affected by solar reflection which are not modelled in the simulations. Figure 3 shows the HIRS channel 19 minus AVHRR channel 3b which has the same larger spread for the GAC data but this time the peak of the difference is more constant with incident radiance with a constant offset from zero of 1.5K. The LAC data were not available as both the NOAA-15 overpasses were in daylight over the Lannion area.

In both cases when the 1D-Var and the GAC tests both indicate the HIRS ifov is clear (blue points) the difference values generally all lie close to the cloudfree peak in the brightness temperature differences. The wider spread in Figure 2 at 271K is due to the transition from sea-ice to water because of the GAC and HIRS ifovs sampling different amounts of open water in this transition zone.

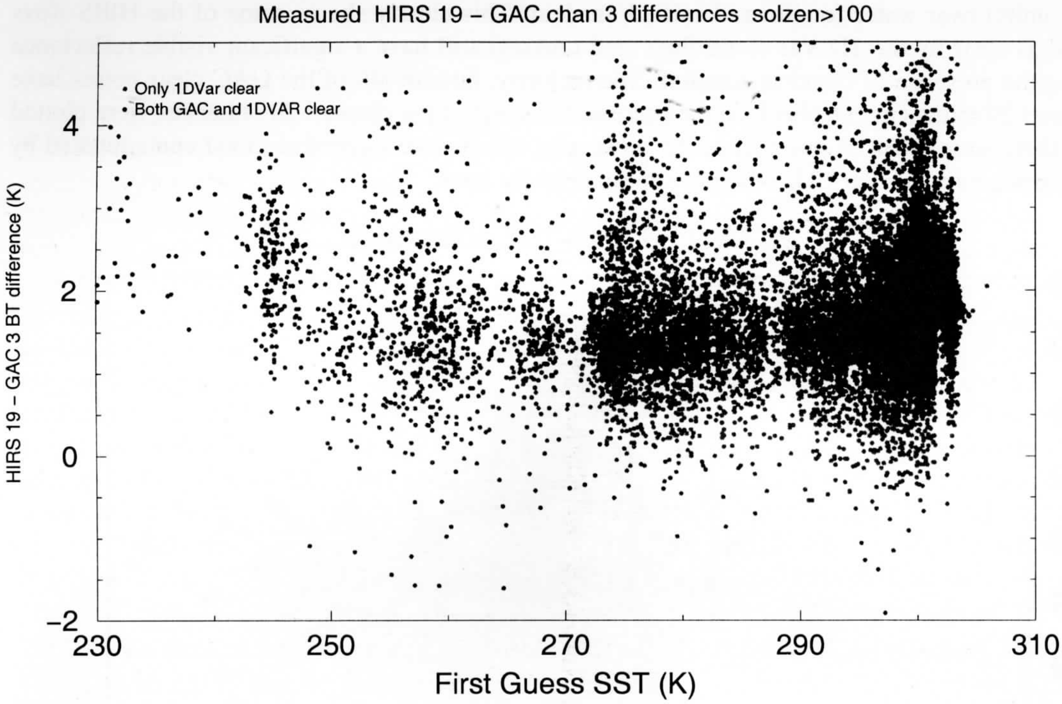

Figure 3. As Fig. 2a but for HIRS channel 19 and AVHRR channel 3b. Only nighttime data is plotted.

The key point for these plots is that the measured differences of the HIRS and GAC radiances that have been identified as 'clear' by either method can be far greater than the simulations predict primarily due to the way the GAC data have sampled the HIRS ifov. The HIRS-GAC radiance differences should therefore only be used for identifying clear HIRS ifovs with caution but the HIRS-LAC differences are a good indicator of cloud.

Over the Lannion area the LAC cloud flag can be used as the 'truth' and the performance of the 1D-Var and GAC tests compared with it. For the NOAA-15 09Z overpass only 12.7% of the LAC cloudy ifovs were flagged by the 1D-Var and 28.1% flagged by the GAC tests. The combined GAC+1D-Var test had a 28.4% success rate similar to the GAC only. This is confirmed by the larger spread of the 1D-Var clear values in Figure 2b. For the afternoon pass the success rates of both tests were significantly higher but the 1D-Var was again well below the GAC success rate.

For the global dataset the most reliable indicator of a clear ifov would seem to be where both the GAC and 1D-Var tests have identified the HIRS ifov as cloudy. To quantify the number of ifovs flagged as cloudy by each test, 75% of the ifovs were flagged by the 1D-Var test and 93.5% by the GAC test leaving only 6.5% identified as clear by both tests. Hence by applying both cloud tests this would significantly reduce the number of 'clear' HIRS ifovs available for assimilation. However it is important to note that the AVHRR cloud test may be too stringent as the effect of the cloud only needs to be reduced to below the assumed HIRS observation + forward model error which for the HIRS window channels is 0.4 degK in the Met Office 1D-Var processing. The determination of the exact threshold for rejection for assimilation (by altering the GAC cloud flag criteria) will require some assimilation experimentation as it will depend on the assigned observation and background errors for all the HIRS cloud affected channels.

In order to try and further validate the cloud tests the HIRS visible channel radiances (channel 20) were used for solar zenith angles less than 70 degrees. Figure 4 shows the HIRS minus AVHRR(45) GAC brightness temperature differences plotted against the HIRS visible channel 20 radiances (in arbitrary units) over water for ifovs identified as clear. This clearly shows some of the HIRS ifovs identified as clear by the 1D-Var cloud flags (red crosses) still have a significant visible reflectance indicating the presence of cloud or sunglint. The majority, but not all, of the GAC clear points have low channel 20 radiances. To check on the presence of sunglint the channel 20 radiances were plotted to see if there were areas on one side of the orbit only which were flagged as cloud contaminated by AVHRR and not by 1D-Var. This did not appear to be the case.

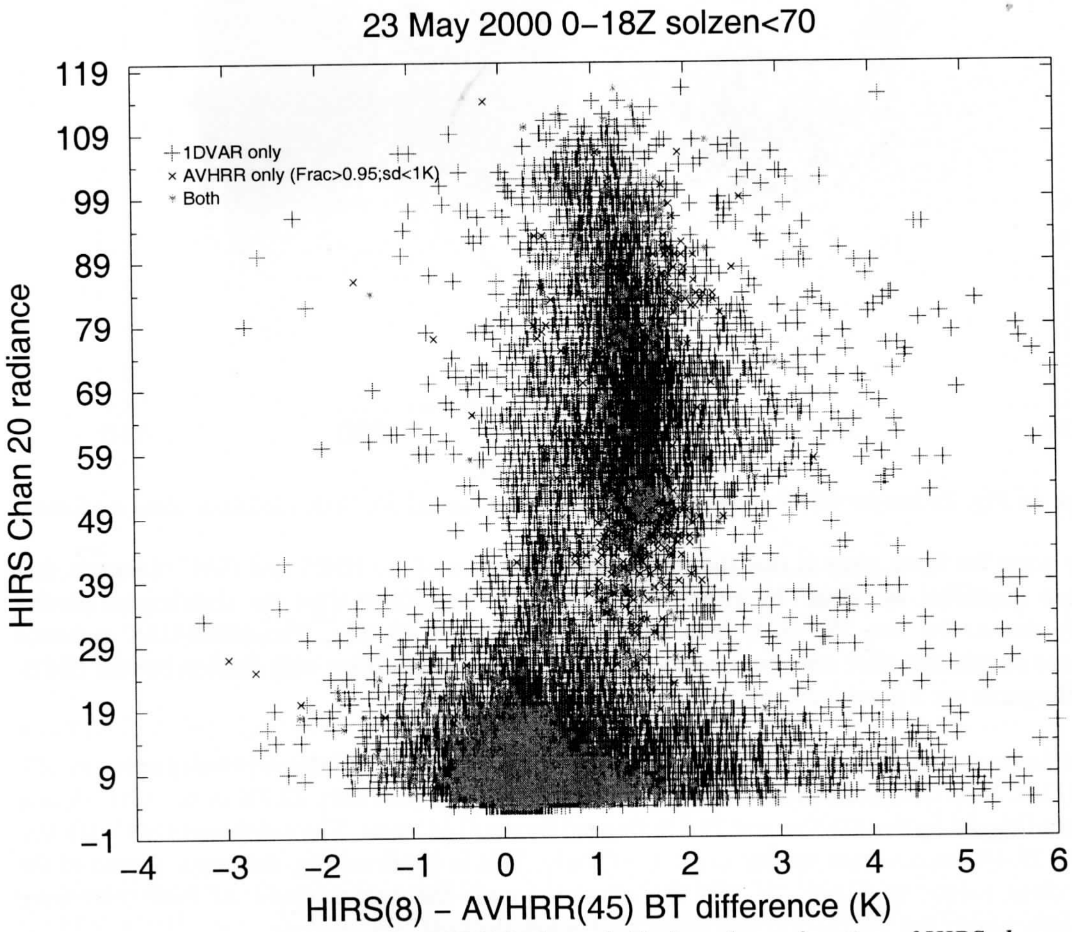

Figure 4. HIRS channel 8 minus AVHRR channel 45 plotted as a function of HIRS channel 20 radiance for solar zenith angles less than 70 deg.

Finally Figure 5 shows the HIRS(8) observed–first guess (Ob–Fg) brightness temperature difference over the Lannion area plotted as a function of the LAC AVHRR channel 4 standard deviation. The first guess values were computed from 6 hr forecast fields of the Met Office unified model. The LAC clear points (green) all have small (Ob–Fg) values (<1K), the GAC+1D-Var clear points (blue) have larger differences (–2K to +1K) and also larger LAC standard deviations (up to 4K) suggesting some residual undetected cloud is present. The 1D-Var only clear points (red) show many more points with larger LAC standard deviations (up to 6K) and a tendency for the Ob-Fg values to be negative (–2K) again suggestive of cloud contaminated HIRS radiances being passed by the 1D-Var cloud test. Note that the 1D-Var cloud test will be related to the Ob-Fg values of all the ATOVS channels, including HIRS-8, so very large Ob-Fg values should not be present.

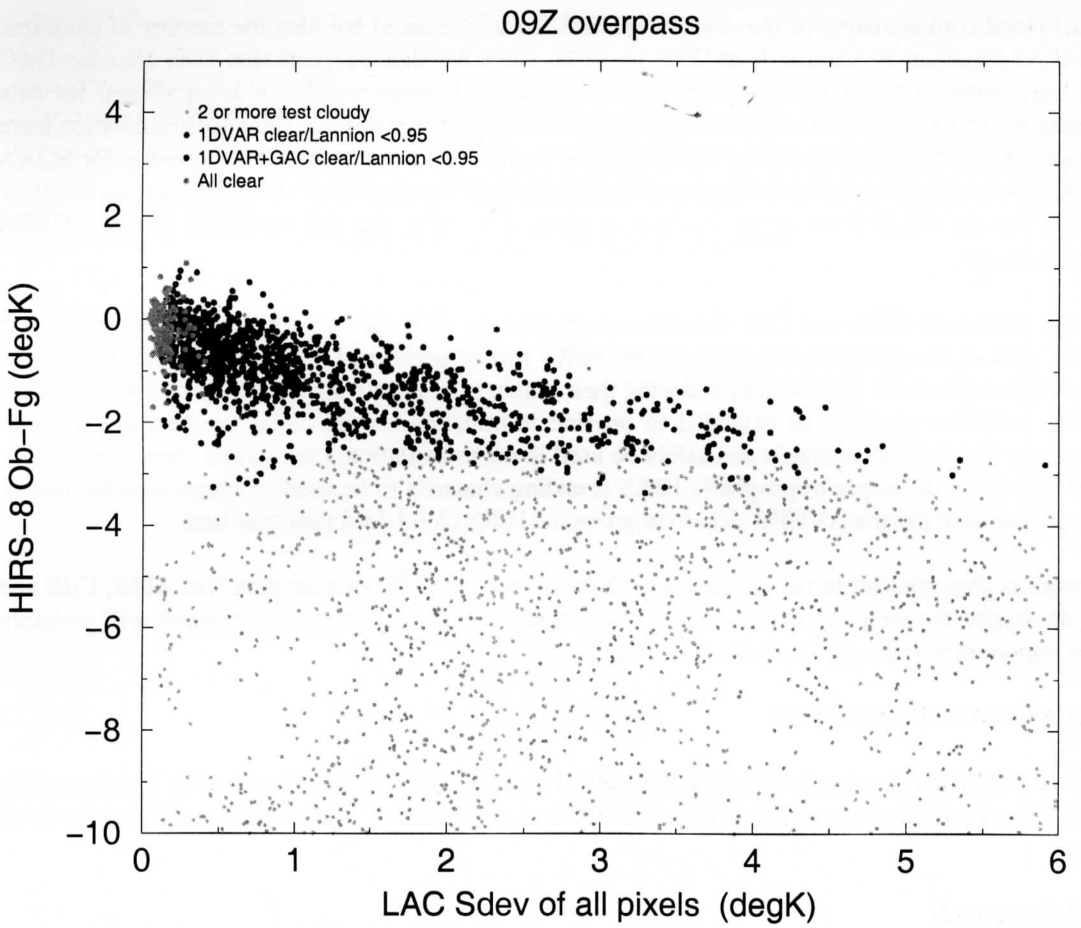

Figure 5. HIRS channel 8 observed minus first guess brightness temperature differences plotted as a function of the LAC AVHRR channel 4 brightness temperature standard deviation.

5. CONCLUSIONS

A comparison of NOAA-15 HIRS window channel radiances and the corresponding AVHRR radiances averaged over the HIRS ifovs has been carried out to ascertain if the AVHRR GAC dataset could be used to improve the cloud detection for HIRS ifovs. Simulations show over cloudfree ocean/ice the expected brightness temperature differences between the HIRS channel 8 and mean of AVHRR channels 4 and 5 should all be between (–0.2K and +1.2K). Over a limited area the clear AVHRR LAC data confirm this for HIRS channel 8 but globally the clear AVHRR GAC data exhibits a scene dependent bias (from +2K for 250K scenes to –1K for 300K scenes). A comparison of LAC and GAC channel 4 radiances suggest the bias is due to differences in the NESDIS and AAPP calibration of the AVHRR data. For HIRS channel 19 minus AVHRR channel 3b radiance differences there is a constant bias of +1.5K but no comparison with LAC radiances were made. These apparent differences in AVHRR calibration should be investigated further. The HIRS - GAC differences also exhibit a much larger spread of radiance differences than with the LAC data, which is due to the incomplete sampling of the HIRS ifov by the GAC data. On average the variance of the GAC data within a HIRS ifov is the same as that computed with the LAC data.

The 1D-Var cloud flag used operationally at the Met Office was found to miss a significant number of cloud contaminated HIRS ifovs determined by comparing with the GAC cloud tests, the LAC tests, HIRS channel 20 visible radiances and HIRS-8 Ob-Fg values. When the GAC cloud flag is also used the residual cloud contamination of the remaining HIRS ifovs is reduced but also the number of cloudfree HIRS ifovs significantly reduces from 25% to 6.5%. The LAC data suggests that even after the GAC cloud tests, some of the data are still cloud contaminated although whether it is significant for data assimilation purposes is not clear. If it is significant this suggests for infrared radiance assimilation there is a requirement for the full resolution AVHRR to be available in every HIRS ifov. Currently for NOAA satellites this is only achievable for local area datasets as only sampled GAC AVHRR data are available globally. For the METOP era (post 2005) it is planned to make the full resolution global AVHRR dataset available.

Once the NOAA-16 HIRS and GAC datasets are available in 2001 data assimilation experiments using the GAC data as an additional cloud flag for the HIRS will be performed to ascertain if the assimilation of the HIRS radiances is improved by reducing their number but improving their quality. The use of the AVHRR radiances can also be extended to provide information on the cloud top height and hence guidance on which HIRS channels can safely be used in the assimilation. Low stratus cloud for instance should still allow the upper tropospheric HIRS sounding channels to be used. Another area for further investigations is to use the AVHRR data to improve the HIRS cloud detection over land.

This work is also relevant to the assimilation of future advanced IR sounder data (i.e. AIRS, CrIS and IASI) as despite the larger spectral coverage the imagers associated with these sounders will probably still be important to improve the cloud screening.

6. ACKNOWLEDGEMENTS

E. Brown (NESDIS) developed the global AVHRR dataset. P. Dibben, K. Whyte and R. Renshaw (Met Office) helped with the processing of the AVHRR data. P. Brunel of MétéoFrance provided the LAC dataset.

7. REFERENCES

Chevallier, F., A. Chédin, F. Chéruy and J.J. Morcrette. 2000 TIGR-like atmospheric profile databases for accurate radiative flux computation. *Q.J.Roy.Meteorol.Soc.* **126** *777-786.*

Derrien, M. and H. LeGleau 1999 Cloud classification extracted from AVHRR and GOES imagery. *Proc. of EUMETSAT Meteorological Satellite Data Users' Conference, Copenhagen, Denmark 6-10 September 1999 EUM P 26 ISSN 1011-3932, 545-553.*

English, S.J., J.R. Eyre and J.A. Smith 1999 A cloud detection scheme for use with satellite sounding radiances in the context of data assimilation for numerical weather prediction. *Q.J.Roy.Meteorol.Soc.* **125** *2359-2378.*

English, S.J., R.J. Renshaw, P.C.Dibben, A.J. Smith, P.J. Rayer, C. Poulsen, F.W. Saunders, and J.R. Eyre 2000 A comparison of the impact of TOVS and ATOVS satellite sounding data on the accuracy of numerical weather forecasts. *Q.J.Roy.Meteorol.Soc.* **126** *2911-2932..*

Joiner, J. and L. Rokke 2000 Variational cloud clearing with TOVS data. *Q.J.Roy.Meteorol.Soc.* **126** *725-748*

Klaes, D. and R. Schraidt 1999 The European ATOVS and AVHRR Processing Package (AAPP) development. *Technical Proc. of 10^{th} International ATOVS Study Conference Boulder Colo. 27 Jan-2 Feb 1999 Ed. J. LeMarshall 288-294.*

McNally, A.P., J.C. Derber, W. Wu and B.B.Katz 2000 The use of TOVS level-1b radiances in the NCEP SSI analysis system. *Q.J.Roy.Meteorol.Soc.* **126** *689-724*

Reale, A., M. Chalfant, E. Brown and L. Wilson 2001 NOAA operational sounding products from polar orbiting environmental satellites. *Technical Proc. of 11th International ATOVS Study Conference Budapest 20-26 Sept 2000. Ed. J. LeMarshall (in this issue).*

Saunders, R.W. and K.T. Kriebel 1988 An improved method for detecting clear sky and cloudy radiances from AVHRR data. *Int. J. of Remote Sensing* **9** *123-150.*

Saunders R.W., M. Matricardi and P. Brunel 1999 An Improved Fast Radiative Transfer Model for Assimilation of Satellite Radiance Observations. *Q.J.Roy.Meteorol.Soc.* **125** *1407-1425*

TECHNICAL PROCEEDINGS OF THE ELEVENTH INTERNATIONAL ATOVS STUDY CONFERENCE

Budapest Hungary

20-26 September, 2000

Edited by

J.F. Le Marshall and J.D. Jasper

Bureau of Meteorology Research Centre, Melbourne, Australia

Published by

Bureau of Meteorology Research Centre

PO BOX 1289K, GPO Melbourne, Vic., 3001, Australia

June 2001