

Mid-tropospheric CO₂ retrieval in the tropical zone from AIRS observations

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Abstract

The new 2378 channel high spectral resolution NASA/Aqua/Atmospheric Infrared Sounder (AIRS) launched in May 2002 is used to retrieve mean concentration of atmospheric carbon dioxide (CO₂). A reduced set of AIRS channels, presenting a high sensitivity to variations of the atmospheric CO₂ and reduced sensitivities to variations of other atmospheric components, and well covering the mid-troposphere (from 700 hPa to the tropopause), is first selected using the Optimum Sensitivity Profile (OSP) method. A cloud elimination procedure based on AIRS and Atmospheric Microwave Sounding Unit (AMSU) observations is then performed to detect clear fields of view. The resulting AIRS and AMSU measurements, the latter being not sensitive to CO₂ variations, are used in a neural network inference procedure. This non-linear regression scheme has already proven its efficiency in the retrieval of mid-tropospheric CO₂ from NOAA polar satellites. The first results obtained with AIRS give hope to improve the accuracy of the retrieval. Maps of monthly mean mid-tropospheric CO₂ concentration are obtained for a few months in the tropics [20S;20N]. The retrievals show good agreements with aircraft observations.

Introduction

Progress in both basic earth-system science and in managing the carbon cycle to mitigate climate change requires robust and verifiable understanding of the current behaviour of the system (Schimel et al. 1995, IPCC, 1998). Knowledge of today's carbon sources and sinks, including their spatial distribution and their variability in time, is essential for predicting the future carbon dioxide (CO₂) atmospheric concentration levels. The atmosphere being a superb integrator of spatially and temporally varying surface fluxes (Tans et al. 1990), the distribution of CO₂ atmospheric concentration and its evolution in time and space can be used to quantify surface fluxes. However, this approach is currently limited by the sparse and uneven distribution of the global flask sampling programs. Satellite measurements of the distribution of global atmospheric CO₂ concentration would in principle fill this gap in scale (Rayner and O'Brien 2001). Densely sampling the atmosphere, in time and space, they would provide a crucial constraint on the models.

The feasibility of retrieving CO₂ and other trace-gas concentrations from space has been proven with the National Oceanic and Atmospheric Administration (NOAA) Television Infrared Observation Satellite (TIROS-N) Operational Vertical Sounder (TOVS) radiometers (Chédin et al. 2002, 2003ab). For the first time, 4 years of monthly mean CO₂ concentration has been retrieved from

TOVS observations over the tropics [20S;20N] for the period 1987-1991. A rough estimate of the method-induced standard deviation of these retrievals is of the order of 3 ppmv (0.85 % of the mean CO₂ concentration).

The new high-spectral-resolution Atmospheric Infrared Sounder (AIRS) launched onboard the NASA/Aqua platform in May 2002 is expected to improve the accuracy of trace gas retrievals and will allow to make comparison with TOVS observations in terms of space and time variability of CO₂ atmospheric concentration which potential benefits for global carbon research are invaluable.

Data description

AIRS measures 2378 frequencies at high spectral resolution and covers most of the infrared spectrum. Also flying onboard Aqua, the Advanced Microwave Sounding Unit (AMSU-A) measures 15 microwave frequencies. Since April 2003, LMD downloads AIRS and AMSU data from NESDIS. These data are the restricted set of 324 AIRS channels, the 15 AMSU-A channels, for the 9 AIRS Fields Of View (FOVs) and for every other AMSU FOVs.

AIRS channels sensitive to CO₂ are located into two spectral bands, near 15 μm and 4.3 μm. To avoid huge computation time, and to eliminate the signals that could interfere with CO₂ signal, a set of 43 AIRS channels presenting the best properties to retrieve CO₂ has been selected with the Optimum Sensitivity Profile (OSP) method (Crevoisier et al. 2003). These channels present a high sensitivity to CO₂ variations and low sensitivity to other atmospheric components such as water vapour, ozone (O₃), nitrous oxide (N₂O), carbon monoxide (CO), and surface parameters. They are located in both CO₂ bands and well cover the vertical, with the exception of the tropopause and the boundary layer, as can be seen on Figure 1 which shows the CO₂ Jacobians (partial derivative of the channel brightness temperature to a layer CO₂ concentration) for the 43 OSP channels, as computed by the 4A forward model in its latest version (Scott et al., in preparation; <http://ara.lmd.polytechnique.fr/>). As a result, AIRS channels are sensitive to CO₂ variations in the range 700 to 100 hPa.

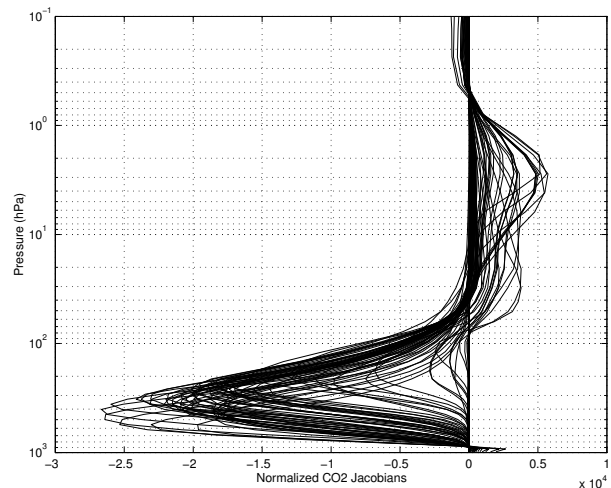


Fig. 1: CO₂ Jacobians of the 43 OSP channels.

Only clear-sky situations are used to retrieve CO₂. Not-clear situations (clouds, aerosols) are detected by numerous tests based on thresholds. Basically, three kinds of tests are used. They are detailed in Table 1. All together, there are 15 differences between brightness temperatures (BT) : (1) 8 differences between BT of AIRS and AMSU channels, the latter being not sensitive to clouds; (2) 5 differences between BT of AIRS channels and their “clear-sky” prediction from AMSU channels 5, 6 and 8 through regressions. The regression coefficients are computed from the TIGR atmospheric database using least-squares. The statistical results show no mean and a standard deviation of about 0.5 K; (3) 2 differences between window channels. The threshold values were obtained from 5 days in February 2003. As a result, in the tropics, over sea, during night, about 82% of the situations are found not-clear.

$$\begin{aligned}
& |T_B(213) - T_B(A6)| < 2.25 \text{ K} \\
& |T_B(1947) - T_B(A6)| < 2.25 \text{ K} \\
& |T_B(2106) - T_B(A6)| < 2.25 \text{ K} \\
& |T_B(2110) - T_B(A6)| < 2.25 \text{ K} \\
& |T_B(151) - T_B(A8)| < 2.75 \text{ K} \\
& |T_B(2106) - T_B(A8)| < 2.75 \text{ K} \\
& |T_B(2110) - T_B(A5)| < 2.75 \text{ K} \\
& |T_B(2112) - T_B(A5)| < 2.75 \text{ K}
\end{aligned}$$

$$\begin{aligned}
& |T_B(308) - T_B^{\text{reg}}(308)| < 2.5 \text{ K} \\
& |T_B(309) - T_B^{\text{reg}}(309)| < 2.5 \text{ K} \\
& |T_B(2106) - T_B^{\text{reg}}(2106)| < 2.5 \text{ K} \\
& |T_B(2110) - T_B^{\text{reg}}(2110)| < 2.5 \text{ K} \\
& |T_B(2112) - T_B^{\text{reg}}(2112)| < 2.5 \text{ K} \\
& |T_B(787) - T_B(2226)| < 2.75 \text{ K} \\
& |T_B(787) - T_B(2333)| < 2.75 \text{ K}
\end{aligned}$$

Table 1: AIRS clear-sky tests. $T_B(213) - T_B(A6)$ stands for AIRS channel 213 brightness temperature minus AMSU channel 6 brightness temperature. $T_B^{\text{reg}}(308)$ stands for the prediction from AMSU channels 5, 6 and 8 through regressions of AIRS channel 308 brightness temperature.

As validation, a comparison with the cloud fields retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS) also flying onboard Aqua has been performed for the month of April 2003 (products available on <http://modis-atmos.gsfc.nasa.gov/>). A comparison between AIRS clear-sky test results and MODIS cloud-top-pressure product is shown on Figure 2 for April 27th, 2003. According to the MODIS cloud top pressures, all the clouds above 800 hPa are detected. Remaining low clouds are not detected. However, this does not affect the retrieval of CO_2 concentration that is performed above 700 hPa.

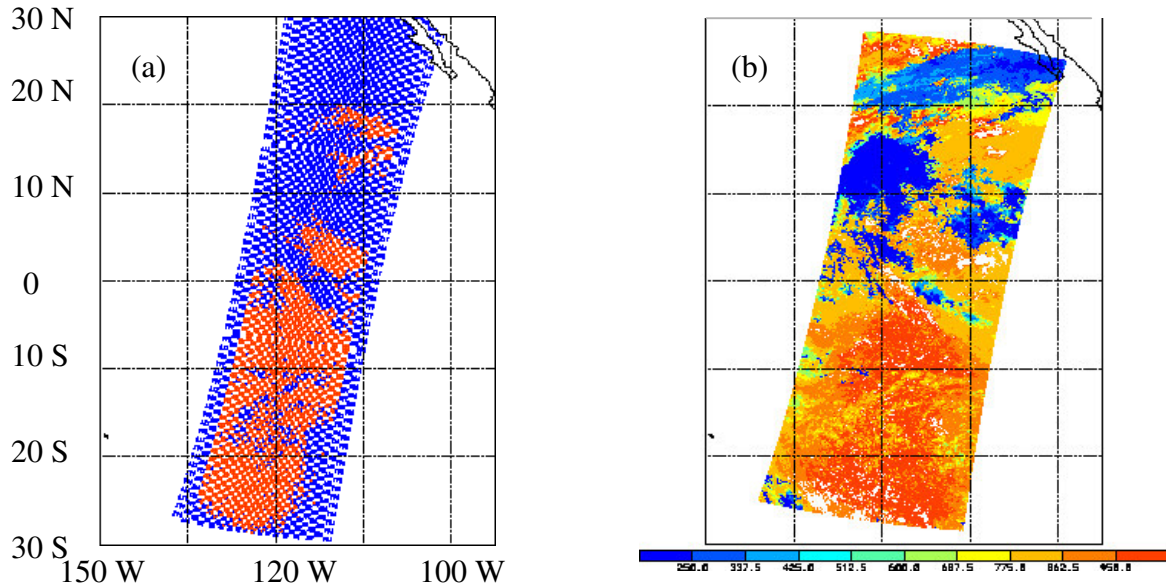


Fig. 2: For 27 April 2003, [30N;30S] and [150W;105W], (a) clear (red) and unclear (blue) situations as given by AIRS clear-sky test ; (b) corresponding MODIS cloud-top-pressure.

A neural network approach

The signal induced on AIRS brightness temperatures by the variations of CO_2 concentration remains weak (a few tenth of Kelvin). Therefore, as done in Chédin et al. (2003), a method based on neural network using Multilayer Perceptron (MLP) has been preferred to a more classical one and is now being described. A detailed description of the method, already used for TOVS observations, can be found in Chédin et al. (2003).

The MLP network (Rumelhart et al. 1986) is a non-linear mapping model composed of parallel processors called “neurons”. These processors are organized in distinct layers. The first layer groups the inputs of the network (the predictors). The intermediate layers are called the “hidden layers”. The last layer groups the outputs of the network (the predictands). Each neuron is connected

to the neurons of the previous and following layers, a weight being given to this connection. These weights contain the whole information of the network. To optimise the weights, a minimization of a positive-define cost function measuring the mismatch between neural outputs and desired outputs is performed for a set of representative patterns, the so-called “learning set”, for which inputs and outputs are known. Use is made of the Error Back-Propagation algorithm (Rumelhart et al. 1986), with stochastic steepest descent. The learning step is made sample by sample, chosen iteratively and stochastically in the learning set.

For this study, the tropical atmospheric situations of the Thermodynamic Initial Guess Retrieval (TIGR) database (Chédin et al. 1985, Chevallier et al. 1998) are used as the training set. Each situation is described by its profiles of temperature, water vapour and ozone. The trace gases are assumed constant along the vertical. CO₂ concentration varies in the range 352-392 ppmv, with a mean value at 372 ppmv. N₂O and CO concentrations are assumed to be equal to 324 ppbv and 100 ppbv respectively. These are the predicted concentration values for the year 2003 (IPCC 2001). Clear-sky AIRS brightness temperatures, transmittances and Jacobians (partial derivative of the channel brightness temperature to a layer physical variable such as temperature, gas concentration for H₂O, O₃, CO₂, N₂O, CO, surface temperature and emissivity) are then computed for all the profiles using the fast line-by-line 4A model. AMSU brightness temperatures are computed using the MW-STRANSAC model. The computation is performed for 15 scan angles between 0° (nadir) and 57° for, so far, a single value of surface pressure (1013 hPa). The present study is limited to the tropics, because of the reduced temperature variability in this region, and to sea cases (single surface pressure). The simultaneous use of the infrared measurements, sensitive to both temperature and CO₂ variations, and the microwave measurements, sensitive only to temperature variations, allows separating the two effects.

According to the above considerations, the chosen neural architecture is the following. The input layer is composed of: (1) 15 AIRS brightness temperatures of tropospheric channels chosen among the OSP selection (173, 175, 180, 185, 193, 213, 218, 250, 1946, 1947, 1948, 2106, 2107, 2108, 2109), (2) 5 AMSU-A brightness temperatures of channels 6, 8, 9, 10 and 11, and (3) 4 differences between AIRS and AMSU brightness temperatures. All together, there are 24 predictors. The output layer of the network is composed of: (1) the difference between the true (associated with inputs) value of CO₂ concentration and the reference one (372 ppmv), and (2) 15 differences between the “true” AIRS brightness temperatures (associated to the true CO₂ concentration value) and the “reference” one (associated to the reference CO₂ concentration value). All together, there are 16 predictands. Our past experience and several trials have led us to chose 80 neurons for the first hidden layer and 50 for the second one.

To take into account the instrument noise, a Gaussian noise defined by the equivalent noise temperature computed at the temperature of each channel is added to the input brightness temperatures at each step of the learning phase.

A total of 10 MLPs have been trained for a single surface pressure (1013 hPa) and 10 scan angles (from nadir to 40° to avoid the edges of the orbits).

The MLPs are trained with simulated data. Therefore, before presenting observations to the network, the eventual brightness temperatures systematic biases between simulations and observations must be taken into account and removed. In the absence of enough radiosonde measurements, this is done by comparing satellite observations with simulations based on our forward model and European Centre for Medium-Range Weather Forecast (ECMWF) analyses. For each channel, the bias is obtained by averaging on the whole period and the whole tropics, the differences between clear-sky AIRS observed brightness temperatures and the brightness temperatures computed from the nearest

(time and space collocation) ECMWF analyses. The biases show no strong latitudinal variations, nor significant time variations.

Results and Discussion

Retrieval of CO₂ mid-tropospheric concentration has been performed for seven months of AIRS observations from April to October 2003, in the tropics [20S;20N], over sea, at night. Daytime observations are not considered to avoid possible contamination by solar radiation: use is made of the AIRS observations at 1:30 am local time. The tropical region is of first interest for carbon study as the flask network is less efficient in this part of the globe. Moreover, the strong convective vertical mixing existing in the tropics transmits surface carbon flux variations to that part of atmosphere seen by AIRS.

Two maps of monthly mean retrieved mid-tropospheric CO₂ concentration are shown on Figure 3 at a resolution of 15° × 15° (0.75° × 0.75° moving average) for the months of April and September 2003. This resolution was chosen to combine a relatively dense spatial coverage with robust statistics. Boxes having not enough situations, because of the removing of not-clear situations, are not considered (blank areas on Figure 3). They mostly follow the regions of deep convection. The resulting number of situations per month and per grid-box is about 2000 in regions where clear-sky is preponderant but can reach 500 in more cloudy areas.

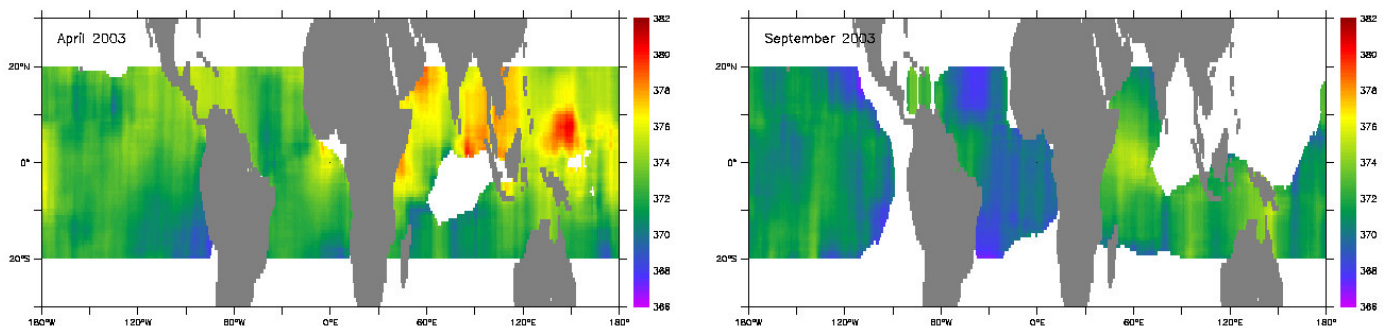


Fig. 3: Monthly mid-tropospheric CO₂ concentration as retrieved from AIRS observations in the tropics for April (left) and September (right) 2003 at a resolution of 15°×15°.

The decrease of CO₂ concentration from April (maximum) to September (minimum), especially in the northern hemisphere, is well seen. For the seven months analysed, the obtained variability of CO₂ concentration matches the known behaviour of the gas. The maximum of variability is found in Spring (April and May). On the contrary, autumnal months (September, October) show a relatively low variability of CO₂. The high concentration found in Asia starts to disappear at the beginning of summer with the increase of photosynthesis activities of the northern biomass. The latitudinal gradient found in April is 6 ppmv from southern to northern tropics and goes down to -1.5 ppmv in September. These values are coherent with several studies made on latitudinal variation of CO₂ (Machida et al. 2003, Vay et al. 1999). From July to September, a maximum of CO₂ concentration is found east of Africa in the equatorial region. This strong signature, already found with TOVS observations in the years 1987-1991, might be due to pollution in Asia going down to this region. Such result is of great importance to validate carbon transport models.

A first way to estimate the dispersion of the retrievals goes through the study of the induced standard deviation (std) of each monthly 15° × 15° box (Chédin et al. 2003). A globally dispersion around 3 ppmv (0.8 % of the mean CO₂ concentration) is observed, the maximum std being found in

the months of April-May (3.2 ppmv), when the natural variability of CO₂ is high, and the minimum std being found in the months of July-September (2.7 ppmv), when the natural variability of CO₂ is low. The observed std may be seen as the combination of the std of the method (σ_M) and of the std of the natural variability (σ_V). Doing so, σ_M comes to 2.5 ppmv (0.8 % of the mean CO₂ concentration) and σ_V comes to 1 ppmv for April and to 2.1 ppmv for July-September. These values look reasonable as the retrievals are only performed over sea and therefore do not take into account the variability of CO₂ over land.

Our knowledge of CO₂ distribution in the middle and high troposphere is reduced, most of the measurements having been made by flasks at the surface. Fortunately, in situ observations made by commercial airliners from April 1993 to March 2003 and partly analysed in Matsueda et al. (2002) have been collected by the World Data Centre for Greenhouse Gases (WDCGG) as part of the Global Atmosphere Watch (GAW) programme. These observations cover the altitude range 9-13 km, between Japan and Australia. The monthly mean CO₂ variations obtained in the northern [0;20N] and southern [20S;0] tropics are shown on Figure 4 in black. The seasonal cycle is clearly seen in the northern tropics whereas the southern hemisphere variation is more complex.

Monthly mean of CO₂ concentration as retrieved from AIRS observations for the whole tropics is shown on the same figure for the period April-October 2003 (red line). The shift between the two plots may be explained by the different geographical regions considered (the regions covered by aircraft observations can present high concentrations as clearly seen on Figure 3, giving a CO₂ signal higher than the one obtained for the whole tropics), and by the bias removal procedure described in Section 2 that is not optimal. Efforts are made to improve the results by using radiosonde measurements instead of analyses for the determination of the empirical corrections.

Apart this difference in the mean value, the AIRS retrieved variation of CO₂ agrees with the aircraft measurements: in the northern tropics, a maximum is found in April, a minimum in September, with a peak-to-peak variations of 3.5 ppmv; in the southern tropics, the signal is more complex but can be directly compared to the one observed by aircrafts in 2002.

Also, the latitudinal variation of the mean AIRS retrieved seasonal cycle as seen in 8 latitude bands of 5° each from 20°N to 20°S shows once more a very good agreement with aircraft observations.

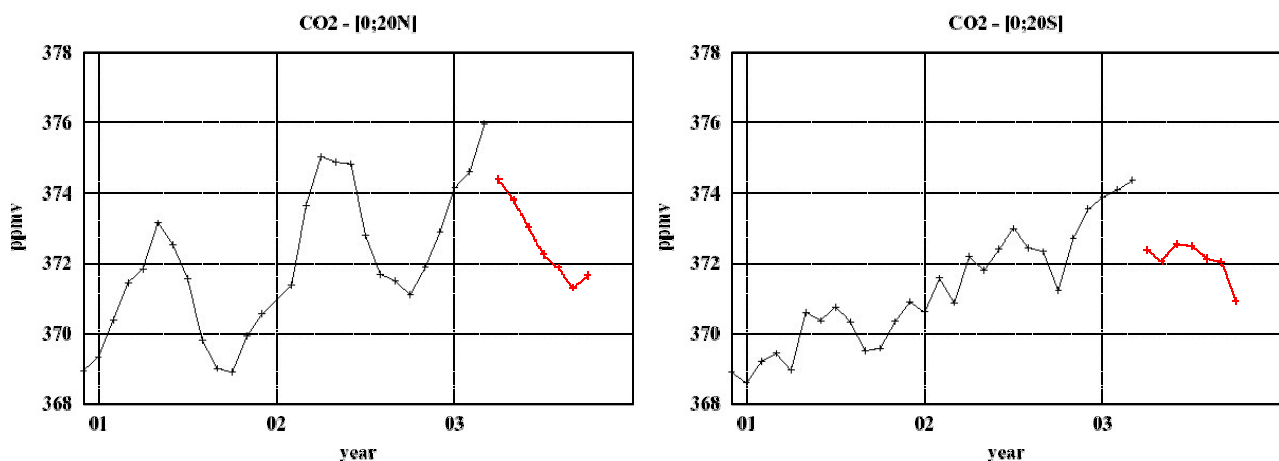


Fig. 4: Monthly mean of CO₂ concentration as retrieved in the northern (left) and southern (right) tropics from AIRS observations (from April to October 2003, in red) and as observed by aircraft (from January 2001 to March 2003, in black).

Conclusion

Mid-tropospheric CO₂ concentration has been retrieved in the tropics, over sea, at night from AIRS observations. The extension of the retrieval to land and daytime cases will allow us to study the effect of diurnal cycle. A comparison with carbon flux inversion models is in progress in cooperation with the Laboratoire des Sciences du Climat et de l'Environnement, Saclay, France, and the Max-Planck Institute for Biogeochemistry, Jena, Germany within the frame of the European COCO project. The first results have shown the extraordinary potential of space observations to better understand the behaviour of CO₂ in the atmosphere.

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