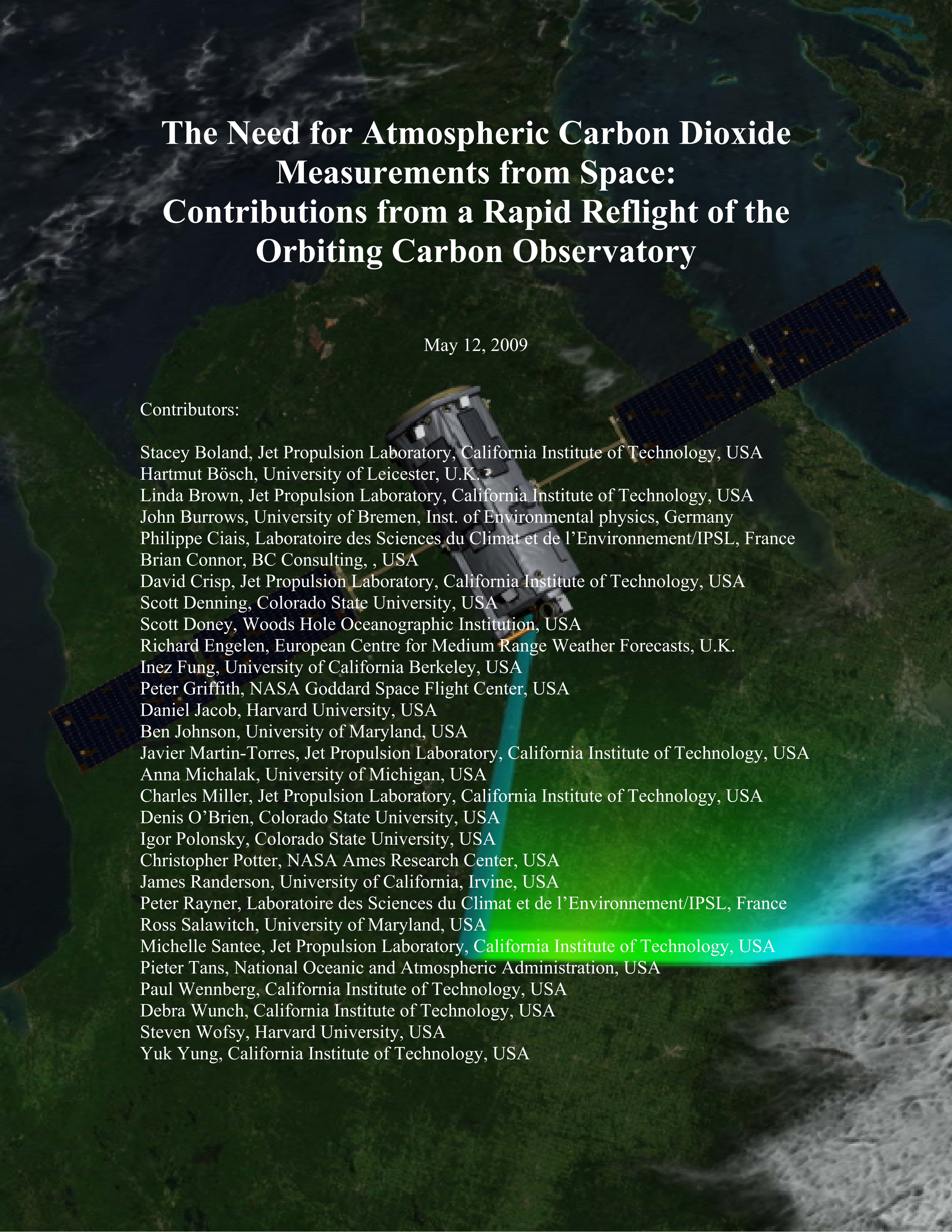

The Need for Atmospheric Carbon Dioxide Measurements from Space: Contributions from a Rapid Reflight of the Orbiting Carbon Observatory

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Contents

Executive Summary

"I think a strong case can be made that the [Orbiting Carbon Observatory] should be reproduced as soon as possible. Here we are, on the verge of new international agreements, without thinking about how to monitor them. We are neglecting climate as an element of national security. We're not getting the information we need. Where are [climate] changes happening, and where are they going to happen?"
-Ralph Cicerone, President of the National Academy of Sciences
Speaking to Congress, 4 March 2009

Human activities now emit more than 32 billion tons of carbon dioxide (CO_2) into the atmosphere each year, and the annual emissions rate has increased steadily since the dawn of the Industrial Age. Over half of this CO_2 has been absorbed by natural sinks on land and in the ocean; the remainder stays in the atmosphere. Measurements made by the international carbon cycle science community have substantially improved our understanding of CO_2 sources and sinks, and their relationship to climate change. Despite this progress, knowledge of the nature and location of CO_2 sources and sinks, as well as the processes that will affect their future evolution, continues to be limited by a lack of high precision global measurements of atmospheric CO_2. This knowledge is needed to accurately predict how CO_2 sinks will change, how this change will affect the rate of CO_2 buildup in the atmosphere, the impact on climate, and to measure the effects of low carbon energy policy.

In 2002, NASA selected the Orbiting Carbon Observatory (OCO) to return space-based measurements of atmospheric CO_2 with the sensitivity and spatial and temporal sampling required to quantify CO_2 sources and sinks. This is the most challenging atmospheric trace gas measurement ever attempted from space. The OCO team devised several innovations to realize this measurement. While there have been advances in space-based CO_2 measurement capabilities since 2002, including the recent launch of the Japanese Greenhouse gases Observing Satellite (GOSAT), no existing or confirmed satellite sensor can provide the measurements needed to quantify both CO_2 sources *and* sinks. Pre-flight tests of the OCO instrument, retrieval algorithms, and data validation network indicate that OCO, combined with other ground- and space-based assets, would have met these stringent requirements. If OCO launched successfully, it would have also demonstrated a technology ideal for future long-term monitoring of CO_2.

Advances in carbon cycle science have intensified the need for accurate global observations of CO_2 from space. The unfortunate loss of OCO delays delivery of these critical data. The OCO mission was conceived to address a fundamental carbon cycle and climate science question with policy relevance. The science question is still unanswered, and OCO measurements had become widely viewed as essential to provide the scientific basis for greenhouse gas policies currently under consideration. Meeting the science and policy imperatives on the needed time scale can only be accomplished by launching an OCO rebuild on a fast-track schedule that capitalizes on the project's assets and innovations and adds value to other missions.

The OCO Project has developed a rebuild schedule starting in June 2009 that would lead to launch as early as Fall 2011 and delivery of exploratory atmospheric CO_2 data products as soon as early 2012.

1. OCO's Contributions to Earth Science

OCO was designed to revolutionize our understanding of the global carbon cycle by returning space-based measurements of atmospheric carbon dioxide (CO_2) with the sensitivity and sampling density required quantify regional scale carbon sources and sinks and characterize their interannual variability.

1.1. Carbon Source/Sink Uncertainties

Since the beginning of the Industrial Age, fossil fuel combustion and cement manufacturing have emitted 304 ± 30 billion tons of carbon (GtC) into the atmosphere as carbon dioxide (CO_2) [Marland and Rotty, 1984; Andres *et al.,* 1999; Marland *et al*., 2008]. Since 1850, an additional 162 ± 160 GtC has been added by deforestation and land use change [DeFries *et al*., 1999; Houghton 1999]. In response to these emissions, the atmospheric CO_2 concentration has increased by 37%, from ~280 parts per million by volume (ppm) in the 1750's to more than 385 ppm today. For more than 50 years, precise atmospheric CO_2 measurements have been collected from a sparse network of surface stations. These measurements indicate that, on average, less than half of the CO_2 emitted into the atmosphere by human activities remains there. The balance is apparently being absorbed by the ocean and by plants and soils on land (**Figure 1**).

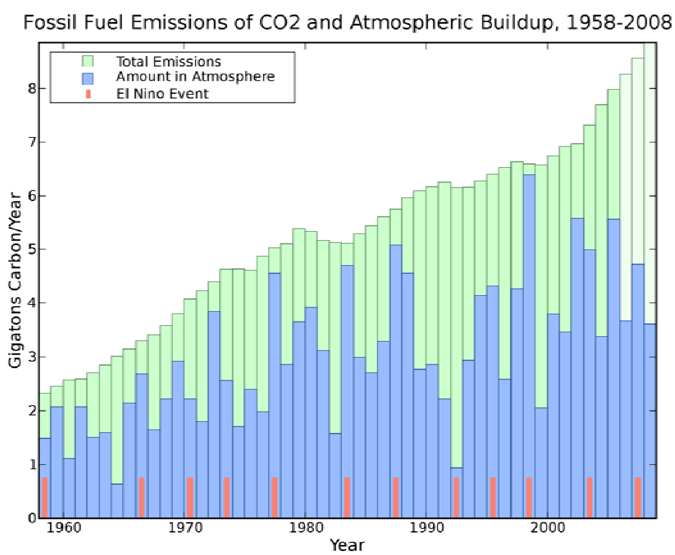

Figure 1. Global average atmospheric carbon emissions from fossil fuel combustion (green) are compared to year-to-year changes in the atmospheric carbon buildup measured at Mauna Loa Observatory, Hawaii (blue). Fossil fuel emissions from 1958-2005 are from Marland *et al.,* [2008]. Values for 2006-2008 are extrapolated assuming a growth rate of 3.5% per year. Emissions for land use practices and other human activities add an additional ~1.5 GtC/year. The atmospheric buildup rates at Mauna Loa are taken from the NOAA ESRL, Cooperative Air Sampling Network [Tans, 2009]. Globally averaged values since 1980 are similar. The area in green represents the carbon absorbed by the terrestrial biosphere and ocean. The dramatic year-to-year variations in atmospheric CO_2 growth rates are poorly understood.

While estimates of the ocean sink for anthropogenic carbon are converging on average values near 2 GtC/year [Manning and Keeling, 2006; Gruber *et al.,* 2009], the carbon fluxes over the Southern Ocean are still poorly quantified. In addition, we lack a quantitative understanding of the strength and geographic distribution of carbon fluxes from the terrestrial biosphere. The processes responsible for the dramatic year-to-year variations in the atmospheric CO_2 accumulation are also largely unknown. An improved understanding of these sinks, the underlying processes that control their efficiency, and their possible evolution in response to climate change, is essential to enable accurate predictions of future increases in atmospheric CO_2 and its impact on the climate [Fung *et al*., 2005; Houghton, 2007; IPCC 2007].

Measurements of atmospheric CO_2 provide a powerful integral constraint on surface sources and sinks. It is also possible to infer the distribution of the carbon sources and sinks from small gradients in CO_2 concentration. These gradients are subtle (1 – 3 ppm) and must be discerned against a relatively large background signal (~385 ppm) as well as diurnal (5 – 25 ppm), synoptic (2 – 40 ppm), seasonal (2-10 ppm) and interannual (1 – 4 ppm) variations, [Olsen and Randerson, 2004], and sporadic sources, such as fires, whose signals become severely damped by atmospheric diffusion in times as short as one week [Dufour and Breon, 2003]. Therefore, there is a strong need for accurate, global atmospheric CO_2 measurements with dense coverage in space and time. The primary supplier of atmospheric CO_2 measurements is the Cooperative Air Sampling Network, managed by the NOAA Earth Systems Research Laboratory (NOAA ESRL). This network has expanded continuously over the past 50 years, and now provides the precision and sampling densities needed to define global CO_2 trends. However, it still lacks the coverage or resolution to map sources and sinks on regional scales over the globe. The network is particularly sparse in the tropics and over the oceans.

NASA selected the Orbiting Carbon Observatory (OCO) in 2002 to address these issues. OCO was designed to make space-based measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize CO_2 sources and sinks on regional scales and quantify their variability over the seasonal cycle. This is a particularly challenging space-based measurement because the surface sources and sinks of CO_2 must be inferred from subtle spatial and temporal variations in the column averaged CO_2 dry air mole fraction, X_{CO2}. Existing measurements and modeling studies indicate that X_{CO2} variations rarely exceed 2% (8 ppm against an ambient ~385 ppm background) on regional scales (1000 km by 1000 km). Modeling studies indicate that X_{CO2} measurements with accuracies near 0.3 to 0.5 % (1 to 2 ppm) on regional-to-continental scales are needed to identify surface CO_2 sources and sinks at these spatial resolutions and characterize their variability over the seasonal cycle [Miller *et al.*, 2007].

To meet these stringent measurement requirements, OCO carried a 3-channel imaging grating spectrometer designed to measure the absorption of sunlight by CO_2 and molecular oxygen (O_2) with unprecedented sensitivity and resolution over the sunlit hemisphere. This instrument recorded high spectral resolution ($\lambda/\Delta\lambda > 24{,}000$) measurements of CO_2 absorption at near infrared wavelengths near 1.61 and 2.06 microns (μm), to yield estimates of the column integrated CO_2 abundance with their greatest sensitivity near the surface, where most of the sources and sinks are located. These data were to be combined with measurements of O_2 absorption in the 0.765 μm A-band to eliminate biases introduced by uncertainties in the surface pressure, scattering by thin clouds and aerosols, and pointing errors. To maximize the sensitivity and sampling rate, the instrument combined a fast (f/1.8), efficient optical system with state-of-the-art diffraction gratings and focal plane arrays pioneered for use in the next generation Hubble Space Telescope and James Webb Space Telescope instruments. With these assets, the OCO instrument could record up to 24 soundings per second, yielding estimates of X_{CO2} with single-sounding precisions between 0.5 and 3 ppm over 95% of the range of latitudes on the sunlit hemisphere (even latitudes as high as Moscow on clear days in the winter). It could record up to 10^6 soundings every day, with measurement footprints small enough (< 3 km^2 at nadir) to ensure that some cloud free soundings are collected even in partially cloudy regions. Extensive independent reviews of the results from pre-launch testing of the instrument, calibration algorithms, and X_{CO2} retrieval algorithms indicated that the instrument met or exceeded its performance requirements. A few minor flaws identified during pre-launch tests (weak residual image in two channels and a 70 arc-second misalignment between the bore-sights) will be fixed in hardware in any OCO rebuild. To ensure that OCO could also meet its stringent requirements in space, a comprehensive ground-based validation network was built, calibrated, and deployed.

The failure of the OCO launch has prompted a reevaluation of the needs for space based CO_2 measurements. Much has been learned about the global carbon cycle since OCO was selected in 2002. New insights from measurements by ground-based networks, ocean monitoring campaigns, aircraft, and satellite observations are reviewed in **Section 1.2**. This review focuses primarily on improvements in our understanding of carbon cycle interactions with the atmosphere, since this is the scientific area most affected by the loss of OCO. These new measurements and modeling studies reinforce the urgent need for the precise, high resolution, global, space-based measurements of atmospheric CO_2 that OCO was designed to provide.

In addition, since the selection of the OCO mission, other space based instruments have started to return measurements of atmospheric CO_2. For example, thermal infrared sounders including the Atmospheric Infrared Sounder (AIRS) on the Earth Observing System (EOS) Aqua platform, the Tropospheric Emission Spectrometer (TES) on the EOS Aura platform, and the European Space Agency (ESA) Infrared Atmospheric Sounding Interferometer (IASI) on its operational meteorological platform, MetOp, can make CO_2 measurements with accuracies of ~1% (4 ppm) at altitudes between 5 and 15 km. While these measurements have improved our understanding of the CO_2 distribution at these altitudes, they have very limited sensitivity near the surface, where the CO_2 sources and sinks are located. Other instruments such as the TANSO-FTS on the Japanese Greenhouse Gases Observing Satellite (nicknamed, IBUKI) can make global measurements of CO_2 near the surface, but with *substantially lower sensitivity and spatial resolution* than OCO. In short, while simultaneous observations from these satellites will yield much additional insight into our understanding of CO_2 sources and sinks, none of these sensors provide the sensitivity and resolution needed to replace OCO.

Specific innovations developed by the OCO team to meet its stringent requirements are summarized in **Section 2**. The OCO measurement capabilities are compared to those of the other space-based atmospheric CO_2 measurements in **Section 3**. **Section 4** describes the OCO mission in the context of the National Research Council's Decadal Survey for Earth Sciences, which identifies this mission as a critical pathfinder for the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission. **Section 5** describes the increasing importance of data like that to be collected by OCO to policy makers.

1.2. Advances in Carbon Cycle Science since the Selection of OCO

Since OCO was selected in 2002, the international carbon cycle science community has made substantial progress in observing and understanding CO_2 sources and sinks, and their relationship to climate change. Much of this work was motivated by the anticipation of OCO measurements. Carbon cycle science is a uniquely interdisciplinary field that requires coordinated advances in oceanography, terrestrial ecology, and atmospheric science. Anticipation of the OCO mission prompted advances in observing and understanding of all three "spheres" (atmosphere, ocean, and land biosphere) over the past 8 years (see below).

The observational network for atmospheric CO_2 was initially designed to document the slow rise (less than 1%/year increase) of the mixing ratio of CO_2 throughout the world. In 2002, it consisted of about 100 cooperative sampling stations in remote “background” locations far from large sources or sinks (**Figure 2**). Flasks of air were collected about once a week at these remote sites and sent to the NOAA ESRL (formerly, the Climate Monitoring and Diagnostics Laboratory, CMDL) for analysis. These data were averaged into monthly or annual means, and were used to estimate carbon sources and sinks at continental to global scales by comparing time-averaged spatial variations in CO_2 [e.g., Gurney *et al*., 2002, Baker *et al*., 2006a].

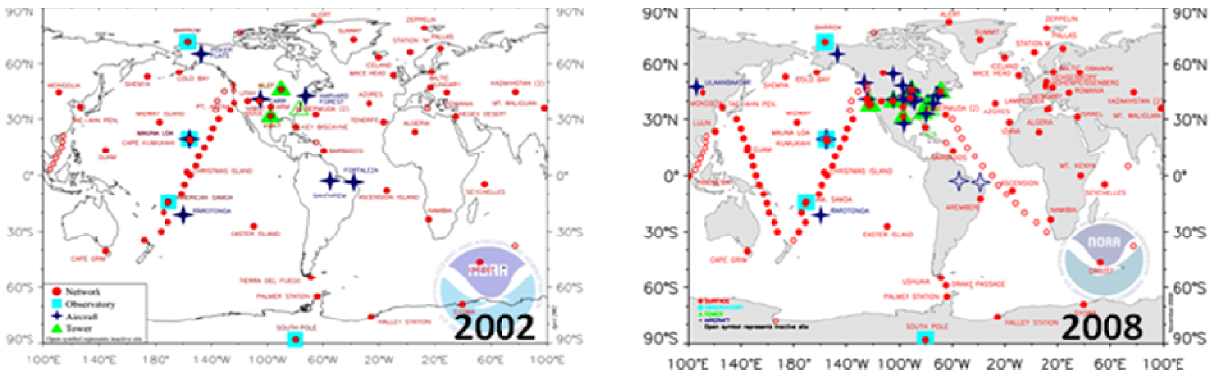

Figure 2. Comparison of the global network of surface (red filled circles) tower (green triangles) and aircraft (blue stars) observations of atmospheric CO_2 in 2002 (left) and 2008 (right) [see http://www.esrl.noaa.gov]. Open circles indicate inactive sites. Several new stations have been established in North America and Europe since the selection of OCO in 2002. Yet the network remains extremely sparse throughout the tropics, Africa, South America, and Australia (and indeed throughout the entire Southern Hemisphere). As a result, the empirical determination of CO_2 sources and sinks for much of the world is accompanied by large uncertainties.

Measured annual-mean, CO_2 concentration differences from the Arctic to the Antarctic were on the order of 4 ppm (~1%) at the surface and east-west variations were typically smaller than 0.5 ppm (~0.1%) between some North American stations. Consequently, extremely precise long-term measurements are crucial for interpretation of sources and sinks on a broad geographic scale. When OCO was selected in 2002, the state-of-the-art for CO_2 source-sink interpretation was represented by the Atmospheric Tracer Transport Model Intercomparison Project (TransCom), which attempted to diagnose annual mean and seasonal sources and sinks for 11 land and 11 ocean regions using near-surface measurements of monthly mean CO_2 from a few dozen remote locations [Gurney *et al.*, 2002]. They found that ~25% of the CO_2 emissions from fossil fuel combustion were absorbed by the ocean and another ~25% of these emissions were taken up by poorly quantified terrestrial processes.

Despite significant advances in our understanding of the global carbon cycle and the expansion of the *in situ* CO_2 network since 2002, large regions of the world (tropical continents and the Southern Ocean poleward of 58°S) remain so sparsely observed that the uncertainty ranges do not allow us to determine whether these regions are sources or sinks [Gurney *et al.*, 2008; Gruber *et al.*, 2009]. The processes governing variations and trends in carbon exchanges are even less well-quantified. We need to understand these controlling processes to predict the future carbon balance of the land and ocean [Fung *et al.*, 2005; Friedlingstein *et al.*, 2006].

1.2.1. Oceans

Arguably the most important new ocean carbon constraints over the last eight years were based on analysis and synthesis of two in-situ sampling programs: full-depth water column measurements made by ship surveys in the 1990's through the World Ocean Circulation Experiment (WOCE) and Joint Global Ocean Flux Study (JGOFS) programs [Sabine *et al.*, 2004] and a rapidly growing archive of surface water CO_2 partial pressure (pCO_2) measurements from volunteer observing ships (both commercial and research vessels) [Takahashi *et al.*, 2002; Takahashi *et al.*, 2009]. The high-quality WOCE/JGOFS data provide the first comprehensive global assessment for ocean concentrations of dissolved inorganic carbon and the partial pressure of dissolved CO_2, allowing the partitioning of the cumulative anthropogenic CO_2 signature from the background (preindustrial) carbon chemistry in the oceans [Sabine *et al.*, 2004].

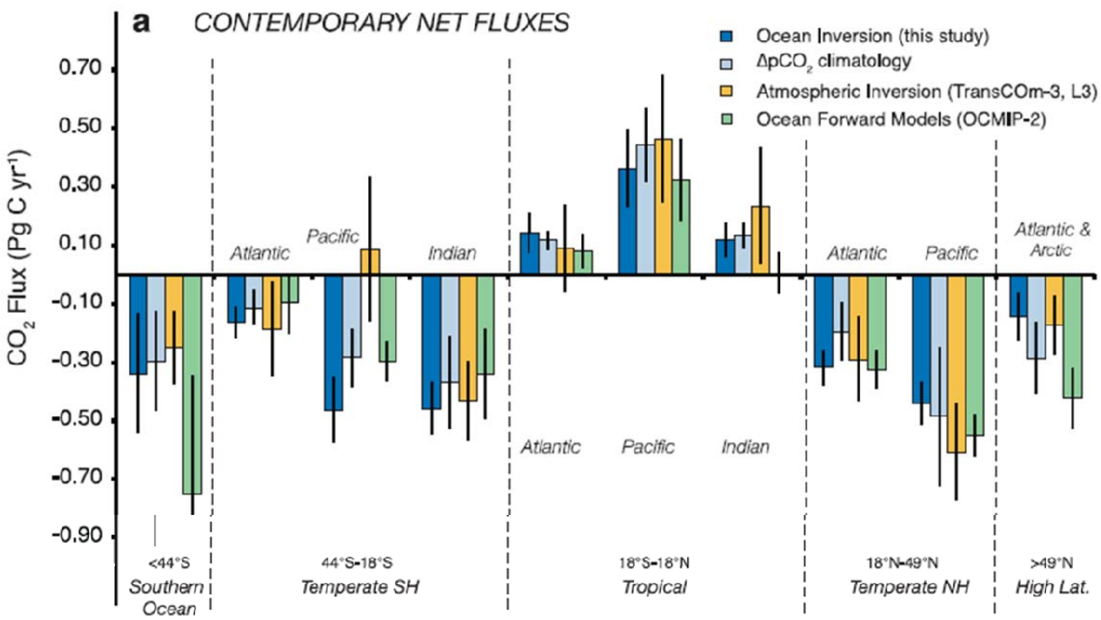

Figure 3. Air-sea CO_2 fluxes retrieved for 10 ocean regions, using Ocean Inversion, pCO_2, Atmospheric Inversion, and ocean forward models [from Gruber *et al.,* 2009]. The improving convergence of the results from these methods is encouraging, and shows that the ocean is both a source and a sink of CO_2, with fluxes characterized by emissions in the tropics, uptake in mid-latitudes, and comparatively small fluxes at high latitude of both hemispheres. These flux results provide important constraints on the time-averaged response of the ocean to the current climate and atmospheric CO_2 inputs, but provide little insight into how the ocean will change in response to changes in the climate or further increases in atmospheric CO_2.

These data have been used to estimate the time-averaged regional CO_2 budgets of the oceans quite precisely [Gloor *et al.*, 2003, Mikaloff-Fletcher *et al.*, 2007, Gruber *et al.*, 2009]. The total oceanic uptake of CO_2 for 1995 to 2002 was estimated to be 2.2 ± 0.3 GtC/yr based on the inversion method and 1.9 ± 0.3 GtC/yr based on the pCO_2 method, which agrees remarkably well with the oceanic uptake rate of 1.9 ± 0.6 GtC/yr for 1990 to 2000 estimated from the decline in atmospheric O_2/N_2 [Manning and Keeling, 2006]. The large ranges previously reported for the annual mean, Southern Ocean air-sea CO_2 flux are now converging, although, as noted in Section 1.1, the uptake of carbon by the Southern Ocean poleward of 58°S remains highly uncertain [Gruber *et al.*, 2009] (**Figure 3**).

Over much of the ocean, particularly in the southern hemisphere, atmospheric CO_2 variability reflects air-sea CO_2 fluxes [Nevison *et al*., 2008]. Unfortunately, the current *in situ* CO_2 network is far too sparse to characterize the processes controlling these fluxes. Gruber *et al.* [2009] state: "our analysis is by design limited to the long-term mean state and does not provide insight on how strong and fast the ocean carbon cycle will respond to changes in external forcing". A number of studies indicate decreasing effectiveness of the ocean carbon sinks in the Southern Ocean [Le Quere *et al*., 2007; Lovenduski *et al.*, 2008] and North Atlantic [Schuster and Watson, 2007]. Significant controversy surrounds these findings and in particular whether climate induced trends have actually been detected [Böning *et al*., 2008; Thomas *et al*., 2008].

Future projections of oceanic carbon uptake depend in part on establishing the response of the Southern Ocean to climate change and in particular whether increases in wind speed over this region of the world either reduces (as suggested by Le Quere *et al*. [2008]) or increases (as suggested by Law *et al*. [2007]) carbon uptake by the Southern Oceans. Space-borne observations of atmospheric CO_2 with sufficient accuracy, precision, and spatial resolution over the Southern Oceans would have contributed to assessing whether this region is a net source or sink of carbon to the atmosphere under present-day conditions. Establishing the direction of the net flux of carbon, particularly for the region poleward of 58°S, is a prerequisite for assessing the ability of models to accurately simulate the response of the Southern Ocean to climate change.

The largest source of interannual variability in the ocean carbon system is in the Equatorial Pacific, associated with the El Niño/Southern Oscillation (ENSO). This region is reasonably well constrained by oceanic observations. However, for most of the rest of the globe, *in situ* ocean sampling is grossly inadequate for resolving interannual variability in air-sea CO_2 fluxes, and even the seasonal cycle is poorly known in many regions [Doney *et al*., 2009b; Doney *et al*., 2009c]. Again, space-based observations from OCO, acquired using its glint observing mode, were expected to have the unprecedented sensitivity and spatial resolution needed to assess these oceanic carbon fluxes.

The past eight years also have seen the emergence of ocean acidification as a major science issue in global change [Feeley *et al*., 2004; Orr *et al*., 2005; Doney *et al*., 2009a]. While the ocean can sequester carbon for centuries to millennia because of the long lifetime of carbon in this reservoir, this process is expected to lead to a considerable increase in ocean acidification, resulting in profoundly negative consequences for oceanic ecosystems [e.g., Orr *et al.*, 2005; Doney, 2006]. Organisms that make their hard shells from aragonite, a form of calcium carbonate, are most vulnerable. Projections suggest their shells may be unable to form throughout much of the Southern Ocean by the middle of this century. While this problem has been known for many years, it has not received the same attention as many other consequences of climate change. Ken Caldeira told the March 2009 Copenhagen conference:

> *The choice to continue emitting carbon dioxide means that we will be an agent of biological change of a force and magnitude exceeded only by the causes of the great mass extinction events. If we do not cut CO_2 emissions deeply and soon, the consequences of ocean acidification will stand out against the broad reaches of geologic time. Those consequences will remain embedded in the geologic record as testimony from*

a civilization that had the wisdom to develop high technology, but did not develop the wisdom to use it wisely.
http://www.guardian.co.uk/environment/2009/mar/10/carbon-emissions-oceans-copenhagen

The recent determination that the ocean solubility and biological pumps are indeed sequestering carbon at a rate of ~2 GtC/yr [Gruber *et al.*, 2009] establishes the seriousness of potential future increases in ocean acidity. OCO measurements would have provided additional insight into the spatial distribution of oceanic CO_2 sources and sinks. This information is critical for understanding the underlying mechanisms and deducing trends associated with climate change. This information would be particularly valuable over the huge expanse of the Southern Ocean. Baker *et al.* [2008] drew attention to the possibility that data from OCO would contribute to improved understanding of carbon uptake by the Southern Ocean, particularly if the satellite could collect measurements through relatively clear patches in the pervasive cloud fields. The small measurement footprint and high sensitivity of OCO provided the best hope for reducing the uncertainty in the Southern Ocean sink using space-based observations of column CO_2.

1.2.2. Land

Advances in 3 areas have dominated the development of our understanding of the terrestrial carbon cycle over since 2002: (1) the role of land management, fires (both wildfire and intentional burning) and other disturbances on the current land sink; (2) the integration of image-based remote sensing and continental-scale *in situ* flux networks to characterize the interannual variability in terrestrial carbon fluxes; and (3) improved understanding of the role of carbon-climate feedbacks in predictions of the future atmospheric CO_2 growth rate.

It has become clear from a decade of ecosystem manipulations (especially Free Air Carbon Enrichment Experiments – FACE) that "CO_2 fertilization" can account for only a fraction of the historical terrestrial sink [DeLucia *et al*., 2005]. Other mechanisms are tied to human land management [Hurtt *et al*., 2006]: forest regrowth in the developed world, forest fire suppression, woody encroachment; or inadvertent modification of ecosystems. Nitrogen deposition and lengthening boreal growing seasons account for much of the current land sink [King and Dilling, 2007]. Quantitative understanding of spatial, seasonal, and interannual variations in terrestrial carbon budgets for various ecosystems has benefited tremendously from data collected by a network of over 300 ecosystem-level measurement studies conducted from eddy covariance towers around the world [Baldocchi, 2008]. However, these measurements are at the scale of individual ecosystems (a few hectares) and require substantial upscaling to be linked to regional and global budgets. The role of climate fluctuations has been confirmed by detailed interdisciplinary data sets from coordinated field campaigns and *in situ* measurements in Europe following the heat wave and drought of 2003 [Ciais *et al*., 2005], and the role of fire as a major driver of interannual variations has been confirmed by analysis of combustion gases [Langenfelds *et al*., 2002] and land remote sensing and modeling [van der Werf *et al*., 2006].

Remote sensing measurements from instruments such as the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua and the Advanced Land Imager (ALI) on Landsat have provided key information to understand variability in ecosystem dynamics across space and time [*e.g.*, Potter *et al*., 2007]. A decade ago, terrestrial carbon cycle researchers struggled to explain the nature and location of sinks. As noted above, numerous hypotheses to explain the terrestrial carbon sink have now been put forward and we have a much better understanding of how various processes interact to enhance or diminish terrestrial carbon uptake. Remote sensing of land use change has documented the extent of global deforestation and the impact of deforestation on the global carbon cycle [e.g., DeFries *et al*., 2008; Hansen *et al*., 2008; IPCC, 2007 (Chapter 7)].

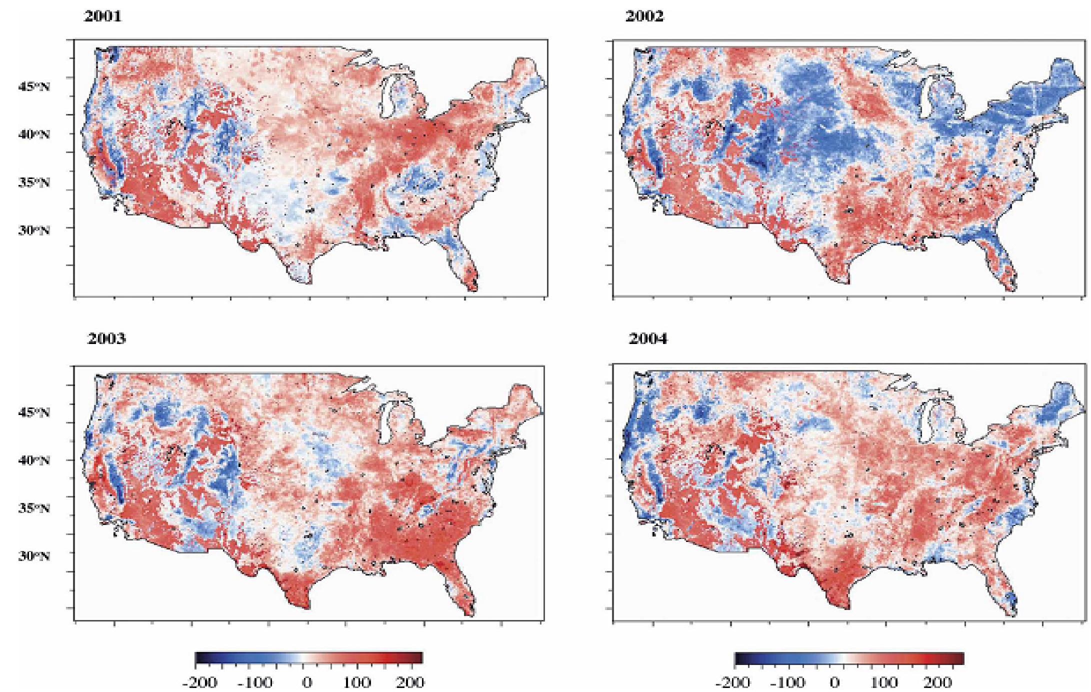

Figure 4. Estimates of net ecosystem production (NEP) derived using the CASA model driven by MODIS enhanced vegetation index (EVI) inputs for the 48 contiguous United States from 2000-2004. NEP is expressed in Pg C per year, with red shading indicating annual carbon sinks and blue shading as annual carbon sources [Potter *et al.,* 2007]. Climate patterns, such as the lower annual mean temperatures and increased precipitation in the eastern U.S. in 2003 increased the strength of the predicted sinks there. Comparisons between modeling results and measurements from CO_2 flux towers show good agreement over much of the U.S. However, there are still areas of substantial disagreement, such as over the Canadian boreal forests (not shown here), where the models overestimate the observed sink strength.

For example, as part of the North American Carbon Program (NACP), regional model results are being synthesized to estimate net fluxes of carbon, expressed as the net ecosystem exchange (NEE) from terrestrial ecosystems across North America. These studies were designed to determine the magnitudes and spatial distributions of carbon sources and sinks, and their uncertainties during 2000-2005, and whether inverse (atmospheric) and forward (ecosystem) model results show consistent spatial patterns in response to the 2002 drought [Potter *et al.,* 2007]. The CASA (Carnegie-Ames-Stanford Approach) forward simulation model was used in this study, driven with satellite observations of monthly vegetation cover (Vegetation Index, VI) from MODIS to simulate ecosystem variations in both time and space. Regional climate patterns were reflected in the predicted annual NEE flux from the CASA model, which showed extensive carbon sinks in ecosystems of the southern and eastern regions in 2003–2004, and major carbon source fluxes from ecosystems in the Rocky Mountain and Pacific Northwest regions in 2003–2004 (**Figure 4**). Annually summed NEE results confirmed that the drought year of 2002 stood out from the other years 2000–2004 with relatively large CO_2 source fluxes in ecosystems of the northeastern and north-central regions of the contiguous U.S. Similar results have been seen in Europe, where the severe heat wave during the summer of 2003 was associated with the release of about 2 Gt of CO_2 into the atmosphere, negating five years of CO_2 uptake by European ecosystems [Ciais *et al.,* 2005]. Unfortunately, this event could not be analyzed in detail due to the lack of sufficiently dense atmospheric CO_2 measurements at that time.

Preliminary synthesis results presented at the February 2009 NACP Investigators Meeting highlighted several modeling and data inputs uncertainties that a sensor like OCO could have reduced. First, the bottom-up ecosystem carbon models are in closer agreement with one-another than with the top-down inversion approaches for total annual net sink fluxes over North America and the major geographic patterns in these predicted NEE fluxes. Furthermore, some of the top-down inversion models predict large annual CO_2 sink fluxes over extensive areas of western boreal Canada that are comparable in magnitude to regional sink fluxes in the southeast United States, whereas few (if any) of the bottom-up ecosystem carbon models predict these types of large annual CO_2 sink fluxes over extensive areas of the boreal forest region. Without regular measurements of atmospheric CO_2 from a sensor like OCO, the top-down models will continue to generate high uncertainties in distinguishing regions from one another in terms of annual NEE fluxes.

Other carbon cycle research focuses on quantifying the persistence and saturation of terrestrial sinks and the potential to turn land ecosystems that are currently sequestering carbon into future powerful sources of CO_2. Nearly every mechanism proposed to explain the current land carbon budget contains the expectation of a “built-in” saturation process. Once forest regrowth is complete, or nitrogen demand has been satisfied, or forest fires burn protected lands, the carbon sink disappears. A particular concern has emerged over the fate of the tropical forests under climate change that induces drought [Cox *et al*., 2000, 2004]. Transient droughts have been shown to enhance photosynthesis, which is light limited in tropical rainforests [Saleska *et al*., 2003; Huete *et al*., 2006], while permanent droughts are expected to cause dieback of forests. In some coupled simulations of climate and the carbon cycle, changes in precipitation forced by changes in ocean circulation lead to catastrophic loss of forests (and their stored carbon) across South America, and the release of many Gt of nonfossil CO_2 into the atmosphere. Warming boreal climate can allow shrub encroachment into formerly tundra-dominated ecosystems (sequestering carbon), but continued warming could lead to melting of permafrost, exposing organic matter fixed over thousands of years to microbial decomposition and dramatically increasing the loading of atmospheric CO_2 [Zimov *et al*., 2006]. Future projections indicate that a flux as large as 1 billion tons of CO_2 each year could be released to the atmosphere by the irreversible melting of permafrost and decomposition of frozen carbon stores [Khvorostyanov *et al*., 2008].

One of the most important scientific results in carbon cycle science since OCO was selected was the realization that uncertainty in the projection of climate for the 21st century is driven as much by our inability to quantify the feedback between biogeochemical cycles and climate change as it is by uncertainty in the physical modeling of the cloud and water vapor feedback or economic projections of CO_2 emissions from fossil fuels. Given identical fossil fuel emissions, models that represent the coupling of climate and the carbon cycle project a range of almost 300 ppm for atmospheric CO_2 concentrations by 2100 (**Figure 5**).

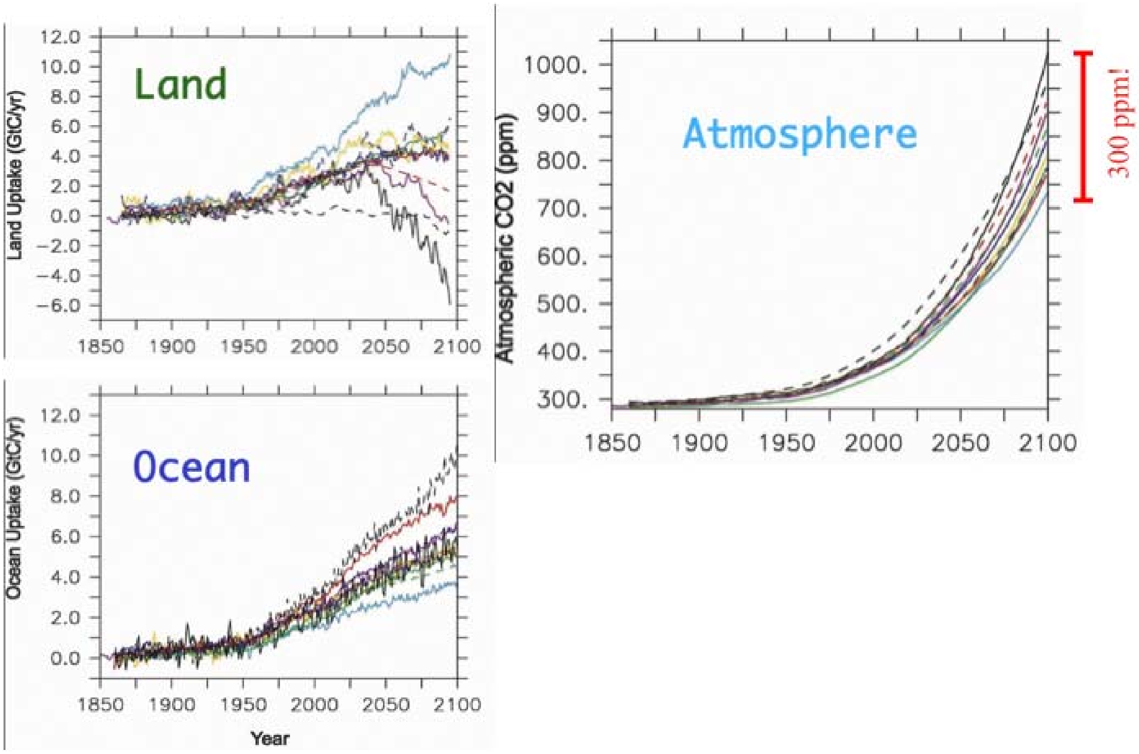

Figure 5. Intercomparison of 250 years of simulated carbon uptake by land and oceans, and the resulting atmospheric CO_2, by 11 coupled models of climate and the carbon cycle, using identical fossil fuel emissions (Friedlingstein *et al.*, 2006).

This range for atmospheric CO_2 is comparable to the difference between high and low emission scenarios for non-interactive models, and leads to differences in future physical climate commensurate with the range predicted by variations in the physical modeling of the cloud and water vapor feedback for models with prescribed future CO_2 [Friedlingstein *et al*., 2006]. It is well-known that the physics of clouds and aerosol limit the ability of climate models to predict how much warming will arise from a given change in CO_2. Similarly, it would be a serious oversimplification to assume that the amount of CO_2 in the atmosphere in the future is predictable for a given level of fossil fuel emissions. The lesson from these simulations is that even for a prescribed fossil fuel emission scenario, current coupled carbon-climate models are unable to predict CO_2 levels in 2100 to within 300 ppm, which is equivalent to about 40 years of present anthropogenic CO_2 emission levels.

While space based imaging observations of land use change provide indirect evidence for carbon release and sequestration by a variety of ecosystems, measurements of atmospheric CO_2 have not yet been made on the same scale, so we cannot determine how these land use changes affect the carbon balance. For instance, the community has not been able to ascertain the impact of reforestation on the global carbon cycle, particularly during the early stages of forest re-growth [IPCC 2007, section 7.3.3.1.6]. The lack of precision for the impact of reforestation on the carbon cycle contributes, in large part, to the overall uncertainty in the effect of land use change on the abundance of atmospheric CO_2.

It is easy to imagine the remarkable scientific advances that could have been realized by combining net carbon fluxes inferred from OCO measurements of X_{CO2} with the understanding of terrestrial ecosystems afforded by remote sensing measurements by instruments such as MODIS and Landsat. OCO observations would have closed the loop by providing direct measurements of the CO_2 fluxes associated with land use changes, fires, and other disturbances. Without OCO X_{CO2} data, the terrestrial imaging measurements will not attain their full potential. While much of the community will now focus on synergies between terrestrial biosphere data and measurements from GOSAT, these results will have to be averaged over larger areas and longer time scales than those anticipated from OCO. One compelling rationale for a near immediate replacement OCO is to obtain overlap with the long-term data sets from MODIS and Landsat sensors, in advance of their replacements with the Visible/Infrared Imager/Radiometer System (VIIRS) on the National Polar Orbiter Environmental Satellite System (NOPESS) and the Advanced Land Imager (ALI) on the Landsat Data Continuity Mission (LDCM).

1.2.3. Atmosphere

Advances in atmospheric CO_2 observations since the selection of OCO in 2002 include:

- expansion of the surface *in situ* monitoring network onto continents, where the CO_2 mixing ratio varies with high frequency and requires accurate continuous monitoring;
- acquisition of regular aircraft profiles of CO_2 from multiple locations;
- measurements of X_{CO2} from several Fourier Transform Spectrometer (FTS) stations installed for studies of the global carbon cycle and validation of OCO and GOSAT data.

Building on the foundations of the Cooperative Air Sampling Network, there are now emerging networks of continuous *in situ* atmospheric CO_2 analyzers deployed on towers in North America and Europe, and smaller networks in Japan, Brazil, and Australia. Aircraft profiles of CO_2 are routinely obtained at a number of extra-tropical northern hemisphere (NH) locations. Measurements of the total column mixing ratio of CO_2 from a network of upward-looking FTS stations have offered new insights into the seasonal and spatial distribution of carbon sources and sinks and provided confidence that space-borne measurements of column CO_2 can be properly validated [Washenfelder *et al*., 2006; Yang *et al*., 2007]. These data also suggest that our understanding of the terrestrial carbon cycle might be considerably revised in the light of widespread column-integrated measurements.

The regular measurement of atmospheric CO_2 from aircraft has allowed quantitative characterization of vertical variations and the seasonal cycle aloft [Stephens *et al*., 2007; Crevoisier *et al*., 2006; Miyazaki *et al*., 2009]. Stephens *et al*. [2007] reported that models that correctly simulate measured altitude and seasonal variations of atmospheric CO_2 for the extra-tropical NH, exhibit much more terrestrial carbon uptake in the tropics, and much less uptake in the extra-tropical NH, than is commonly believed to occur. This study challenges pre-conceived notions regarding the efficiency of the tropical and extra-tropical NH terrestrial sinks and establishes the need for additional measurements, particularly in the tropics, to test their hypothesis (they presented no tropical measurements of CO_2). Interestingly, when inversion models based on measurements of atmospheric CO_2 are "forced" towards the values for ocean carbon uptake inferred from the cruise data (section 1.2.1), the location of the terrestrial land carbon sink shifts from the tropics to the extra-tropical north [Jacobson *et al*., 2007; Baker, 2007]. Clearly, the location of the terrestrial carbon sink remains highly uncertain, both as a function of latitude (i.e., tropics *vs.* extra-tropical NH) and longitude.

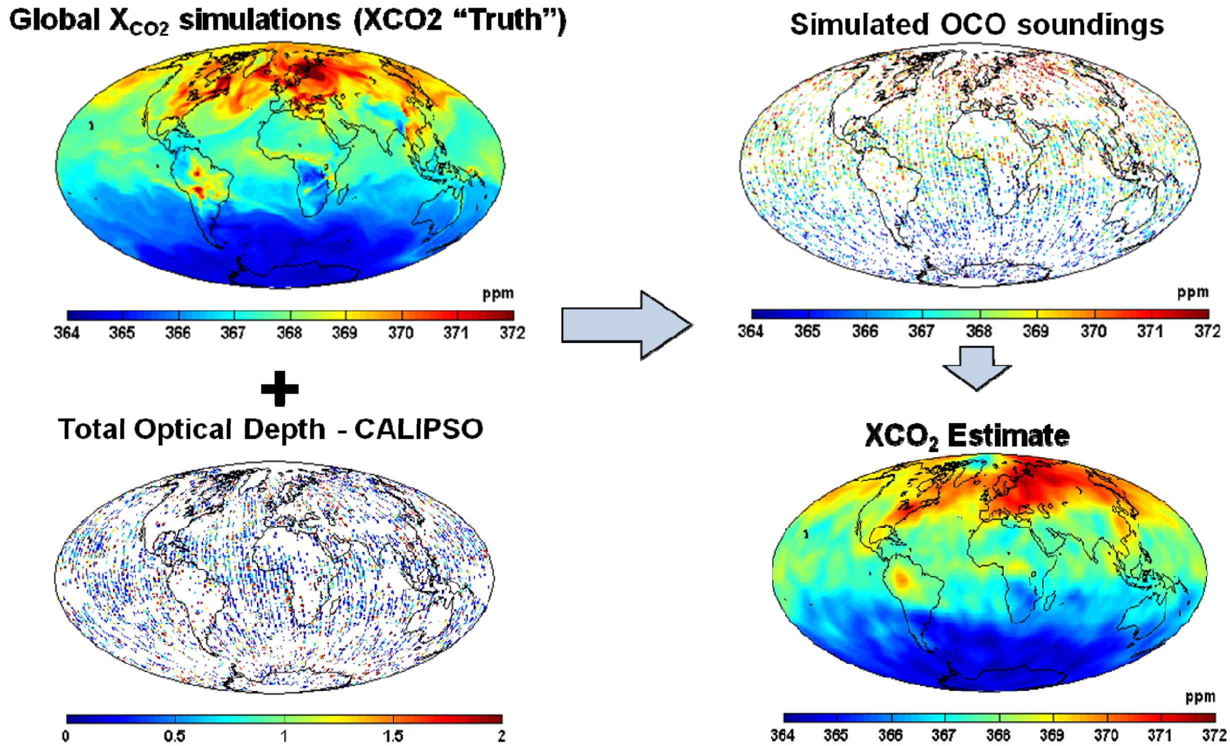

Figure 6: Modeling studies performed with the PCTM/GEOS-4 (top left; from Randy Kawa, GSFC) illustrate the spatial gradients in CO_2 that have come to be known as "carbon weather." While these CO_2 variations are still small (< 8 ppm), the spatial gradients, and their correlation with local weather systems is substantially more pronounced than anticipated from earlier measurements from isolated ground based sites. To assess the impact of these variations on the accuracy of the X_{CO2} fields retrieved by OCO, the time dependent fields are first sampled along the OCO orbit tracks. Scenes that are sufficiently cloud and aerosol free for X_{CO2} retrievals are then identified using optical depth measurements from CALIPSO (bottom left). Observation noise, based on results from pre-flight testing of the OCO instrument, is then added, (top right) to simulate the X_{CO2} field sampled by OCO. Geostatistical methods are used to process the sampled X_{CO2} field and fill gaps and create maps (bottom right) that can be used to assess the information content of the OCO sampling approach. While some of the carbon weather features are lost over the 16-day ground track repeat cycle, OCO, with its high sampling rates, will still capture the primary features of the X_{CO2} field [Anna Michalak and Alanood Alkhaled, U. Michigan]. Instruments with a larger measurement footprint, and greater

The salient new finding from the continuous observation of atmospheric CO_2 is the much greater variation of surface concentrations on synoptic ("weather") time scales relative to the subtle variations of CO_2 previously inferred from measurements at remote locations [e.g., Geels *et al*., 2004; Wang *et al*., 2007; Parazoo *et al*., 2008]. The near-surface atmosphere in continental areas exhibits an order of magnitude more "signal" than we had previously been trying to interpret (**Figure 6**). These new measurements reveal that "CO_2 weather" is characterized by strong gradients (>10 ppm on regional scales) over a day or two, organized along synoptic systems. Previously, the "CO_2 climate" observed at Mauna Loa or the South Pole was based on the interpretation of differences in CO_2 as small as tenths of a ppm. The emergence of "CO_2 weather" has dictated the need to observe atmospheric CO_2 much more densely. Just as weather satellites have advanced numerical weather prediction and our understanding of atmospheric dynamics, the atmospheric carbon community understands that accurate, precise, high spatial resolution space-borne measurements of CO_2 are now needed to quantitatively advance our understanding of the processes that drive fluctuations in the global carbon cycle.

The OCO instrument was optimized to yield individual soundings with X_{CO2} precisions near 1 ppm, within measurement footprints no larger than 3 km^2 at nadir so that it could collect some cloud-free data even in partially cloudy regions. In addition, it was designed to collect large numbers of soundings (> 500,000) over the sunlit hemisphere each day. Simulations with realistic cloud fields show that these features are essential for resolving spatially contiguous sources and sinks and capturing the spatial structures associated with CO_2 weather (**Figure 6**). With the loss of OCO, the atmospheric carbon cycle community must now focus on the use of GOSAT observations to complement ground based, tower, and aircraft data. The reduced single-sounding precision combined with the larger surface footprint (85 km^2) and lower sampling rate (~18,700 soundings/day) [Hamazaki *et al.*, 2007; Shomi *et al.*, 2007] will increase the probability of hitting clouds and pose additional challenges for resolving CO_2 weather.

1.2.4. Source/Sink Modeling Tools

The quantitative tools used to calculate surface sources and sinks from atmospheric CO_2 data have advanced dramatically since 2002. When OCO was selected, models estimated fluxes for continent- or ocean basin-sized regions with monthly mean flask samples at a few dozen locations, using simple techniques based on multiple regression [e.g., Gurney *et al.*, 2002]. Since that time, the community has developed a rich suite of variational [e.g., Baker *et al.*, 2006b; Chevalier *et al.*, 2005, 2006, 2007a,b] and ensemble methods [e.g., Peters *et al.*, 2005, 2007; Zupanski *et al.*, 2007; Lokupitiya *et al.*, 2008; Feng *et al.,* 2008] capable of assimilating the huge X_{CO2} data vectors that will be generated by satellites. Atmospheric trace gas transport simulations during this era developed from using 4×5 degree grid cells to grid cells as small as 0.5 degrees globally or even 1 km for limited areas [Corbin *et al.*, 2008]. In addition, correlations between CO_2 and CO could be exploited to improve the inverse modeling of carbon fluxes [Suntharalingam *et al.*, 2004; Palmer *et al.*, 2006]. While CO is not measured by either GOSAT or OCO, SCIAMACHY measures column CO [Buchwitz *et al.*, 2007a] and measurements above the middle troposphere are currently being made by MOPITT [Deeter *et al.*, 2003], TES [Luo *et al.*, 2007], and AIRS [McMillan *et al.*, 2005].

The community will undoubtedly benefit from the use of GOSAT measurements of X_{CO2}. However, the complementary nature of OCO and GOSAT would have provided unique information on the proper use of orbital and sub-orbital observations of atmospheric CO_2 for constraining the magnitude and location of diffuse carbon sinks. The glimpse of "CO_2 weather" obtained by the atmospheric global carbon cycle community since the original selection of OCO has created strong incentive to push for a re-build and re-launch of OCO to enable overlap with GOSAT, so that the issues such as the finer spatial resolution of OCO (which increases the probability of seeing the surface through scattered clouds) versus the across-track sampling strategy of GOSAT (which allows neighboring air masses to be sampled more frequently) can be properly evaluated. Finally, a near future launch of OCO will likely provide overlap with CO observations obtained by one or more of the A-train instruments that measure this species, which will improve the accuracy of the inferred carbon fluxes.

1.2.5. Human Impacts

Since 2002, there has been a realization that people manage the global carbon cycle in many ways (both intentionally and inadvertently), such that an understanding of energy economics, fossil fuel emissions processes, and land use practices is required to isolate anthropogenic fluxes from the natural background. We have seen greatly improved quantification of fossil fuel emissions at high space/time resolution, over the U.S., with projects like Project Vulcan: (http://www.purdue.edu/eas/carbon/vulcan/GEarth/index.html). Similar advances have been made for European emissions.

However, over this same period, China and other rapidly developing countries have taken the lead in CO_2 emissions from fossil fuels. A preliminary analysis by the Netherlands Environmental Assessment Agency [2007], based on data from the International Energy Agency (IEA), British Petroleum (BP), and the US Geological Survey (USGS), indicates that CO_2 emissions from China surpassed those from the US for the first time in 2006. China accounts for ~22% of the global fossil fuel CO_2 emissions while the US contributes ~19%. However, these calculations are limited by uncertainties in the underlying data (3-5% for the US and 15-20% for China) [Gregg *et al.*, 2008] and rely on official Chinese statistics [Guan *et al.*, 2009]. Evaluation of these inventories requires data that can only be provided by a platform such as OCO.

Another change has been the degree of institutional commitments to this work. In 2002, carbon cycle science was being done primarily by academics and research labs. In 2009, there are a number of pseudo-operational carbon data assimilation products supported by major government entities: at ECMWF/GEMS [e.g., Hollingsworth *et al.*, 2008], NASA GMAO, and NOAA ESRL, including timely delivery of products to stakeholders and the public through easy-to-use websites like Google Earth and NOAA CarbonTracker:

http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/.

Dramatic improvements in data are now needed to fully exploit these new tools. Responding to this need, international and multiagency efforts have been initiated in North America [NACP: Denning *et al.*, 2005; and SOCCR: King and Dilling, 2007] and Europe [CarboEurope: Dolman *et al.*, 2008] to measure and quantify the carbon cycle at continental scales. They find that much of the current land sink is directly tied to human land management for agriculture, suburban development, and commercial forestry. Similar efforts are needed across Asia and in the tropics, but are not practical for economic and geopolitical reasons.

The climate policy environment has evolved significantly over the past decade, and it requires timely science information to formulate changes that may eventually rival the industrial revolution in terms of their impact on the world economy. The urgency of the situation mandates prompt action. OCO remains the best mechanism for providing global observations to verify and validate the scientific basis for carbon cycle and climate policy and management in the timeframe required to inform imminent international treaty negotiations and regulatory efforts.

2. OCO Innovations

The OCO team developed multiple unique innovations in instrument design, observing strategy, retrieval algorithm, and validation approach that are critical to delivering accurate, bias-free space-based X_{CO2} data and the resulting carbon source/sink estimates.

OCO was the first NASA mission designed to return space-based measurements of atmospheric CO_2 with the sensitivity and spatial and temporal sampling required to quantify CO_2 sources and sinks on regional scales over the sunlit hemisphere. This is the most challenging atmospheric trace gas measurement ever attempted from space. **Table 1** summaries some of the unique innovations needed to realize this objective.

Table 1. Summary of OCO innovations

System	Innovation	Impact
Instrument Payload	Acquire NIR measurements of CO_2 absorption in reflected sunlight.	NIR measurements of reflected sunlight are most sensitive to CO_2 near the surface, where sources and sinks are located.
	Bore-sighted measurements of CO_2 at 1.61 and 2.06 μm and the O_2 A-band at 0.762 μm.	Minimize bias due to uncertainties in surface pressure, surface topography, cloud and aerosol scattering, and pointing.
	Optical design combines high spectral resolution, high signal-to-noise ratio (SNR), small footprint	Single sounding X_{CO2} retrievals with random errors between 0.5 and 3 ppm
	High spectral Resolution (>20,000:1)	Maximize CO_2 sensitivity and reduce bias due to spectrally-dependent uncertainties in clouds, aerosols, & surface reflectance.
	Optically fast (f/1.8) spectrometers	High SNR in short exposures, yielding small footprints
Observing Strategy	Nadir Observations	Minimize footprint size and bias over land
	Glint Observations	Maximize SNR over dark ocean and ice
	Target Observations	Dedicated validation mode
	Routine & special calibration modes	Ensure stability and accuracy on orbit
Retrieval Algorithms	Accurate scalar and polarized radiative transfer model	Provides X_{CO2} with minimum inherent bias and adequate error characterization
	Physics-based retrieval algorithm	Retrievals of X_{CO2} for all clear soundings
	Spectroscopic line list	Minimizes retrieval bias
Validation Strategy	TCCON – network of ground based FTSs	Assures accuracy of space-based X_{CO2}; duplicates spectral range and uses same retrieval algorithm used by OCO
	Traceability to the in situ WMO CO_2 standard	Assures accuracy of X_{CO2} and facilitates combination of space-based and ground based measurements of CO_2
	Target Mode observations	Yields many observations over a range of viewing angles for each overpass, facilitating identification of biases.

2.1. Instrument Payload

During the development of the OCO mission, Observational System Simulation Experiments (OSSEs) were performed to identify the key requirements for space based measurements of atmospheric CO_2. These OSSEs showed that a number of innovations in instrument technology were needed to measure X_{CO2} with accuracies of 1 ppm on regional scales.

2.1.1. Spectral Ranges

The OSSEs confirmed that measurements of the absorption of reflected sunlight by CO_2 at near infrared (NIR) wavelengths were extremely sensitive to the CO_2 concentration near the surface, where its sources and sinks are located. NIR measurements provide estimates of the number of molecules along the entire optical path, from the top of the atmosphere, to the surface, and back to the instrument. The weak CO_2 band centered near 1.61 μm was very well suited for identifying sources and sinks because the absorption in this band increases almost linearly with the CO_2 amount and is most sensitive to the CO_2 near the surface.

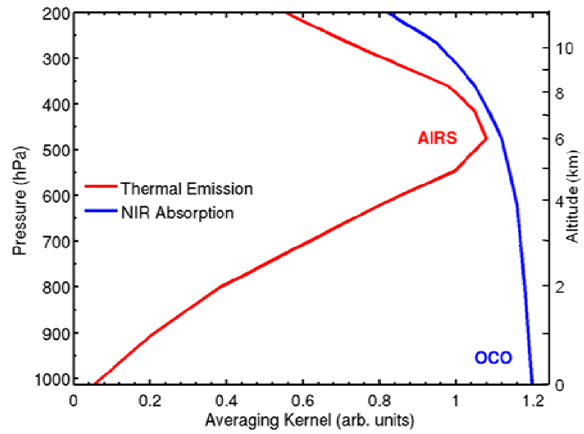

Figure 7. Representative vertical averaging kernels for column CO_2 soundings using NIR absorption of reflected sunlight in the 1.61 μm CO_2 band (blue)and thermal IR emission near 14.3 μm (red). TIR soundings are less sensitive to near-surface CO_2 because of the small surface–atmosphere temperature contrast (Crisp *et al.*, 2004; Chahine *et al.*, 2005).

In contrast, thermal infrared (TIR) measurements, like those being collected by AIRS, TES, and IASI, are sensitive to CO_2 in the middle and upper troposphere, but have far less sensitivity to CO_2 near the surface (**Figure 7**). TIR measurements have low sensitivity to near-surface CO_2 because an absorbing gas will only produce a spectral signature against a bright emitting background if the temperature of the gas differs from that emitting background. CO_2 molecules at low altitudes are at almost the same temperature as the surface below and produce little detectable signal. With these small signals, small uncertainties in the atmospheric temperature profile or optical properties, or surface emissivity can introduce biases in the retrieved concentration of CO_2 (or other trace gas) that are much larger than 1%.

Our OSSEs also showed that measurements of the "total column CO_2" alone, would not provide the accuracy needed to retrieve surface sources and sinks. When OCO was originally proposed, the *Earth Science Enterprise Strategic Plan 2000-2010* identified global maps of *total column CO_2* and *carbon sources and sinks* as required knowledge and recommended that an *exploratory CO_2 column mission* be initiated by 2010 (Objectives 1.2, 1.3). The NASA Carbon Cycle Initiative had identified *global column CO_2* as its highest measurement priority. However, our OSSEs showed that sources and sinks could be detected far more easily using measurements of the column averaged CO_2 dry air mole fraction, X_{CO2}, than from column CO_2. The reason for this is that the measured CO_2 column abundance is affected by a number of factors in addition to the CO_2 concentration, such as the ambient surface pressure, variations in topographic elevation within the footprint of the sounding, and presence of any scattering by clouds and aerosols along the optical path. For example, uncertainties as small as 3 hPa in the surface pressure or 25 meters (m) in the mean elevation of the footprint will introduce a 1 ppm bias in the column-averaged CO_2 dry air mole fraction inferred from the column CO_2 measurement.

To avoid these errors, the OCO instrument was designed to make simultaneous, co-bore sighted measurements of the column abundances molecular oxygen, O_2, and CO_2. These measurements were then used to derive the column averaged CO_2 dry air mole fraction,

$$X_{CO2} = 0.20995 \times [CO_2] / [O_2] .$$

In this expression, the brackets "[ ]" indicate the column integrated gas amount. Molecular oxygen is an ideal proxy for the total atmospheric mass because constitutes 20.995% of dry air everywhere on Earth. We found that high resolution spectroscopic measurements in the 0.765 μm O_2 A-Band were the best suited for this measurement. OCO A-Band measurements provide estimates of surface pressure with accuracies of 1 hPa (0.1%) in individual footprints over much of the Earth. These data are intended to detect and correct atmospheric pathlength biases associated with optically-thin clouds or uncertainties in surface topography or pointing.

Even with co-bore sighted measurements in the 1.61 μm CO_2 band and the O_2 A-band, we found that uncertainties in aerosol scattering could introduce optical pathlength uncertainties that could produce significant errors in X_{CO2} retrievals. The A-Band measurements are very sensitive to aerosols, but were not adequate because aerosol optical properties can change substantially between the A-band and the 1.61 μm CO_2 band. The very strong CO_2 band near 2.06 μm proved well-suited to providing a direct constraint on the aerosol optical properties at near infrared wavelengths. The absorption in this band is far more sensitive to aerosol scattering than the 1.61 μm band, and much less sensitive to the CO_2 abundance because most of the absorption lines in this band are completely opaque (saturated) in their cores. The OCO instrument therefore included three channels: the 1.61 μm channel provides the most sensitive measurements of CO_2, the 0.765 μm O_2 A-band channel constrains cloud and aerosol profiles and the total atmospheric mass along the path, and the 2.06 μm channel provides additional information about both aerosol optical properties and the CO_2 amount (**Figure 8**).

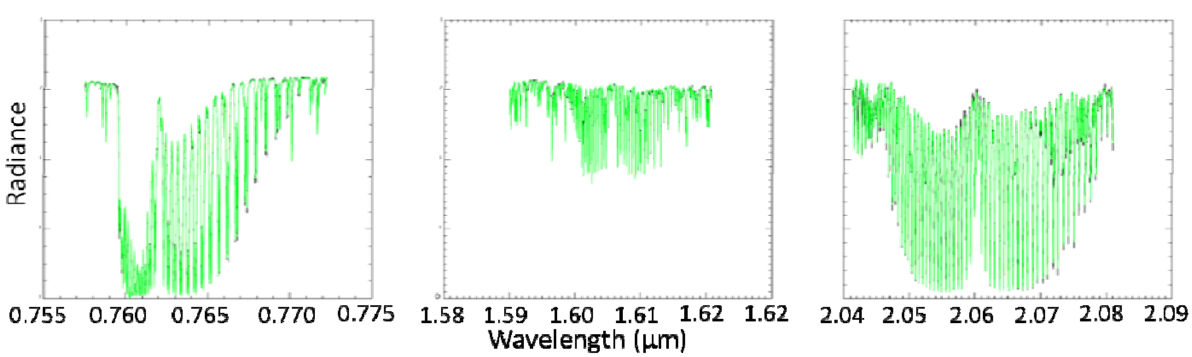

Figure 8. Atmospheric O_2 and CO_2 spectra measured during the pre-launch testing of the OCO instrument. The high spectral resolution resolves individual gaseous absorption features from the underlying continuum to increase the sensitivity and minimize biases associated with variations in the continuum. [Crisp *et al.* 2004; 2008].

2.1.2. Instrument Optical Design

Given these three spectral channels, we still needed an instrument with an unprecedented combination of sensitivity, dynamic range, and speed to measure X_{CO2} with accuracies of 1 ppm on regional scales. To maximize the sensitivity to CO_2 and O_2 variations, and to minimize biases introduced by uncertainties in the wavelength dependent scattering by clouds, aerosols, or the surface, we found that the instrument had to clearly resolve the individual gas absorption lines from the adjacent continuum (**Figure 8**). This required a resolving power, $\lambda/\Delta\lambda > 20,000$ for the O_2 and CO_2 bands chosen here [Crisp *et al*., 2004; Crisp *et al*., 2008].

As the resolving power increases, the available signal measured by each detector decreases and detector read, shot, and photon noise limits the sensitivity of the spectrometer. This is particularly challenging for this application because high signal to noise ratios (SNR) are needed in the absorption line cores as well as in the continuum regions in each of the 3 spectral channels for soundings collected over bright surfaces (Sahara desert, sun glint) near the sub-solar latitude, and dark surfaces (ocean or ice) at very high latitudes (solar zenith angles > 80°).

To meet these sensitivity requirements, we adopted an extremely efficient, optically fast (f/1.8), spectrometer design to maximize the available signal. We further increased the signal and minimized the noise by adopting ultra-low noise Focal Plan Array (FPA) detectors that were designed for use in the next generation Hubble Space Telescope and James Web Space Telescope instruments. We recorded these FPAs using an innovative rolling readout method that minimized dead time between exposures. To further reduce the impact of measurement noise, the FPAs recorded spectra that extended across the entire absorption band in each of the 3 channels, as well as some of the continuum on each side of each band (**Figure 8**). This increased the number of absorption line and continuum measurements recorded for each sounding. Because X_{CO2} retrievals involve a least square fit of a synthetic spectrum to a measured spectrum, this approach improves the band-averaged SNR substantially over that of any single detector.

The OCO instrument was also designed to acquire data very quickly. The Observatory moves along its orbit track at about 7 km/sec, such that, longer exposure times produce larger footprints. This can add uncertainty to X_{CO2} soundings if there are significant changes in the optical path length due to surface topographic variations, clouds, or the solar zenith angle during an exposure. Clouds are a particular problem. Cloud studies using MODIS, Geoscience LASER Altimeter System (GLAS), and Cloud-Aerosol and Infrared Pathfinder Satellite Observation

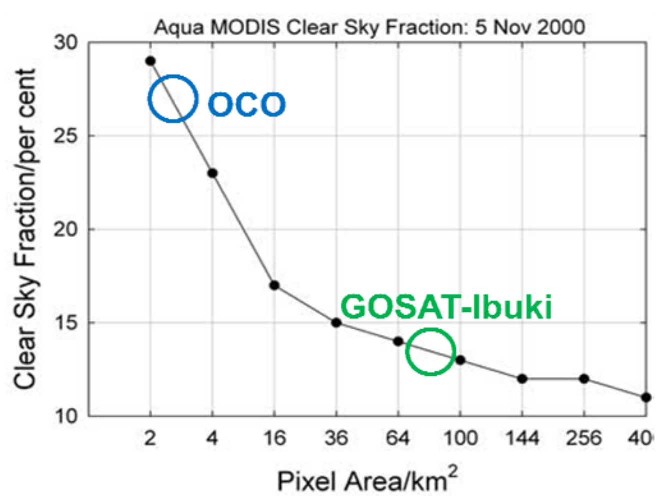

Figure 9. Studies using MODIS cloud fields show that the probability of acquiring cloud free soundings increases with decreasing footprint size [Miller *et al.*, 2007]. Global clear sky frequencies for the OCO < 3 km^2 footprint are compared to those for the GOSAT-TANSO FTS 85 km^2 footprint for 5 November 2000.

(CALIPSO) data show that the probability of hitting a cloud increases quickly with the footprint size. The footprint size can be reduced somewhat by image motion compensation, but, for longer exposures, that approach introduces optical path length errors associated with the varying observation angle.

To avoid both of these sources of bias, the OCO instrument was designed to collect measurements in 4 to 8 adjacent soundings at 3 Hz (12 to 24 sounding/second) as it traveled along its orbit track, yielding a down-track resolution of 2.25 km. We found that with this footprint size, >20% of all soundings will be sufficiently free of cloud contamination and topographic variation to yield reliable X_{CO2} soundings [Bréon *et al*., 2005; Bösch *et al*., 2006; Miller *et al.,* 2007]. By comparison, only ~10% of the soundings meet these criteria for a 10.5 km diameter footprint (85 km^2 area), like that used by the GOSAT TANSO-FTS (**Figure 9**). For larger footprints, like the 30 km × 60 km (1800 km^2) footprint of SCIAMACHY, the fraction of scenes that meet this requirement is substantially smaller.

Given these specifications for spectral range, spectral resolution, dynamic range, SNR, and exposure time, a variety of spectrometer designs were considered by the OCO. Grating and Fourier Transform spectrometer (FTS) designs were the only candidates that could meet the requirements for spectral range and resolution. We found that an FTS design similar to that used by GOSAT could meet the spectral range and resolution requirements, but this approach was rejected because practical systems required long (several second) exposure times. It also required a moving part, which potentially compromised its lifetime. An imaging grating spectrometer design appeared to meet all of our requirements, but even that required additional innovations. The first was to adopt an unusually fast focal ratio (f/1.8) for a spectrometer working at a resolving power near 20,000. Then, to further increase the sensitivity state-of-the-art, very-low-noise focal plane arrays (FPA's) recently developed for astronomical applications, were adopted [Crisp *et al*., 2008].

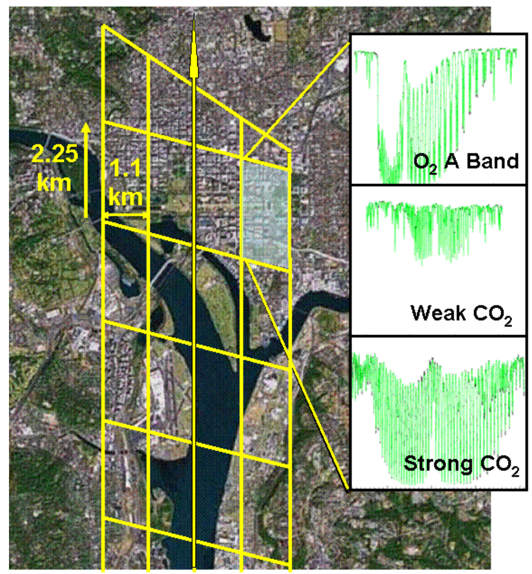

Figure 10. OCO nadir footprints are shown for a track across Washington DC. OCO returns 3 co-bore sighted spectra in 4 to 8 footprints every 0.333 seconds as it traverses the sunlit hemisphere. Single sounding random errors in X_{CO2} were estimated to be 0.5 - 3 ppm for nadir observations, and typically < 1 ppm for glint observations. With its small footprint, OCO could acquire useful sounding even in partially cloudy regions as well as regions with significant surface elevation variations.

2.1.3. Spatial Sampling

Several additional innovations were incorporated into the instrument design to further improve its sensitivity, stability, and accuracy. For example, each 0.333 second exposure records a 1016-element spectrum at 190 spatial locations along a ~0.85° wide slit in each of the spectral channels. Each spectrum therefore describes the CO_2 or O_2 absorption along a 0.004° by 0.18° instantaneous field of view (~100 m by 2.25 km footprint near nadir, **Figure 10**). Because this produces far too much data to return to the ground, the instrument sums groups of ~20 spatially-contiguous pixels on board, and returns 4 to 8 high SNR spatially-binned spectra for each 0.333 second exposure. When the instrument is pointed to the local nadir, and the spectrometer entrance slits are oriented roughly perpendicular to the ground track, this yields a surface footprint of 1.29 x 2.25 km (<3 km^2).

To reduce downlink costs for OCO, only 4 spectra were to be returned every 0.33 seconds. This yields 37,000 soundings per orbit, ~500,000 soundings per day, and 8 million soundings per 16-day repeat cycle. Pre-flight instrument tests showed that for a reference scene at 60° solar zenith angle over a surface with an albedo of 5%, the SNR for the OCO 0.765, 1.61 and 2.06 µm channels would be >300:1, >300:1 and >240:1, respectively [Crisp, *et al.*, 2008]. These values are about ten larger than the SNR values reported by the GOSAT team, when scaled to these illumination levels [Shiomi *et al.*, 2007; Akihiko Kuze, personal communication 2009] even though the GOSAT TANSO-FTS footprint is 30 times larger (3 km^2 vs. 85 km^2).

To further mitigate biases associated with clouds and other sources of inhomogeneity within each sounding, between 4 and 20 of the 1016 “colors” recorded by each spectrometer are returned at the full spatial resolution, with no on-board binning. This is essentially a 4 to 20 channel cloud camera built into each of the OCO spectrometer channels [Crisp *et al.*, 2008].

2.2. Observing Modes

To enhance the quality and verify the validity of mission data, the Orbiting Carbon Observatory was designed to collect science data in three standard observational modes: nadir, glint and target (**Figure 11**). The instrument collects 12 - 24 soundings/second in all 3 modes.

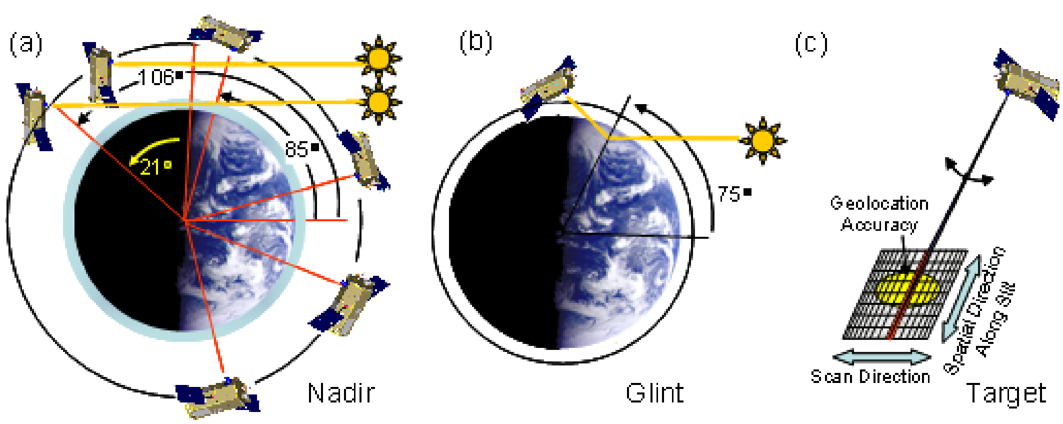

Figure 11. Nadir, Glint, and Target observations. (a) Nadir observations are acquired over the sunlit hemisphere at latitudes where the surface solar zenith angle is less than 85°. On all orbits except downlink orbits, as the Observatory passes over the northern terminator, it pitches up to point the instrument aperture at the sun for solar radiometric calibrations. It maintains an inertial pointing until the sun sets through the Earth’s limb. (b) Glint observations are made at latitudes on the sunlight hemisphere where the solar zenith angle is less than 75°. (c) For Target observations, the bus points the instrument at a stationary surface target as it flies over. A small-amplitude sinusoidal oscillation in the pitch axis is superimposed on the nominal Target pointing to scan the spectrometer slit across the Target [from Crisp *et al.*, 2008].

In nadir mode, the satellite points the instrument bore-sight toward the local nadir while on the sunlit side of Earth. Nadir mode provides the highest spatial resolution with surface footprint sizes ranging from 0.3 - 3 km^2. This mode was expected to return more spatially uniform soundings in regions that were partially cloudy and that have significant surface topography. Nadir observations will have low SNR over dark ocean surfaces or at high latitudes over surfaces covered by snow or ice, which have low reflectance at near infrared wavelengths.

In glint mode, the spacecraft points the instrument toward the bright "glint" spot where sunlight is specularly reflected from the surface. Glint observations over the ocean can provide up to 100 times more signal than nadir observations. Observations of column CO_2 by instruments that lack a glint observing mode, such as SCIAMACHY, can only acquire soundings with adequate SNR to retrieve X_{CO2} over land [e.g., Schneising *et al*., 2008]. TANSO-FTS can take glint observations only when the glint spot is within ±35° of local nadir, precluding high SNR measurements over the North Pacific, North Atlantic, and Southern Ocean.

The OCO mission was designed to alternate between nadir and glint modes on alternate 16-day global ground track repeat cycles so that the entire Earth is mapped in each mode on roughly monthly time scales. With these two observing modes, OCO was expected to acquire X_{CO2} retrievals with single-sounding random errors between 0.5 to 3 ppm over more than 95% of the range of latitudes on the sunlit hemisphere, yielding useful measurements as far north as Oslo, Helsinki, and Moscow on clear days throughout the winter. Recent OSSEs performed by the OCO science team show that the higher SNR and information content of glint observations might compensate for the higher probability of encountering clouds along the line of sight [Baker *et al*., 2008]. During the first 6 months of operations, the OCO had placed a high priority on the evaluation of the X_{CO2} retrievals and carbon fluxes inferred from these retrievals in both nadir and glint modes. If one mode could clearly be shown to provide better quantification of carbon fluxes, we might choose to proceed with use of that mode as the primary operating condition for the duration of the mission.

Target mode was another OCO innovation that was critical for achieving the mission objectives. In this mode, the observatory points the instrument at a stationary surface target as it rises over the horizon, and tracks that target until it sets on the receding horizon. A single Target over-flight can last for up to nine minutes, allowing the observatory to collect as many as 12,960 soundings at surface zenith angles between ±75°. Target observations were a critical part of the OCO validation plan (see below). As frequently as once each day, Target observations were to be acquired over validation Total Column Carbon Observing Network (TCCON) sites, with ground-based, high resolution, solar-looking Fourier Transform Spectrometers. Because X_{CO2} varies little during a single Target overflight, and the spectrometers use the same spectral channels and the same sun-to-earth optical path as the OCO instrument, comparisons of these provide a sensitive means for identifying and correcting observation angle dependent biases in the space-based measurements.

2.3. Advanced Retrieval Algorithms

A number of innovations in radiative transfer models and remote sensing algorithms were needed to accurately estimate X_{CO2} from space based measurements of CO_2 and O_2 absorption.

The OCO team developed two highly complementary, state of the art retrieval algorithms, which, together, were vital to our mission success. The data products from these algorithms were designed in consultation with the carbon flux inversion community to provide the detail necessary for optimal use of the data.

The Full Physics (FP) retrieval algorithm has been described in Boesch *et al.* [2006] and Connor *et al.* [2008]. The FP algorithm uses a spectrum-resolving radiative transfer forward model to simulate the spectrally-dependent, polarized, solar radiation field within each of the OCO spectral bands. To include the effects of absorption, multiple scattering, and polarization by gases, airborne particles (clouds, aerosols), and the surface, this model combines results from a linearized scalar eigenvector/adding multiple scattering model [Spur and Christi 2007] with a polarization "correction" from a fast, vector 2-Orders of Scattering approach [Natraj *et al.*, 2007]. The model generates both the wavelength-dependent radiances and radiance Jacobians (also known as "weighting functions") that are used by the inverse model to retrieve improved estimates of the atmospheric state properties, including surface reflectance, surface pressure, cloud and aerosol profiles, and X_{CO2} from each sounding. A fast "low-streams interpolator" reduces the time required to generate the high angular resolution-descriptions of the radiance field needed to analyze the Glint and Target observations. We know of no other radiative transfer model that can match the FP forward model in accuracy, speed, and versatility.

The FP inverse model uses an optimal estimation approach [Rodgers, 2000; Connor *et al.,* 2008] to minimize the bias among retrieved values by fitting all relevant atmospheric and surface quantities expected to vary between soundings. It has been designed to diagnose and characterize uncertainties, bias, and its own performance to aid carbon cycle modelers make best use of its output. The same computer code can be used to retrieve X_{CO2} from radiances measured by the space-based observatory and the ground-based FTS validation systems, minimizing errors due to differences between algorithms.

While the OCO Retrieval Algorithm Team expended enormous effort to increase the computational speed of this "full physics" retrieval algorithm, it still takes far too long to process all of the data from a mission that will collect more than 100,000 cloud free soundings each day. A second retrieval algorithm, called the Apparent Optical Path Difference (AOPD) algorithm, was therefore developed to provide the speed required to process all "almost clear" OCO scenes. This algorithm exploits the strong correlations in the optical pathlength dependent behavior between selected O_2 and CO_2 channels. This method is "trained" using simulations of the radiative transfer in the atmosphere-surface system generated with an accurate full-physics radiative transfer forward model. While this method does not generate the full range of error statistics produced by the FP algorithm, the accuracy of the AOPD estimates of X_{CO2} meets the OCO mission requirement in realistic full-orbit simulations. The combination of the FP algorithm with the AOPD algorithm was expected to meet or exceed the mission requirements for both speed and accuracy.

Cloudy scenes cannot yield full-column estimates of X_{CO2}, and are screened from the production processing stream. To screen for clouds, the algorithm uses neural networks developed specifically for the high resolution OCO spectra. The cloud screening algorithm provides preliminary estimates of other parameters including the effective height and total optical thickness of the scattering layer(s), the surface reflectivity, as well as photon path length information. To maximize its sensitivity to partial cloud cover within individual footprints, it uses the high resolution spatial measurements from the un-averaged color-slices mentioned previously. Testing on simulated OCO measurements demonstrated good classification skill.

2.4. World-class Spectroscopy

Ultimately, the success of the OCO mission depends on precise quantification of the spectroscopy of CO_2 and O_2. The OCO mission has benefited from the presence on our Science Team, of world leaders in the laboratory measurement and theoretical understanding of the spectroscopy of these two constituents.

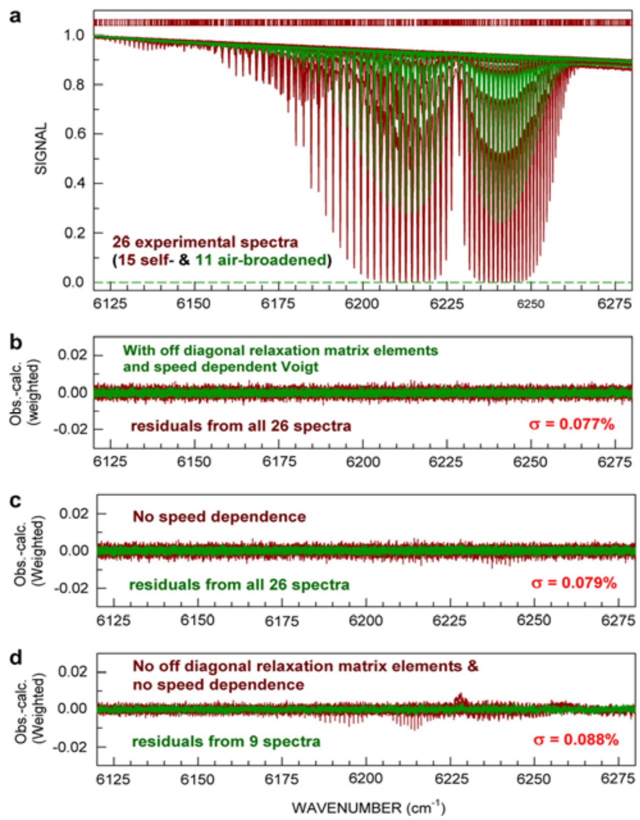

Figure 12. (a) Laboratory spectra of CO_2 absorption in the 1.61 μm window. (b) Fitting residuals for models that include both non-Voigt line shapes and line mixing, (c) model using only line mixing, and (d) conventional methods (Voigt line shapes with no line mixing (from Devi *et al.* 2007].

Throughout the development phase of our mission, we dramatically advanced the state of the art in measuring the spectral line positions, line intensities, and pressure-broadened line shapes and pressure shifts of CO_2 and O_2 absorption features. Much of the new spectral analyses were obtained using different spectrometers (the McMath-Pierce FTS at Kitt Peak National Observatory and Bruker 125 IFS at JPL, Cavity Ringdown Spectrometer at NIST). For near-IR CO_2 alone, 11 peer-reviewed papers [Miller *et al*., 2005; Toth *et al*., 2006a,b, 2007a,b, 2008 a,b, Devi *et al*., 2007a,b; Predoi-Cross, 2009; Sung *et al*., 2009] provided the precisions essential for OCO, GOSAT, SCIAMACHY as well as ground-based observations. Even CO_2 broadened by water vapor was characterized [Sung *et al*., 2009]. Similarly improved O_2 A-band parameters were obtained [Robichaud *et al*., 2008a,b; Robichaud *et al*., 2009]. These results are being incorporated into electronic databases for delivery to the remote sensing community [Toth, 2008a; Rothman, 2009].

Most importantly, we have been able to evaluate the impact of new spectroscopic constraints on retrievals of X_{CO2} using spectra obtained from our ground based FTS instruments (**Figure 12**). These studies show, for example, that non-Voigt line shapes and line mixing are needed to retrieve values of column O_2 accurately, based on rigorous comparisons to surface pressure measured at the FTS sites. By infusing the rapidly advancing spectroscopic databases into our analysis of spectra from the ground based FTS instruments, we were able to assess and improve the quality of the spectral fits that we could expect from the space-based observatory.

2.5. Validation Strategy

When OCO was selected, there was no practical means for validating space-based X_{CO2} measurements. The OCO team proposed to NASA a daunting task: we would build a validation network from scratch, and calibrate the data from this network to the World Meteorological Organization (WMO) Standard for in situ measurements of atmospheric CO_2. Eight years later, this network, called the Total Carbon Column Observing Network, TCCON, is in place, operational, and has been calibrated to the WMO Standard [Washenfelder *et al.*, 2006]. Target observations over TCCON sites are a critical component of the OCO validation strategy.

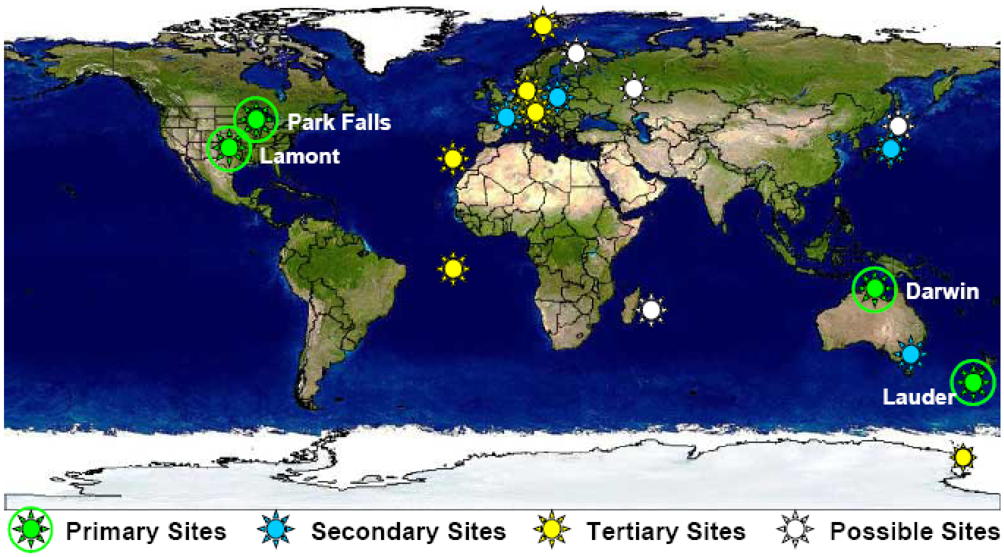

Figure 13. Location of the TCCON sites showing the distribution across latitudes and hemispheres.

Figure 13 shows the location of the TCCON stations. (http://www.tccon.caltech.edu). Each station uses a high-resolution, ground-based, solar-looking Fourier Transform Spectrometer (FTS) to retrieve X_{CO2} from measurements of direct sunlight in the same near-infrared CO_2 and O_2 bands used by the OCO and GOSAT flight instruments. However, the TCCON FTS's are much less sensitive to random errors and biases than the space-based instrument. Their higher spectral resolution increases sensitivity to CO_2 and O_2 absorption and reduces biases associated with absorption by other gases within these spectral ranges. Direct observations of the solar disk reduce biases associated with aerosol scattering and other factors that contribute uncertainties in the optical path length. They also preclude uncertainties contributed by the spectral dependence of the surface reflectance and provide much higher signal to noise ratios than the space-based measurements of reflected sunlight. The OCO Validation Plan [Salawitch *et al.*, 2008] defines Primary, Secondary, and Tertiary TCCON sites. The Primary sites are those directly operated by the OCO Science Team, for which we will be responsible for obtaining aircraft over flights. Secondary Sites are those expected to provide data of the same quality as the Primary stations, but are operated by partners, who are responsible for supporting aircraft over flights. Tertiary Sites are new or not yet fully operational sites that were expected to come on line during the OCO mission.

For *any measurements* of CO_2 to be used by the global carbon cycle science community, they must be referenced to a common standard. The OCO validation strategy references the space-based measurements of X_{CO2} to the WMO Standard. The full effort is described in the OCO Validation Plan [Salawitch *et al.*, 2008]. This was another significant, innovation by the OCO Science Team, representing the efforts of many dozens of people, supported by numerous international agencies, over the past decade.

The WMO reference standard for CO_2 traces atmospheric in situ measurements of CO_2 to a series of calibration references maintained by NOAA ESRL, in Boulder, CO. To validate the TCCON measurements against this standard, the OCO team arranged for over flights of FTS stations by aircraft carrying instruments that obtain in situ measurements of CO_2. These instruments carry the WMO Standard CO_2 calibration gases and are capable of sampling from the boundary layer to the middle troposphere. Profiles of in situ CO_2 over the site are integrated to arrive at a value of X_{CO2}. As of 24 February 2009, the FTS measurements of X_{CO2} had been "calibrated" to the WMO Standard at Park Falls, WI, Lamont, OK, and Darwin, Australia (**Figure 14**), with plans in place for flights over Lauder, NZ.

The FTS measurements of X_{CO2} shown in **Figure 14** have a slope that differs by < 1 % from the 1:1 line, which represents an error that is well within laboratory uncertainties in the line strengths of CO_2 and O_2. Our partners have, or soon will, conduct similar over flights of the TCCON stations in Wollongong, Australia and Tsukuba, Japan and in Orleans, France and Bialystok, Poland.

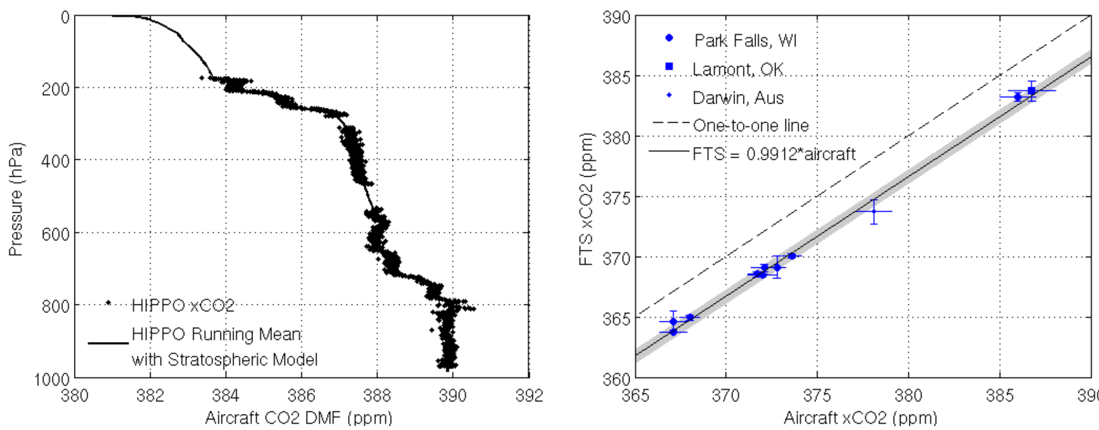

Figure 14. In situ profile of CO_2 over the Lamont, OK TCCON site (left) and a comparison of X_{CO2} measured by the FTS instrument versus X_{CO2} from the aircraft profiles at various sites (right).

The Validation Plan defines a timeline of activities to assure the space-based data are calibrated to the WMO Standard. The essential elements of this plan are designed to assess which elements of the state vector of the Full Physics X_{CO2} retrieval algorithm correlate best with errors, as defined by the difference between space-based and ground-based X_{CO2}; working with the Full Physics algorithm development team to improve the physical representation of these geophysical quantities (physics based solution); once improvement in using the physics based solution is optimized, defining bias matrices that define the relation between errors in space-based X_{CO2} and elements of the state vector; use of these bias matrices in the training of the AOPD algorithm.

3. Existing Space-based CO_2 Remote Sensing Assets

No existing or planned satellite sensor can replace OCO's unique contributions to Carbon Cycle and Climate Science.

Here we discuss the present situation regarding measurements of the global carbon cycle in light of the launch failure of OCO, the successful launch of GOSAT on 23 January 2009, the National Research Council of the National Academies Decadal Survey, the cornerstone of future NASA Earth Science Missions (http://nasascience.nasa.gov/earth-science/decadal-surveys) and the availability of space-borne observations of CO_2 from the SCIAMACHY, AIRS, and CanX-2 instruments. A summary of the satellite sensors is given in **Table 2** and the salient performance characteristics of the total column CO_2 sensors are given in **Table 3**.

Table 2. Summary of Current of Proposed Space-based CO_2 Sensors

Measurement Method	Instrument	CO_2 Measurement	Measurement Precision	Down-track Sampling	TRL
Reflected Sunlight	OCO	Total Column	1 ppm	2.3 km	8
	SCIAMACHY	Total Column	3-10 ppm	60 km	9
	GOSAT	Total Column	4 ppm	10.5 km	9
Thermal Emission	AIRS	Mid-Trop	1 – 2 ppm	45 km	9
	IASI	Mid-Trop	38 ppm	100 km	9
	TES	Mid-Trop	~5 ppm	~50 km	9
Active (LIDAR)	ASCOPE	Lower-trop	2 – 4 ppm	~100 km	4
	ASCENDS	Lower-trop	2 – 4 ppm	~100 km	4

3.1. AIRS, TES and IASI

AIRS was designed to measure accurate temperature and water vapor profiles to improve weather forecasting and support climate research.

The AIRS (Atmospheric Infrared Sounder) instrument on the NASA Aqua satellite was designed to improve weather forecasting and support climate research. Its core data products are atmospheric temperature and water vapor profiles [Aumann *et al.*, 2003]. AIRS has demonstrated a phenomenal 16 mK/year radiance calibration stability [Aumann *et al.*, 2006], making it a powerful instrument for climate research. Le Marshall *et al.* [2006] report that the assimilation of AIRS data into NCEP improved global weather forecasts by 6 hours in 6 days. This is a remarkable achievement. The AIRS team has also reported retrievals of CO_2 profiles for the mid-troposphere [Chahine *et al*., 2008].

As noted in Section 2, an important limitation of AIRS and other thermal infrared emission sounders for inferring surface sources and sinks of CO_2 is their lack of sensitivity to CO_2 variations near the surface (**Figure 7**). This insensitivity is primarily a result of the small thermal contrast between the surface and the lower troposphere. Strow and Hannon [2008] report that the 791.7 cm^{-1} AIRS channel has a sensitivity to CO_2 of 33 ppm/K, which corresponds to a minimum uncertainty in CO_2 because of radiometric error of 3 – 7 ppm (for a 0.1 – 0.2 K on-orbit radiometric uncertainty). Thus, nearly perfect knowledge of atmospheric temperature is needed to enable accurate retrievals of CO_2 from AIRS spectra.

Despite this limitation, there has been intense interest in the potential to retrieve CO_2 from AIRS. Retrievals of CO_2 profiles for the mid-troposphere have been reported by the AIRS science team [Chahine *et al*., 2008; Maddy *et al.*, 2008; Strow and Hannon, 2008] and others [Crevoisier *et al*., 2004; Engelen *et al*., 2004; Engelen and McNally, 2005]. The AIRS measurements of CO_2 in the middle troposphere compare well with aircraft in situ data and illustrate pathways for atmospheric long-range transport of CO_2 [Chahine *et al*., 2008]. Engelen *et al*. [2009] assimilated AIRS data for the European GEMS (Global and regional Earth-system atmosphere Monitoring using Satellite and in situ data) project. They state:

> *[T]here is no significant change at 1000 m [altitude] between the unconstrained model and the AIRS reanalysis, both in bias and standard deviation. This is not surprising, because the AIRS sensitivity to CO_2 is very low at this level [of the atmosphere]. Therefore, any information from the observations can only change CO_2 concentrations at this level [of the atmosphere] through the transport or through the information spreading of the background covariance matrix.*

This paper also states:

> *First results are encouraging, although using AIRS observations only is not sufficient to estimate accurate surface fluxes on regional scales. We think that our two step system will come to its full potential when more accurate satellite observations will become available from the forthcoming OCO and GOSAT instruments.*

We are unaware of any new insight into *surface sources and sinks* of CO_2 described in the peer reviewed literature based on analysis of AIRS data. Jiang *et al*. [2008] concluded "convection in the 3-D models is likely too weak in boreal winter and spring" based on an analysis of AIRS CO_2 but do not draw any firm conclusions about model representation of surface sources or sinks. Even with these limitations, there is significant enthusiasm in the community for the potential benefits of combining upper tropospheric CO_2 measurements from AIRS with full column measurements like those expected from OCO and GOSAT to infer the vertical distribution of CO_2.

The NASA Tropospheric Emission Spectrometer (TES) and the ESA Infrared Atmospheric Sounding Interferometer (IASI) [Crevoisier, *et al.*, 2009] will also be able to retrieve measurements of atmospheric CO_2. Like AIRS, these instruments both also sample thermal emission spectra. Consequently, the atmospheric CO_2 measurements obtained by these sensors will have little sensitivity to ambient CO_2 near the surface.

3.2. GOSAT

GOSAT is designed to detect emissions of multiple Greenhouse Gases rather than quantify CO_2 sinks.

The Japanese Aerospace Exploration Agency (JAXA) successfully launched the Greenhouse gases Observing SATellite, (GOSAT, recently nick-named "IBUKI") on 23 January 2009. First light was achieved on 7 February 2009 (http://www.jaxa.jp/press/2009/02/20090209_ibuki_e.html). The GOSAT TANSO-FTS will provide near global measurements of CO_2, CH_4, H_2O, and O_3 from Fourier transform spectrometers (FTSs) operating in the thermal and near infrared. GOSAT also carries a cloud and aerosol imager to characterize scattering interferences in the FTS fields of view. Given the successful GOSAT launch and initial spacecraft/instrument checkout, why should NASA consider a re-build and re-launch of OCO?

Table 3: Total Column CO_2 Sensors using Reflected Sunlight

	SCIAMACHY	GOSAT	OCO
Tropospheric Gases Measured	O_3, O_4, N_2O, NO_2, CH_4, CO, CO_2, H_2O, SO_2, HCHO	CO_2, CH_4, O_2, O_3, H_2O^* *red-> TIR Channel	CO_2, O_2
Instruments	8-Channel Grating Spectrometer	SWIR/TIR FTS, CAI	3-Channel Grating Spectrometer
Viewing Modes	Limb / Nadir	Nadir / Glint (±35°)	Nadir / Glint / Target
IFOV/Swath (km)	30 x 60 / 960	FTS: 10.5 / 80-790	1.29 x 2.25 / 5.2
Samples/day	8600	18700	500,000
Spectral Ranges (µm)	0.24–0.44, 0.4–1.0, 1.0-1.7, 1.94-2.04, 2.265-2.38	0.758-0.775, 1.56-1.72, 1.92-2.08, 5.56-14.3	0.757-0.772, 1.59-1.62, 2.04-2.08
SNR (nadir, 5% albedo)	<100 @ 1.57 µm	~120 @ 1.56-1.72 µm ~120 @ 1.92-2.08	>300 @ 1.59-1.62 µm >240 @ 2.04-208 µm
X_{CO2} Precision	4 - 6 ppm goal	3 – 4 ppm (1ppm goal)	1 ppm
Orbit Altitude	800 km	666 km	705 km
Local Time	10:00	13:00±0:15	13:30±0:1.5
Revisit Time	35 Days/501	3 Days/44 Orbits	16 Days/233 Orbits
Launch Date	March 2002	January 2009	February 2009
Nominal Life	7+ Years	5 Years	2 Years

OCO and GOSAT were both designed to measure the absorption of sunlight reflected from the surface; however, their measurement strategies and system designs address different mission objectives. OCO was optimized to return the space-based X_{CO2} data needed to characterize both CO_2 sources *and sinks*. The requirement to detect the weak, spatially diffuse CO_2 signature from natural sinks drove the OCO design towards high SNR, high spectral resolution, and small spatial fields of view. Glint observations were added to meet the SNR requirements over the oceans and Target observations were added to meet the stringent (1 ppm) accuracy requirements.

The GOSAT TANSO-FTS was optimized to return the space-based observations needed to characterize CO_2, CH_4, H_2O and O_3 emissions during the initial Kyoto enforcement period (2008 – 2012). The need to measure all of these gases drove the GOSAT design toward broad spectral coverage while still maintaining high spectral resolution. However, because the GOSAT objectives focused on CO_2 emission sources associated with human activities, which tend to be more intense and spatially localized than weak natural sinks, their SNR requirements were less challenging (3-4 ppm) than those of OCO. While the OCO team chose grating spectrometers for their inherently high SNR, the GOSAT team exploited the advantages of Fourier transform spectrometers to detect multiple species over a wider spectral range.

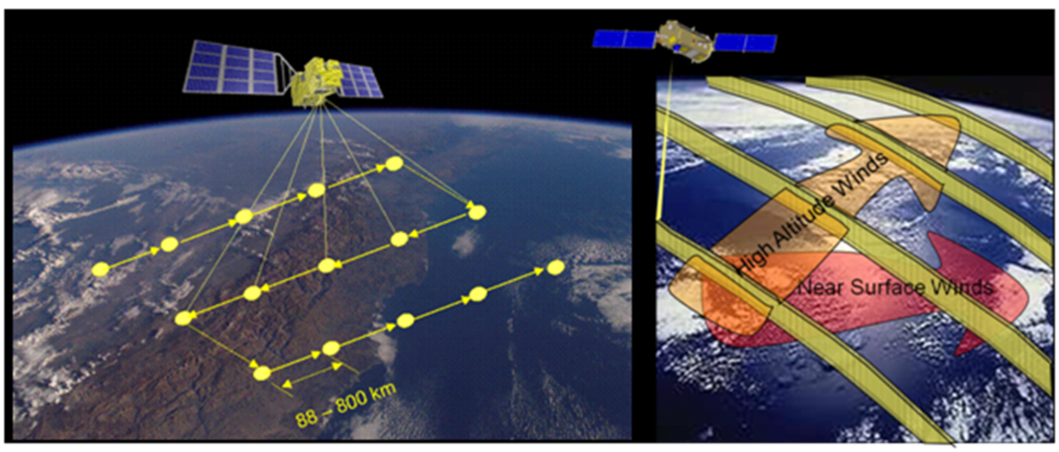

Figure 15. The GOSAT sampling approach (left) is compared to that planned for OCO (right). GOSAT uses a scanner to acquire isolated soundings with 10.5 km diameter footprints across a wide cross-track swath. OCO was to collect contiguous high resolution sounding along a narrow cross-track swath.

GOSAT, like OCO, was designed to orbit the Earth ~15 times each day in a near-polar sun-synchronous orbit that provides nearly complete coverage of the sunlit hemisphere. The GOSAT TANSO-FTS routinely records soundings at 2-second intervals, yielding ~18,700 each day, or ~56,000 soundings over each 3-day ground repeat cycle. The field of view of each sounding is a circular footprint with a diameter of ~10.5 km at nadir (85 km^2). By comparison, OCO would have collected 12 to 24 samples/second, yielding 500,000 to 1,000,000 high resolution (3 km^2) measurements along a narrow, continuous track each day, or 8 to 16 million soundings over each 16-day ground track repeat cycle (**Figure 15**).

Because GOSAT is a nadir-pointing spacecraft, TANSO-FTS includes a cross-track scanner provide more uniform coverage between its widely spaced GOSAT orbit tracks.

Subsequent tracks separated by ~25° of longitude, but this distance is reduced to ~8° of longitude over its 3-day repeat cycle. In its nominal operating mode over land, the cross-track scanner collects soundings that are separated by ~160 km. By comparison, OCO instrument was pointed by the spacecraft and there was no cross-track scanner. It was designed to collect soundings at 2.25 km intervals along narrow (0.1 to 10.4 km) tracks. Like GOSAT, the spacing between subsequent orbit tracks is ~25° of longitude, but this spacing is reduced to roughly half that after 2 days, and to only 1.5° of longitude after 16 days.

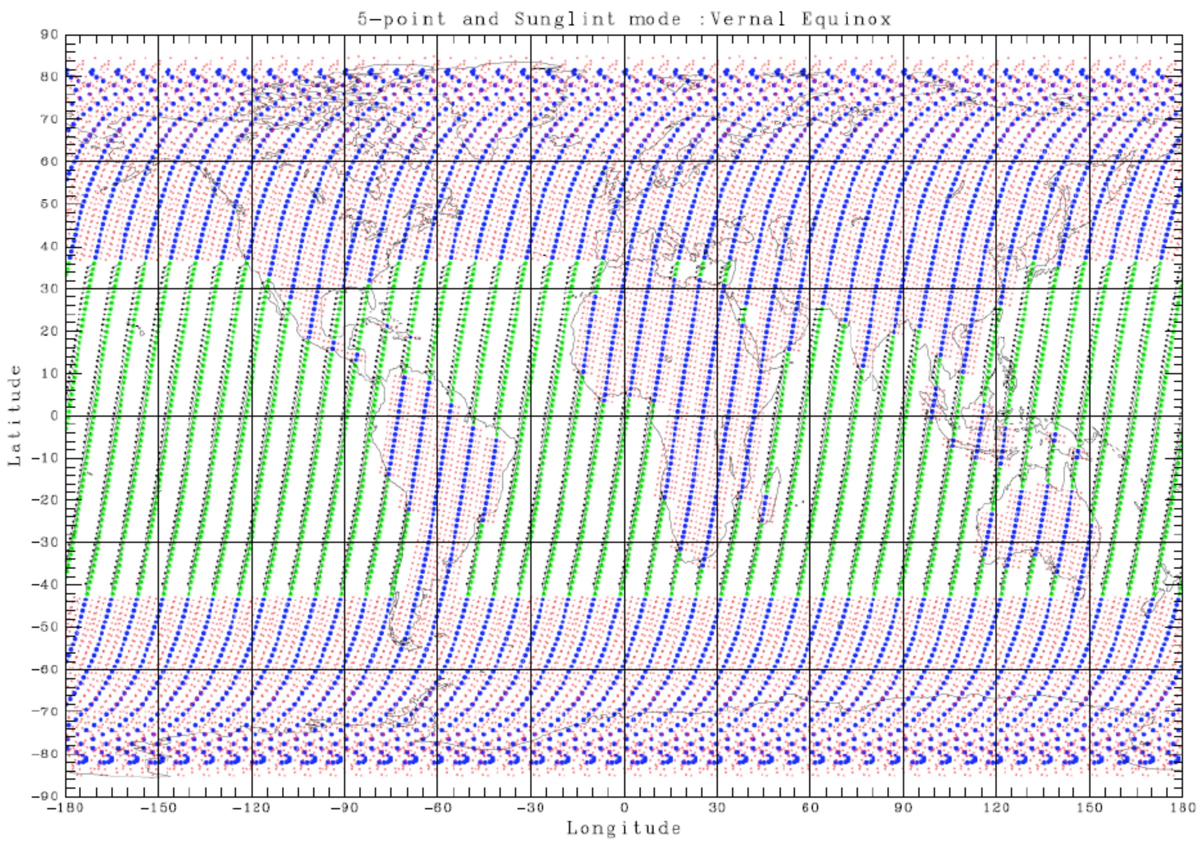

Figure 16. GOSAT sampling strategy showing glint mode sampling over ocean scenes for latitudes less than approximately 35° and standard 5-point raster sampling over land and for latitudes greater than ~35° [T. Yokota, private communication, 2009]. The lack of glint observations over the Southern Ocean, the North Pacific and North Atlantic may compromise the accuracy of the global flux estimates obtained from assimilation of GOSAT data.

The TANSO-FTS scanner can also be used to point the field of view at the glint spot over the ocean, but its range of motion restricts glint pointing to ±35° latitude (**Figure 16**). This yields some advantages at low latitudes, but precludes glint observations at high latitudes, where they provide their largest benefits to SNR over dark, ocean and ice and snow covered land surfaces. In addition, while the TANSO-FTS scanner provides image motion compensation over 2 to 4 second exposures, it has not been programmed to target stationary surface validation sites over the large range of viewing angles provided by the OCO target mode. This will limit the precision that can be achieved for individual passes over vicarious calibration and TCCON validation sites. In spite of this, the OCO and GOSAT teams have worked closely together for over 4 years to implement a cross-calibration and cross-validation strategy based on measurements over these sites. The objective of this effort was to facilitate the combination of the OCO and GOSAT data sets to exploit the advantages of the two highly complementary spatial sampling strategies. The GOSAT project manager Takashi Hamazaki was recently quoted in Nature News [doi:10.1038/news.2009.124]:

> *His team can calibrate GOSAT using ground monitors, but the process would have been much faster and perhaps more accurate using OCO as well. Running the two satellites in parallel also might have produced insights into how both instruments work. "We believe we can get the results, but the cooperation added value. That was lost."*

Figure 17 compares measurements of X_{CO2} obtained in a recent aircraft transect down the Pacific (S. Wofsy, private communication, 2009) with the regional-scale measurement requirements of OCO and GOSAT. While both missions were expected to meet their minimum requirements with significant margin, measurements meeting the more stringent OCO accuracy requirements would capture the details of the latitude-dependent CO_2 variations observed in this transect, while measurements meeting the minimum GOSAT accuracy requirements would be challenged even to resolve the pole-to-pole gradient.

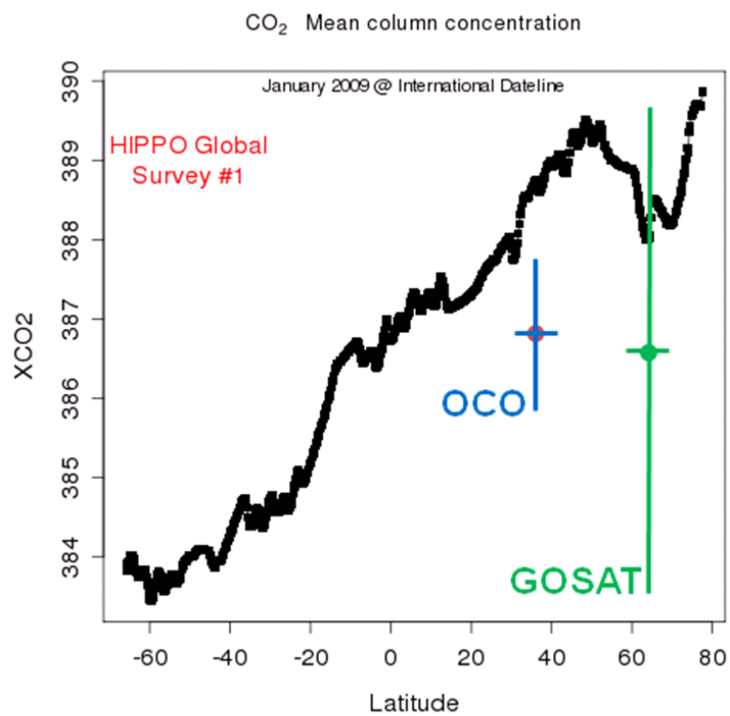

Figure 17. The nominal, regional scale X_{CO2} precision targets for the OCO and IBUKI instruments (blue and green, as indicated) are compared to the X_{CO2} cross-section measured by recent transects of the NSF HIAPER aircraft (S. Wofsy, private communication, 2009). While both missions were expected to improve on their minimum accuracy requirements, OCO was optimized to resolve the subtle latitude dependent variations in CO_2, like those shown here.

OCO's high single-sounding sensitivity and dense observation sampling was also expected to enable the characterization of CO_2 sinks over much smaller spatial regions, and on much shorter time scales, than will be possible from GOSAT. The OCO mission was designed to quantify the net flux of CO_2, into and out of the atmosphere, over a region the size of the state of Colorado (1000 x 1000 km^2) on monthly time scales. Perhaps even more importantly, the higher precision designed into individual OCO soundings is essential for determining and eliminating bias in the validation effort. Without sufficient precision it is much more challenging to evaluate the space-based CO_2 observations using coincident ground-based or aircraft column measurements.

The global carbon cycle science community eagerly awaits data from GOSAT. A proposal to JAXA by the OCO Science Team has been selected which will provide early access to the data. Indeed, the OCO Science Team is keenly interested in assisting our GOSAT colleagues in maximizing the science return from this instrument. Nonetheless, there is concern that the signal to noise ratio and sampling strategy of GOSAT will limit our ability to quantify diffuse CO_2 sinks, which impart a subtle signal on atmospheric CO_2 Quoting a recent editorial by Palmer and Rayner [Nature Geosciences, vol 2, pg 247, April 2009]:

> *Indeed, GOSAT will soon provide the data-starved carbon-cycle community with thousands of global measurements of carbon dioxide and methane each month. The loss of the OCO will limit what we can learn about natural carbon dioxide sinks — which are diffuse and unlikely to generate a strong atmospheric signature, compared with the measurement sensitivity of GOSAT. This may mean that sinks need to be quantified over larger spatial and temporal scales. However, GOSAT should provide us with a robust understanding of natural and human-produced carbon dioxide sources, which tend to be more localized and intense, generating a stronger atmospheric imprint.*

3.3. SCIAMACHY

SCIAMACHY is a visible, NIR spectrometer designed to investigate processes responsible for stratospheric ozone loss and survey tropospheric air quality.

The SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) instrument is a multichannel diode array spectrometer on the European Space Agency's (ESA) ENVISAT satellite. ENVISAT launched in March 2002 and flies in sun-synchronous orbit with 10:00 am local solar equator crossing time. SCIAMACHY covers the spectral range 240 to 2385nm with moderate spectral resolution (0.2 – 1.6 nm) [Burrows *et al.*, 1995; Bovensmann *et al.*, 1999]. It measures scattered, reflected, and transmitted solar radiation in nadir, limb, and solar and lunar occultation viewing modes. Atmospheric CO_2, CH_4 and CO column amounts are retrieved from NIR nadir radiances in Channels 6 (1−1.75 µm, resolution 1.48 nm FWHM) and 8 (2.26–2.38 µm, 0.26 nm FWHM). For nadir observations SCIAMACHY has a horizontal resolution of 30 km ×60 km in Channel 6 (CO_2, CH_4) and 30 km × 120 km in Channel 8 (CO). The radiance measurements from SCIAMACHY have been used in the development of the OCO retrieval code [Bösch *et al*., 2006].

Total column CO_2 is routinely retrieved using the WFM-DOAS (Weighting Function Modified Differential Optical Absorption Spectroscopy) algorithm [Buchwitz *et al.*, 2006; Schneising *et al.*, 2008]. Early versions of these retrievals exhibited significant offsets with respect to correlative data [e.g., Buchwitz *et al.*, 2005; Dils *et al.*, 2006]. Version 1.0 has shown major improvements due to improved spectroscopy and more accurate representation of surface albedo [Buchwitz, 2007; Schneising *et al.*, 2008]. Retrievals of column CO_2 obtained from SCIAMACHY spectra show good agreement with the amplitude and phase of the seasonal cycle for column CO_2 recorded at the Park Falls, Wisconsin and over Bremen, Germany TCCON sites [Schneising *et al.*, 2008]. SCIAMACHY X_{CO2} measurements are illustrated in **Figure 18**.

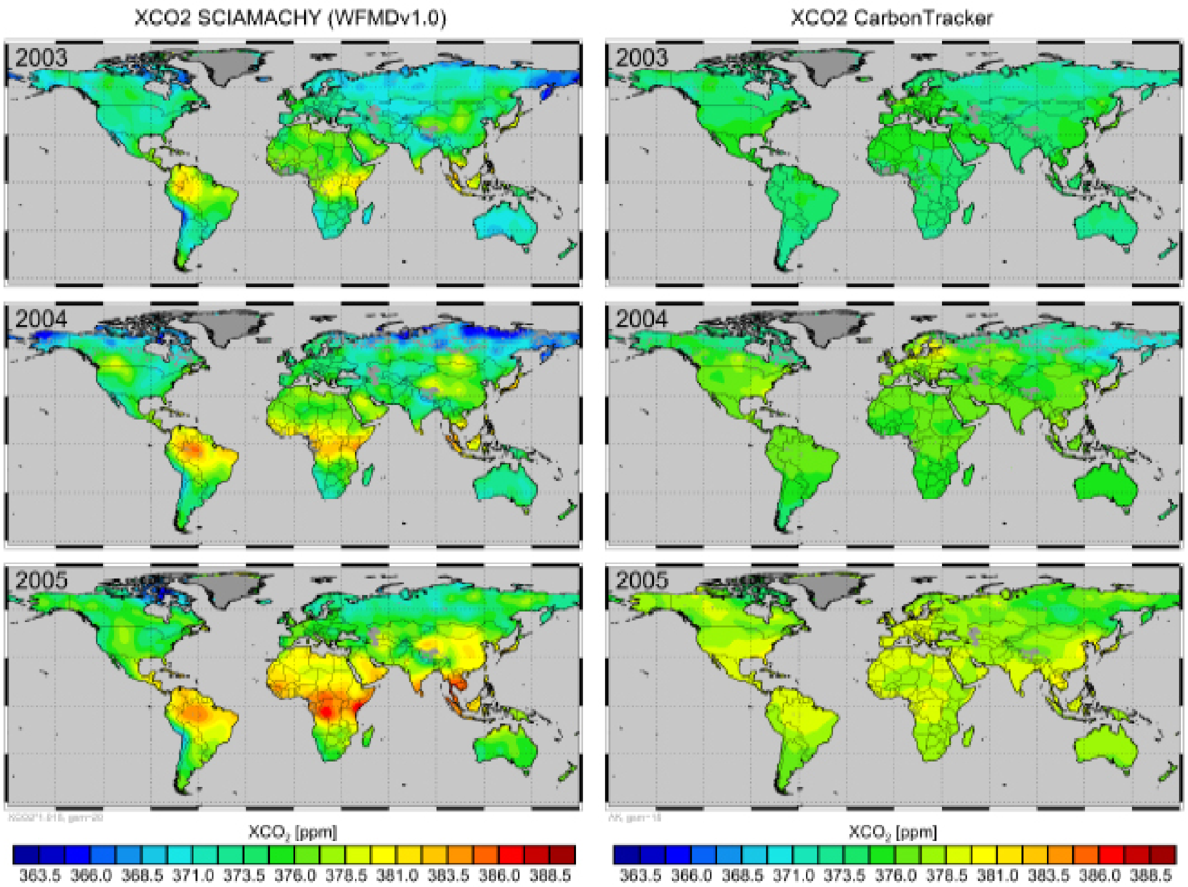

Figure 18. Measurements of X_{CO2} from SCIAMACHY for three years (2003 to 2005) compared to estimates of total X_{CO2} from the NOAA Carbon Tracker data assimilation system. Annual averages are shown. Note that the SCIAMACHY and CarbonTracker color scales are different, reflecting the high variability in the SCIAMACHY X_{CO2} (±12.5 ppm) compared to the CarbonTracker X_{CO2} (±6.0 ppm).

Several aspects of the SCIAMACHY measurements are immediately apparent. The observations are limited to the atmospheric column above land, because the ocean is dark in the near-IR spectral region and SCIAMACHY lacks a glint observing mode. Additionally, SCIAMACHY bi-monthly CO_2 maps exhibit large data gaps in the tropics due to the pervasive interference of cloud and aerosol in the 1800 km^2 IFOV [*e.g.*, figure 14 of Schneising *et al.*, *2008*]. SCIAMACHY CO_2 measurements are biased low by about 1.5% relative to the values of total column CO_2 produced by the Carbon Tracker data assimilation system. Furthermore, the precision of the SCIAMACHY retrievals of CO_2 is 3 – 6 ppm (1-2%) for monthly averages on a spatial scale of 7°×7° (latitude/longitude). In contrast, the expected precision of OCO was 1 ppm (0.3%) 16-day averages over 1000 km×1000 km regions.

OCO was expected to yield much higher precision due to an instrument design that combined high SNR and high spectral resolution to distinguish CO_2 absorption features from aerosol scattering interference. Also, with its high data rate and small sounding footprint, OCO could collect many more soundings that sampled the total atmospheric column, even in the presence of patchy clouds. The design of SCIAMACHY favored spectral coverage over signal-to-noise, spectral resolution, and small footprint size; consequently, the SCIAMACHY retrievals show considerable bias for dusty locations, such as the Sahara. For the retrievals shown in

Schneising *et al.* [2008], an Absorbing Aerosol Index based on data from the NASA Earth Probe TOMS instrument has been applied. Schneising *et al*. [2008] conclude:

> *We have shown that significant progress has been made in our understanding and the quality of the carbon dioxide data product derived from the SCIAMACHY nadir observations and that the new WFM-DOAS data set comes closer to the demanding accuracy and precision requirements of 1% or better needed for significant CO_2 surface flux uncertainty reduction. We identified primarily two aspects which need further study: [i) the identification of the cause (or causes) of the significantly (about a factor of two) higher variability of the SCIAMACHY X_{CO2} compared to CarbonTracker, and [related to this) (ii) an assessment of the significance of the observed regional X_{CO2} spatio-temporal pattern with respect to their information content on regional CO_2 sources and sinks.*

In other words, while the SCIAMACHY team is making great progress in providing a product that looks geophysically plausible over land, and further progress is expected, the precision and accuracy is not yet adequate to advance our understanding of the global carbon cycle.

3.4. CanX-2

Following the OCO launch failure, the media posted reports of a Canadian nanosatellite called “CanX-2” that claimed:

> *While NASA lost a $285-million U.S. satellite this week, a Canadian microsatellite that does the same job is chugging along happily in orbit – at one-1,000th the cost. The 30-centimetre-long University of Toronto satellite is searching for the "missing" carbon dioxide – the vast amount of Earth's main greenhouse gas that somehow vanishes each year. That's what NASA's OCO (Orbiting Carbon Observatory) satellite would have done if it had survived launch on Tuesday. The big difference: Canada built and launched its tiny version for $300,000.*

http://www.canada.com/Technology/Canada+little+satellite+that+could/1336265/story.html

The CanX project is part of a low-cost research program for aerospace students. The CanX spacecraft “are designed and built by Masters students at the University of Toronto, under supervision of professional staff.” (http://www.utias-sfl.net/nanosatellites/CanXProgram.html) The matchbox-sized spectrometer on board CanX-2, named Argus, was designed by Dr. Brendan Quine at York University. It measures near infrared spectra in the 900 – 1700 nm range with a spectral resolution of 6 nm (http://www.thoth.ca/spectrometers.htm). This spectral resolution is about 100 times lower than that of OCO and far too coarse to yield the sensitivity required for high precision column CO_2 measurements. The system also makes no measurement of O_2. Brendan Quine himself noted that the OCO and Argus measurements would be of vastly differing scientific quality: “Argus is the lowest-possible-cost approach to making this measurement. NASA was probably the highest-possible-cost approach… so the instruments are not going to be exactly commensurate.”Quine noted that there are no publications on the retrievals of GHGs from the Argus team, as this is an ongoing graduate student project [Brendan Quine, personal communication, 2009]. The publicly released spectra can be viewed at http://www.thoth.ca/argus.htm. The Argus spectrometer in no way diminishes the urgent need for a re-build and re-flight of OCO.

4. OCO in the Context of the Earth Science Decadal Survey

> "By definition, decadal surveys are forward-looking documents that build on a stable foundation of existing and approved programs."(Decadal Survey, page xiv).

OCO, as an ESSP mission selected prior to the beginning of the Decadal Survey effort, was part of the foundation of the NASA Earth science program upon which Decadal Survey priorities for new measurements were based. Though the Decadal Survey doesn't explicitly say what to do if a precursor mission was lost, it does acknowledge that the mission list might need to evolve to meet changing needs (pg 37), and acknowledges the challenge of responding to unexpected shocks which erode the foundation upon which it was built (pg xiv). This section examines how an OCO rebuild and launch is responsive to the Decadal Survey's vision and priorities.

4.1. Explicit References to OCO in the NRC Earth Science Decadal Survey

> "The current state-of-the-art for space-based remote sensing of atmospheric CO_2 is the Orbiting Carbon Observatory (OCO)" (Decadal Survey, Chapter 7).

There is no doubt that the panels writing and reviewing the Decadal Survey considered OCO an integral part of the NASA observing strategy for advancing understanding of Earth Systems Science. OCO is explicitly referenced throughout the Decadal Survey. OCO is called out as a "precursor mission" to ASCENDS in Chapter 4 ("Summaries of Recommended Missions"), and as an important contributor to our understanding of the carbon cycle and climate in Chapters 7 ("Land-Use, Ecosystems, and Biodiversity Panel") and 9 ("Climate Variability and Change"). OCO innovations are acknowledged in Chapter 7, where it states "The current state-of-the-art for space-based remote sensing of atmospheric CO_2 is the Orbiting Carbon Observatory (OCO), scheduled for launch in 2008." This chapter also describes plans of the European Centre for Medium-Range Weather Forecasts (ECMWF) for assimilation of OCO radiances to achieve operational estimates of the sources and sinks of CO_2. Chapter 9 notes the "high precision column concentrations of CO_2" provided by OCO as being an important component of the "major climate variables and forcing factors" needed for an integrated understanding of "climate variability and change."

4.2. OCO as Part of the Decadal Survey Vision and Priorities

The OCO mission exemplifies the vision and priorities set forth in the Decadal Survey. Specifically, passive CO_2 measurements from OCO address two key Decadal Survey themes: (1) enabling simultaneous scientific discovery and societal applications, and (2) providing a foundation for long-term sustained climate measurements.

In Chapter 1 the Decadal Survey sets forth a vision for an integrated Earth science program which advances both scientific understanding and societal benefit. It calls for "renewal of the national commitment to a program of Earth observations from space in which attention to securing practical benefits for humankind plays an equal role with the quest to acquire new knowledge about Earth" (Decadal Survey, pg. 19). The OCO mission was to answer important and timely science questions for both the carbon cycle and climate science communities while also providing essential information to policymakers. Knowing the strength and location of carbon sinks would enable policymakers and regulators to make more informed land use and ocean management decisions. A quantified understanding of the processes that control atmospheric CO_2 buildup rates today would help predict how fast this greenhouse gas will build up in the future, and how much time we will have to adapt to the resulting climate change. An immediate OCO rebuild would be consistent with delivering on the Decadal Survey's promise of providing for both scientific discovery and societal benefit.

Chapter 3 of the Decadal Survey highlights the challenges associated with securing long-term access to research-quality measurements. One of the OCO Mission Success Criteria was to "Validate a space based measurement approach and analysis concept that could be used for future systematic CO_2 monitoring systems." OCO's passive remote sensing technology is well suited for long-term sustained measurements because it has few life-limiting components, and requires lower mass and power than other competing technologies. Rebuilding OCO as a dedicated exploratory mission would both demonstrate the feasibility of making CO_2 remote sensing observations from space and allow an assessment of the minimal requirements for long-term monitoring of carbon sources and sinks. This information could be used to assess the impact of future design simplifications that could potentially reduce future payload accommodation requirements without introducing unacceptable biases into the data set.

4.3. OCO as a Necessary Precursor to ASCENDS

"A laser-based CO_2 mission - the logical next step after the launch of NASA's Orbiting Carbon Observatory (OCO), which uses reflected sunlight - will benefit directly from the data-assimilation procedures and calibration and validation infrastructure that will handle OCO data. In addition, because it will be important to overlap the new measurements with those made by OCO, the ASCENDS mission should be launched in the 2013-2016 time frame at the latest." (NRC Decadal Survey, 2007)

The Decadal Survey recommends active (LIDAR) remote sensing measurements of CO_2 via the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission as the logical next step after the OCO mission, building on the laboratory measurement, validation, and data assimilation infrastructure put in place by OCO. However, when compared to OCO, *ASCENDS is a different mission concept which uses a different technology to answer a different set of science questions.* By collecting more than 100,000 clear-sky soundings each day with single-sounding sensitivities between 1 and 3 ppm over 95% of the range of latitudes on the sunlit hemisphere, OCO was optimized to uncover the global distribution of both CO_2 sources and sinks and to demonstrate a technique for sustained (long-term) space-based CO_2 observations. ASCENDS is to provide measurements at the very highest latitudes in the winter hemisphere (> 60° latitude at winter solstice) and at night.

Both OCO and ASCENDS are important missions; neither is a substitute for the other.

There have been some calls to accelerate development of ASCENDS in lieu of an OCO rebuild. However, Prof. Daniel Jacob (Harvard Univ.), chair of the NASA Advisory Council's Earth science subcommittee warns in *Space News* that, "rushing ASCENDS to the front of the line threatens to disrupt the carefully constructed set of priorities laid out in the National Research Council's Decadal Survey." An OCO rebuild and launch is the only practical way to recover its intended science and applications advances, while restoring the foundation upon which the Decadal Survey's new measurement priorities were established.

There are also practical reasons for pursuing a rapid re-build of OCO rather than an acceleration of ASCENDS. It is unlikely, even with an aggressive technology development plan, that ASCENDS could be launched before 2015. Preliminary studies indicate that a re-build of OCO could be launched as soon as 30 months after selection. The nominal mission lifetime of GOSAT is 5 years. Hence, an OCO re-build has a reasonable chance of overlapping GOSAT. If we have learned anything from the myriad of instruments (and techniques) used to monitor atmospheric ozone over the past several decades, it is that overlap of sensors with different technologies (i.e., the grating spectrometers of OCO and the FTSs of GOSAT) is vital for quantifying the nuances of each measurement technique. Indeed, there remains a strong desire for passive capabilities before and with the active measurement to relax the LIDAR measurement requirements and maximize the science return from ASCENDS.

5. OCO Delivers Critical Information for Policy Makers

NASA is charged with "studying Earth from space to advance scientific understanding and *meet societal needs*" (http://nasascience.nasa.gov/ - emphasis added). To address this charge and to respond to the Decadal Survey vision of an integrated Earth science program that emphasizes both scientific advance and societal benefits, we consider the role of atmospheric CO_2 observations in the development and implementation of national policies to address the challenges of global climate change.

When originally proposed, the OCO mission was a carbon science priority with clear relevance to future national policy. Today, OCO measurements remain a high-priority carbon and climate science need and have risen in both relevancy and urgency to national policy. Emissions of CO_2 from fossil fuel use in China, India, and other rapidly developing countries have increased dramatically in the past few years, and there are increasingly large uncertainties in their contributions to the buildup of atmospheric CO_2. While most of this white paper has focused on the ability of OCO to measure weak, spatially diffuse natural sinks, its high SNR and small footprint also make it extremely sensitive to CO_2 emission sources. OCO's observations would have contributed directly to GHG source verification and quantification efforts by providing observational verification of CO_2 emissions derived from fossil fuel inventories. As the US government considers mechanisms to address climate change through limiting greenhouse gas emissions, reliable, independent global measurements of atmospheric CO_2 will fulfill critical policy needs.

The US is funding research in carbon capture and sequestiration from coal-fired power plants to ruduce US CO_2 emissions. According to a Barons editorial (2 March 2009)

"In addition to developing new technologies for carbon capture and sequestration, the US must be prepared to transfer the technologies to the developing world, including China."[see: http://online.barrons.com/article/SB123577849818797453.html].

Carbon capture and sequestration technologies could be costly to develop, and even more costly to operate based on previous air quality emissions reduction efforts. OCO observations would have provided direct measures of CO_2 release and a critical assessment of the net efficiency of capture and sequestration strategies on regional, national, and international scales.

To date, the science community has struggled to arrive at a transparent and verifiable mechanism for quantifying GHG uptake due to land use change. By identifying and mapping natural sinks, OCO data would also have enabled more informed land-use decisions, accounting for their potential impact on atmospheric CO_2. The National Carbon Accounting System (NCAS) of Australia (http://www.climatechange.gov.au/ncas/), based on remote sensed images of land use changes, has been proposed as a template for bridging the gap between carbon markets and scientific measurements (e.g., http://www.csiro.au/science/forestandcarbon.html). To tie such a policy tool to large-scale mitigation strategies we need to ascertain the relationship between the changes in land cover and subsequent changes in carbon flux. OCO measurements provided our best chance of making this link.

The precise, high spatial resolution X_{CO2} measurements that were to be provided by OCO offer an ideal complement to present efforts to quantify the impact of land-use change on the global carbon cycle. It is straightforward to envision carbon fluxes inferred from measurements of X_{CO2} from a rebuilt OCO mission playing a central role in long-term, strategic plan for assessing flows within the global carbon cycle.

6. Conclusions

Advances in carbon cycle science have intensified the need for accurate global observations of CO_2 from space. The unfortunate loss of OCO delays delivery of this critical data. The OCO mission was conceived to address a fundamental carbon cycle and climate science question with policy relevance. The science question is still unanswered, and OCO measurements had become widely viewed as essential to provide the scientific basis for greenhouse gas policies currently under consideration. Meeting the science and policy imperatives on the needed time scale can only be accomplished by launching an OCO rebuild on a fast-track schedule that capitalizes on the project's assets and innovations.

At the direction from NASA HQ, the OCO team performed a quick assessment to determine what it would take to replace the OCO capabilities. They found that the fastest approach would be to produce a build-to-print ("carbon copy") of the instrument and spacecraft. With a start date in early June 2009, a carbon copy of OCO could be ready for launch in about 30 months. With a fall 2011 launch date, the OCO science team could begin delivering an X_{CO2} data product to the OCO archive within 2 years of the original commitment date (January 2012, vs. January 2010).

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References

Alkhaled, A. A., A. M. Michalak, S. R. Kawa, S. C. Olsen, and J.-W. Wang, A global evaluation of the regional spatial variability of column integrated CO_2 distributions, *J. Geophys. Res.*, *113*, D20303, doi:10.1029/2007JD009693, 2008a.

Alkhaled, A. A., A. M. Michalak, and S. R. Kawa, Using CO_2 spatial variability to quantify representation errors of satellite CO_2 retrievals, *Geophys. Res. Lett.*, *35*, L16813, doi:10.1029/2008GL034528, 2008b.

Alley, R. *et al.*, Climate Change 2007: The Physical Science Basis, Summary for Policy Makers, Intergovernmental Panel of Climate Change, http://www.ipcc.ch/pub/spm22-01.pdf, 2007.

Andres, R.J., D.J. Fielding, G. Marland, T.A. Boden, N. Kumar, and A.T. Kearney, Carbon dioxide emissions from fossil fuel use, 1751-1950. Tellus B, 51(4), 759-765, 1999.

Aumann, H. H., M.T. Chahine, C. Gautier, M. D. Goldberg, E. Kalnay, L.M. McMillin, H. Revercomb, P.W. Rosenkranz, W.L. Smith, D.H. Staelin, L.L. Strow, J. Susskind, AIRS/AMSU/HSB on the Aqua Mission: Design, Science Objectives, Data Products, and Processing Systems, *IEEE Trans. Geosci. Remote Sens. 41*, 253, 2003.

Aumann, H. H., S. Broberg, D. Elliott, S. Gaiser, D. Gregorich, Three years of Atmospheric Infrared Sounder radiometric calibration validation using sea surface temperatures, J. Geophys. Res. 111, D16S90, doi:10.1029/2005JD006822, 2006.

Baker, D. F., R. M. Law, K. R. Gurney, P. Rayner, P. Peylin, A. S. Denning, Bousquet, L. Bruhwiler, Y.-H. Chen, P. Ciais, I. Y. Fung, M. Heimann, J. John, T. Maki, S. Maksyutov, K. Masarie, M. Prather, B. Pak, S. Taguchi, and Z. Zhu, TransCom 3 inversion intercomparison: Impact of transport model errors on the interannual variability of regional CO2 fluxes, 1988–2003. Global Biogeochem. Cycles, 20, GB1002, 10.1029/2004GB002439, 2006a.

Baker, D. F., S. C. Doney, and D. S. Schimel, Variational data assimilation for atmospheric CO2. Tellus 58B, 359-365, doi:10.1111/j.1600-0889.2006.00218.x, 2006b.

Baker, D. F., Reassessing Carbon Sinks, *Science 316*, 1708-9, 2007.

Baker, D.F. H. Bösch, S.C. Doney, and D.S. Schimel, 2008.Carbon source/sink information provided by column CO_2 measurements from the Orbiting Carbon Observatory, *Atmosp. Chem. Phys. Disc.*, *8*, 20051-20112, 2008.

Baldocchi, D., Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. *Australian J. Botany*, *56*, 1-26, 2008.

Bopp, L., C. Le Quéré, M. Heimann, A. C. Manning, and P. Monfray, Climate-induced oceanic oxygen fluxes: Implications for the contemporary carbon budget, *Global Biogeochem. Cycles*, 16, 1022, doi:10.1029/2001GB001445, 2002.

Böning, C.W., A. Dispert, M. Visbeck, S.R. Rintoul, and F.U. Schwarzkopf, The response of the Antarctic Circumpolar Current to recent climate change, Nature Geosciences, 1, 864-869, 2008.

Bösch, H. et al., Space-based Near-infrared CO2 Measurements: Testing the OCO Retrieval Algorithm and Validation Concept Using SCIAMACHY Observations over Park Falls, Wisconsin, J. Geophys. Res., 111, D23302, doi:10.1029/2006JD007080, 2006.

Bovensmann, H. et al., SCIAMACHY: Mission objectives and measurement modes, J. Atmos. Sci., 56, 127-150, 1999.
Breon, F. M., D. M. O'Brien, and J. D. Spinhirne, Scattering layer statistics from space borne GLAS observations, GRL, 32, L22802, doi:10.1029/2005GL023825, 2005.
Buchwitz, M et al., Carbon monoxide, methane and carbon dioxide columns retrieved from SCIAMACHY by WFM-DOAS: year 2003 initial data set, Atmos. Chem. Phys., 5, 3313-3329, 2005.
Buchwitz, M. et al., Atmospheric carbon gases retrieved from SCIAMACHY by WFM-DOAS: version 0.5 CO and CH4 and impact of calibration improvements on CO2 retrieval, Atmos. Chem. Phys., 6, 2727-2751, 2006.
Buchwitz, M., I. Khlystova, H. Bovensmann, J.P. Burrows, Three years of global carbon monoxide from SCIAMACHY: comparison with MOPITT and first results related to the detection of enhanced CO over cities, Atmos. Chem. Phys., 7, 2399-2411, 2007a.
Buchwitz, M., SCIAMACHY WFM-DOAS methane, carbon monoxide, and carbon dioxide columns: Algorithm description and product specification, IUP-SCIA-WFMD-ADPS-0003, Vers 2, Bremen, Germany, 2007b.
Burrows, J. P. *et al.*, SCIAMACHY- Scanning Imaging Absorption Spectrometer for Atmospheric Chartography, *Acta Astronautica, 35*, 445-451, 1995.
Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., and Marland, G., Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc. Nat. Acad. Sci. USA*, *104*, 18870–18886, 2007.
Chahine, M. T., L. Chen, P. Dimotakis, X. Jiang, Q. Li, E. T. Olsen, T. Pagano, J. Randerson, and Y. L. Yung, Satellite remote sounding of mid-tropospheric CO_2, *Geophys. Res. Lett.*, *35*, L17807, doi:10.1029/2008GL035022, 2008.
Chevallier, F., M. Fisher, P. Peylin, S. Serrar, P. Bousquet, F.-M. Breon, A. Chedin, P. Ciais, Inferring CO_2 sources and sinks from satellite observations: Method and application to TOVS data, *J. Geophys. Res*., *110*, D24309, doi:10.1029/2005JD006390, 2005.
Chevallier, F., N. Viovy, M. Reichstein, P. Ciais, On the assignment of prior errors in Bayesian inversions of CO_2 surface fluxes, *Geophys. Res. Lett., 33*, L13802, doi:10.1029/2006GL026496, 2006.
Chevallier, F., Impact of correlated observation errors on inverted CO_2 surface fluxes from OCO measurements, *Geophys. Res. Lett.*, *34*, L24804, doi:10.1029/2007GL030463, 2007a.
Chevallier, F., F.-M. Bréon, and P. J. Rayner, Contribution of the Orbiting Carbon Observatory to the estimation of CO_2 sources and sinks: Theoretical study in a variational data assimilation framework, J. Geophys. Res., 112, D09307, doi:10.1029/2006JD007375, 2007b.
Chahine, M., C. Barnet, E. T. Olsen, L. Chen, and E. Maddy, On the determination of atmospheric minor gases by the method of vanishing partial derivatives with application to CO_2, Geophys. Res. Lett., 32, L22803, doi:10.1029/2005GL024165, 2005.
Ciais, P., M. Reichstein, N. Viovy, A. Granier, J. Ogée, V. Allard, M. Aubinet, N. Buchmann, Chr. Bernhofer, A. Carrara, F. Chevallier, N. De Noblet, A. D. Friend, P. Friedlingstein, T. Grünwald, B. Heinesch, P. Keronen, A. Knohl, G. Krinner1, D. Loustau, G. Manca, G. Matteucci, F. Miglietta, J. M. Ourcival, D. Papal, K. Pilegaard18, S. Rambal, G. Seufert, J. F. Soussana, M. J. Sanz, E. D. Schulze, T. Vesala & R. Valentini, Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature, 437*, 529-533, doi:10.1038/nature03972, 2005.
Connor, B. J., H. Boesch, G. Toon. B. Sen, C. Miller, and D. Crisp, Orbiting Carbon Observatory: Inverse method and prospective error analysis, *J. Geophys. Res.*, *113*, D05305, doi:10.1029/2006JD008336, 2008.
Corbin, K. D., A. S. Denning, L. Lu, J.-W. Wang, I. T. Bake, Possible representation errors in inversions of satellite CO_2 retrievals, *J. Geophys. Res., 113*, D02301, doi:10.1029/2007JD008716, 2008.

Cox, P. M, R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell, Acceleration of global warming due to carbon-cycle feed-backs in a coupled climate model. *Nature*, *408*, 184–187, 2000.

Cox, P. M, R. A. Betts, M. Collins, P. P. Harris, C. Huntingford, and C. D. Jones, Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theor. Appl. Climatol.*, *78*, 137–156, 2004.

Crevoisier, C., S. Heilliette, A. Chedin, S. Serrar, R. Armante, and N. A. Scott, Midtropospheric CO2 concentration retrieval from AIRS observations in the tropics, Geophys. Res. Lett., 31, L17106, doi:10.1029/2004GL020141, 2004.

Crevoisier C., Gloor E., Gloaguen E., Sarmiento J. L., Horowitz L. W., Sweeney C. and Tans P. P., A direct carbon budgeting approach to infer carbon sources and sinks. Design and synthetic application to complement the NACP observation network. *Tellus 58B*, 366-375, 2006.

Crevoisier, C., A. Chedin, H. Matsueda, T. Machida, R. Armante, N. A. Scott, First year of upper tropospheric integrated content of CO_2 from IASI hyperspectral infrared observations, *Atmos. Chem. Phys. Discuss., 9*, 8187–8222, 2009.

Crisp D. R. M. Atlas, F.-M. Breon, L. R. Brown, J. P. Burrows, P. Ciais, B.J. Connor, S.C. Doney, I. Y. Fung, D .J. Jacob, C. E. Miller, D. O'Brien, S. Pawson, J. T. Randerson, P. Rayner, R. J. Salawitch, S. P. Sander, B. Sen, G.L. Stephens, P.P. Tans, G.C. Toon, P.O. Wennberg, S.C. Wofsy, Y.L. Yung , Z. Kuang , B. Chudasama, G. Sprague, B. Weiss, R. Pollock, D. Kenyon, and S. Schroll, The Orbiting Carbon Observatory (OCO) Mission, *Advances in Space Research*, *34*, 700-709, 2004.

Crisp, D. 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; DOI:10.1117/1.2898457. 2008.

Crisp, D., The Orbiting Carbon Observatory: NASA's First Dedicated Carbon Dioxide Mission, *Proc. SPIE*, *7106*, DOI: 10.1117/12.802194, 2008.

Deeter, M. N., *et al.*, Operational carbon monoxide retrieval algorithm and selected results for the MOPITT instrument, *J. Geophys. Res., 108*, 4399, doi:10.1029/2002JD003186, 2003.

DeFries, R., Field, C., Fung, I., Collatz, G. and Bounoua, L., Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity, *Global Biogeochem. Cycles, 13*, 803-815, 1999.

DeFries R. S., D. C. Morton, G. R. van der Werf, L. Giglio, G. J. Collatz, J. T. Randerson, R. A. Houghton, P. K. Kasibhatla, any Y. Shimabukuro, Fire-related carbon emissions from land use transitions in southern Amazonia, *Geophys. Res. Lett.*, *35*, L22705, doi:10.1029/2008GL035689, 2008.

DeLucia, E. H., D. J. Moore, and R. J. Norby, Contrasting responses of forest ecosystems to rising atmospheric CO_2: Implications for the global C cycle, *Global Biogeochem. Cycles*, *19*, GB3006, doi:10.1029/2004GB002346, 2005.

Denning, A.S. *et al.*, *Science Implementation Strategy for the North American Carbon Program*. Report of the NACP Implementation Strategy Group of the U.S. Carbon Cycle Interagency Working Group. Washington, DC: U.S. Carbon Cycle Science Program, 68 pp, 2005.

Devi, V. M., D. Chris Benner, L. R. Brown, C. E. Miller and R. A. Toth, Line mixing and speed dependence in CO_2 at 6348 cm^{-1}: Constrained multispectrum analysis of intensities and line shapes in the 30012 ← 00001 band, *J. Mol. Spectrosc.*, *242*, 90-117, 2007a.

Devi, V. M., D. Chris Benner, L.R. Brown, C.E. Miller and R.A. Toth, Line mixing and speed dependence in CO_2 at 6227.9 cm^{-1}: Constrained multispectrum analysis of intensities and line shapes in the 30013 ← 00001 band, *J. Mol. Spectrosc*., *245*, 52-80, 2007b.

Dils, B. *et al.*, Comparisons between SCIAMACHY and ground-based FTIR data for total columns of CO, CH_4, CO_2, and N_2O, *Atmos. Chem. Phys.*, *6*, 1953-1976, 2006.

Dolman, A.J., A. Freibauer, and R. Valentini (Eds). *The Continental Scale Greenhouse Gas balance of Europe*. Springer Ecological Series 203. Springer, New York. 390 pp., 2008.

Doney, S. C., The dangers of ocean acidification, *Scientific American*, *294*, 58–65, 2006.

Doney, S. C., V. J. Fabry, R. A. Feely, and J. A. Kleypas, Ocean acidification: the other CO_2 problem, *Ann.. Rev. Mar. Sci.*, 1, 169-192, 2009a.
Doney, S. C., I. Lima, R.A. Feely, D.M. Glover, K. Lindsay, N. Mahowald, J. K. Moore, and R. Wanninkhof, 2009b. Mechanisms governing interannual variability in the upper ocean inorganic carbon system and air-sea CO_2 fluxes: physical climate and atmospheric dust, *Deep-Sea Res. II, in press*, 2009b.
Doney, S. C., B. Tilbrook, S. Roy, N. Metzl, C. Le Quéré, M. Hood, R. A. Feely, and D. Bakker, Surface ocean CO_2 variability and vulnerability, *Deep-Sea Res. II, in press,* 2009c.
Dufour, E. and F.-M. Breon, Spaceborne estimate of atmospheric CO_2 column by use of the differential absorption method: error analysis, Appl. Opt. 42, 3595 – 3609, 2003.
Engelen, R. J., E. Andersson, F. Chevallier, A. Hollingsworth, M. Matricardi, A. P. McNally, J.-N. Thepaut, P. D. Watts, Estimating atmospheric CO_2 from advanced infrared satellite radiances within an operational four-dimensional variational (4D-Var) data assimilation system: Methodology and first results, J. Geophys. Res., 109, D19309, doi:10.1029/2004JD004777, 2004.
Engelen, R. J., and A. P. McNally, Estimating atmospheric CO_2 from advanced infrared satellite radiances within an operational four-dimensional variational (4D-Var) data assimilation system: Results and validation, J. Geophys. Res., 110, D18305, doi:10.1029/2005JD005982, 2005.
Engelen R. J., S. Serrar, and F. Chevallier, Four-dimensional data assimilation of atmospheric CO_2 using AIRS observations, *J. Geophys. Res.*, *114*, D03303, doi:10.1029/2008JD010739, 2009.
Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero, Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans. *Science, 305* 362–366. doi:10.1126/science.1097329, 2004.
Feng, L., P. I. Palmer, H. Bösch, and S. Dance, Estimating surface CO_2 fluxes from space-borne CO_2 dry air mole fraction observations using an ensemble Kalman Filter, *Atmos. Chem. Phys. Discuss.*, *8*, 19917–19955, 2008.
Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W. Von Bloh, V. Brovkin, P. Cadule, S. Doney, M. Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K. Lindsay, H. D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, A. J. Weaver, C. Yoshikawa, and N. Zeng, Climate–Carbon Cycle Feedback Analysis: Results from the C^4MIP Model Intercomparison. *J. Clim.*, *19*, 3337-3353, 2006.
Fung, I., S. C. Doney, K. Lindsay, and J. John, Evolution of carbon sinks in a changing climate, *Proc. Natl. Acad. Sci. USAA.*, *102*, 11,201–11,206, doi:10.1073/pnas.0504949102, 2005.
Geels, C., S. C. Doney, R. Dargaville, J. Brandt, J. and J. H. Christensen, Investigating the sources of synoptic variability in atmospheric CO_2 measurements over the Northern Hemisphere continents: a regional model study, *Tellus*, *56B*, 35-50, 2004.
Gloor, M., N. Gruber, J. Sarmiento, C. L. Sabine, R. A. Feely, and C. Rodenbeck, A first estimate of present and preindustrial air-sea CO_2 flux patterns based on ocean interior carbon measurements and models. *Geophys. Res. Lett.*, *30*, 1010, 2003.
Gregg, J. S., R. J. Andres, G. Marland, China: Emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production, *Geophys. Res. Lett., 35*, L08806, doi:10.1029/2007GL032887, 2008.
Gruber, N., M. Gloor, S.E. Mikaloff Fletcher, S.C. Doney, S. Dutkiewicz, M.J. Follows, M. Gerber, A.R. Jacobson, F. Joos, K. Lindsay, D. Menemenlis, A. Mouchet, S.A. Müller, J.L. Sarmiento, and T. Takahashi, Oceanic sources, sinks, and transport of atmospheric CO_2, *Global Biogeochem. Cycles, 23*, GB1005, 2009.
Guan, D., G. P. Peters, C. L. Weber, K. Hubacek, Journey to world top emitter: An analysis of the driving forces of China's recent CO_2 emissions surge, *Geophys. Res. Lett., 36*, L04709, doi:10.1029/2008GL036540, 2009.
Gurney, K.R., R. M. Law, A. S. Denning, P. J. Rayner, D. Baker, P. Bousquet, L. Bruhwiler, Y.-H. Chen, P. Ciais, S. Fan, I.Y. Fung, M. Gloor, M. Heimann, K. Higuchi, J. John, T. Maki, S.

Maksyutov, K. Masarie, P. Peylin, M. Prather, B.C. Pak, J. Randerson, J. Sarmiento, S. Taguchi, T. Takahashi and C.-W. Yuen, Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. *Nature*, *415*, 626-630, 2002.

Gurney, K. R., D. Baker, P. Rayner, and S. Denning, Interannual variations in continental-scale net carbon exchange and sensitivity to observing networks estimated from atmospheric CO_2 inversions for the period 1980 to 2005, Global Biogeochem. Cycles, 22, GB3025, doi:10.1029/2007GB003082, 2008.

Hales, B., C. Sabine, W.-J. Cai, O. Schofield, and B. G. Mitchell, North American Continental Margins: A Synthesis and Planning Workshop. http://www.whoi.edu/cms/files/NACM_04.25_35943.pdf, 2008.

Hamazaki, T., Y. Kaneko, A. Kuze, and H. Suto, Greenhouse Gases Observation from Space with TANSO-FTS on GOSAT, in Fourier Transform Spectroscopy/ Hyperspectral Imaging and Sounding of the Environment, OSA Technical Digest Series, Optical Society of America, paper FWB1, 2007.

Hansen, M. C., S. V. Stehman, P. V. Potapov, T. Loveland, J. R. G. Townshend, R. DeFries, K. W. Pittman, B. Arunarwati, F. Stolle, M. K. Steininger, M. Carroll and C. DiMiceli, Humid tropical forest clearing from 2000 to 2005 quantified using multi-temporal and multi-resolution remotely sensed data, P*roceedings of the National Academy of Sciences*, *105*, 9439-9444, 2008.

Huete, A. R., K. Didan, Y. E. Shimabukuro, P. Ratana, S. R. Saleska, L. R. Hutyra, W. Yang, R. R. Nemani, R. Myneni, Amazon rainforests green-up with sunlight in dry season, *Geophys. Res. Lett.*, *33*, L06405, doi:10.1029/2005GL025583, 2006.

Hollingsworth, A., R. J. Engelen, C. Textor, A. Benedetti, O. Boucher, F. Chevallier, A. Dethof, H. Elbern, H. Eskes, J. Flemming, C. Granier, J. W. Kaiser, J.-J. Morcrette, P. Rayner, V.-H. Peuch, L. Rouil, M. G. Schultz, A. J. Simmons, and The GEMS Consortium, Toward a Monitoring and Forecasting System For Atmospheric Composition: The GEMS Project, *Bull. Am. Meteorol. Soc.*, *89*, 1147–1164, 2008.

Houghton, R. A., Magnitude, distribution and causes of terrestrial carbon sinks and some implications for policy, *Climate Policy*, *2,* 71-88, 2002.

Hurtt G. C., S. Frolking, M. G. Fearon, B. Moore, E. Shevliakova, S. Malyshev, S. W. Pacala, and R. A. Houghton, The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood harvest activity, and resulting secondary lands. *Global Change Biol*., *12*,1208–1229, 2006.

IPCC, 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 [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New Tork, NY, USA, 996 pp., 2007.

Jacobson, A. R., S. E. Mikaloff Fletcher, N. Gruber, J. L. Sarmiento, M. Gloor, A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide: 1. Methods and global-scale fluxes, *Global Biogeochem. Cycles*, *21*, GB1019, doi:10.1029/2005GB002556, 2007a.

Jacobson, A. R., S. E. Mikaloff Fletcher, N. Gruber, J. L. Sarmiento, M. Gloor, A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide: 2. Regional results, *Global Biogeochem. Cycles*, *21*, GB1020, doi:10.1029/2006GB002703, 2007b.

Jiang, X., Q. Li, M.-C. Liang, R.-L. Shia, M. T. Chahine, E. T. Olsen, L. L. Chen, and Y. L. Yung, Simulation of upper tropospheric CO_2 from chemistry and transport models, *Global Biogeochem. Cycles*, *22*, GB4025, doi:10.1029/2007GB003049, 2008.

Khvorostyanov, D. V., P. Ciais, G. Krinner, and S. A. Zimov, Vulnerability of east Siberia's frozen carbon stores to future warming, Geophys. Res. Lett., 35, L10703, doi:10.1029/2008GL033639, 2008.

King, A. W. and L. Dilling (Eds.) The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle. Synthesis and Assessment Product 2.2, Report by the US Climate Change Science Program and the

Subcommittee on Global Change Research, 2007. Available at http://cdiac.ornl.gov/SOCCR/pdf/sap2-2-final-all.pdf.

Langenfelds, R. L., Francey, R. J., Pak, B. C., Steele, L. P., Lloyd, J., Trudinger, C. M., and Allison, C. E., Interannual growth rate variations of atmospheric CO_2 and its delta C-13, H_2, CH_4, and CO between 1992 and 1999 linked to biomass burning, *Global Biogeochem. Cycles*, **16**, doi:10.1029/2001GB001466, 2002.

Law, R. M., W. Peters, C. Rödenbeck, C. Aulagnier, I. Baker, D. J. Bergmann, P. Bousquet, J. Brandt, L. Bruhwiler, P. J. Cameron-Smith, J. H. Christensen, F. Delage, A. S. Denning, S. Fan, C. Geels, S. Houweling, R. Imasu, U. Karstens, S. R. Kawa, J. Kleist, M. C. Krol, S.-J. Lin, R. Lokupitiya, T. Maki, S. Maksyutov, Y. Niwa, R. Onishi, N. Parazoo, P. K. Patra, G. Pieterse, L. Rivier, M. Satoh, S. Serrar, S. Taguchi, M. Takigawa, R. Vautard, A. T. Vermeulen, and Z. Zhu, TransCom model simulations of hourly atmospheric CO_2: Experimental overview and diurnal cycle results for 2002, *Global Biogeochem. Cycles*, *22*, 10.1029/2007GB003050, 2008.

Le Quéré, C., C. Rödenbeck, E.T. Buitenhuis, T. J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, N. Gillett, and M. Heimann, Saturation of the Southern ocean CO_2 sink due to recent climate change, *Science*, *316*, DOI:10.1126/science.1136188, 1735-1738, 2007.

Le Quéré, C., C. Rödenbeck, E.T. Buitenhuis, T. J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, M. Ramonet, T. Nakazawa, N. Metzl, N. Gillett, and M. Heimann, Response to Comments on "Saturation of the Southern ocean CO_2 sink due to recent climate change", *Science*, *319*, 570c, 2008.

Le Marshall, J., J. Jung, J. Derber, M. Chahine, R. Treadon, S. J. Lord, M. Goldberg, W. Wolf, H. C. Liu, J. Joiner, J. Woollen, R. Todling, P. van Delst, and Y. Tahara, Improving Global Analysis and Forecasting with AIRS, Bull. of the Amer. Meteor. Soc., 87, 891–894, 2006.

Lokupitiya, R. S., D. Zupanski, A. S. Denning, S. R. Kawa, K. R. Gurney, and M. Zupanski, Estimation of global CO_2 fluxes at regional scale using the Maximum Likelihood Ensemble Filter. *J. Geophys. Res. 113*, D20110, doi:10.1029/2007JD009679, 2008.

Lovenduski, N. S., N. Gruber, and S. C. Doney, Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink, *Global Biogeochem. Cycles*, *22*, GB3016, doi:10.1029/2007GB003139, 2008.

Luo, M., C. P. Rinsland, C. D. Rodgers, J. A. Logan, H. Worden, S. Kulawik, A. Eldering, A. Goldman, M. W. Shephard, M. Gunson, M. Lampel, Comparison of carbon monoxide measurements by TES and MOPITT: Influence of a priori data and instrument characteristics on nadir atmospheric species retrievals, *J. Geophys. Res., 112*, D09303, doi:10.1029/2006JD007663, 2007.

Maddy, E. S., C. D. Barnet, M. Goldberg, C. Sweeney, and X. Liu, CO_2 retrievals from the Atmospheric Infrared Sounder: Methodology and validation, J. Geophys. Res., 113, D11301, doi:10.1029/2007JD009402, 2008.

Manning, A.C., and R.F. Keeling, Global oceanic and land biotic carbon sinks from the Scripps atmospheric oxygen flask sampling network, *Tellus, 58B,* 95–116, 2006.

Marland, G. and R.M. Rotty, Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1982. *Tellus B*, 36(4), 232-261, 1984.

McGillis, W. R., J. B. Edson, C. J. Zappa, J. D. Ware, S. P. McKenna, E. A. Terray, J. E. Hare, C. W. Fairall, W. Drennan, M. Donelan, M. D. DeGrandpre, R. Wanninkhof, and R. A. Feely, Air-sea CO_2 exchange in the equatorial Pacific. *J. Geophys. Res., 109*, C08S02. 10.1029/2003JC002256, 2004.

McMillan, W. W., C. Barnet, L. Strow, M. T. Chahine, M. L. McCourt, J. X. Warner, P. C. Novelli, S. Korontzi, E. S. Maddy, S. Datta, Daily global maps of carbon monoxide from NASA's Atmospheric Infrared Sounder, *Geophys. Res. Lett., 32*, L11801, doi:10.1029/2004GL021821, 2005.

Mikaloff Fletcher, S. E., N. Gruber, A. R. Jacobson, S. C. Doney, S. Dutkiewicz, M. Gerber, M. Gloor, M. Follows, F. Joos, K. Lindsay, D. Menemenlis, A. Mouchet, S. A. Müller, and J. L. Sarmiento, Inverse estimates of the oceanic sources and Sinks of natural CO_2 and their implied oceanic transport. *Glob. Biogeochem. Cyc.*, *21*, GB1010, doi:10.1029/ 2006GB002751, 2007.

Miller, C. E., L. R. Brown, R. A. Toth, D. C. Benner and V. M. Devi, Spectroscopic challenges for high accuracy retrievals of atmospheric CO_2 and the Orbiting Carbon Observatory (OCO) experiment, *Comptes Rendus Physique*, 6, 876-887, 2005.

Miller, C. E., D. Crisp, P. L. DeCola, S. C. Olsen, J. T. Randerson, A. M. Michalak, A. Alkhaled, P. Rayner, D. J. Jacob, P. Suntharalingam, D. B. A. Jones, A. S. Denning, M. E. Nicholls, S. C. Doney, S. Pawson, H. Bösch,B. J. Connor, I. Y. Fung, D. O'Brien, R. J. Salawitch, S. P. Sander, B. Sen, P. Tans, G. C. Toon, P. O. Wennberg, S. C. Wofsy, Y. L. Yung, and R. M. Law, Precision requirements for space-based X_{CO2} data, *J. Geophys. Res.*, *112*, D10314, doi:10.1029/2006JD007659, 2007.

Miyazaki, K., T. Machida, P. K. Patra, T. Iwasaki, Y. Sawa, H. Matsueda, and T. Nakazawa, Formation mechanisms of latitudinal CO_2 gradients in the upper troposphere over the subtropics and tropics, *J. Geophys. Res., 114*, D03306, doi:10.1029/2008JD010545, 2009.

Natraj, V., H. Boesch, R. J. D. Spurr and Y. L. Yung, Retrieval of X_{CO2} from simulated Orbiting Carbon Observatory measurements using the fast linearized R-2OS radiative transfer model, *J. Geophys. Res.*, 113, D11212, doi:10.1029/2007JD009017, 2008.

National Research Council, Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation, The National Academies Press, Washington, D.C., ISBN: 978-0-309-10387-9, 456 pgs, 2007.

Netherlands Environmental Assessment Agency, China now no. 1 in CO2 emissions; USA in second position, press release, Bilthoven, Netherlands, 19 June 2007.

Nevison, C.D., N. M. Mahowald, S. C. Doney, I. D. Lima, G. R. van der Werf, J. T. Randerson, D. F. Baker, P. Kasibhatla, and G. A. McKinley, Contribution of ocean, fossil fuel, land biosphere and biomass burning carbon fluxes to seasonal and interannual variability in atmospheric CO_2, *J. Geophys. Res. Biogeosci., 113*, G01010, 2008.

Olsen, S. C., and J. T. Randerson, Differences between surface and column atmospheric CO_2 and implications for carbon cycle research, *J. Geophys. Res., 109*, D02301, doi:10.1029/2003JD003968, 2004.

Orr J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A.Ishida, F. Joos, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R. G. Najjar, G.-K. Plattner, K. B. Rodgers, C. L. Sabine, J. L. Sarmiento, R. Schlitzer, R. D. Slater, I. J. Totterdell, M.-F. Weirig, Y. Yamanaka and A. Yool, Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, *437*, 681–686, 2005.

Pacala, S. W., G. C. Hurtt, D. Baker, P. Peylin, R. A. Houghton, R. A. Birdsey, L. Heath, E. T. Sundquist, R. F. Stallard, P. Ciais, P. Moorcroft, J. P. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M. E. Harmon, S.-M. Fan, J. L. Sarmiento, C. L. Goodale, D. Schimel, and C. B. Field, Consistent land- and atmosphere-based US carbon sink estimates, *Science*, *292*, 2316-2320, 2001.

Pak, B. C. and M. J. Prather, CO_2 source inversions using satellite observations of the upper troposphere, Geophys. Res. Lett., 28, 4571–4574, 2001.

Palmer, P. I., P. Suntharalingam, D. B. A. Jones, D. J. Jacob, D. G. Streets, Q. Fu, S. A. Vay, and G. W. Sachse, Using CO_2:CO correlations to improve inverse analyses of carbon fluxes, *J. Geophys. Res., 111*, D12318, doi:10.1029/2005JD006697, 2006.

Parazoo, N., A. S. Denning, R. Kawa, K. Corbin, R. Lokupitia, I. Baker, and D. Worthy, Mechanisms for synoptic transport of CO_2 in the midlatitudes and tropics. *Atmos. Chem. Phys., 8,* 7239-7254, 2008.

Peters, W., J.B. Miller, J. Whitaker, A.S. Denning, A. Hirsch, M.C. Krol, D. Zupanski, L. Bruhwiler, and P.P. Tans, An ensemble data assimilation system to estimate CO_2 surface fluxes from atmospheric trace gas observations. *J. Geophys. Res*. doi: 2005JD006157R., 2005.

Peters, W., A. R. Jacobson, C. Sweeney, A. E. Andrews, T. J. Conway, K. Masarie, J. B. Miller, L. M. P. Bruhwiler, G. Pétron, A. I. Hirsch, D. E. J. Worthy, G. R. van der Werf, J. T.

Randerson, P. O. Wennberg, M. C. Krol, and P. P. Tans, An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker. *Proc. Nat. Acad. Sci.*, *104*, 18925-18930; doi:10.1073/pnas.0708986104, 2007.

Potter, C., S. Klooster, A. Huete, V. Genovese, Terrestrial Carbon Sinks for the United States Predicted from MODIS Satellite Data and Ecosystem Modeling. *Earth Interactions*, *11*, 1–21, 2007.

Predoi-Cross, A., A. R. W. McKellar, D. Chris Benner, V. Malathy Devi, R. R. Gamache, C. E. Mille5, R. A. Toth and L. R. Brown, Temperature dependences for air-broadened Lorentz half width and pressure-shift coefficients in the 30013←00001 and 30012←00001 bands of CO_2 near 1600 nm, *Can. J. Phys*. (accepted), 2009.

Rayner, P. J., 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.

Robichaud, D. J., J. T. Hodges, L. R. Brown, D. Lisak, M. Okumura, and C. E. Miller, Experimental intensity and line shape parameters of the oxygen A-Band using frequency-stabilized cavity ring-down spectroscopy, *J. Mol. Spectrosc.*, *248*, 1-13, 2008a.

Robichaud, D. J., J. T. Hodges, P. Masłowski, L. Y. Yeung, M. Okumura, C. E. Miller, and L. R. Brown, High-accuracy transition frequencies for the O_2 A-Band, *J. Mol. Spectrosc.*, *251*, 27-37, 2008b.

Robichaud, D. J., L. Y. Yeung, D. A. Long, D. K. Havey, J. T. Hodges, M. Okumura, C. E. Miller, and L. R. Brown, Experimental line parameters of the $b^1\Sigma^+_g \leftarrow X^3\Sigma^-_g$ band of oxygen isotopologues at 760 nm using frequency-stabilized cavity ring-down spectroscopy, *J. Quant. Spectrosc. Rad. Transfer*, in press, 2009.

Rodgers, C. D., *Inverse Methods for Atmospheric Sounding*, World Sci., Singapore, 2000.

Rothman, L.S., *et al.*, The HITRAN 2008 molecular spectroscopic database, *J. Quant. Spectrosc. Rad. Transfer*, in press, 2009.

Sabine, C. L., R. A. Feely, N. Gruber, R. M. Key, K. Lee, J. L. Bullister, R. Wanninkhof, C. S. Wong, D. W. R. Wallace, B. Tilbrook, F. J. Millero, T.-H. Peng, A. Kozyr, T. Ono, and A. F. Rios, The oceanic sink for anthropogenic CO_2, *Science*, *305*, 367–371, 2004.

Salawitch, R. J., P. O. Wennberg, C. E. Miller, D. Crisp, and T. Livermore, OCO Project Validation Plan, JPL Document D–29081, Pasadena, Ca., 88 pg, 2008.

Saleska, S. R., *et al.*, Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance-induced losses, *Science*, *302*, 1554–1557, 2003.

Schneising, O., 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.

Schuster, U., and A. J. Watson, A variable and decreasing sink for atmospheric CO_2 in the North Atlantic, *J. Geophys. Res.*, *112*, C11006, 2007.

Shiomi, K., S. Kawakami, T. Kina, Y. Mitomi, M. Yoshida, N. Sekio, F. Kataoka, and R. Higuchi, Calibration of the GOSAT sensors, Sensors, Systems, and Next-Generation Satellites, XI, editied by R. Meynart, S. P. Neeck, H. Shimoda, and S. Habib, Proc. SPIE Vol. 6744, 67440G. 0277-786X/07/$18. Doi: 10.1117/12.738206, 2007.

Spurr, R. J .D., and M. J. Christi, Linearization of the interaction principle: Analytic Jacobians in the ''Radiant'' model, *JQSRT*, *103*, 431-446, 2007.

Stephens, B. B., K. R. Gurney, P. P. Tans, C. Sweeney, W. Peters, L. Bruhwiler, P. Ciais, M. Ramonet, P. Bousquet, T. Nakazawa, S.Aoki, T. Machida, G. Inoue, N. Vinnichenko, J. Lloyd, A. Jordan, M. Heimann, O. Shibistova, R. L. Langenfelds, L. P. Steele, R. J. Francey, and A. S. Denning, Weak northern and strong tropical land carbon Uptake from vertical profiles of atmospheric CO_2, *Science*, *316,* 1732-1735, 2007.

Strow, L. L., and S. E. Hannon, A 4-year zonal climatology of lower tropospheric CO_2 derived from ocean-only Atmospheric Infrared Sounder observations, J. Geophys. Res., 113, D18302, doi:10.1029/2007JD009713, 2008.

Sung, K. L. R. Brown, R. A. Toth, and T. J. Crawford, FTIR measurements of H_2O-broadened half-widths of CO_2 at 4.3 μm, *Can. J. Phys.* (accepted), 2009.

Suntharalingam, P., D. J. Jacob, P. I. Palmer, J. A. Logan, R. M. Yantosca, Y. Xiao, M. J. Evans, D. G. Streets, S. L. Vay, G. W. Sachse, Improved quantification of Chinese carbon fluxes using CO2/CO correlations in Asian outflow, *J. Geophys. Res., 109*, D18S18, doi:10.1029/2003JD004362, 2004.

Takahashi, T., Sutherland, S. C., Sweeney, C., Poisson, A., Metzl, N., Tillbrook, B., Bates, N., Wanninkhof, R., Feely, R. A., Sabine, C., Olafsson, J. and Nojiri, Y., Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects, *Deep-Sea Res. II*, *49*, 1601-1622, 2002.

Takahashi, T., S. C. Sutherland, R. Wanninkhof, C. Sweeney, R. A. Feely, D. W. Chipman, B. Hales, G. Friederich, F. Chavez, C. Sabine, A. J. Watson, D.C.E. Bakker, U. Schuster, N. Metzl, H.Y. Inoue, M. Ishii, T. Midorikawa, Y. Nojiri, A. Koertzinger, T. Steinhoff, J. M. J. Hoppema, J. Olafsson, T. S. Arnarson, B. Tilbrook, T. Johannessen, A. Olsen, R. Bellerby, C.S. Wong, B. Delille, N.R. Bates, and H. J. W. de Baar, Climatological mean and decadal change in surface ocean pCO_2, and net sea–air CO_2 flux over the global oceans. *Deep-Sea Research II*, in press, 2009.

Tans, P.P., The atmospheric buildup rate for carbon is based on measurements of CO_2 at Mauna Loa obtained by the NOAA Earth System Research Laboratory, 2009. Available at ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_gr_mlo.txt, www.esrl.noaa.gov/gmd/ccgg/trends/.

Thomas, H., A.E. Friederike Prowe, I.D. Lima, S.C. Doney, R. Wanninkhof, R.J. Greatbatch, U. Schuster, and A. Corbière, Changes in the North Atlantic Oscillation influence CO_2 uptake in the North Atlantic over the past 2 decades, *Global Biogeochem. Cycles, 22*, GB4027, 2008.

Toth, R. A., L. R. Brown, C. E. Miller, V. Malathy Devi, D. Chris Benner, and M. Dulick, Line strengths of $^{12}C^{16}O_2$: 4550-7000 cm^{-1} , *J. Mol. Spectrosc.*, 239, 221-242, 2006a

Toth, R. A., L. R. Brown, C. E. Miller, V. Malathy Devi, D. Chris Benner, and M. Dulick, Self-broadened widths and shifts of CO_2, *J. Mol. Spectrosc., 239*, 243-271, 2006b.

Toth, R. A., C. E. Miller, L. R. Brown, V. Malathy Devi, and D. Chris Benner, Line positions and strengths of $^{16}O^{12}C^{18}O$, $^{18}O^{12}C^{18}O$ and $^{17}O^{12}C^{18}O$ between 2200 and 7000 cm^{-1}, *J. Mol. Spectrosc*., 3, 43-61, 2007a.

Toth, R. A., C. E. Miller, V. M. Devi, D. C. Benner and L. R. Brown, Air-broadened width and pressure shift coefficients of $^{12}C^{16}O_2$: 4700 – 7000 cm^{-1}, *J. Mol. Spectrosc*., *246*,133-157, 2007b.

Toth, R. A., L. R. Brown, C. E. Miller,V. Malathy Devi, and D. C. Benner, Spectroscopic database of CO_2 line parameters: 4300 – 7000 cm^{-1}, *J. Quant. Spectrosc. Radiat. Transfer***,** 109, 906-921, 2008a.

Toth, R. A. C. E. Miller, L. R. Brown, V. M. Devi, and D. C. Benner, Line strengths of $^{16}O^{13}C^{16}O$, $^{16}O^{13}C^{18}O$, $^{16}O^{13}C^{17}O$ and $^{18}O^{13}C^{18}O$ between 2200 and 6800 cm^{--1}, *J. Mol. Spectrosc*., *251*, 4-89, 2008b.

van der Werf, G.R., J.T. Randerson, L. Giglio, G.J. Collatz, P.S. Kasibhatla, and A.F. Arellano, Jr., Interannual variability in global biomass burning emissions from 1997 to 2004, *Atmos. Chem. Phys*., *6*, 3423–3441, 2006.

Wang, H., D. J. Jacob, M. A. Kopacz, J. A. Fisher, D. B. A. Jones, and P. N. Suntharalingam, Error correlation between CO_2 and CO as constraint for CO_2 flux inversions using satellite data, *Atmos. Chem. Phys. Dis.*, submitted, 2009.

Wang, J.-W., A. S. Denning, L. Lu, I. T. Baker, K. D. Corbin, and K. J. Davis, Observations and simulations of synoptic, regional, and local variations in atmospheric CO_2, *J. Geophys. Res.,* 112, D04108, doi:10.1029/2006JD007410, 2007.

Washenfelder, R. A., G. C. Toon, J.-F. Blavier, Z. Yang, N. T. Allen, P. O. Wennberg, S. A. Vay, D. M. Matross, and B. C. Daube, Carbon dioxide column abundances at the Wisconsin Tall Tower site, *J. Geophys. Res*., *111*, D22305, doi:10.1029/2006JD007154, 2006.

Yang, Z., R. A., Washenfelder, G.Keppel-Aleks, N. Y. Krakauer, J. T. Randerson, P. P. Tans, C. Sweeney, and P. O. Wennberg, New constraints on Northern Hemisphere growing season net flux. *Geophys. Res. Lett*., **34**, L12807, 2007.

Zimov, S. A, E. A. G. Schuur, and F. S. Chapin III, Permafrost and the Global Carbon Budget. *Science*, **312**, 1612–1613, DOI: 10.1126/science.1128908, 2006.

Zupanski, D., A. S. Denning, M. Uliasz, M. Zupanski, A. E. Schuh, P. J. Rayner, W. Peters, and K. D. Corbin, Carbon flux bias estimation employing the Maximum Likelihood Esemble Filter (MLEF). *J. Geophys. Res.* **112**, D17107, doi:10.1029/2006JD008371, 2007.

Glossary of Terms

AIRS – Atmospheric Infrared Sounder (http://airs.jpl.nasa.gov/)
AOPD – Apparent Optical Path Difference retrieval algorithm
ASCENDS – Active Sensing of CO_2 Emissions over Nights, Days and Seasons
CALIPSO - Cloud-Aerosol and Infrared Pathfinder Satellite Observation
CarbonTracker – (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/)
C4MIP – Coupled Carbon Cycle Climate Model Intercomparison Project (http://www.atmos.berkeley.edu/c4mip/home.html)
ECMWF – European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int/)
ENSO – El Nino Southern Oscillation
ENVISAT – ESA Satellite (http://envisat.esa.int/)
ESA – European Space Agency (http://www.esa.int/esaCP/index.html)
ESRL – NOAA's Earth System Research Laboratory (http://www.esrl.noaa.gov/)
ESSP – Earth System Science Pathfinder (http://nasascience.nasa.gov/programs/earth-system-science-pathfinder)
FACE – Free Air Carbon Enrichment Experiments (http://www.bnl.gov/face/)
FP – Full Physics retrieval algorithm
FPA – Focal Plane Array
FTS – Fourier Transform Spectrometer
GEMS – Global and regional Earth-system atmosphere Monitoring using Satellite and in situ data (http://gems.ecmwf.int/)
GHG – Greenhouse Gas
GLAS – Geoscience LASER Altimeter System
GMAO – Global Modeling and Assimilation Office (http://gmao.gsfc.nasa.gov/)
GOSAT – Greenhouse gases Observing SATellite (http://www.jaxa.jp/projects/sat/ibuki/index_e.html), nick-named IBUKI after launch
IASI – Infrared Atmospheric Sounding Interferometer (http://smsc.cnes.fr/IASI/)
IBUKI – Japanese for "breath"; the nickname of GOSAT
IR – Infrared
JAXA – Japan Aerospace Exploration Agency (http://www.jaxa.jp/index_e.html)
JGOFS – Joint Global Ocean Flux Study (http://www1.whoi.edu/)
NACP – North American Carbon Program (http://www.nacarbon.org/nacp/)
NASA – National Aeronautics and Space Administration (http://www.nasa.gov/)
NCAS – NOAA Center for Atmospheric Sciences (http://www.gs.howard.edu/atmosci/default.htm)
NCEP – National Centers for Environmental Protection (http://www.ncep.noaa.gov/)
NOAA – National Oceanic and Atmospheric Administration (http://www.noaa.gov/)
NWP – Numerical Weather Prediction
OCO – Orbiting Carbon Observatory (http://oco.jpl.nasa.gov/)
OSSE – Observing System Simulation Experiment
pCO_2 – partial pressure of CO_2.
ppm – Parts per million
SCIAMACHY – SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (http://envisat.esa.int/instruments/sciamachy/)

TCCON – Total Carbon Column Observing Network (http://www.tccon.caltech.edu/)
TES – Tropospheric Emission Spectrometer (http://tes.jpl.nasa.gov/)
TOMS – Total Ozone Mapping Spectrometer (http://toms.gsfc.nasa.gov/)
TransCom – The Atmospheric Tracer Transport Model Intercomparison Project (http://www.purdue.edu/transcom/transcom.php)
TRL – Technology Readiness Level
WFM-DOAS – Weighting Function Modified Differential Optical Absorption Spectroscopy
WOCE - World Ocean Circulation Experiment (http://www.noc.soton.ac.uk/OTHERS/woceipo/ipo.html)