Measuring Atmospheric Carbon Dioxide from Space: The GOSAT and OCO-2 Missions

David Crisp and the OCO-2 Team
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A

David.Crisp@jpl.nasa.gov

Abstract: The Japanese Greenhouse gases Observing Satellite (GOSAT) is providing new insight into atmospheric carbon dioxide trends. The NASA Orbiting Carbon Observatory–2 (OCO-2) Mission will build on this record with increased sensitivity resolution, and coverage.

1. Introduction

Human activities are currently emitting over 30 billion tons of carbon dioxide (CO_2) into the atmospheric every year [1]. While fossil fuel combustion accounts for most of this emission, and it sources are reasonably well known, other emission sources are much less well characterized. In addition, the nature and geographic distribution of the natural CO_2 "sinks" that are currently absorbing about half of the CO_2 that we are emitting are even less well understood. The ground-based greenhouse gas monitoring network has grown steadily over the past 50 years, and now provides the accurate global estimates of the rate of change of CO_2 and other greenhouse gases. However, this network still does not have the spatial resolution needed to discriminate CO_2 sources and sinks on regional scales. The network is particularly sparse in the tropics and over the ocean.

One way to improve the spatial resolution, coverage, and sampling frequency of greenhouse gas measurements is to make spatially resolved observations of the column averaged CO_2 dry air mole fraction (X_{CO2}) from space [2,3]. Precise measurements are needed for this application because surface sources and sinks of CO_2 produce small spatial and temporal variations in X_{CO2}. While the atmospheric CO_2 mixing ratio can vary by as much as 8% near the ground, these perturbations decay rapidly with height, such that X_{CO2} variations rarely exceed 2% on regional scales. Existing data show that X_{CO2} variations are usually no larger than 0.3% on regional scales, and that these variations have representative spatial scales that range from 100 km over continents to 1,000 km over the ocean.

The SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) instrument on the European Space Agency's ENVISAT was the first space based sensor designed to monitor greenhouse gases by making spectroscopic measurements of reflected sunlight at short wave infrared wavelengths. This pioneering sensor was launched in 2002 and has been returning measurements of both CO_2 and methane (CH_4) since then [4]. While these data provide a valuable proof of concept of this measurement technique, their sensitivity is not adequate to resolve the sources and sinks of these gases on regional scales, or to characterize their behavior over the seasonal cycle. The Japanese GOSAT and the NASA Orbiting Carbon Observatory (OCO) were first two space based sensors designed specifically for this task. The GOSAT mission was successfully launched January 2009, and is currently returning measurements of both CO_2 and CH_4. The OCO mission suffered a major setback in February 2009, when its launch vehicle malfunctioned and the satellite failed to reach orbit. In early 2010, NASA authorized a "carbon copy" of OCO, called OCO-2, which is currently on track for launch as early as 2013.

2. Experience with GOSAT

GOSAT (nick-named "Ibuki") was a joint project of Japan Aerospace Exploration Agency, the Ministry of Environment (MOE), and the National Institute for Environmental Studies (NIES) [5]. GOSAT flies in a 666 km altitude, 98°-inclination, orbit with a 12:49 PM nodal crossing time and a 3-day (44-orbit) ground track repeat period. GOSAT carries two instruments, the Thermal and Near Infrared Sensor for carbon Observations (TANSO) Fourier Transform Spectrometer (FTS), and the TANSO Cloud and Aerosol Imager (CAI). TANSO-FTS records high resolution spectra of reflected sunlight within molecular absorption bands of oxygen (O_2), CO_2, and CH_4 in three discrete channels at wavelengths between 12900 and 5200 cm^{-1} (0.757 and 2.08μm). It also includes a broad (700 to 1800 cm^{-1} or 5.56 to 14.3 μm) channel designed measure the absorption of thermal radiation by water vapor (H_2O), ozone (O_3), and CO_2. The O_2 A-Band channel between 12900 and 13200 cm^{-1} has a resolution of ~0.6 cm^{-1}, while all other bands have a resolution of ~0.27 cm^{-1}. At 4-second intervals, TANSO-FTS collects co-bore-sighted spectra within a circular, 0.0157 radian diameter instantaneous field of view (IFOV), yielding 10.5 km diameter footprints at nadir. A 2-axis pointing mirror is used to direct this IFOV within ~ 35° of nadir in the cross-track direction and within ~ 20° of nadir along the spacecraft ground track, and to provide image motion compensation during the 4-second exposures. In routine operations over continents or over the ocean at latitudes > 20° away from the sub-solar latitude, the scanner acquires soundings at either 5 (prior to August 1, 2009) or 3 (after August 1, 2009) cross-track locations, separated by ~160 (5-point mode) or 280 km (3-point mode). When flying over the ocean at latitudes within 20° of the sub-solar latitude, the scanner can point the field of view at the bright glint spot, where sunlight is specularly reflected from the surface, to maximize the signal.

TANSO-CAI was designed to facilitate the detection of clouds and optically thick aerosols within the TANSO-FTS field of view. The TANSO-CAI has a nadir spatial resolution of ~0.5 km over a 900 km wide swath for spectral channels centered near 0.38, 0.674, and 0.870 μm and a nadir spatial resolution of ~1 km over a 450 km swath at 1.6 μm. The TANSO FTS collects ~10,000 X_{CO2} soundings over the sunlit hemisphere each day. When averaged over the globe, 10 - 15% of these soundings are sufficiently cloud free to yield full-column X_{CO2} retrievals.

The OCO and GOSAT teams formed a close collaboration prior to the launch of these two missions, which were expected to operate simultaneously. The initial objectives of this collaboration were to cross calibrate their instruments and develop methods to validate their CO_2 retrievals against common standards so that the two data sets could be combined for studies atmospheric CO_2. After the loss of the OCO spacecraft, the GOSAT team invited the OCO team to join their efforts to analyze GOSAT data. NASA responded by reformulating the OCO science team as the “Atmospheric CO_2 Observations from Space” (ACOS) team. The ACOS-GOSAT collaboration has focused in three primary areas: (1) joint vicarious calibration campaigns in Railroad Valley, Nevada in 2009, 2010, and 2011 to track and correct changes in the radiometric calibration of TANSO-FTS; (2) modification and use of the OCO retrieval algorithm to generate estimates of X_{CO2} from GOSAT measurements; and (3) validation of the ACOS and GOSAT X_{CO2} retrievals against the ground-based FTS retrievals of X_{CO2} from the Total Carbon Column Observing Network (TCCON) [7].

This collaboration has yielded benefits for both teams. The vicarious calibration experiments have helped to identify and correct drifts in the pre-launch GOSAT radiometric calibration [8]. These campaigns have also helped to refine techniques for conducting ground based vicarious calibration campaigns for OCO-2 and other satellite-based greenhouse gas sensors. This collaboration has also accelerated the development of X_{CO2} retrieval algorithms. Comparisons of preliminary GOSAT and ACOS X_{CO2} retrievals with TCCON results showed that the ACOS GOSAT retrievals were about 2% lower than those from TCCON. About half of this bias has been attributed to a 1% high bias in the O_2 column abundance, which was first revealed as a 10 hPa overestimate in the retrieved surface pressure [6]. This error is thought to be due to uncertainties in the absorption cross sections for O_2 A-band. The remainder is associated with unresolved instrument calibration uncertainties, errors in the CO_2 spectroscopy, and errors or oversimplifications in the retrieval algorithms.

To quantify these biases and gain greater insight into their cause, Wunch et al. [6] compared ACOS GOSAT X_{CO2} retrievals to TCCON X_{CO2} retrievals taken at latitudes between 25°S and 45°S, where the X_{CO2} variations are known to be small. These experiments revealed correlations between the X_{CO2} biases and several environmental factors, including surface pressure, slant path length, surface albedo, and the A-band signal levels. They developed a regression relation to correct the biases within this latitude band. They show that this expression substantially improves the agreement between ACOS-GOSAT and TCCON retrievals over the full range of latitudes sampled by TCCON (80 N to 45 S). Several of these biases have recently been traced to A-band calibration uncertainties. Others have been traced to limitations in X_{CO2} retrieval algorithm’s ability to detect and characterize low clouds over bright surfaces, and other more subtle errors. Corrections have been implemented in the latest version of the ACOS X_{CO2} retrieval algorithm and are currently being tested to assess their impact on the global data set.

3. Expectations of the OCO-2 Mission

OCO-2 data are expected to complement the GOSAT X_{CO2} measurements while providing improvements in coverage, resolution, and sensitivity [3]. Like OCO, OCO-2 will fly in formation with the Earth Observing System Afternoon Constellation (EOS A-Train). This 705 km altitude, near-polar, sun synchronous orbit has a 1:30 PM nodal crossing time and a 16-day ground track repeat period. Formation flying facilitates coordinated calibration and validation campaigns with other A-Train instruments and synergistic use of OCO-2 data with measurements from instruments on other A-Train platforms. This orbit also crosses the GOSAT orbit several times each day, providing opportunities for cross calibrating the data from the two missions while their operational phases overlap.

Like OCO, the OCO-2 spacecraft bus carries and points a single instrument, which incorporates 3, co-bore-sighted high-resolution, imaging, grating spectrometers designed to measure reflected sunlight within the two CO_2 bands centered near 1.61 and 2.06 μm, and within O_2 A-band, centered near 0.764 μm. Each spectrometer collects 3 samples per second in 4 to 8 spatial footprints along its narrow (14 mrad, or 0.8°) slit as it flies over the sunlit hemisphere. This sampling approach yields 200 to 400 soundings per degree of latitude or 500,000 to 1,000,000 soundings each day. The relatively small sounding footprints (1.29 km by 2.25 km at nadir) provide high spatial resolution along the measurement track. In addition, with this small footprint, cloud studies indicate that 20 to 30% of these footprints should be sufficiently cloud free to retrieve full-column estimates of X_{CO2}.

To obtain high signal-to-noise data over both oceans and continents, OCO-2 can view either the local nadir or the glint spot over the full range of latitudes on the sunlit hemisphere. Nadir observations provide the highest spatial resolution and yield more useful clear-sky soundings in regions that are partially cloudy or have rough surface topography. Glint observations provide much higher SNR over dark, ocean and ice-covered surfaces. By combining global maps created in nadir and glint modes on alternate 16-day ground track repeat cycles, the OCO mission can acquire useful observations over both continents and ocean at monthly intervals.

The co-bore-sighted CO_2 and O_2 spectra from each sounding will be analyzed with a remote sensing retrieval algorithm to estimate X_{CO2}. The OCO-2 algorithm evolved from the OCO "full physics" retrieval algorithm [8], which is currently being validated using GOSAT data, as noted above. This algorithm incorporates (i) a pre-screening step to screen out corrupted spectra and clouds, (ii) a "Forward" radiative transfer model for generating synthetic spectra and spectral Jacobians (weighting functions), using a spectrum-resolving (line-by-line) multi-stream, multiple scattering model, (iii) an instrument model that simulates the OCO-2 (or GOSAT) instrument line shape, (iv) an inverse model based on optimal estimation to update the atmospheric state, and (v) a post-processing screening step to identify and reject bad retrievals. The primary challenges for this algorithm are the simultaneous requirements for accuracy and speed. While it is approaching its accuracy goals, large increases in computational efficiency are still needed to process all of cloud free data expected from OCO-2. These developments are ongoing.

4. Conclusions

Global, space-based measurements of CO_2 are an essential element of the evolving greenhouse gas measurement network. The GOSAT and OCO-2 missions are the first two satellites designed specifically for this application. GOSAT is currently returning global maps of X_{CO2} every three days. If all goes as planned, the OCO-2 will be launched as early as 2013 to complement and extend the space based CO_2 measurement record.

5. Acknowledgements

Part of the research described in this white paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

6. References

[1] Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller (Eds.) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (Cambridge Univ. Press, Cambridge, U. K., 2007).

[2] P. J. Rayner and D. M. O'Brien, "The utility of remotely sensed CO_2 concentration data in surface source inversions," Geophys. Res. Lett., **28**, 175-178, (2001).

[3] D. Crisp, C. E. Miller, P. L. DeCola, NASA Orbiting Carbon Observatory: measuring the column averaged carbon dioxide mole fraction from space, J. Appl. Remote Sens., **2**, 023508, (2008), doi:10.1117/1.2898457.

[4] O. Schneising , M. Buchwitz, J. P. Burrows, H. Bovensmann, M. Reuter, J. Notholt, R. Macatangay, and T. Warneke, Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite – Part 1: Carbon dioxide, Atmos. Chem. Phys., **8**, 3827–3853, (2008).

[5] A. Kuze, H. Suto, M. Nakajima, M., T. Hamazaki, Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring. Appl. Opt., **48**, pp. 6716–6733, (2009).

[6] A. Kuze, D. M. O'Brien, T. E. Taylor, J. O. Day, C. O'Dell, F. Kataoka, M. Yoshida, Y. Mitomi, C. Bruegge, H. Pollock, R. Basilio, M. Helmlinger, T. Matsunaga, S. Kawakami, K. Shiomi, T. Urabe, and H. Suto, Vicarious calibration of the GOSAT sensors using the Railroad Valley desert playa, IEEE Trans. Geosci. Remote Sens. **49**, 1781-1795, (2011). doi: 10.1109/TGRS.2010.2089527.

[7] D. Wunch, P. O. Wennberg, G. C. Toon, B. J. Connor, B. Fisher,, G. B. Osterman, C. Frankenberg, L. Mandrake, C. O'Dell, P. Ahonen,S. C. Biraud, R. Castano, N. Cressie, D. Crisp, N. M. Deutscher, A. Eldering, M. L. Fisher, D. W. T. Griffith, M. Gunson, P. Heikkinen, G. Keppel-Aleks, E. Kyrö, R. Lindenmaier, R. Macatangay, J. Mendonca, J. Messerschmidt, C. E. Miller, I. Morino, J. Notholt, F. A. Oyafuso,M. Rettinger, J. Robinson, C. M. Roehl, R. J. Salawitch, V. Sherlock, K. Strong, R. Sussmann, T. Tanaka, D. R. Thompson, O. Uchino, T. Warneke., and S. C. Wofsy: A method for evaluating bias in global measurements of CO_2 total columns from space, Atmos. Chem. Phys. Discuss., **11**, 20899-20946, (2011), doi:10.5194/acpd-11-20899-2011.

[8] B. Connor, B., H. Boesch, G. Toon, B. Sen, C. Miller, and D. Crisp, Orbiting Carbon Observatory: Inverse method and prospective error analysis, J. Geophys. Res., **113**, 20903-20919, (2008). D05305, doi:10.1029/2006JD008336.