Validation of the Radiometric Stability of the Atmospheric Infrared Sounder

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ABSTRACT

It has been widely accepted that an infrared sounder in low polar orbit is capable of producing climate quality data, if the spectral brightness temperatures have instrumental trends of less than 10 mK/yr. Achieving measurement stability at this level is not only very demanding of the design of the instrument, it is also pushes the state of art of measuring on orbit what stability is actually achieved. We discuss this using Atmospheric Infrared Sounder (AIRS) L1B data collected between 2002 and 2011. We compare the L1B brightness temperature observed in cloud filtered night tropical ocean spectra (obs) to the brightness temperature calculated based on the known surface emissivity, temperature and water vapor profiles from the ECMWF ReAnalysis (ERA) and the growth rates of CO_2 , N_2O and Ozone. The trend in (obs-calc) is a powerful tool for the evaluation of the stability of the 2378 AIRS channels. We divided the channels into seven classes: All channels which sound in the stratosphere (at pressure levels below 150 hPa), 14 um CO_2 sounding, 4 um CO_2 P-branch sounding, 4um CO_2 R-branch sounding, water vapor sounding, shortwave surface sounding and longwave surface sounding. The peak in the weighting function at 1050 hPa separates sounding and surface channels. The boundary between shortwave and longwave is 5 µm. Except for the stratosphere sounding channels, the remaining six groups have (obs-calc) trends of less than 20 mK/yr. The longwave surface channels have trends of 2 mK/yr, significantly less than the 8 mK/yr trend seem in the shortwave window channels. Based on the design of the instrument, trends within a group of channels should be the same. While the longwave and shortwave trends are less than the canonical 10 mK/yr, the larger trend in the shortwave channels could be an artifact of using the pre-launch determined calibration coefficients. This is currently under evaluation. The trend in (obs-calc) for the non-surface sounding channels, in particular for stratosphere sounding and upper tropospheric water channels, is dominated by artifacts created in calc, most likely due to changes in the ERA Ozone and water vapor. Based on this argument the best estimate of the trend for the channels within a channel group is given by the surface sensitive channels within the group. Based on this consideration we estimated the trend of all AIRS longwave channels as 2 mK/yr, while the shortwave channels have a trend of 8 mK/yr.

Keywords: Climate, CO_2, N_2O, Calibration, hyper-spectral, infrared

1. INTRODUCTION

It has been argued that an infrared sounder in low polar orbit produces climate quality data, if trends in the spectral brightness temperatures due to instrumental artifacts are less than 10 mK/yr (Ohring et al. 2006). With this stability, and assuming a lifetime of five or more years, the accuracy and stability of the measurements can be measured globally over many seasons, and residual biases or trends can be further reduced by reprocessing the data at the end of the instrument's life. This reasoning makes a number of assumptions, which are not necessarily satisfied. We have to assume that 1) the calibration is vigorously monitored through the life of the instrument, 2) that no significant on-board data processing steps have made the calibration irreversible, and 3) that the theory and the details of the ground-based calibration software is sufficiently well documented, and that physical based corrections can be implemented in the final revision of the calibration algorithm. An accurately calibrated data set of climate quality can then be created at the end of the instrument life. Achieving stability at the 10 mK/yr level is very demanding of the design of the instrument. An excellent on-board blackbody is a necessary, but not sufficient, condition to insure a high degree of measurement stability. However, at the 10 mK/yr level changes in contamination on instrument surfaces do not necessarily cancel in the conventional two point calibration, nor do other effects, such as changes in instrument non-linearity due to prolonged exposure to space radiation. Measuring what stability is actually being achieved on orbit at the level of 10mK/yr or better is very difficult. Two techniques are promising for instruments in polar orbit: Simultaneous Nadir Overpasses (SNO) and (obs-calc). SNO (Tobin et al. 2008) uses the fact that all polar orbits cross at some point every day. At that point infrared sounders on both satellites see nearly the same scene through the same air mass, and a time record of the difference as function of frequency can be used to assess relative stability. The spatial and temporal window colocation error in principle adds noise with zero bias. For a sufficiently large number of observations the noise cancels and the bias and bias trend may be attributed to one or both instruments. The number of usable SNO pairs depends on details of the orbits, and the time and space window defining "simultaneous". The second technique makes use of (obs-calc). Here we compare observations (obs) to the value calculated (calc) based on other high quality "truth" data. If the observations are under cloud free conditions and the information used for calc has no trends, then the statistical properties of (obs-calc) will be white noise with some bias. The bias will be the combination of a potential biases in the instrument calibration, in the radiative transfer algorithm (RTA), in the cloud filter algorithm and in the truth data. Since a consistent RTA algorithm can be assumed, any trend in (obs-calc) will be a combination of a trend "obs" or a trend in the "truth" data. For (obs-calc) we use only night time tropical ocean spectra which pass a Spatial Coherence Clear test (SCT), which is based on a threshold. Each day typically 6,000 clear spectra in the night tropical oceans pass the SCT (Aumann et al. 2006). These spectra are saved in the AIRS Calibration Data Subset (ACDS). For these spectra we calculate brightness temperature (calc) based on the knowledge of the "truth", in this case the known ocean surface emissivity and the temperature and moisture profiles from the ECMWF Reanalysis (ERA) (Strow et al. 2006). We then analyze the trend in the time series of the difference between the observed (obs) and the calculated (calc) brightness temperatures. In the following we analyze the bias=(obs-calc) technique using 9 years of AIRS (Aumann et al. 2003) L1b data. The L1b calibration algorithm uses the prelaunch determined calibration coefficients.

2. RESULTS

AIRS has 2378 spectral channels. We first illustrate the (obs-calc) method using one channel, the 1231 cm^{-1} atmospheric window channel, bt1231.

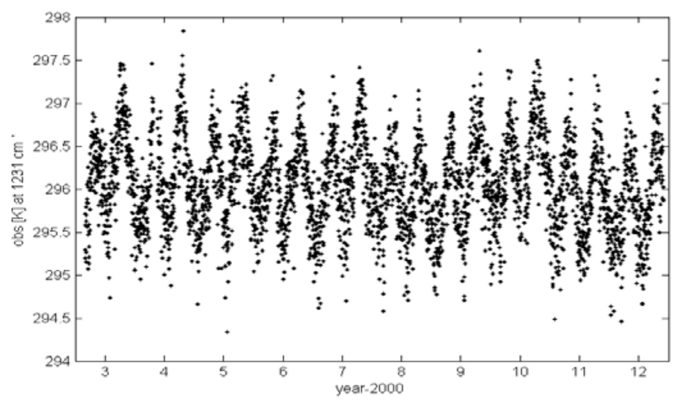

Figure 1. Time series of the "obs" bt1231.

Figure 1 shows the time series of the brightness temperature. Each dot is the daily mean calculated for typically 6000 "cloud free" night tropical ocean observations. The mean of the data is 296.05K, with a very obvious seasonal variability of 0.5K (standard deviation). The two peaks per year are due to the fact that we are using data between 30S and 30N, i.e. the Sun crosses the equator twice per year. The seasonal component can be isolated by fitting obs to a low order harmonic series. The anomaly, defined as obs minus the seasonal component, has zero mean and highlights multi-annual variability. The anomaly of obs is shown in Figure 2. The mean anomaly is zero (by definition), the standard deviation is 0.36K. The heavy trace is the anomaly smoothed with a 128 point running mean. The Least Squares Fit (LSQ) fit through the anomaly time series is anomaly trend, in the following referred to simply as "trend". The trend in obs is -22+/-3 mK/yr. This trend is dominated by the general cooling of the tropical oceans related to ElNino/LaNina events in 2008 and 2010.

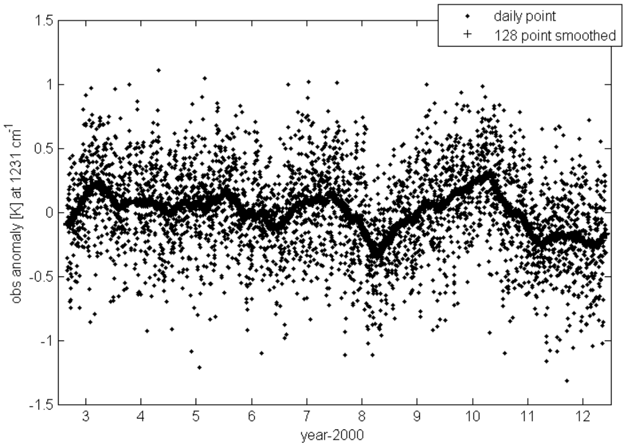

Figure 2. Anomaly of the 1231 cm^{-1} brightness temperature.

Figure 3a shows the daily (obs-calc) for the 1231 cm^{-1} channel. The heavy trace, the result of a 128 point running mean, highlights an annually varying component of (obs-calc) , unlike obs, which has two cycles per year. The mean cold bias of -0.29K is due to the combination of a fixed instrument calibration bias and a seasonally variable cold cloud leak. The value of bias is sensitive to the thresholds used in the SCT filter. As the threshold is made tighter, the bias approaches and the number of spectra identified as SCT clear approach zero (Aumann et al. 2006). Figure 3b shows the corresponding anomaly time series. The trend is +3.2±1 mK/yr. This trend could be an instrumental artifact, or it could be due to a change in the character of the clouds in the past nine years, which changes the efficiency of the way the SCT filter rejects clouds.

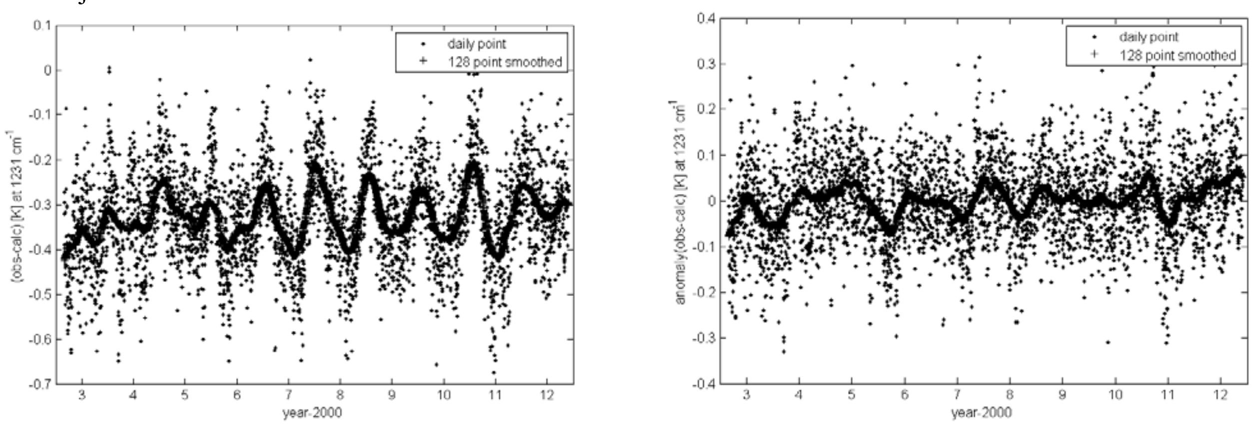

Figure 3. (obs-calc) . a) (left) the time series b) (right) the anomaly time series

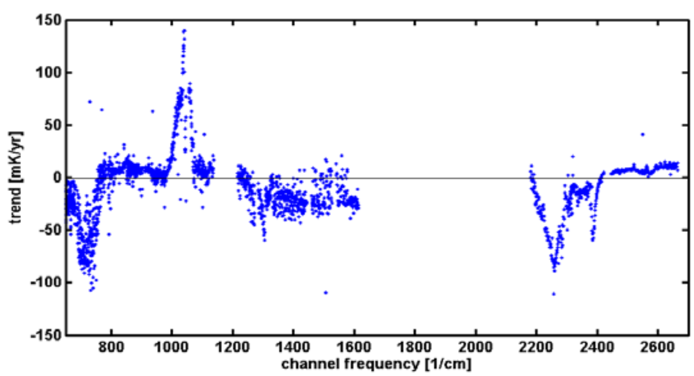

Figure 4. (obs-calc) trend as function of channel frequency, calculated for 2310 of the 2378 spectral channels.

The (obs-calc) analysis can be carried out for all AIRS spectral channels. Figure 4 shows the (obs-calc) trend as function of channel frequency, calculated for the 2310 of the 2378 spectral channels which had less than 5 K NEDT. The average NEDT is 0.2K. Of the 2310 channels, 967 have a trend of less than 10 mK/yr. Some of the outliers are channels with non-gaussian noise, i.e. the noise in a large number of observations does not average to zero. These channels are not shown on the subsequent figures. AIRS has no spectral channels between 1650 and 2150 cm^{-1}.

3. DISCUSSION

The typical surface temperature for tropical oceans is 299K. Due to surface emissivity and water vapor absorption the best atmospheric window channels measure brightness temperatures of about 295K. Of the 2310 AIRS channels shown in Figure 4 we can identify 922 "near surface and surface channel" as those channels which have tropical ocean climatology brightness temperature warmer than 290 K. These "near surface channels" are sensitive to the knowledge of the surface temperature and the total water vapor, but relatively insensitive to the temperature, water vapor and ozone profiles specified by the ERA. The remaining 1388 channels are "sounding channels". Since the surface skin temperature and water vapor over the tropical oceans are accurately known, the expected brightness temperatures for surface and near surface channels can be accurately calculated. The mean (obs-calc) trend for the "near surface" channels is +8 mK/year and standard deviation of 4.1 mK/yr , with some channels as low as -6 mK/yr , and a few as high as +30 mK/yr. Typically 6000 spectra are pass the SCT clear tropical ocean night clear test. This daily count has changed insignificantly (+0.01±0.12 %/year). The small trend in the "near surface" channels is therefore not likely due to a change in the character of the clouds which may effect the SCT. However, many sounding channels have trends as high as150 mK/yr. This requires a more detailed discussion.

The inconsistency between the trends observed in surface channels and sounding channels is inconsistent with the design of the AIRS spectrometer, where instrumental trends, if any, would be correlated for large groups of channels. Some of the large trends seen in Figure 4 are due to the change in CO_2, some may be due to small shift in the SRF. The sensitivity of the AIRS channels to CO_2 allows AIRS to make temperature profile measurements. All calculations assumed a fixed amount of CO_2, while in reality the CO_2 mixing ratio increased at the rate of about 2±0.1 ppmv per year. The CO_2 Jacobian gives the change in the observed brightness temperature as function of channel frequency due to a change in the CO_2 mixing ratio. Since we are using data from the tropical oceans, we used the tropical climatology spectrum to calculate the Jacobian. The trend correction which corrects for the changing CO_2 abundance ranges from -75±7 mK/yr for tropospheric sounding channels to +35±4 mK/yr for stratospheric sounding channels, with the uncertainty based on the uncertainty of the trend in the CO_2 abundance.

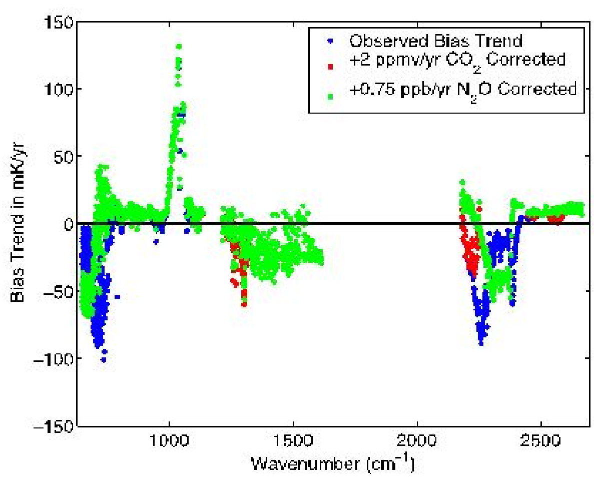

Figure 5. Overlay of the directly calculated (obs-calc) trend on the trend corrected for 2 ppmv/yr and 0.75 ppb/yr increase in CO_2 and N_2O, respectively.

Figure 5 shows an overlay of the directly calculated trend (blue), the trend corrected for 2 ppmv/yr increase in CO_2 (red) and the trend corrected for a change of +0.75 ppb/yr in N_20. The trends seen in many sounding channels are much larger than 10 mK/yr. The trends are in groups of sounding channels. This is seen in Figure 6. In Figure 6 we plot the CO_2 and SRF corrected trend as function of pressure level, pmax in units of hPa, which denotes the pressure of peak response for each channel, for a tropical climatology profile. The data are color encoded into longwave channels (f<960 cm^{-1}), water channels (1250<f<1615 cm^{-1}), CO_2 P-branch (2182<f<2340 cm^{-1}), R-branch (2340<f<2395 cm^{-1}), and shortwave window (f>2450 cm^{-1}). In Figure 6 we excluded the O_3 lines near 1100 cm^{-1} , which have more than 50 mK/yr trends (Figure 5). The sounding CO_2 channels below 200 hPa have an increasing negative trend of up to -50 mK/yr, while the lower tropospheric channels have a trend of about +10 mK/yr. The water sounding channels have trends which increase from zero to -25 mK/yr as the channel sounds closer to the tropopause. The fact that the trends are grouped by sounding species and sounding pressure level excludes an Spectral Response Function (SRF) shift as potential cause of the trend: Since the line manifolds are spectrally resolved we have sounding channels on both sides of line manifolds, i.e. uncorrected SRF effects would create a positive trend for channels on one side, while creating a negative trend on the other, but would not create a mean trend for a group of sounding channels.

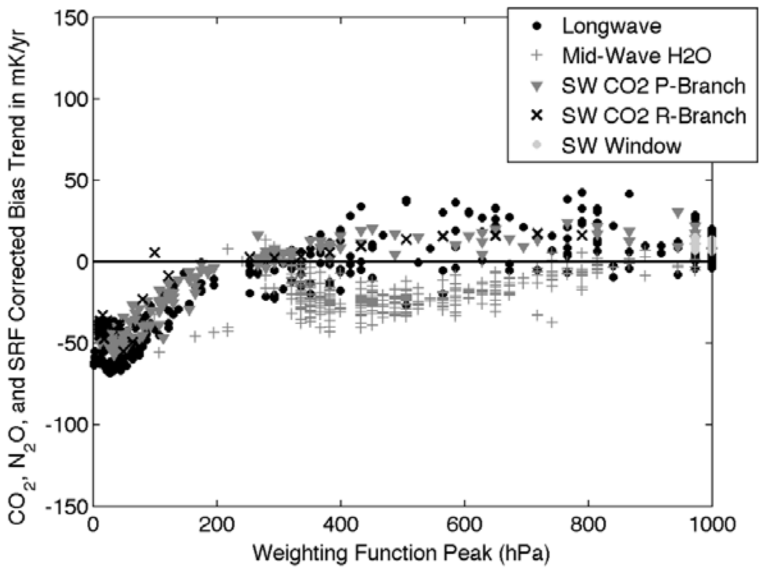

Figure 6. CO_2 , N_2O, and SRF corrected (obs-calc) trend as function of pressure level, pmax, in units of hPa. Almost all of the big outliers are due to Ozone contamination of the longwave channels.

Examination of the time dependence of the bias between the AIRS O_3 radiances and those computed from the ERA reanalysis shows that this large positive trend in the bias is due to an instantaneous jump in the ERA reanalysis O_3 time series, presumably due to inclusion of a new instrument data set into the reanalysis. The water channels show a clear bias trend in the stratosphere and in the troposphere, while both the shortwave and longwave temperature channels show a noisy positive bias of 10-20 mK/year. However, a number of longwave channels have some O_3 contamination that could cause outliers above the 20 mK/year level.

The primary advantage of the ERA is that data collected over a long time period by many instruments are processed with the latest software version. However, this does eliminate changes due to non-uniformity in the data caused by the entry of new or exit of old instruments from the data used for the analysis. These changes can cause trend artifacts, such as with Ozone as discussed above. The P-branch channels and the mid-tropospheric longwave temperature sounding channels have some sensitivity to water vapor. Rather than showing the trend in (obs-calc), Figure 7 shows, on the same vertical scale as Figure 6, the trend in the AIRS directly observed brightness temperatures (obs), corrected for the trend introduced by CO_2 , N2O, and SRF changes, as function of the pmax. The distribution is much tighter about a zero mean for the water vapor channels, suggesting that the ERA water vapor trend may be in error. This interpretation is confirmed with Figure 8. Figure 8 shows the AIRS BT obs trends, corrected for the trend introduced by CO_2 , N2O, and SRF changes, as function wavenumber on the same vertical scale as the BT (obs-calc) trend in figure 5 (green dots). There is much less scatter, particularly in the water and Ozone channels. However, the offset between the longwave window obs trend (close to zero) and the shortwave obs trend of about 12 mK/year appears to be an artifact of the AIRS L1b calibration in the shortwave.

Table 1 summarizes the “obs” and (obs-calc) trends and trend uncertainties for seven broad sounding regions: All 390 channels which sound in the stratosphere (below 150 hPa), the shortwave surface sounding channels at frequencies higher than 2400 cm^{-1}, longwave surface sounding between 780 and 1300 cm^{-1}, water vapor sounding channels, and three temperature sounding regions in the CO_2 bands. All channels where the weighting function peaks at 1050 hPa for the tropical ocean atmosphere are defined as surface channels. This definition fits 702 of the 2378 AIRS channels.

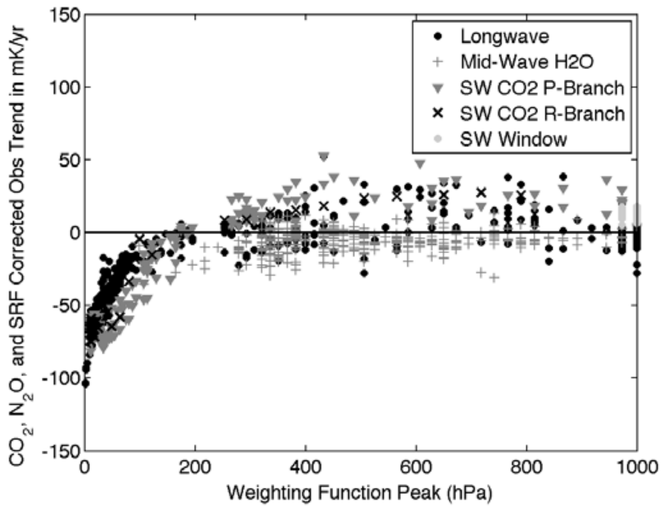

Figure 7. CO_2, N_2O and SRF corrected trend in obs as function of pressure level, pmax, in units of hPa.

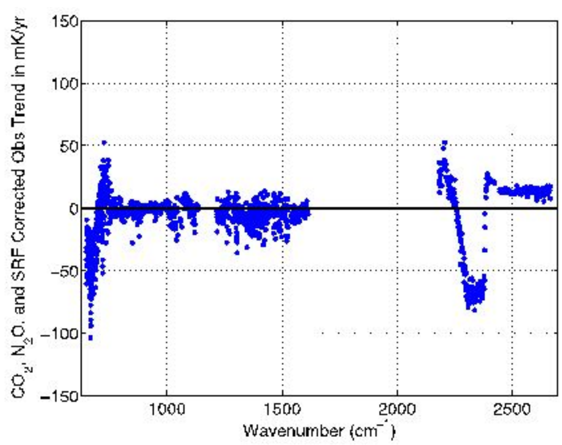

Figure 8: Same CO_2, N_2O and SRF corrected data as in Fig. 7, but plotted as a function of wavenumber.

	Number of channels	obs trend [mK/yr]	(obs-calc) trend [mK/yr]
Shortwave surface channels	221	+12.0 +/- 2.2	+7.7 +/- 2.6
Longwave surface channels	481	+8.1 +/- 5.0	+2.1 +/- 4.8
Water sounding channels	451	-20 +/- 9.1	-7.7 +/- 6.1
4 um R-branch	37	+20.5 +/- 2.9	+12.3 +/- 2.9
4 um P-branch sounding channels	73	-11.2 +/- 13.9	-18.8 +/-11.7
14 um sounding channels	605	-1.5 +/- 9.4	+4+/- 12.6
Stratospheric sounding channels	390	-38.8+/-27.3	-41.9 +/- 15.5

Table 1. Trends and trend scatter in obs and (obs-calc).

Statistically all six of the seven channels groups have trends of less than 20 mK/yr. The longwave surface channels have trends of about 2 mK/yr, significantly less than the 8 mK/yr trend seem in the shortwave window channels. The shortwave sounding channels also have a trend of the same magnitude as the shortwave window channels. While both trends are less than the canonical 10 mK/yr, the larger trend in the shortwave channels could be an artifact of using the pre-launch determined calibration coefficient in the L1B calibration algorithm. This is currently under evaluation. All stratospheric sounding channels show a significant cooling trend, virtually the same in obs as in obs-calc, but the trend uncertainty is considerable. A large fraction of this uncertainty in calc is due to changes in the Ozone and water vapor in the ERA, which affects the sounding channels, while the surface and near surface channels are much less affected. We conclude that the trend within wavelength group is given by the surface sensitive channels within the group.

It is interesting to note that the dramatic stratospheric cooling observed in the past ten years is clearly seen in the AIRS obs trend and in the ERA (obs-calc) trend. Note that for AIRS both the shortwave and longwave upper stratospheric channels give the same amount of stratospheric temperature cooling. Interpretation of the mid-tropospheric trends is not straightforward, given their small values, and the interfering effects of ozone and water vapor in many of those channels. The retrieval of the trends of the individual components (SST, temperature and water profiles, ozone) using a standard optimal estimation retrieval would give additional insight.

It has been argued that an infrared sounder in low polar orbit produces climate quality data, if the spectral brightness temperatures have instrumental trends of less than 10 mK/yr (Ohring et al. 2006). A claim of performance at this level can only be validated with the new generation of hyper-spectral infrared radiometers, like AIRS, IASI and CRIS. We shows that the direct verification of stability at this level is limited to surface (atmospheric window) channels. The availability of exceptionally transparent atmospheric window channels, which all but eliminate sensitivity to interfering species, makes the calculation of the expected brightness temperatures insensitive to external information. Comparisons of the observations from these window channel with highly accurate and stable ocean surface temperature products appears to be the most straightforward ways to estimate the long-term stability of the radiometry at the level required for climate studies. Although the ERA reanalysis products are very accurate, the absorption in non-window channels is so large that residual uncertainties due small changes in the ERA and the CO_2 and N_2O growth rates can create large trend artifacts. The stability of AIRS at the 10 mK/year level over the past ten years and the fact that the raw detector and associated calibration data (Level 0 data) were archived, will allow a further refinement of the calibration software from the currently used pre-launch software and calibration coefficients. A complete reprocessing of the data at the end of the AIRS instrument's life is planned to optimize the utility of the AIRS radiances for climate research.

There are two properties which distinguish the new generation of hyper-spectral infrared radiometers from legacy instruments, like HIRS, GOES and AVHRR, which use interference filters to define broad spectral pass-bands. One is the above mentioned availability of exceptionally transparent atmospheric window channels, the other is the fact that the SRF's of the hyper-spectral sounder resolve the atmospheric line manifolds, which allows the SRF centroid to be calibrated relative to fundamental gas absorption lines. Both properties are key to establishing the radiometric stability at the level required for climate quality.

4. SUMMARY

The (obs-calc) technique is a powerful tool for the evaluation of the stability of any infrared hyper-spectral sounder. The availability of exceptionally transparent atmospheric window channels, which all but eliminate sensitivity to interfering species, is the key. The potential of the (obs-calc) method for atmospheric sounding channels is limited by uncertainties of trends in the abundances of the absorbing species in the atmosphere and by artifacts in the ERA. Such artifacts may be created by the addition or deletion of instruments during the re-analysis period, which create artifacts in the (obs-calc) trends in the sounding channels. Such changes have much less effect on the surface and near surface channels. For AIRS the trend in the surface and near surface long wave channels is +2 mK/yr, while the shortwave surface channels have a trend of +8 mK/yr. Based on the evaluation of the trend seen in obs compared to obs-calc and instrument design considerations, we estimate the instrument related trends of all AIRS channels on the basis of the trend seen in the surface sensitive channels at similar wavelength regions.

5. ACKNOWLEDGMENT

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