What we have learnt from the AIRS experience, and prospects from NPOESS/CrIS

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1. Introduction

The Atmospheric Infrared Sounder (AIRS) measures the upwelling infrared radiance spectra of the Earth in 2378 channels between 3.7 um and 15.4 um for 95% of the globe every day with exceptional radiometric performance. The AIRS and the Advanced Microwave Sounding Unit (AMSU) were successfully launched on May 4, 2002 and placed into a low earth sun-synchronous polar orbit at an altitude of 705 km and is continuing to operate exceptionally well. The improved vertical resolving power of the AIRS (Aumann et al. 2003) has resulted in improved accuracy of temperature (1 Kelvin per 1 km layers) and moisture soundings (15% per 2 km layers) and nearly a six hour improvement in the five day forecast (LeMarshall et al., 2005). The vertical resolution of AIRS is between 1 – 2 km, in contrast to 3 – 5 km from current NOAA operational sounders. Two microwave sounders, the Advanced Microwave Sounding Unit-A (AMSU-A) and Humidity Sounder for Brazil (HSB), accompany the AIRS. The HSB is essentially the same as the NOAA AMSU-B instrument without the 89 GHz channel. AIRS/AMSU/HSB products will be used for both weather and climate applications. Unfortunately, the HSB malfunctioned near the end of 2002, but has not appreciably impacted the integrated set of products.

AIRS is much more than an improved temperature and moisture sounder. Since AIRS measures upwelling infrared radiation over a relatively large spectral domain with relatively high spectral resolution, the measurements are very sensitive to changes in critical climate forcings and feedbacks. AIRS data contain information about the distribution of ozone (O3), carbon dioxide (CO2,) carbon monoxide (CO), methane (CH4), and other relevant forcing factors such as cloud distribution, cloud opacity and aerosols. Converting these observations into information useful to study global environment will require a broad understanding of atmospheric chemistry, radiation, and dynamics processes as well as their combined effects on the climate system (Chahine et al, 2006). Fig. 1 shows the AIRS spectral coverage and gaseous absorption.

The Cross-track InfraRed Sounder (CrIS) on the future NPP and NPOESS platforms is expected to have similar performance with respect to temperature, moisture and ozone profiling, and for some trace gases. However, because the interferograms are truncated on board, the CrIS will not be able to derive accurate CO products.

Key factors in generating trace gases and climate quality products from AIRS are adequate spectral resolution and coverage, excellent signal to noise performance and long term stability. AIRS has been successful in meeting those factors. Excellent accuracy and stability were expected based on the repeatability of the AIRS pre-flight sensor calibration (Pagano et al. 2003). The radiometric accuracy and stability of AIRS radiances has been confirmed by several fundamentally different types of comparisons, including (1) the results of the daily measurements of sea surface temperature (SST), (2) direct spectral radiance comparisons from aircraft observations, and (3) low temperature surface radiances from Antarctica.

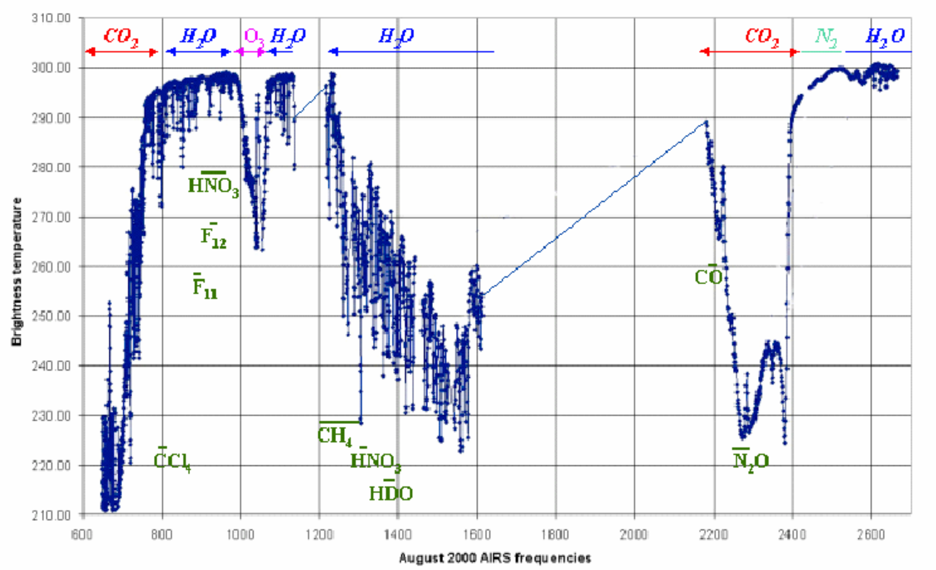

Figure 1: Measured AIRS infrared spectrum contains a wealth of information on the atmosphere including water vapor, temperature and trace gases constituents such as CO2, CO, CH4, O3 and SO2

2. Retrieval Methodology

The AIRS/AMSU retrieval process includes an AMSU initial guess, cloud clearing, an Empirical Orthogonal Functions (EOF) regression initial guess (Goldberg et al. 2003) and a physical retrieval (Susskind et al. 2003). The cloud clearing algorithm is a critical step since it increases the global percentage of clear scenes from 5% to more than 50%. The cloud clearing algorithm is described in Susskind *et al*. (2003). Cloud-clearing begins with an AMSU physical retrieval (Rosenkranz, 2001) of atmospheric temperature, moisture (liquid and vapor), microwave spectral emissivity, and skin temperature. The AMSU retrieval is used to compute an estimate of the AIRS radiances for the clear component of the scene. Cloud clearing assumes that the only difference between a set of AIRS field of views (fovs) is the amount of clouds, therefore, the clear radiance estimate can be used to retrieve a set of extrapolation parameters from a set of AIRS cloudy fovs. Scenes that fail the cloud clearing assumptions, have a poor clear state estimate, or are too cloudy are rejected. The extrapolation parameters for accepted scenes are then used to compute the cloud cleared radiances for any channel that is sensitive to clouds. Channels that are not sensitive to clouds are averaged over the 9 fovs.

The traditional use of a microwave instrument as a clear estimate for infrared cloud clearing suffers from the fact that the current microwave instruments have low information content in the lower troposphere due to the small number of channels and error in the antenna pattern side-lobe corrections. In addition, the microwave surface properties are inherently different than those at infrared wavelengths. The addition of MODIS information content can be used to create a more accurate AIRS cloud cleared radiance product. MODIS, which is also on AQUA, has 1 km spatial resolution broad-band infrared channels which can be superimposed within the AIRS fov. A weighted average of the clear MODIS data, determined by the MODIS "confident" clear mask within an AIRS fov, is used within the AIRS cloud clearing algorithm in two ways. First, the MODIS clear data is used to improve the knowledge of the infrared surface to allow cloud clearing to discriminate clouds near the surface. This is accomplished by using MODIS to specify an infrared emissivity first guess based on MODIS surface type classification and, in addition, using MODIS thermal window channels to constrain the retrieval of the surface emissivity and temperature from AIRS. Secondly, the MODIS clear thermal imager sounder channels contain additional information about the clear infrared radiance in the lower troposphere (specifically MODIS channels 27, 28, 33-36) and these can improve the clear estimate of AIRS channels used for cloud clearing. The improved knowledge of the infrared surface and the increase information content in the lower troposphere will allow for an improved cloud cleared radiance product from AIRS. This, in turn, improves all of AIRS geophysical products.

The direct use of MODIS clear observations as described above is currently under development. The results reported here are based on using MODIS to quality control AIRS. This is currently accomplished by averaging the clear-sky 1 km MODIS fovs within the AIRS 3 x 3 arrays. Then the AIRS radiances are convolved using the MODIS spectral response functions. Currently we use only MODIS channel 33. We require that the clear-sky MODIS channel 33 and the convolved cloud-cleared AIRS to MODIS channel 33 agree within 0.5 K. The results of this test are shown in Fig. 2. This figure shows the bias and rms of differences between a) cloud-cleared radiances and clear radiance simulated from the ECMWF analysis (46% of all cases), b) absolutely clear cases and ECMWF clear radiances (4% of the 46%), and c) MODIS QC AIRS cloud-cleared radiances minus ECMWF clear radiances (50% of the 46%). The results demonstrate that when MODIS is used for QC, the rms errors are virtually identical to the clear-only cases. Even though the population is reduced by half, the QC AIRS cloud-cleared radiance population is greater than clear-only by more than a factor of 20.

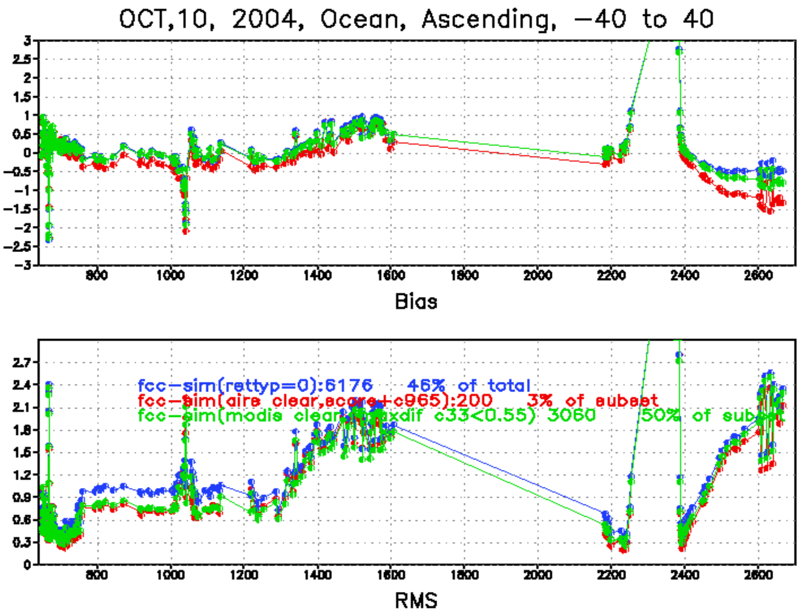

Figure 2: Bias and rms of differences between a) cloud-cleared radiances and clear radiance simulated from the ECMWF analysis (blue), b) absolutely clear cases and ECMWF clear radiances (red), and c) MODIS QC AIRS cloud-cleared radiances minus ECMWF clear radiances (green)

The retrieval accuracy of temperature and moisture has been shown to be consistently near 1 K over 1 Km layers and near 15% over 2 km layers, respectively (Chahine et al, 2006). As shown in Fig. 3, we have found further improvement in temperature accuracy when MODIS is used as quality control (QC). In Fig. 3 the comparison of the purple (without MODIS QC) and red (with MODIS QC) curves demonstrates the significant improvement of accuracy by using MODIS to quality control the AIRS cloud-cleared radiances. Note the relatively good accuracy achieved by combining MODIS and AMSU (cyan). This is the result of spatial convolving MODIS to the AIRS spatial resolution resulting in a significant reduction in the MODIS instrumental random noise due to averaging hundreds of MODIS 1 km pixels.

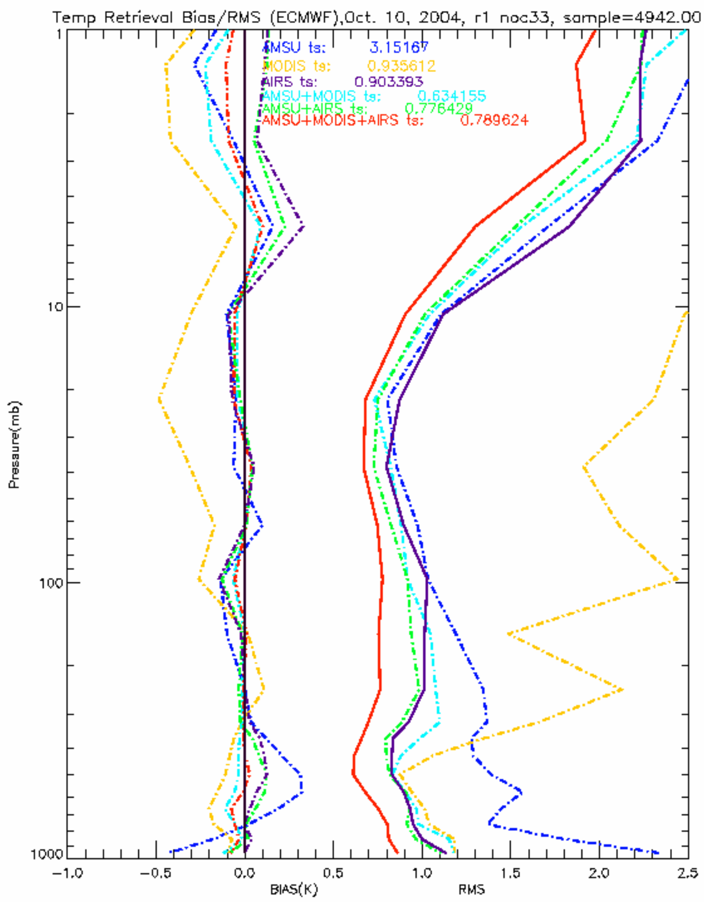

Figure 3: Temperature profile retrieval Bias and RMS compared to ECMWF analysis for MODIS only (yellow), for AMSU only (blue), for MODIS and AMSU (cyan), AIRS without MODIS Quality Control (QC) (purple), AIRS and AMSU without MODIS QC (green), AIRS and AMSU with MODIS QC (red).

3. AIRS Trace Gas Research Products

Deriving accurate trace gases requires not only high spectral resolution and excellent noise performance; it also requires accurate background state for temperature and water vapour. The core AIRS algorithm derives the background state by avoiding channels that are overly sensitive to trace gases. The trace gases are then derived by iterating the physical retrieval with the trace gas channel set. However, since temperature and CO2 are strongly coupled, both of these parameters are solved simultaneously and information about the correlation of the strength of neighboring CO2 absorptions lines is used as an additional constraint. The following describes each trace gas product (as given in Chahine et al., 2006). They are considered research products and require additional validation and development.

Carbon Dioxide: CO2 is one of the most important trace gases retrieved from AIRS spectral radiances in the 712-750 cm-1 region. The AIRS CO2 retrieval uses an analytical method based on the properties of partial derivatives for the determination of carbon dioxide and other minor gases in the troposphere from AIRS spectra. Chahine et al. (2005) applied this method to derive the mixing ratio of carbon dioxide and compared the AIRS results to aircraft flask measurements of carbon dioxide made by Matsueda et al. (2002). The results of AIRS CO2 retrieval demonstrated skill in tracking the flask measured seasonal variation with an accuracy of 0.43 ± 1.20 ppmv.

Carbon monoxide. Tropospheric carbon monoxide CO abundance is retrieved from the 2180-2230 cm-1 region of the IR spectrum. Given that CO is the direct product from the combustion of fossil fuel and biomass burning and that it has a role as a smog and tropospheric ozone precursor, fine-scale global observations of CO are crucial for modeling tropospheric chemistry and assessing the impact of biomass burning on the atmosphere. Using the AIRS 1600 km cross-track swath and cloud-clearing retrieval capabilities, the retrieved daily global CO maps cover approximately 70% of the Earth. As shown in Fig. 4, extremely high CO concentration can be seen as a result of biomass burning over central South America, Africa, and Indonesia with significant transport to the South Atlantic and Indian Oceans. Preliminary validation by McMillan et al. (2005) indicates that AIRS CO retrievals are approaching the 15% accuracy target set by pre-launch simulations.

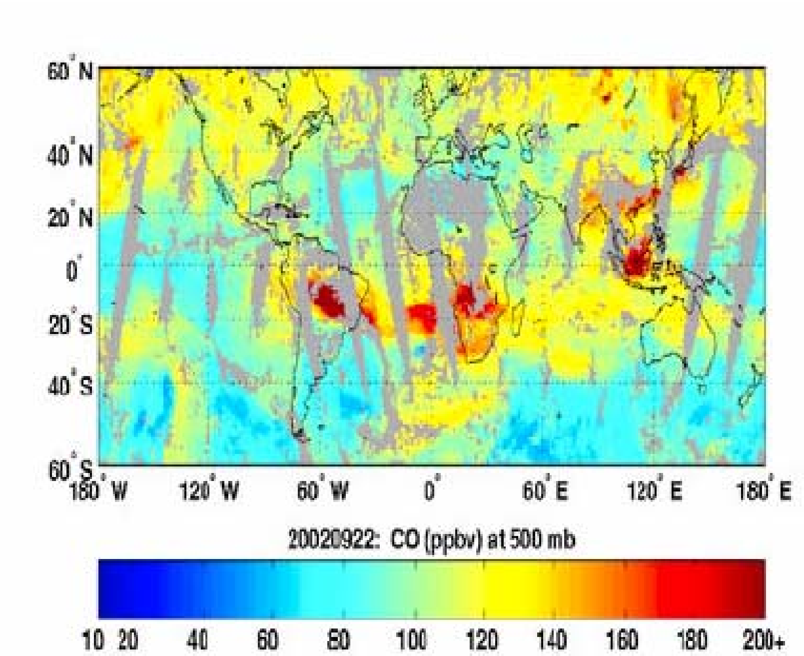

Figure 4: AIRS CO for September 29, 2002 shows biomass burning in South America, Africa and Indonesia.

Ozone: AIRS radiance data in the 9.6 µm band are used to retrieve column ozone and ozone profiles for both day and night (including the polar night). When compared with the Total Ozone Mapping Spectrometer, AIRS tends to be lower than TOMS in the tropical western Pacific, and preliminary evaluations suggest that this difference is related to interference from high, cold cirrus clouds. AIRS also tends to be higher than TOMS throughout much of the northern (summer) hemisphere. This difference may be due to interference by dust and aerosol from biomass burning, and errors in emissivity over land areas. However, it *may* be possible that AIRS legitimately yields higher column amounts than TOMS in some regions because of scattering of the TOMS signal in the lower troposphere. (See Martin et al. 2002, and references therein.) Work to quantify and validate AIRS sensitivity to tropospheric ozone is currently underway.

Aerosols: AIRS can detect the infrared signature of aerosols in the atmosphere. Silicate aerosols feature peaks in the 900-1100 cm-1 region, while both ice and aerosols show minimal absorption around at 1232 cm-1. Aerosol features currently affect the accuracy of temperature and water vapor retrievals, but it is believed that a variant of this aerosol detection algorithm can be used as a quality control measure or as a means to correct for the aerosol effects in the meteorological retrieval process.

Sulfur dioxide. AIRS spectra have been used to observe the total column of sulfur dioxide (SO2) injected into the atmosphere during a volcanic event, by a simple two-channel extraction of the SO2 signature. AIRS channels at 1258.90 cm-1 and at 1354.10 cm-1 were used in the analysis. Both channels are sensitive to water vapor, but one of the channels is also sensitive to SO2. By subtracting out the common water vapor signal in both channels, the SO2 feature remains as a clear feature in the difference image.

4. Processing AIRS Climate Products at NESDIS

The radiometric precision, accuracy and stability of AIRS instrument continue to meet climate quality requirements. Nearly every critical parameter required for monitoring climate variability and change are imbedded in the AIRS radiances. The challenge is to extract these parameters very accurately and to reprocess the entire AIRS data record when sufficient knowledge in the science methodology has been achieved. At NOAA/NESDIS we have developed a thinned AIRS radiance dataset which is approximately 1/35 the size of the original. This dataset is a 3 x 3 degree latitude/longitude gridded field, where each gridbox contains the nearest centroid 3x3 array of AIRS fovs and the corresponding AMSU. There are two gridded files each day, one for the ascending orbits and the other for descending. This thinned dataset is used to periodically test new algorithms by reprocessing the entire record. This approach is very economical since computer processing requirements are reduced by a factor of 35. Recommendations to reprocess the full resolution will not be made until confidence and community consensus is obtained. Fig. 5 shows for July 2004, a 4 panel figure of monthly mean CO2 (upper left), and following clockwise, CO, CH4 and O3. Note the large CO concentration from the well publicized Alaskan fires.

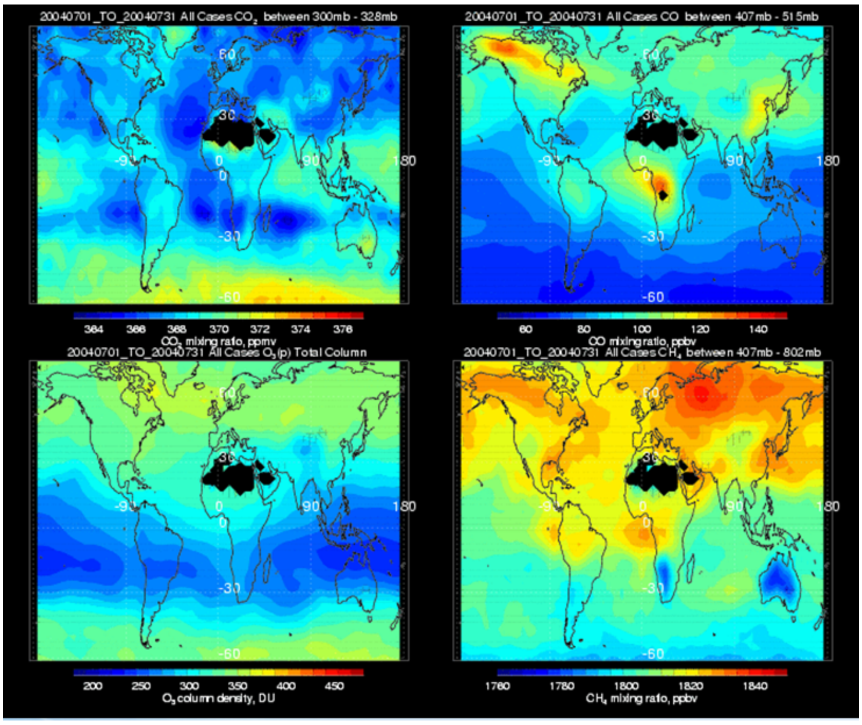

Figure 5: AIRS derived July 2004 monthly mean CO2 (upper left), CO (upper right), CH4 (lower right) and Ozone (lower left)

4.1. Radiance Climatology

Radiance climatology is important for monitoring climate change and for validation of the climate and weather models. The model can be validated by comparing AIRS radiances simulated from the model with the observed radiances. Since AIRS is a cross-track scanning sensor, the radiances from the different view angles will be limb adjusted to a fixed angle (e.g. nadir). The basis of limb adjustment is that the brightness temperature for a given channel near nadir has a weighting function that is similar to the weighting function of a nearby channel at a different view angle (Goldberg et al. 2000). Limb adjustment provides the optimal combination of channels to yield a channel radiance that appears to be independent of scan position and only dependent on airmass. Fig. 6 shows a comparison of the original and limb-adjusted brightness temperatures for AMSU channel 5 on AQUA. Only the limb-adjusted data can be averaged to derive a radiance climatology.

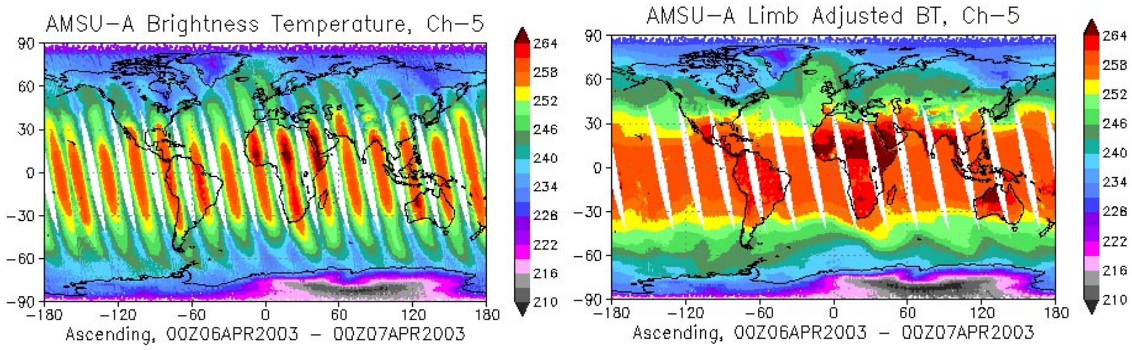

Figure 6: Observed and limb adjusted brightness temperatures for AMSU channel 5

The AIRS limb adjustment methodology is based on the AMSU approach with the exception that the limb adjustment is performed by principal component analysis. Specifically we limb adjust the first 200 principal component scores and then reconstruct the limb adjusted radiances from the limb adjusted principal component score. The predictors for limb adjusting a given principal component score for an off-nadir position to a nadir value is the given principal component score plus the first four principal component scores. Linear regression is used to generate the predictor coefficients. The left panel of Fig. 7 shows an image of the original AIRS radiances and the limb adjusted radiances for an ozone channel. Note the limb effect in the lower image. On the right panel of Fig. 7, we show the monthly averaged field. Again the lower image is the original data without any limb adjustment. Note the signal is not nearly as intense as the upper image, because we did not account for the limb effect.

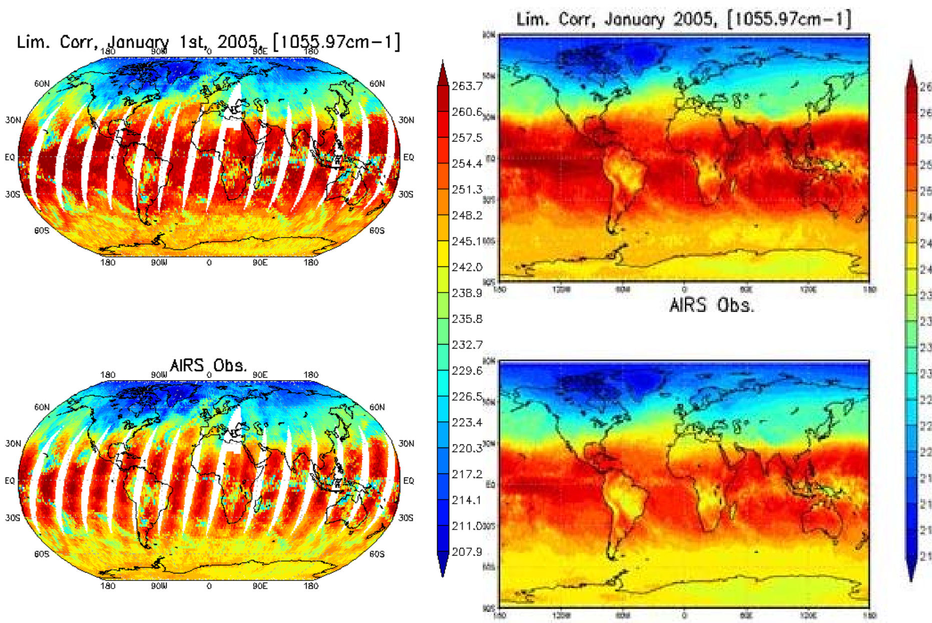

Figure 7: Limb corrected (upper left) and original observed (lower left) AIRS radiance; monthly averaged limb corrected (upper right) and original (lower right) AIRS radiance.

As mentioned previously, a very powerful application of the radiance climatology is to compare model analyses simulated radiances with observed. Fig. 8 shows the differences for an upper tropospheric water vapor channel of observed AIRS minus simulated ECWMF brightness temperature for September 2003, 2004 and 2005. Fig. 9 shows the comparable figure using the NCEP analysis. ECMWF and NCEP started to use assimilate AIRS radiances operationally in October 2003, and May 2005, respectively. Fig. 8 shows

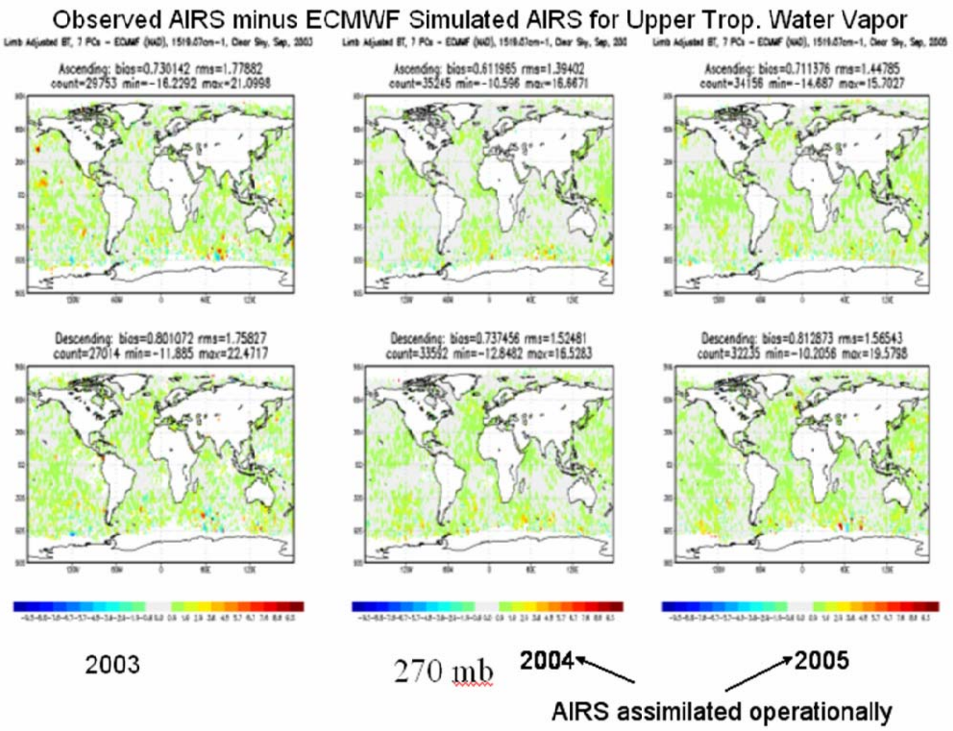

Figure 8: AIRS Observed minus ECMWF Simulated for 1519 cm-1 water vapor channel

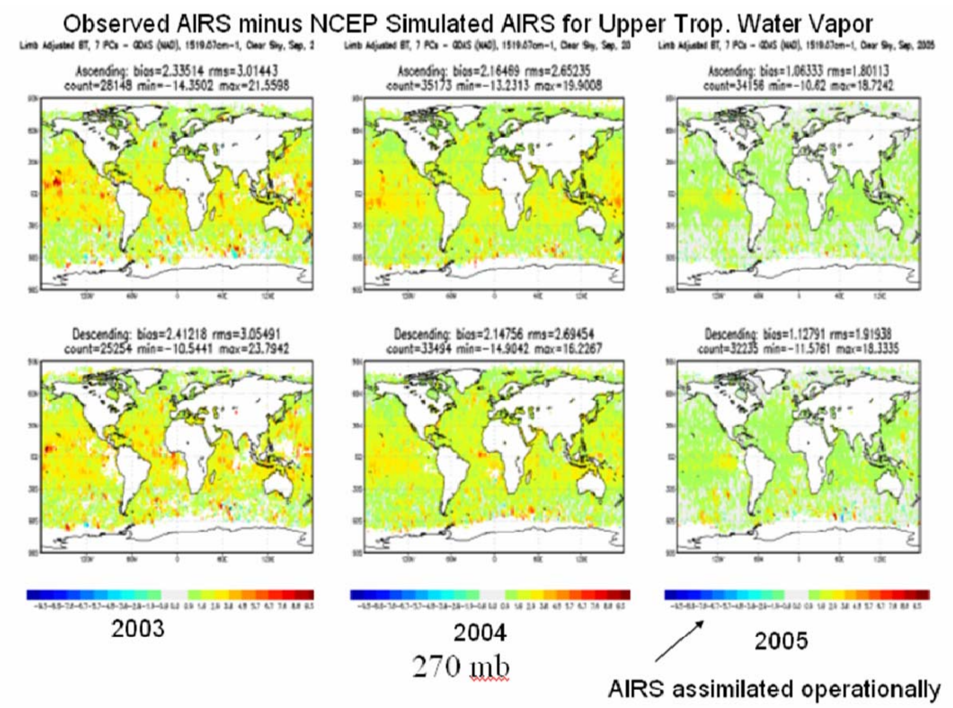

Figure 9: AIRS Observed minus NCEP Simulated for 1519 cm-1 water vapor channel

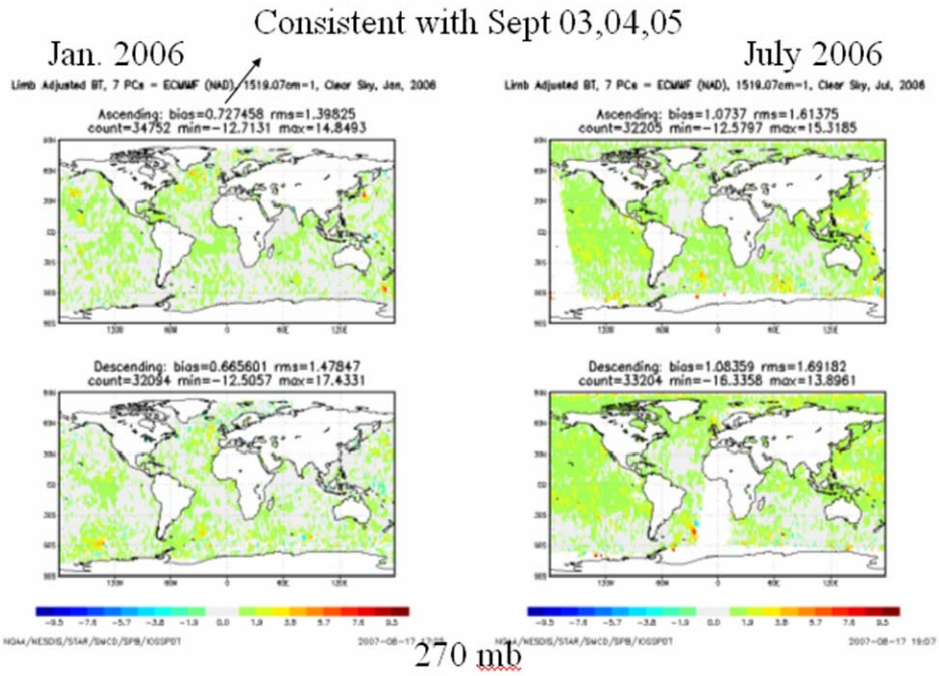

Figure 10: AIRS Observed minus ECMWF Simulated for 1519 cm-1 water vapor channel after ECMWF operational upgrade.

relatively smaller biases for all three periods, demonstrating that ECMWF analysis water vapor fields were relatively accurate even before AIRS was assimilated. Note that the absence of locally large deviations after 2003. In Fig. 9, after AIRS was used operationally by NCEP, there was a very large reduction in the bias (September 2005). Although, the ECWMF bias is still much lower. However after an operational upgrade of the ECMWF data assimilation system in 2006, the bias increased and is now comparable to NCEP (Fig. 10). Hence, the use of AIRS radiances to validate model analyses is quite important because of its sensitivity to detect changes in both model physics and data assimilation procedures.

Summary

The AIRS is unique because the instrument meets both weather and climate requirements. The original requirements for AIRS were focused on very accurate temperature and moisture profiles with accuracies approaching those of radiosondes (when compared at normalized resolutions). The spectral coverage and resolution, radiometric precision and stability of AIRS will allow the derivation of key climate forcing greenhouse gases, the validation of climate and weather model analyses (and reanalyses),and can be used as a benchmark measurement to intercalibrate other sensors. NOAA will derive IASI and CrIS product using the methodology developed for AIRS, with periodic reprocessing when algorithm improvements are realized. This will result in consistent products for weather and long-term climate applications.

References

Chahine M, T. Pagano, H. Aumann, R.Atlas, C. Barnet, J. Blaisdell, L. Chen, M. Divakarla E. Fetzer, M. Goldberg, C. Gautier, S. Granger, S. Hannon, F. Irion, R. Kakar, E. Kalnay, B. Lambrigtsen, S-Y.Lee, J.Le Marshall, W.McMillan, L. McMillin, E. Olsen, H. Revercomb, P. Rosenkranz, W. Smith, D. Staelin, L. Strow, J. Susskind, D. Tobin, W.Wolf and L. Zhou, 2006: The Atmospheric Infrared Sounder (AIRS): Improving Weather Forecasting And Providing New Data On Greenhouse Gases, *Bulletin of American Meteor. Soc (BAMS) In Press*

Chahine, M., C. Barnet, E.T. Olsen, L. Chen, and E. Maddy, 2005: On the Determination of Atmospheric Minor gases by the Method of Vanishing Partial Derivatives with application to CO2, *Geophys. Res Lett.*, **32,** L22803, doi:10.1029/2005Gl024165

Goldberg, M.D., Y. Qu, L.M. McMillin, W. Wolf, L. Zhou, and M. Divakarla, 2003: AIRS near-real-time products and algorithms in support of operational numerical weather prediction, *IEEE Trans. Geosci. Remote Sensing*, Vol. **41**, pp 379-389, Feb. 2003

Goldberg, M.D., D.S. Crosby, and L.Zhou, 2001: The limb adjustment of AMSU-A observations: methodology and validation, Journal Appl. Meteor, 40, 70-83.

LeMarshall J., J. Jung, S. Lord, J. Derber, R.Treadon, J.Joiner, M. Goldberg, W.Wolf, and H.C. Liu, 2005, Impact of Atmospheric Infrared Sounder Observations on Weather Forecasts, 2005, EOS Transactions, Vol 86, No. 11, Page 109;115.

Martin, R. V., D. J. Jacob, J. A. Logan, I. Bey, R. M. Yantosca, A. C. Staudt, Q. Li, A.M. Fiore, B. N. Duncan, H. Liu, P. Ginoux, and V. Thouret, 2002: Interpretation of TOMS Observations of Tropical Tropospheric Ozone with a Global Model and in situ Observations, *J. Geophys. Res*.,**107** (D18), 4351, doi:10.1029/2001JD001480.

Matsueda, H., H.Y. Inoue, and M. Ishii, 2002: Aircraft observation of carbon dioxide at 8–13 km altitude over the western Pacific from 1993 to 1999, Tellus B, 54, no. 1, 1-21(21).

McMillan, W. W., C. Barnet, L. Strow, M. T. Chahine, M. L. McCourt, J. X. Warner, P.C. Novelli, S. Korontzi, E. S. Maddy, and S. Datta 2005: Daily global maps of carbon monoxide from NASA's Atmospheric Infrared Sounder, *Geophys. Res Let*, **23**, L11801,doi:10.1029/2004GL021821.

McPeters, R. D., P. K. Bhartia, A. J. Krueger, J. R. Herman, C. G. Wellemeyer, C. J. Seftor, G. Jaross, O. Torres, L. Moy, G. Labow, W. Byerly, S. L. Taylor, T. Swissler, R.P. Cebula, 1998: Earth Probe Total Ozone Mapping Spectrometer (TOMS) Data Products User's Guide, *NASA Reference Publication 206895*, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland.

Pagano, Thomas S., Hartmut H. Aumann, Denise Hagan, and Kenneth Overoye, 2003: Pre-Launch and In-flight Radiometric Calibration of the Atmospheric Infrared Sounder (AIRS), *IEEE Trans.Geosci. Remote Sensing*, **41**, 266-273.

Rosenkranz, P.W 2001. Retrieval of temperature and moisture profiles from AMSU-A and AMSU-B measurements. *IEEE Trans. Geosci. Remote Sensing*. Vol. **39**, pp. 2429-2435.

Susskind, J, C. Barnet and J. Blaisdell, Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data under cloudy conditions, *IEEE Trans. Geosci. Remote Sensing*, Vol. **41**, pp 390-410, Feb. 2003

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