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SEVEN YEARS OF OBSERVATIONS OF MID-TROPOSPHERIC CO_2 FROM THE ATMOSPHERIC INFRARED SOUNDER

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The Atmospheric Infrared Sounder (AIRS) on the EOS Aqua Spacecraft was launched on May 4, 2002. AIRS acquires hyperspectral infrared radiances in the 3.7-15.4 um spectral region with spectral resolution of better than 1200. The AIRS was designed to measure temperature and water vapor profiles and cloud properties for improvement in weather forecast and improved parameterization of climate processes. Currently the AIRS Level 1B Radiance Products are assimilated by NWP centers and have shown considerable forecast improvement. Scientists have also demonstrated accurate retrievals of minor gases from AIRS including Carbon Monoxide, Methane, and Ozone. The excellent sensitivity and stability of the AIRS instrument has recently allowed the AIRS team to successfully retrieve Carbon Dioxide (CO_2) concentrations in the mid-troposphere (8-10 km) with a horizontal resolution of 100 km and accuracy of 1-2 ppm. The AIRS retrieves over 15,000 measurements per day and can achieve full global coverage in 30 days. The AIRS CO_2 accuracy has been validated against a variety of aircraft measurements in the mid-troposphere and upward looking interferometers. Findings from the AIRS data include higher than expected variability in the mid-troposphere, the presence of a belt of CO_2 in the southern hemisphere, and numerous observations of atmospheric circulation including the effects of El Nino/La Nina on the CO_2 concentrations in the mid-troposphere. The full mid-tropospheric AIRS CO_2 data set is now available at the NASA GES/DISC for almost eight years since AIRS has been operational.

I. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS), shown in Figure 1, is a hyperspectral infrared instrument on the EOS Aqua Spacecraft, launched on May 4, 2002. AIRS has 2378 infrared channels ranging from 3.7 µm to 15.4 µm and a 13.5 km footprint at nadir. The AIRS is a "facility" instrument developed by NASA as an experimental demonstration of advanced technology for remote sensing and the benefits of high resolution infrared spectra to science investigations . AIRS, in conjunction with the Advanced Microwave Sounding Unit (AMSU), produces temperature profiles with 1K/km accuracy on a global scale, as well as water vapor profiles and trace gas amounts for CO_2, CO, SO_2, O_3 and CH_4. AIRS data are used for weather forecasting, climate process studies and validating climate models.

The AIRS products are divided into three types. Level 1B products are calibrated and geolocated upwelling radiances from the four major subsystems on the AIRS/AMSU system. There are 2378 infrared AIRS spectral channel radiances, 4 Vis/NIR AIRS spectral channel radiances, and 15 microwave channels from the AMSU. The second type of data are the Level 2 products. Level 2 products are geolocated cloud-cleared radiances and geophysical quantities, usually offered on the scale of the AMSU footprint which is approximately 45 km at nadir. This is due to the cloud clearing methodology involving a 3x3 matrix of raw AIRS footprints and one AMSU footprint. The third

Figure 1. The Atmospheric Infrared Sounder Instrument at BAE Systems in Lexington Ma.

type of data products are Level 3 products. Level 3 products are gridded spatially (1 degree latitude and longitude bins) and temporally (1 day, 8 day and monthly) and usually contain all standard Level 2 products. There are a number of research products from AIRS including CH4, Dust, and HNO3, and SO2. Recently Outgoing Longwave Radiation (OLR), CO and CO_2 were added to the core products due to their maturity and value to the scientific community. CO_2 data are post processed and resident in a separate file. All AIRS products are available at the Goddard Earth Sciences Data and Information Services Center (GES/DISC) at http://disc.sci.gsfc.nasa.gov. In addition to data products, data readers, user guides and verification/validation reports are also available at this location. Additional information on the AIRS Project and science applications can be found at the AIRS home page http://airs.jpl.nasa.gov.

II. CO_2 PRODUCT DEVELOPMENT

Originally designed for temperature and water vapor profiles, the high information content in the AIRS spectra enabled scientists to extract other trace gas species. Extraction of carbon dioxide is problematic in that the carbon dioxide concentration in the atmosphere is high compared to variability which is only a few percent. To complicate matters, the carbon dioxide absorption features at 4.3 and 15 µm are used in the retrieval of temperature; however sufficient channels remain in the 2378 channels available that can be used for CO_2 retrieval.

Several research scientists have demonstrated the ability to retrieve CO_2 concentrations using AIRS data. Crevoiseir et. al. used a non-linear regression inference method to retrieve CO_2 in the mid troposphere in the tropics (20S-20N) on a 15 x 15 degree horizontal grid with a precision of 2.5 ppm[1]. In a more recent effort, researchers at ECMWF use assimilate AIRS radiances into a 4D VAR radiance assimilation system to constrain the CO_2 mixing ratios[2]. In this latter study, a 50% reduction in CO_2 differences between model and aircraft measurements is achieved. AIRS CO_2 retrievals were also successfully demonstrated at NOAA using a regularized nonlinear least squares solution to minimize the observed radiances and that calculated for the AIRS Rapid Transmittance Algorithm (RTA)[3]. Comparisons with NOAA ESRL/GMD flask measurements using this method over a 2 week average and 200 km radius demonstrate the ability to measure large scale changes in atmospheric CO_2 concentrations of 2 ppmv. Researchers at UMBC derived low to mid-tropospheric CO_2 in clear ocean regions between ±60° by minimizing the computed radiances and the observed radiances by scaling the CO_2 concentrations[4]. To mitigate complications with temperature sensitivity, the ECMWF temperatures are used. Accuracies in the 0.5-1.0 ppm are achieved when compared to aircraft. While all of these methods have been extraordinarily successful, the AIRS project has selected a new retrieval methodology that provides the highest accuracy, yield, and coverage under all cloud conditions.

The CO_2 retrieval method selected for routine production by the AIRS Project is called the method of Vanishing Partial Derivatives (VPD)[5]. The VPD method, which employs the least squares minimization method developed by Carl Friedrich Gauss in 1795, minimizes the difference between the observed cloud cleared radiances and calculated radiances for AIRS where the calculated radiances employ the AIRS RTA. The VPD method applies the minimization independently and sequentially to all geophysical parameters that impact the radiance of a given channel used to retrieve CO_2, i.e. Temperature, Water Vapor, Ozone, and Carbon Monoxide. The retrieval starts with the cloud cleared radiances for CO_2 channels with peak weighting functions in the mid-troposphere (See Figure 2). Channels also exist that have sensitivity to the stratosphere and near surface that will be used for retrievals in these regions at a later time. The retrieval also requires Temperature, Water Vapor, and Ozone from the AIRS standard product (45 x 45 km). Each of these is optimized prior to optimization of the CO_2 and the process is iterated until all the parameters are minimized. Extensive quality control is applied to the retrieval including constraints on the minimization, and uniformity of a 2x2 set of retrievals (clusters) within a specified criterion (i.e. 2 ppm). The resulting product achieves a yield over 15,000 mid-tropospheric CO_2 retrievals per day (see Figure 3), each with a horizontal footprint of 100x100 km and an accuracy of 1-2 ppm.

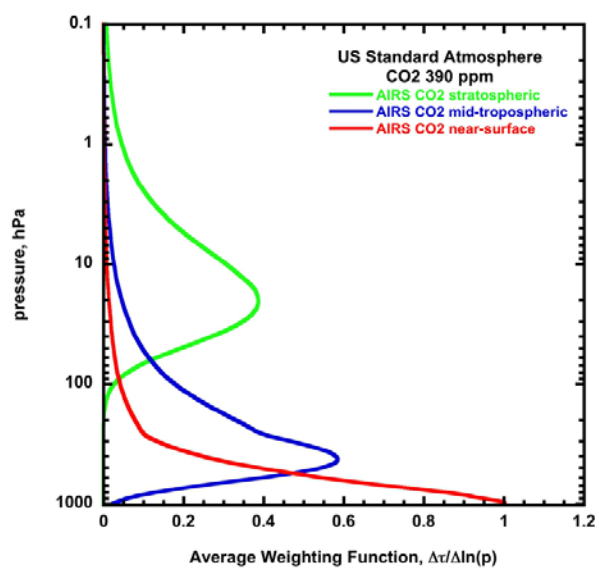

Figure 2. Un-normalized weighting functions for channels used in AIRS CO2 retrievals

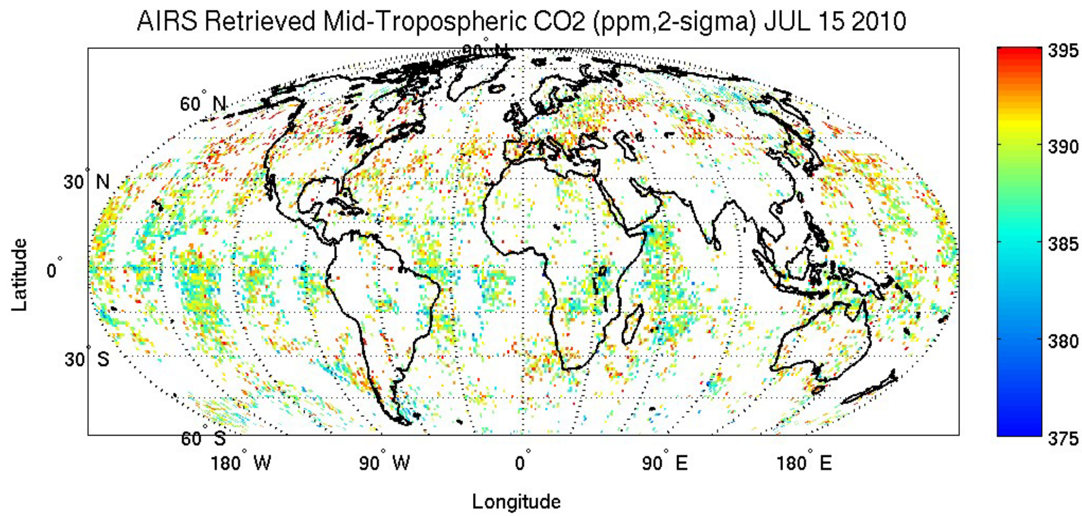

Figure 3. AIRS yields about 15,000 Mid-Tropospheric CO2 measurements per day.

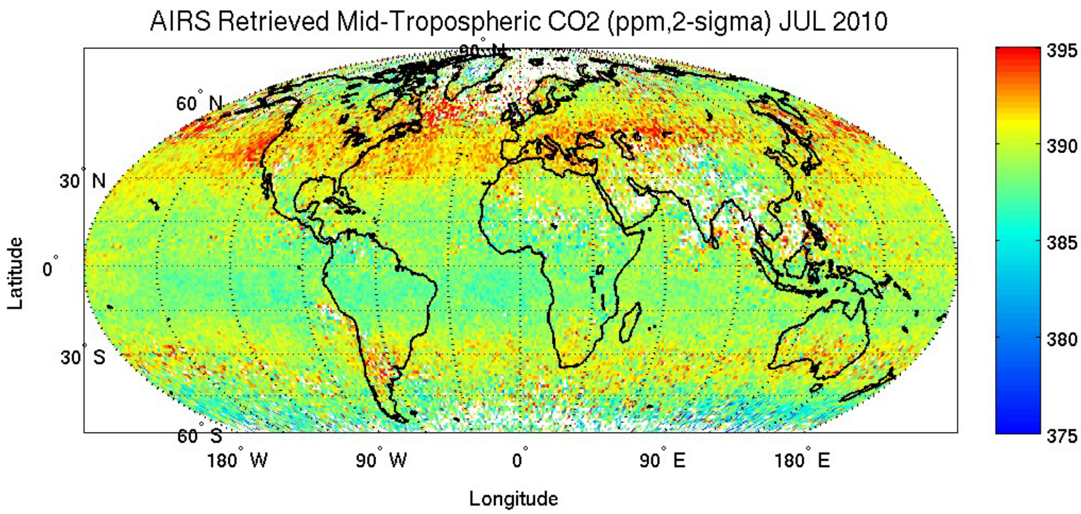

Figure 4. AIRS Mid-Tropospheric CO_2 is a tracer for atmospheric motion particularly in the vertical direction. July, 2010 Monthly average.

III. PRODUCT VALIDATION

AIRS VPD CO_2 retrievals were compared to aircraft measurements made in the mid-troposphere by Matsueda, taken over the Pacific Ocean at ~10 km altitude between Australia and Japan from Sept. 2002 to March 2004[5]. Of the 402 available flask measurements, 223 are co-located with AIRS data within a radius of 150 km and ±4 hours. Subsequently, we exclude from consideration any of the 223 clusters that contain less than three AIRS retrievals and reject all AIRS retrievals that do not seek a minimum during the iteration process. As a result, the 223 clusters and collocated Matsueda measurements are reduced to 103 containing 927 AIRS Retrievals. The comparison results in a bias difference of 1.2 ppmv and a standard deviation of 3.1 ppmv. With the addition of QC on the uniformity of the clusters, the result improves slightly to a bias of 1.0 ppmv, and standard deviation of 3.0 ppmv. Of most interest to note is that the distribution of the difference between the Matsueda aircraft observations and the AIRS CO_2 measurements is highly Gaussian. This implies that monthly averages (see Figure 4) have lower standard deviation. In fact, comparison with 14 months of Matsueda data and AIRS data yielded a mean bias of 0.43 ppmv and a standard deviation of 1.2 ppmv. Additional validation data now exists for other aircraft comparisons that will be presented in a subsequent paper by the authors.

Comparisons have also been made between the AIRS VPD CO_2 retrievals and ground based measurements using an upward looking Fourier

Transform Infrared Radiometer (FTIR) at Park Falls Wisconsin between July 2004 and March 2006[6]. Comparisons are made on monthly average CO_2 retrievals from both sets of data over a 19 month time span. Both data sets agree extremely well with differences as expected. In the winter months, the AIRS and FTIR data agree to better than 2 ppm. However in the summer months the FTIR data show much lower CO_2 concentrations than observed by AIRS ranging from 0 to 7 ppm. The difference is explainable since the FTIR measures the total column whereas the AIRS measures only the mid-troposphere. The increased sensitivity to the near surface of the FTIR means the FTIR measurements are more sensitive to the drawdown of CO_2 from the biomass. The levels observed in the difference meet expectations for CO_2 uptake from the surface.

IV. SCIENCE FINDINGS

Carbon dioxide turns out to be an excellent tracer gas since it does not react with other gases in the atmosphere. We are finding that the AIRS Mid-tropospheric CO_2 is a good indicator of vertical motion in the atmosphere. We know the majority of atmospheric CO_2 is produced and absorbed near the surface and as you go higher in the atmosphere, the age of air gets older. With an annual increase in global CO_2 concentrations of 2ppm/year primarily from anthropogenic emissions, as you go higher in the atmosphere you would expect to see lower concentrations. Since the AIRS Mid-tropospheric CO_2 sees only the mid-troposphere, when we see elevated levels of CO_2 it is most likely caused by airflow into the mid-troposphere from the lower troposphere.

The most obvious finding from the AIRS retrievals is that the distribution of CO_2 is not uniform as indicated in the models[6]. Strong Latitudinal and Longitudinal gradients exist particularly over the large land masses in the Northern Hemisphere. This phenomenon is referred to in the referenced publication as “CO_2 weather”. The large variability in atmospheric circulation due to convection and global and mesoscale transport is responsible for most of the variability seen in the AIRS data. This implies that the AIRS CO_2 data will be extremely useful for validating global scale transport in Global Circulation Models. A second finding in the same paper identifies the stratospheric-tropospheric exchange of air at high latitudes (North of 60° latitude). Comparison of AIRS CO_2 with AIRS O3 shows an anti-correlation expected during a sudden stratospheric warming event. Finally, the AIRS CO_2 data show a prominent belt of elevated CO_2 in the southern hemisphere (Figure 5). This belt was previously undetected in the models and is not well understood at this time.

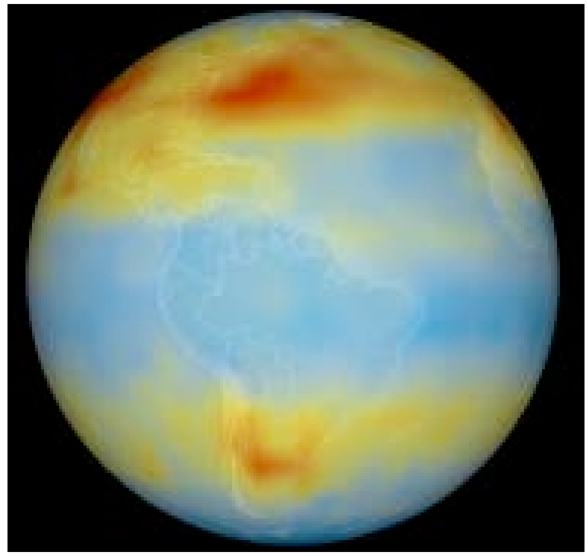

Figure 5. AIRS reveals a belt of increased mid-trop CO2 in the southern hemisphere. (July 2003).

A recent study used AIRS data to observe the response of the atmosphere during the El Nino Southern Oscillation[7]. In this study, the AIRS data are de-trended to remove the 2ppm/year increase and the average horizontal distributions plotted for 11 El Nino months and 17 La Nina months. During El Nino, the CO_2 concentrations over the Central Pacific region is enhanced while it is reduced over the Western Pacific. The same paper also identifies that CO_2 concentrations in the polar regions are diminished if the polar vortex is strong. The AIRS CO_2 is a good tracer for atmospheric transport.

All data from the AIRS mission have now been processed for CO_2 retrievals. A contiguous almost 8 year record now exists for AIRS starting in September 2002 to the present. Figure 6 shows a Hövmoller diagram of the monthly and zonal average CO_2 concentrations for the entire mission. This figure was created by averaging the monthly data sets (Figure 4) into 5 degree latitude bins for all longitudes. The data contain 90 months from September 2002 to February 2010. We see several expected and unexpected features in the data set. First we see the annual increase of 2 ppm/year in the data. A linear fit to the global averages for all months and years yields approximately 2.07 ppm/year from the AIRS CO_2 data. Secondly, we see the seasonal cycle caused by the uptake in of CO_2 primarily in the northern hemisphere. A third observation is the presence of the belt in the southern hemisphere below 20°S. Closer inspection of the Hövmoller diagram has lead the authors to believe there is a flow of CO_2 from the Northern Hemisphere to the Southern Hemisphere with a time scale from 6-8 months. If this latter assumption were true, the presence of the belt may actually be just normal transport and the mystery is related to the lower levels of CO_2 between 0° and -20°. Additional modeling and validation is required to answer these questions.

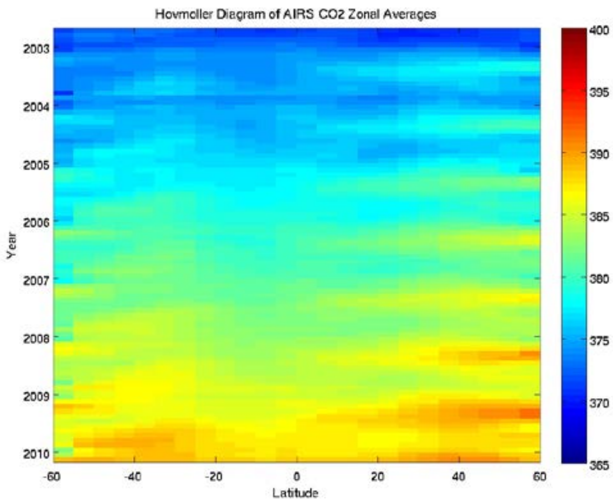

Figure 6. Hovmöller Diagram of AIRS Mid-Tropospheric CO_2 shows seasonal cycle and annual trend. In this figure we can also see the flow of CO_2 from the Northern Hemisphere to the Southern

V. SUMMARY AND CONCLUSIONS

Originally designed to retrieve temperature and water vapor profiles for weather forecast improvement, the Atmospheric Infrared Sounder has become an invaluable tool for measurement if Mid-Tropospheric Carbon Dioxide concentrations. Several researchers have demonstrated the ability to retrieve Mid-Tropospheric CO_2 from AIRS. The retrieval method selected for processing and distribution is called the method of Vanishing Partial Derivatives and results in over 15,000 CO_2 retrievals per day with global coverage and better than 2ppm accuracy. AIRS CO_2 retrievals have been validated using aircraft flask measurements and upward looking FTIR. Mid-tropospheric CO_2 concentrations are an indicator for atmospheric transport and several interesting findings have resulted from analysis of the data. First is the non-uniformity of CO_2, primarily caused by weather. Second is the ability to identify stratospheric-tropospheric exchange during a sudden stratospheric warming event. Third is the presence of a belt in the Southern Hemisphere. Many more findings have been made with the AIRS Mid-tropospheric CO_2 data and should be published in the near future. All data from the mission have been processed to date (almost 8 years) and are available at the GES/DISC.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

[1] Crevoisier C., S. Heilliette, A. Chedin, S. Serrar, R. Armante, N. A. Scott (2004), Midtropospheric CO 2 concentration retrieval from AIRS observations in the tropics, Geophys. Res. Lett., 31, L17106, doi:10.1029/2004GL020141

[2] Engelen, R. J., S. Serrar, and F. Chevallier (2009), Four-dimensional data assimilation of atmospheric CO2 using AIRS observations, J. Geophys. Res., 114, D03303, doi:10.1029/2008JD010739

[3] Maddy, E. S., C. D. Barnet, M. Goldberg, C. Sweeney, and X. Liu (2008), CO2 retrievals from the Atmospheric InfraredSounder: Methodology and validation, J. Geophys. Res., 113, D11301, doi:10.1029/2007JD009402

[4] Strow, L. L., and S. E. Hannon (2008), A 4-year zonal climatology of lower tropospheric CO2 derived from ocean-only Atmospheric Infrared Sounder observations, J. Geophys. Res., 113, D18302, doi:10.1029/2007JD009713

[5] 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

[6] Chahine, M. T., L. Chen, P. Dimotakis, X. Jiang, Q. Li, E. T. Olsen, T. Pagano, J. Randerson, and Y. L. Yung (2008), Satellite remote sounding of mid-tropospheric CO2, Geophys. Res. Lett., 35, L17807, doi:10.1029/2008GL035022

[7] Jiang, X., M. T. Chahine, E. T. Olsen, L. L. Chen, and Y. L. Yung (2010), Interannual variability of mid-tropospheric CO2 from Atmospheric Infrared Sounder, Geophys. Res. Lett., 37, L13801, doi:10.1029/2010GL042823