Analysis of AIRS and IASI System Performance under Clear and Cloudy Conditions[1].

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Abstract

The radiometric and spectral system performance of space-borne infrared radiometers is generally specified and analyzed under strictly cloud-free, spatially uniform and warm conditions, with the assumption that the observed performance applies to the full dynamic range under clear and cloudy conditions and that random noise cancels for the evaluation of the radiometric accuracy. Such clear conditions are found in only one percent of the data. Ninety nine percent of the data include clouds, which produce spatially highly non-uniform scenes with 11µm window brightness temperatures as low as 200K. We use AIRS and IASI radiance spectra to compare system performance under clear and a wide range of cloudy conditions. Although the two instruments are in polar orbits, with the ascending nodes separated by four hours, daily averages already reveal surprisingly similar measurements. The AIRS and IASI radiometric performance based on the mean of large numbers of observation is comparable and agrees within 200 mK over a wide range of temperatures. There are also some unexpected differences at the 200 -500 mK level, which are of significance for climate applications. The results were verified with data from July 2007 through January 2010, but many can already be gleaned from the analysis of a single day of data.

Keywords: Infrared temperature sounder hyperspectral climate radiometric calibration

1. Introduction

The radiometric and spectral system performance of space-borne infrared radiometers is typically specified and analyzed under strictly cloud-free, spatially uniform and warm conditions, typically 280K, with the assumption that this performance applies to the full dynamic range under clear and cloudy conditions and that random noise cancels for the evaluation of the radiometric accuracy using large space and time averages. Extremely clear conditions are found in only one percent of the data. There are a number of instrumental reasons which will cause biases in measured radiances, the accuracy of the onboard blackbody source being just one of them. Ninety nine percent of global measurements in the infrared are "cloud contaminated". Clouds produce spatially highly non-uniform scenes with 11 µm window brightness temperatures as low as 200K. Biases can be zonal, day/night or cloud cover dependent. Climate applications require global observations, which are often analyzed in terms of zonal or coarse gridded mean values and trends. The widely accepted requirement for climate applications, and the performance expected from the new hyperspectral sounders, is 100 mK absolute [1]. With the simultaneous availability of data from two hyperspectral sounders since July 2007, the Advanced Infrared Sounder (AIRS) [2] and the Infrared Atmosphere Sounding Interferometer (IASI) [3], we now have global data to evaluate their relative system performance with respect to climate monitoring accuracy requirements under clear and cloudy conditions. Insight into the comparative radiometric performance of AIRS and IASI can be gained by using clear data, random data and Simultaneous Nadir Overpasses (SNO). The first two can provide statistically significant information from just one day of data. The SNO technique produces typically results from only two crossing orbits per day for the AIRS/IASI orbital configuration, which means that statistically significant information requires collecting about one year of data. For this reason results from SNO are not discussed in this paper.

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2. Data

Our analysis is based on subsets of data collected from AIRS and IASI. AIRS was launched on the EOS Aqua in May 2002, IASI was launched on the MetOp in October 2006. AIRS and IASI have relatively similar functional specifications, i.e. produce spectra between 650 and 2700 cm^{-1} with resolution of about 0.5 - 1 cm^{-1} , sub-sampling the AMSU 45 km field of view (FOV) with 2x2 (IASI) or 3x3 (AIRS) 12 km footprints. AIRS and IASI are both in polar sun-synchronous orbit, but with different ascending nodes, such that IASI day time (night) data are from 9:30 AM (9:30 PM), while day (night) data from AIRS are collected at 1:30 PM (1:30 AM) local time. AIRS and IASI both have 1 km spatial resolution imagers integrated into the instrument. AIRS uses a four channel visible light array (two of the channels emulate AVHRR 2 and 3), IASI uses an 11 µm array, referred to in the following as the IASI imager. While the high level functional requirements are fairly similar, the implementation of the two instruments is very different: AIRS is a cooled Grating Array Spectrometer, IASI is a Fourier Transform Spectrometer (FTS). This difference in implementation causes differences in the error characteristics of the two instruments.

The AIRS Climate Data Subset (ACDS) contains a collection of clear spectra (typically 40,000), random nadir spectra (typically 12,000), deep convective cloud spectra (typically 10,000) and validation site overpass spectra (typically 2000). The ACDS is created daily and is available from the GSFC DIS. For IASI we created a prototype of a similar data set, the ICDS. Clear data were selected at all scan angles using a combination of a spatial coherence test within the AMSU 45 km FOV and a number of relatively coarse spectral tests, designed to eliminate most cirrus and dust contamination. For AIRS we also saved visible light imager data, for IASI we saved the 11µm imager data associated with each spectrum. Along with each spectrum we saved the associated quality indicators, orbital geometry and time.

A consequence of the implementation of AIRS as a Grating Array Spectrometer (GAS) and IASI as a Fourier Transform Spectrometer (FTS) is a differences in quality screening of the data. For AIRS the quality screening is detector oriented, while for IASI the quality screening is spectrum oriented. For the AIRS data the quality of each spectrum is summarized in IRState, a dynamically defined 2378 x 1 array, i.e. one quality estimate per channel, related to noise and calibration. Since in an FTS instrumental or calibration problems effect the entire spectrum, the QFlag for IASI is defined for each spectrum based on a set of thresholds using indicators from the on-board software and ground data processing, including band overlap mismatch, zero path difference error and radiation hit detection.

AIRS and IASI both create more than 20 terra-bytes of data each year. The random nadir spectra are intended to give a statistically accurate representation of global conditions in terms of temperatures and clouds with a two orders of magnitude reduction in data volume. We defined nadir spectra as footprints which spatially sample the AMSU scan position 15 or 16. These positions are centered 1.6 degree to the left and right of nadir. The randomization is accomplished by drawing a uniform random number, RAND, between 0 and 1 for each AMSU scan line at scan positions 15 and 16. If RAND is less than a fixed threshold times the cosine of the latitude where the data is being collected, then all nine AIRS or all four IASI footprints contained in AMSU FOV are saved, independent of IRState or QFlag. The cosine weight essentially eliminates the area over-coverage created by the polar orbit. The thresholds were set to select typically 12,000 spectra each day corresponding to 1% of all IASI spectra, 0.4% of the AIRS spectra.

3. Results

3.1. Clear Data.

Only 0.5% of the spectra are accepted as clear. Although the spatial homogeneity test, which compares the spectra collected in a AMSU field of regard, acts as a very tight quality control filter, we explicitly selected only high quality data (QFlag=0 for IASI, IRState=0 for AIRS) for the analysis of clear spectra.

3.1.1. (Obs-calc)

Clear data can be analyzed as the mean and the standard deviation of the difference between the observed brightness temperatures (obs) and the brightness temperature calculated (calc). The calculation requires knowledge of the state of the atmosphere (we used the ECMWF analysis) and the use of a Radiative Transfer Algorithm (RTA) [4,5]. The RTA can introduce uncertainties of the order of 0.5 K. However, if the RTA is based on the same line parameters, potentially resulting biases in the calculation are seen in both data and can be ignored. Errors in the specification of the state of the atmosphere also appear as biases common to both calculations and can be ignored. Figure 1 shows the result from single night of clear tropical ocean spectra, overlaid for AIRS and IASI. For clarity only a small section of the spectrum is shown, centered on the 1231 cm^{-1} atmospheric window region, and the spectra have not been normalized to the same spectral resolution or sample position.

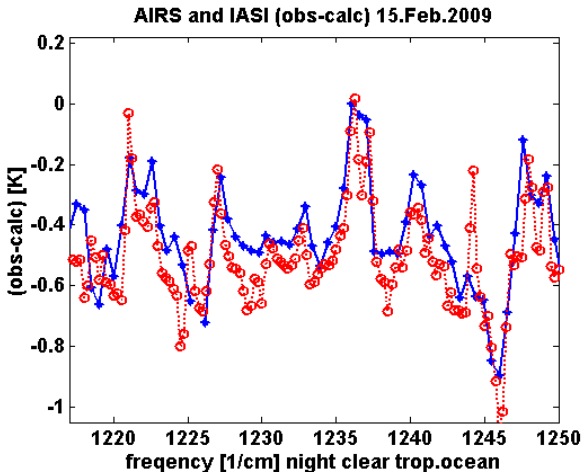

Figure 1. (obs-calc) for IASI (red dotted) and AIRS (blue solid) from a single night of clear ocean spectra.

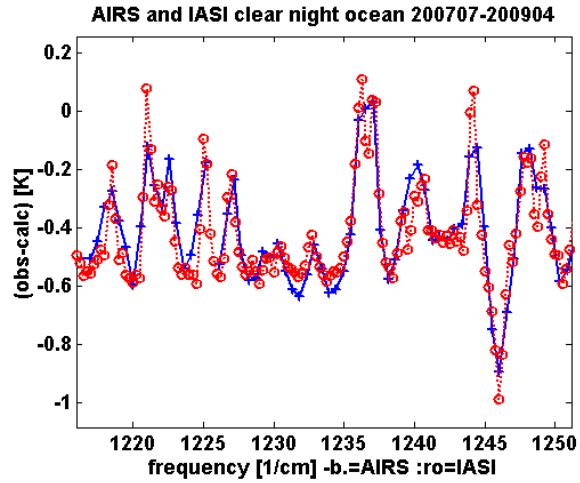

Figure 2. (obs-calc) for IASI (red dotted) and AIRS (blue solid) from night of clear ocean spectra collected between July 2007 and April 2009.

Figure 2 shows (obs-calc) for the same spectra region, but averaged for all clear night ocean spectra between July 2007 and April 2009. The two graphs illustrate three points: 1) The radiances track in this area of the spectrum within 0.1K, in spite of the fact that AIRS and IASI are in different orbits. 2) the impression of the data from a single clear night (Figure 1) is confirmed by the daily average from almost two years of data. Note that for the 1231 cm^{-1} atmospheric window channel, referred to in the following as bt1231, (obs-calc) has a cold bias of about 0.5K for AIRS and IASI.

3.1.2. (Obs-calc) trend for clear window channels

If we calculate (obs-calc) for good window channels over the tropical oceans under clear conditions, the water vapor absorption is small and can be derived from weak water lines in the observed spectrum using model spectra. This method has been used successfully for AIRS [6] and an equivalent approach has been developed for IASI, in both cases using the bt1231 window channel. For the SST we use the NCEP forecast (RTGSST) [7]. The NCEP SST is a daily mean SST, approximately corrected for the skin effect and the diurnal bias [8]. The IASI observations at 9:30 PM require a +0.05K diurnal correction, while the AIRS observations at 1:30 AM require an 0.25 K diurnal cycle correction. Figure 3 shows (obs-calc) for bt1231 for AIRS between September 2002 and January 2010, for IASI between May 2007 and January 2010. During the overlapping data period both AIRS and IASI show a cold bias of about 0.4 K and stdev(obs-cal).bt1231=0.5 K. Similar values are found for all window channels.

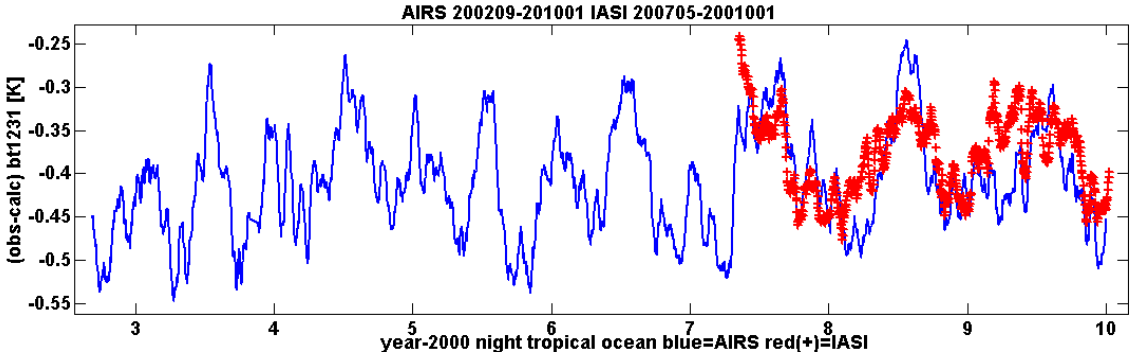

Figure 3. Mean(obs-calc) for the 1231 cm-1 window channel. AIRS (blue) and IASI (+red) trace.

The nominal trend in mean(obs-calc) in 7.5 years of AIRS data is +4 mK/yr with a one sigma trend uncertainty of 2 mK/yr. The IASI mean(obs-calc) for bt1231 overlays the AIRS data within 50 mK between July 2007 and January 2010, but the data period is too short to derive a meaningful trend.

3.2. Random Nadir Spectra.

Climate studies require global and zonal spectra, which represent average conditions without a bias. Cloud filtered data produce radiometrically very clean spectra, but they are not representative of average conditions. All data have to be quality screened. If the quality screening is scene independent, then random nadir spectra produce essentially uniformly sampled data twice each day, once from the ascending and once from the descending orbits. The AIRS quality screening uses IRState. For about 110 of the 2378 AIRS channels, about 5% of all channels, the Noise-Equivalent Delta Temperature (NEDT) at 250 K is either larger than 2 K or other calibration or noise artifacts are detected by the ground data processing. For these channels IRState is set to low quality (IRState(n)=1, where n is the channel number). For 95% of the AIRS channels IRState=0 at all times, i.e. for 95% of the channels the quality screening is scene independent.

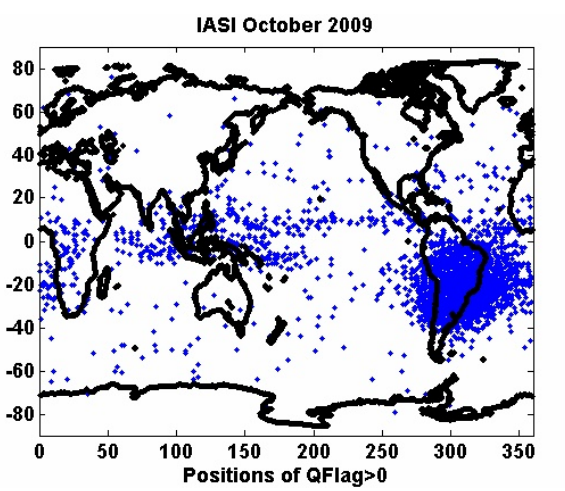

Figure 4. Each "+" represents the location of a spectrum rejected by the IASI quality control in October 2009.

The IASI QFlag is derived from various parameters derived from the interferograms or in the resultant spectra. About 1% of the IASI spectra have QFlag=1, i.e. the entire spectrum is defined as low quality.
Figure 4 shows the location of the 2972 of 320,000 random nadir spectra collected from IASI during October 2009, but rejected by the quality screening. The QFlag=1 spectra are scattered along the equator in regions of strong convection. About 50% of the spectra flagged as low quality are easy to identify, since all spectral elements equal zero. The other QFlag=1 spectra do not immediately look unreasonable, i.e. they could be cloudy spectra.

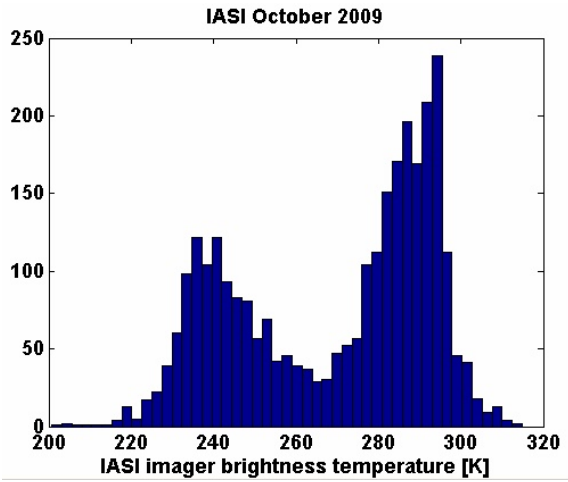

Figure 5. Histogram of the IASI imager brightness temperature of the rejected spectra

Figure 5 shows the histogram of the brightness temperature distribution of the QFlag=1 spectra using the IASI imager. The histogram is bi-modal. The 240-250 K mode of the histogram is associated with the tropical Pacific, i.e. QFlag=1 was set due to problems with some classes of clouds in areas of strong convection. The 290 K mode of the histogram is associated with the outages centered over Brazil. This is the area of the South Atlantic Anomaly (SAA), an area of high energy particle flux which creates spikes in the detectors and possibly in other parts of the electronics.

3.2.1. Observational bias

The spatial non-uniformity of the IASI QFlag produces a radiometric bias. We can estimate the magnitude and the spatial distribution of this bias using data from the IASI 11 µm imager, since the imager data are not affected by indicators used for creating the QFlag. For the random nadir spectra collected globally for land and ocean in October 2009 the mean of all imager brightness temperature was 274.06K, while the mean for QFlag=0 filtered data was 274.11K. The difference is only 50 mK warm bias, largely due to the fortuitous cancellation between warm SAA related cases and cold cloud related cases in the tropical oceans. For the tropical oceans the warm bias is 0.2K, the Tropical Pacific/Indian ocean (longitudes 50-250E) have a warm bias of 0.25 K increasing the 0.4K in the tropical warm pool.

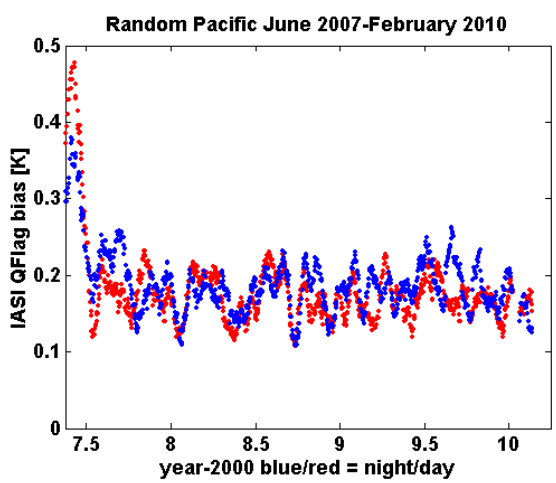

Figure 6. IASI Pacific Ocean day/night QFlag bias for data between May 2007 and January 2010. blue=night, red=day data.

The history of the IASI QFlag bias since June 2007 for day and night observations of the Pacific Ocean (50E to 250E) is shown in Figure 6. The daily values have been smoothed by a 16 day running average. After QFlag related threshold refinements implemented at the start of the operational phase in July 2007, the QFlag bias has remained relatively stable at about 200 mK level, with 100 mK peak-to-peak variability.

3.2.2 Comparisons under cloudy conditions.

The comparison of random spectra for channels which are identified as high quality by AIRS, and associated with QFlag=0 spectra by IASI, provides a valuable insights.

3.2.2.1 Absolute Comparisons under cloudy conditions.

Since random spectra are mostly cloudy, we use the brightness temperature in the 1231.25 cm^{-1} window channel, bt1231, to define cloudiness. For individual spectra bt1231 ranges from 190 K for deep convection in the tropics, to 330 K under clear dry day time desert conditions. If we evaluate (obs-calc) for the bt1231 channel under cloudy conditions, but ignore the effect of clouds in "calc", then the mean (obs-calc)_cloudy or stdev(obs-calc)_cloudy can be used as metric of the effect of clouds. Under clear conditions (obs-calc)_cloudy is within 0.4 K of zero with 0.5K standard deviation, while under cloudy conditions (obs-calc)_cloudy can be as low as -100 K. Figure 7a shows the mean(obs-calc)_cloudy for AIRS (blue ".", mean value=-10.8 K) and IASI (red "x", mean value=-10.3 K) for the night tropical oceans between May 2007 and February 2010). The cloud effect for IASI is slightly less than for AIRS. Figure 7 shows stdev(obs-cal)_cloudy for AIRS (blue ".", mean value=13.2 K) and IASI (red "x", mean value=12.1 K) for the night tropical oceans between May 2007 and February 2010). The cloud effect for IASI is 0.5 K less in terms of the bias and 1.1 K less for the standard deviation than for AIRS. The fact that the difference in the mean cloud effect is only 0.5 K is surprising, given the difference in the sampling of the diurnal cycle. However, for climate applications differences of 0.5 K can not be ignored. The stdev of the cloud effect appears to be relatively stable for AIRS, but appears to be increasing for IASI.

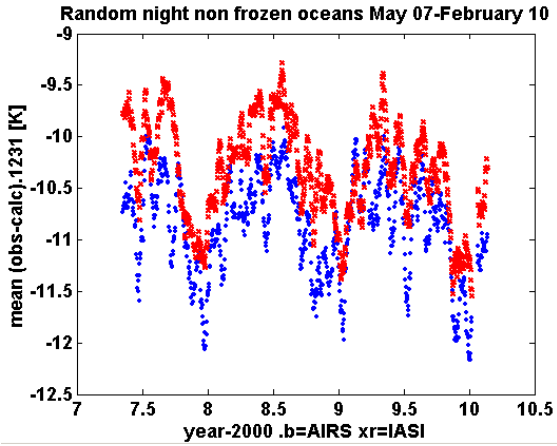

Figure 7a shows an overlay of the mean(obs-calc)_cloudy for AIRS (blue ".") and IASI (red "x")

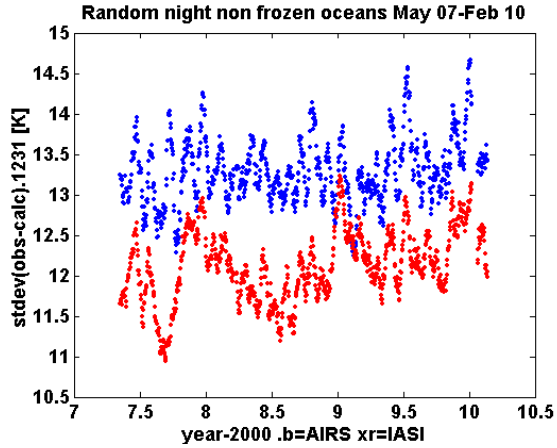

Figure 7b shows an overlay of stdev(obs-calc)_cloudy for AIRS (blue ".") and IASI (red "x")

3.2.2.2. Radiometric comparison within a spectrum.

For random spectra bt1231 ranges from 320 K under clear day desert conditions to below 200K under extreme cloudy conditions. As a consequence, the mean has high variability, which limits the accuracy of the radiometric interpretation of the data. This problem is avoided by the comparison of two radiometrically equivalent channels within a spectrum using pairs of window channels or a pairs of sounding channels. The results are analyzed as the scatter diagram of the selected difference versus cloudiness, i.e. bt1231. If we select two sounding channels, we introduce a potential new complication due to seasonal or cloud related spectral calibration errors. This is the reason that we limit our analysis in this paper to a pair of window channels. Figure 8 shows the difference between the window channels at 1128.5 cm^{-1} and 1231.25 cm^{-1}, from a single day of data, 17 July 2007 from IASI and AIRS.

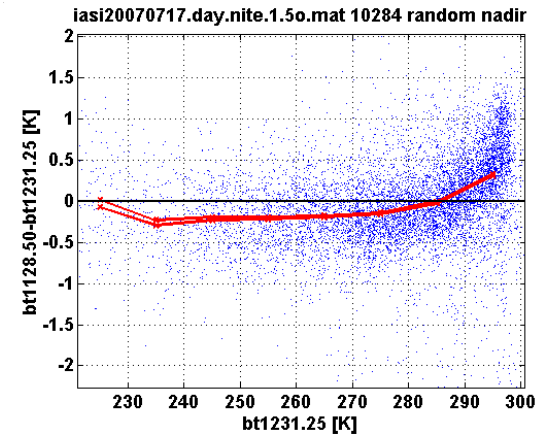

Figure 8a. IASI (bt1128-bt1231) scatter diagram

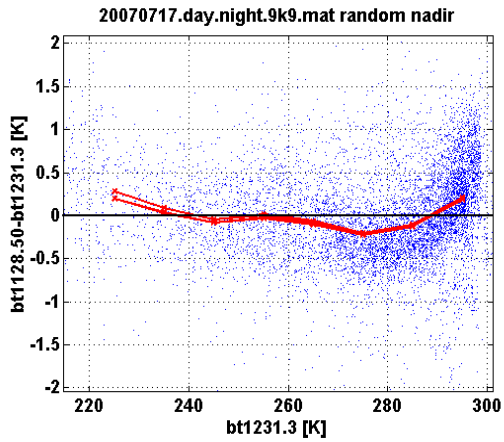

Figure 8b. AIRS (bt1128-bt1231) scatter diagram

Each dot in Figure 8 represents the difference calculated from one spectrum. The solid (red) traces, which represents the mean ±probable error in the ridge of the scatter diagrams, shows that (bt1128-bt1231) changes as function of bt1231, but is always within 200 mK of zero. For relatively clear conditions (bt1231>290K) (bt1128-bt1231)=+0.2K for AIRS and IASI. The mean of bt1128-bt1231 is -0.0155 std=0.60 K for AIRS, -0.0083 std=0.57 K for IASI. The probable error in the mean (from the 10,000 observations) is 0.006 K, i.e. the difference between the AIRS and IASI mean is marginally significant.

The time history of the daily mean of (bt1128-bt1231) for the June 2007 though February 2010 period under night ocean clear is shown in Figure 9a, smoothed by a 16 day running average. Under clear conditions IASI (bt1128-bt1231) is typically -0.17 K colder than AIRS. Figure 9b shows (bt1128-bt1231) under random night ocean conditions on the same horizontal and vertical scale as under clear conditions.

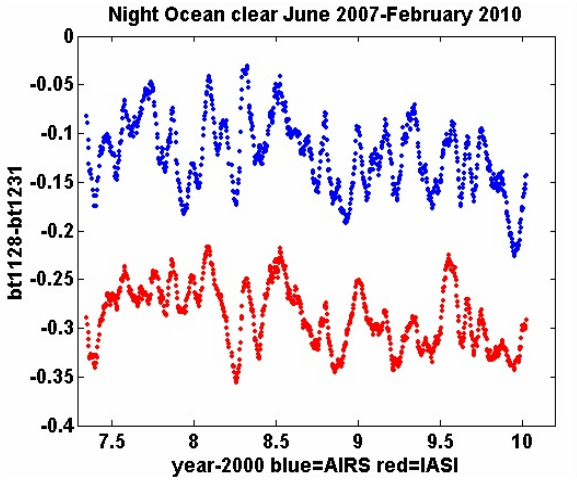

Figure 9a. (bt1128-bt1231) night clear ocean. IASI is the lower trace with -0.3K bias.

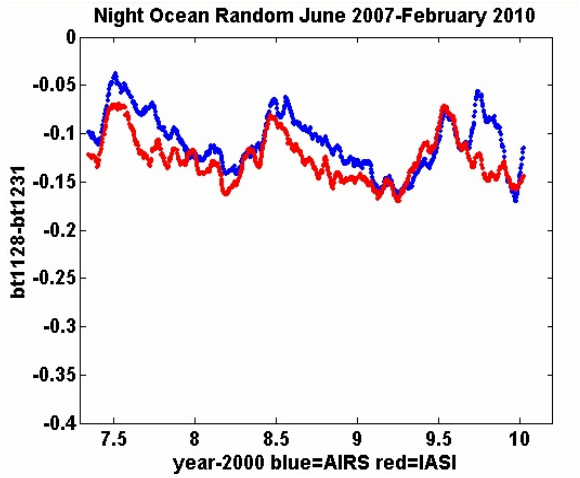

Figure 9b. (bt1128-bt1231) random nadir. IASI data (lower trace) is 40 mK colder.

The mean brightness temperature for the data shown in Figure 9a (clear conditions) was 295 K, while the mean for the data shown in Figure 9b (random, i.e. cloudy conditions) was 280 K. Note the IASI difference shifted by about 0.2K under cloudy conditions, while the AIRS response between clear and cloudy conditions changed less than 50 mK. One could argue that the observed shift in this double difference between AIRS and IASI could be due to diurnal difference in cloud emissivity, i.e. a change in the composition of the cloud top. This would have to be modeled to see if a plausible diurnal change in water/ice content has the ability to shift the bias between these two channels, which are spectrally separated by only 100 cm-1, by 0.2K.

In our analysis we averaged the results from all footprints for AIRS and IASI. In the grating array design (AIRS) there is a different detector for each spectral element, i.e. bt1231 and bt1128 are measured by two independent detectors. In the case of an FTS (IASI) four different detectors (in each of three bands) are used for the four footprints in the AMSU field of regard. By using the mean of the four footprints we are assuming that the four detectors in the two IASI bands are identical. Analysis which separates the four footprints shows little differences in the mean response for window channels, but differences of the order of 0.5 K for channels with moderately steep spectral gradients. A similar footprint related bias has also been reported by others [9] and no further details are presented here.

4. Discussion

In spite off the major difference in the implementation of IASI and AIRS, the analysis of high quality clear and cloudy AIRS and IASI spectra can either be explained as likely differences due to the difference in the diurnal cycle or show general agreement at the 0.2K level for large spatial (zonal) and temporal averages. This can be gleaned from as little as one day of data. We also note that the (obs-calc) bias at 1231 cm-1 window channels under "clear" conditions is close to -0.4K, and similar values are observed for other window channels. The word "clear" is in quotation marks. For AIRS we have shown [6] that about 0.2K of this cold bias is due to residual cloud contamination and about 0.2K is likely due to systematic under-correction for water vapor continuum absorption. Under cloudy conditions we find evidence of other differences between AIRS and IASI data of the order of 0.2 to 0.5 K, but it is not immediately obvious if this is due to the colder scene temperatures, the effects of clouds, diurnal effects or instrument artifacts. The difference in the implementation of AIRS and IASI causes a difference in the bias characteristic. Quality screening is always a critical component in handling the large volume of data created by instruments in Earth orbit. The scene dependence of the IASI QFlag creates zonal biases of the order of 0.2 K.

While 0.2K differences are insignificant compared to IASI and AIRS radiometric accuracy specifications and the primary use of the data for weather forecasting, they have important implications for climate change applications: They exceed the 100 mK absolute accuracy requirements for infrared measurements in support of climate change [1] by a factor of two. If we were to consider AIRS or IASI as prototypes of two instruments separated by decades and analyze the differences as potential climate change indicators, a 200 mK observational bias is equivalent to two decades of global warming at the rate of 100 mK/decade. A 200 mK shift in the mean cloud effect of 10 K could be misinterpreted as a 2% change in the strength of convection. The correlation between QFlag and the SAA introduces the variability of the SAA in response to the changes in the Solar activity as an additional source of a time dependent bias in the case of IASI. These effects have to be factored into error budgets and requirement specifications of future instruments designed to measure climate change.

The fact that the AIRS/IASI comparison allows a performance assessment at the 200 mK level with as little as one day of data, in spite of the fact that the two instruments are in different polar orbits, bodes well for using the same techniques discussed in this paper for the performance evaluation of the Crosstrack Infrared Sounder (CRIS) [10], using either AIRS or IASI data.

5. Conclusions

The radiometric and spectral system performance of space-borne infrared radiometers is generally specified and analyzed under strictly cloud-free, spatially uniform and warm conditions, with the assumption that the observed performance applies to the full dynamic range under clear and cloudy conditions and that random noise cancels for the evaluation of the radiometric accuracy. The validity of this assumption is sensitive to the details of the instrument design and ground-data processing. We show that for these AIRS and IASI this assumption is typically valid for global means at the 200 mK level under clear, a wide range of temperatures and cloudy conditions, in spite of large differences in the instrument implementation. The results were verified with data from July 2007 through January 2010, but they can already be gleaned from the analysis of a single day of data. Zonal biases at the 200 mK level are observed in IASI data due to data loss in areas of know strong convection in the tropical oceans and radiation hits in the SAA. Differences at

the 200 mK level are of significance for climate applications, where they could be interpreted, or in the case of artifacts misinterpreted, as evidence of climate change.

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