Retrieval of mid-tropospheric CO2 directly from AIRS measurements

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ABSTRACT

We apply the method of Vanishing Partial Derivatives (VPD) to AIRS spectra to retrieve daily the global distribution of CO_2 at a nadir geospatial resolution of 90 km x 90 km without requiring a first-guess input beyond the global average. Our retrievals utilize the 15 μm band radiances, a complex spectral region. This method may be of value in other applications, in which spectral signatures of multiple species are not well isolated spectrally from one another.

Keywords: remote sounding, carbon dioxide, free troposphere, vanishing partial derivatives, infrared spectrum

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) is a 2,378 channel hyperspectral grating spectrometer spanning 3.74 μm to 15.4 μm with a nominal spectral resolution $\lambda/\Delta\lambda = 1200$. It was launched on the Aqua spacecraft on May 4, 2002 in a sun-synchronous polar orbit and provides all-weather soundings covering more than 90% of the globe every 24 hours. The system accuracy and a demonstrated stability[1] of 10 mK/yr with a spectral accuracy of center frequency of 2 parts per million enables us to retrieve several trace gases in the free troposphere, among them CO_2.

2. METHOD

AIRS spectra provide coverage of the 15 μm band, in which strong CO_2 absorption features predominate. However, as shown in Figure 1, absorption features due to other species are also present and all overlap due to pressure broadening.
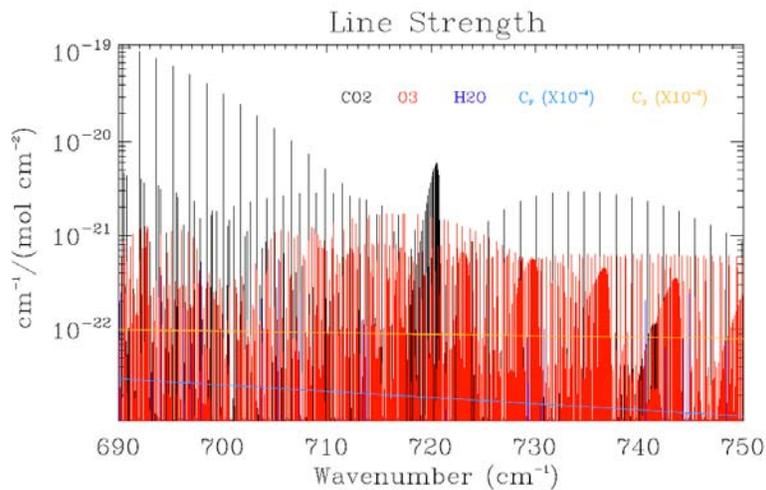

Figure 1. Pressure broadening results in overlapping lines of all species in the 15 μm band. C_s and C_f are the self and foreign component of the continuum absorption.

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The location at which AIRS is sensitive to CO_2 depends upon the line strength. By choosing different transitions, it is possible to focus on specific pressure regimes. Figure 2 shows the normalized average weighting functions for three separate sets of CO_2 channels, chosen for maximum sensitivity at different altitudes.
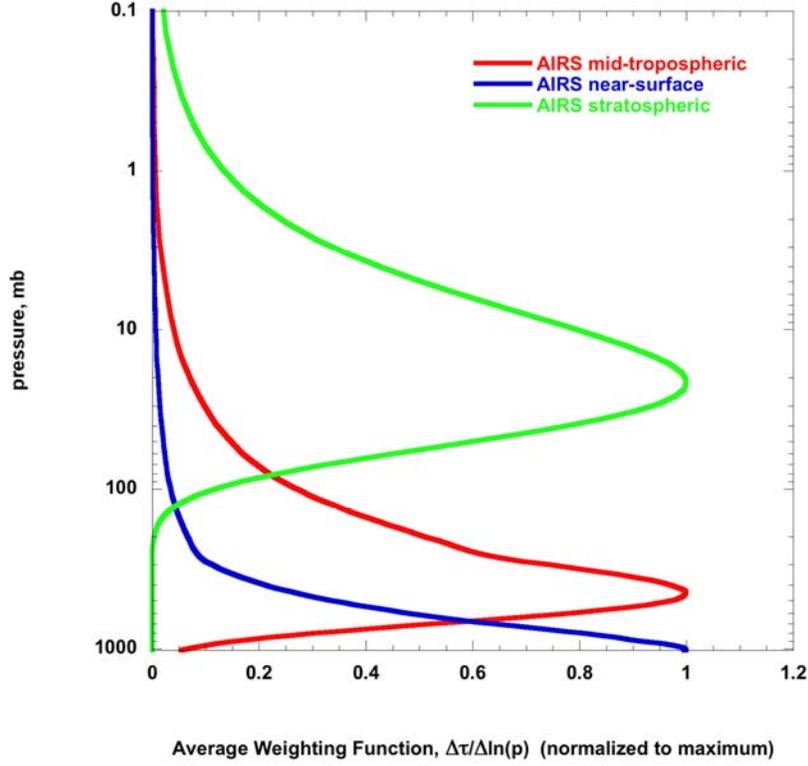

Figure 2. Sensitivity of CO_2 retrievals for three sets of AIRS channels, assuming the US standard tropical atmosphere. By choosing channels of different line absorption strength it is possible to retrieve CO_2 at different levels in the atmosphere.

If the spectral overlap of the various species lines can be overcome analytically, it is possible to retrieve a coarse CO_2 profile using AIRS products. Consider the RMS difference between observed radiances and those calculated from the atmospheric state for a set of AIRS channels:

$$\sum_i \left[I(v_i)_{Observed} - I(v_i, T, q, O_3, CO_2)_{Computed} \right]^2 = F(\overline{v}, T, q, O_3, CO_2) \tag{1}$$

where T, q, O_3, CO_2 are variables (respectively: air temperature, precipitable water vapor, ozone concentration and carbon dioxide concentration) whose values are to be determined by minimizing the RMS residual. That is, as the variables approach their true values, F approaches a minimum. The usual method of solution is to calculate the total derivative (or Jacobian)

$$\Delta F = \frac{\partial F}{\partial T} \Delta T + \frac{\partial F}{\partial q} \Delta q + \frac{\partial F}{\partial O_3} \Delta O_3 + \frac{\partial F}{\partial CO_2} \Delta CO_2 + \varepsilon \tag{2}$$

where ε is the noise. The usual approach is to search for values of T, q, O_3, CO_2 which minimize F so that $\Delta F \rightarrow 0$. Statistics or background models are then employed to constrain the solution, particularly when ε is large.

The strategy we employ is the vanishing partial derivative (VPD) method[2]. Applying it, we seek to minimize F only by requiring each partial derivative to approach zero separately, i.e.:

$$\frac{\partial F}{\partial X_j} \rightarrow 0 \qquad (3)$$

individually for each variable, X_j, whose contribution to the radiance residual is $\frac{\partial F}{\partial X_j} \Delta X_j$.

Our technique is to iteratively minimize the RMS residual radiance using groups of AIRS channels selected for each of the variables (T, q, O_3, CO_2). Channels are selected to maximize the sensitivity to variation in a particular variable while minimizing sensitivity to variation in the other variables. They must also have sensitivity functions that span the same altitude regime. Iteration is required because the variables are not linearly independent, for example all other variables are necessarily dependent upon temperature to a greater or lesser degree.

The iterative process for CO_2 retrieval is initialized with the AIRS cloud-cleared radiances and retrieved geophysical product profiles of T(p), H_2O(p) and O_3(p). We then linearly perturb the temperature and compute the residuals (RMS difference) between the AIRS cloud-cleared radiances and the radiances computed from the perturbed atmospheric state, for the selected temperature channels. The iteration on temperature is terminated when the change in residuals falls below a minimum. The temperature solution is incorporated into the atmospheric state and the iteration on precipitable water vapor is then performed. The solution for water vapor is incorporated and the iteration on ozone is then performed. Finally the iteration on CO_2 is performed. The solution for CO_2 is retained, the atmospheric state is returned to the original profiles of T(p), H_2O(p) and O_3(p) and the iteration sequence begun again. The process is terminated when the change in residuals for the selected CO_2 channels falls below a minimum. The CO_2 solution thus drives the VPD iteration, for we always return to the original atmospheric state in the other parameters before another major iteration step.

The strength of the VPD technique is that it does not require any a prior CO_2 assumption beyond one which ensures that our rapid transmission algorithm remain in a linear regime. We have tested this by beginning the retrievals with two significantly different initial CO_2 mixing ratios, 330 ppmv and 390 ppmv, and found that the CO_2 solution we achieved remained the same to within ±1 ppmv.

The VPD criterion is necessary but in practice may not be sufficient. The requirement that a partial derivative approach zero can lead to a maximum as well as a minimum. Consequently, as a quality check, we only accept solutions whose residuals decrease monotonically with iterations. In addition, we require that a cluster of four adjacent CO_2 retrievals (e.g., a 2x2 array covering a 90x90 km area at nadir) agree to within 2 ppmv in an RMS sense. We accept only clusters satisfying these conditions and report the average of the 2x2 array of CO_2 retrievals. Using this approach, we have shown that the retrieved CO_2 results are independent of the initial value of CO_2 and the error distribution in the retrieved CO_2 mixing ratios is nearly Gaussian.

3. RESULTS

In Figure 3 we compare our retrievals with in situ aircraft flask measurements obtained at cruising altitudes of (9.8-11.6 km) during commercial flights between Australia and Japan[3]. These flask measurements have been conducted biweekly since 1995 and have an estimated accuracy < 0.5 ppmv.
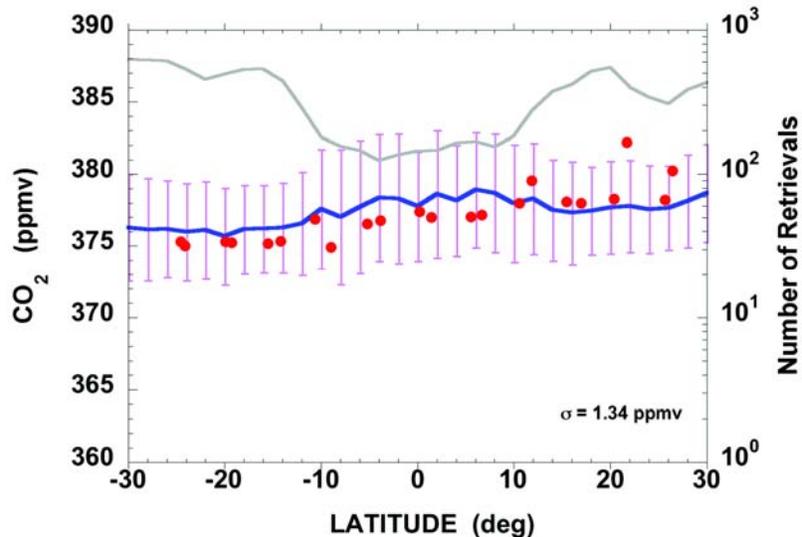

Figure 3. AIRS zonal average retrieved CO_2 (blue line) and Matsueda biweekly aircraft flask measurements (red dots) for April, 2004. AIRS retrievals are averaged over all longitudes in 2° latitude zones for the month. Standard deviations of zonal average AIRS retrievals are shown as purple bars. The number of AIRS retrievals averaged in a latitude zone is shown as the grey curve (scale on right).

There is good agreement between AIRS retrievals and aircraft observations in the tropics. The standard deviation of the differences between the Matsueda measurements and AIRS retrievals for the data shown in Figure 1 is $\sigma = 1.34$ ppmv. Similar comparison with Matsueda airborne measurements for other time periods result in a standard deviation that is less than 2 ppmv in all cases.

Figure 4 compares AIRS CO_2 retrievals against published measurements of the upward viewing Fourier Transform Spectrometer (FTS) at Park Falls Wisconsin (45.93° N, 90.45° W) between July 2004 and March 2006[4]. The data presented in the figure are monthly averages of the FTS measurements and of the AIRS retrievals collocated within 500 km over the 19 month time span. Both measurements capture the seasonal variation of CO_2. The FTS measurements exhibit a greater amplitude due to their sensitivity to the near-surface CO_2, where the impact of the summer uptake by vegetation is more pronounced. The two instruments observe nearly the same air mass in the middle and upper troposphere, but the FTS measurements are sensitive to the near surface CO_2 whereas the AIRS measurements are not. The AIRS measurements are obtained in the presence of clouds and are affected by mid-tropospheric weather. The measurements by the upward viewing FTS are obtained under clear sky conditions and are affected by near surface variations in CO_2.
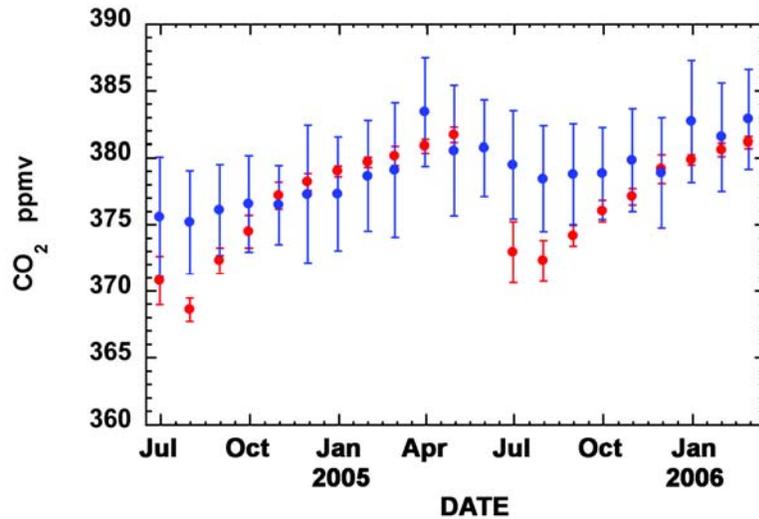
Figure 4. Seasonal variation of monthly average AIRS retrieved CO_2 (blue dots) within 500 km of Park Falls, WI compared to monthly average Park Falls Fourier Transform Spectrometer measured total column CO_2 (red dots). Error bars for both sets are standard deviations of averages of data.

Figure 5 shows a global image of the AIRS retrieved CO_2 averaged over July, 2003. It is readily apparent that the spatial variability of AIRS retrieved CO_2 is consistent with the large-scale circulation features in the pressure regime of peak AIRS sensitivity. Strong latitudinal and longitudinal gradients are apparent around 45° N, the location off the northern hemisphere mid-latitude jet stream. The lower concentrations of CO_2 north of the jet stream are due to the combination of surface uptake by vegetation and vertical redistribution of air with low CO_2 concentrations from the stratosphere. The relatively high concentrations south of the jet stream correspond to the mid-latitudes pollution belt. Continental outflow is also evident of the coast of East Asia.
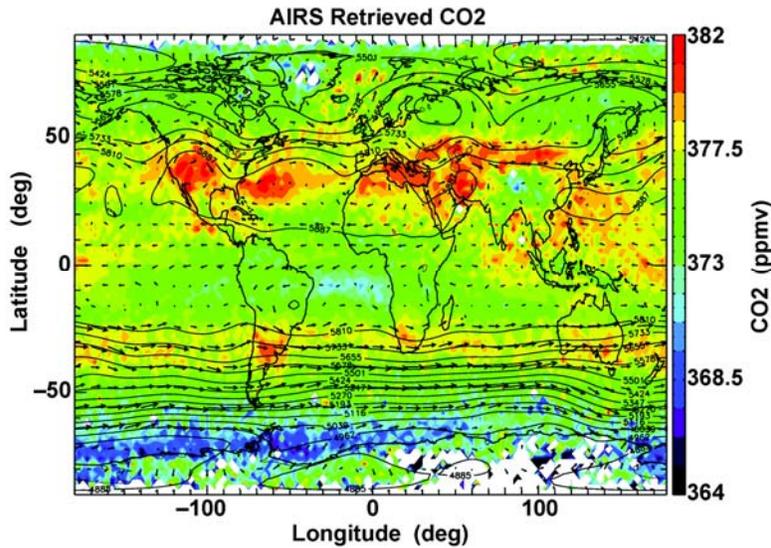

Figure 5. Global image of average of AIRS retrieved CO_2 for July, 2003, overlain by monthly averages of the NCEP2 500 hPa geopotential height and wind vectors for reference.

Also apparent in Figure 5 is a zone of relatively high CO_2 concentration in the southern hemisphere subtropical storm track. The southern mid-latitude jet stream plays a similar role to that of the northern jet. This zone of higher concentrations of CO_2 likely indicates convective activity has lifted boundary layer air into the free troposphere which becomes entrained in the southern hemisphere mid-latitude jet stream for subsequent rapid transport around the globe. The persistence of this zonal band is due to the uniformity of the 500 hPa geopotential heights around the Southern oceans, which acts as an atmospheric conveyor belt.

4. CONCLUSIONS

We have demonstrated that the VPD method can be used to retrieve atmospheric constituent information despite the fact that pressure broadening results in overlapping of the spectral features of multiple species. The application shown here, retrieval of CO_2 in the mid-troposphere using satellite infrared observations, provides a significant new capability to study the distribution and transport of a long-lived minor gas that is also an important greenhouse gas and insight into the underlying dynamic processes in the atmosphere.

ACKNOWLEDGEMENTS

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