Letter Report on the Orbiting Carbon Observatory

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Committee on Methods for Estimating Greenhouse Gas Emissions; National Research Council

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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July 28, 2009

Major General Charles F. Bolden, Jr.
Administrator
National Aeronautics and Space Administration
300 E Street, SW
Washington, DC 20546

Dear General Bolden:

A National Research Council committee is conducting a study on how well greenhouse gas emissions can be measured for treaty monitoring and verification. The committee's analysis suggests that NASA's Orbiting Carbon Observatory (OCO), which failed on launch in February 2009, would have provided proof of concept for spaceborne technologies to monitor greenhouse gas emissions, as well as baseline emissions data. This letter focuses on the capabilities of an OCO and currently deployed satellites that measure atmospheric carbon dioxide (CO_2) and their potential role in monitoring and verifying a greenhouse gas treaty.[1]

The committee's study is focused on emission estimates of the greenhouse gases resulting from human activities (e.g., fossil fuel burning, deforestation, agriculture) that have the greatest potential to warm the planet and in particular on CO_2 (see Attachment B for the committee charge). The committee is currently in the analysis and writing phase, with the expectation that its report will be delivered in December 2009. We are writing you now because a decision on replacing OCO will be made in the coming months,[2] before our final report is completed. Current proposals for an OCO reflight focus on the original scientific objectives of studying natural CO_2 sources and sinks.[3] In addition, it is important to consider the potential contribution of an OCO-like instrument for treaty monitoring and verification. Such capabilities may be an important consideration in treaty discussions at the December 2009 Copenhagen meeting of the United Nations Framework Convention on Climate Change.

If a treaty is negotiated in the coming months, monitoring and verification will initially have to rely on current capabilities and on measurement enhancements that can be deployed quickly. As the committee's final report will describe in more detail, current methods for estimating greenhouse gas emissions have limitations for monitoring a climate treaty. National emission

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[1] This report reflects the consensus of the committee and has been reviewed in accordance with standard NRC review procedures (see Attachment C).
[2] For example, see testimony by Michael Freilich, Director, NASA's Earth Science Division, before the House Committee on Science and Technology, on April 22, 2009.
[3] Boland, S., H. Bösch, L. Brown, P. Ciais, B. Connor, D. Crisp, S. Denning, S. Doney, I. Fung, D. Jacob, B. Johnson, J. Martin-Torres, A. Michalak, C. Miller, D. O'Brien, I. Polonsky, C. Potter, P. Rayner, R. Salawitch, M. Santee, P. Wennberg, D. Wunch, and Y. Yung, 2009, The need for atmospheric carbon dioxide measurements from space: Contributions from a rapid reflight of the Orbiting Carbon Observatory, White paper to NASA, April 2, 2009, 48 pp.

inventories, required under the United Nations Framework Convention on Climate Change, are self-reported and are not required regularly for all countries. Verification requires checking these self-reported emissions estimates. However, independent data against which to verify the statistics used to estimate CO_2 emissions, such as fossil fuel consumption, are not available. Existing instruments and methods for remote monitoring of atmospheric CO_2 are not able, with useful accuracy, to distinguish fossil fuel emissions from natural fluxes or to verify trends in fossil fuel emissions, such as reductions against a baseline.

Atmospheric CO_2 measurements by ground stations, aircraft, and satellites can be combined with atmospheric circulation models to infer emissions from the land surface, a method known as tracer-transport inversion. The principle is that an emission source located between two sites will cause the abundance of the gas to be higher at the downwind site than at the upwind site by an amount proportional to the source strength. However, estimated changes in atmospheric CO_2 abundance due to fossil fuel sources are confounded by errors in the reconstruction of atmospheric transport, by sparse CO_2 observations, and by the much larger changes due to biological sources and sinks.[4] Because of these complications, the tracer-transport inversion method is currently able to estimate emissions with a useful accuracy only for some large continents. The method's accuracy could be improved by expanding the CO_2 sampling network on the ground and from space, and OCO was in fact designed to improve tracer-transport inversions.

A complementary approach to tracer-transport inversion is to measure the increased atmospheric abundance on top of large local sources such as cities or power plants. The majority of fossil fuel emissions emanate from such sources and would likely be a target of mitigation measures. These large sources increase the local CO_2 abundance in the atmosphere by 1-10 ppm, a signal large enough to overwhelm the signal from natural sources and sinks, reducing this source of uncertainty.[5] Because the increased abundances are largest over the source of emissions and disperse within a few tens of kilometers, they can usually be attributed unambiguously to their country of origin. Statistical or systematic sampling of CO_2 from large local sources would thus support treaty verification by providing independent data against which to compare trends in emissions reported by countries, at least for the fossil fuel emissions from cities and power plants.

The existing atmospheric CO_2 sampling network of ground stations, aircraft, and satellites is not well designed for estimation of emissions from large local sources distributed around the globe. Ground stations and aircraft were purposefully deployed away from large fossil fuel sources to better detect natural sources and sinks, but could be deployed to monitor CO_2 emitted from selected cities and power plants. However, this would require international cooperation and such nationally operated stations would still have the verification challenges associated with self-reporting. Satellites obviate these problems. As shown in Attachment A, Japan's GOSAT is the

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[4] Fossil fuel emissions from the United States change the average abundance of atmospheric CO_2 by only ~0.7 parts per million (ppm; less than 0.2 percent) as air moves across the U.S. continent. Depending on season, analogous changes from biological sources will be two to five times larger. The signals produced by most countries are significantly smaller than these. See Tans, P.P., P.S. Bakwin, and D.W. Guenther, 1996, A feasible global carbon cycle observing system: A plan to decipher today's carbon cycle based on observations, *Global Change Biology*, **2**, 309-318.

[5] Riley, W.J., D.Y. Hsueh, J.T. Randerson, M.L. Fischer, J.G. Hatch, D.E. Pataki, W. Wang, and M.L. Goulden, 2008, Where do fossil fuel carbon dioxide emissions from California go? An analysis based on radiocarbon observations and an atmospheric transport model, *Journal of Geophysical Research*, **113**, G04002, doi:10.1029/2007JG000625.

best available spaceborne measurement of CO_2, although it is not optimal for monitoring emissions by large fossil fuel sources. It has lower uncertainty and higher spatial resolution than SCIAMACHY, AIRS, or IASI, and it senses near the surface where emission signals are largest, unlike AIRS and IASI. However, the CO_2 signal produced by the emissions of a large power plant is typically too small to measure with GOSAT.[6] In contrast, OCO would have enabled monitoring of CO_2 emissions from such local sources.[6] No other satellite has its critical combination of high precision, small footprint, readiness, density of cloud-free measurements, and ability to sense CO_2 near the earth's surface (Attachment A). In particular, its 1- to 2-ppm accuracy and 1.29 × 2.25-km sampling area would have been well matched to the size of a power plant.[6]

OCO would have had limitations for monitoring CO_2 emissions from large sources in the context of a climate treaty. It would have sampled only 7-12% of the land surface[7] with a revisit period of 16 days, and its lifetime would be only 2 years (Attachment A). However, many metropolitan areas are large enough to be sampled by OCO, and OCO would have provided a sample of a few percent of the power plants. Monitoring urban and power plant emissions from space is challenging and has not been demonstrated. A replacement OCO could demonstrate these capabilities. Nevertheless, it would be valuable to explore changes in the orbit and other parameters so that a greater fraction of large sources is sampled. For example, consider a precessing orbit covering ~100% of the surface but with only two measurements per year of each location. With 100-500 large local sources in high-emitting countries, it might be possible to obtain a statistical sample of hundreds of measurements of plumes of CO_2 being emitted by the large sources in each of these countries. The trade-offs in optimizing monitoring capabilities while meeting scientific objectives would have to be examined by a technical advisory group.

Because of its two-year mission life, OCO would not by itself have been able to track emission trends. However, it would have provided the first few years of measurements (a baseline) necessary to verify a decadal trend for the large local sources within its footprint, and served as a pathfinder for successor satellites designed specifically to support treaty monitoring and verification. Even with the data and lessons learned from a replacement OCO, a successor mission is unlikely to be ready for almost a decade.[8]

Space-based monitoring of emissions to support a greenhouse gas reduction treaty has received little attention by U.S. scientists and the government. The committee's analysis suggests that existing measurement methods alone are insufficient to independently verify reported emissions trends. Although OCO was not designed for treaty monitoring and verification, it

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[6] Assume that a 500 MW pulverized coal power plant emits ~0.13 t s^{-1} of CO_2 (e.g., 4 Mt CO_2 yr^{-1}) and that the wind speed is 3 m s^{-1}. This would produce a perturbation of approximately 0.5 percent (~1.7 ppm) in the abundance of CO_2 within an OCO sample, which is consistent with the design's estimation error of 1-2 ppm and significantly larger than the ground-tested value of 1 ppm. In contrast, because a GOSAT sample covers a larger area than an OCO sample, the CO_2 perturbation within a GOSAT sample would be approximately 0.1 percent (~0.4 ppm). This is an order of magnitude smaller than GOSAT's estimation error of 4 ppm.

[7] 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. Boesch, 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, 2007, Precision requirements for space-based X_{CO2} data, *Journal of Geophysical Research*, **112**, D10314, doi:10.1029/2006JD007659.

[8] For example, the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission has been recommended for launch in the 2013-2016 time frame. See National Research Council, 2007, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 456 pp.

would have provided baseline emission data from large fossil fuel sources as well as essential tests of the engineering designs and measurement concepts required to develop a robust capability for monitoring emissions from space.

The committee hopes this report helps to inform NASA's upcoming decision on flying a replacement OCO.

Sincerely,

Stephen W. Pacala, *Chair*
Committee on Methods for Estimating Greenhouse Gas Emissions

Attachments
cc: Todd Stern, Special Envoy for Climate Change, State Department
John Holdren, Director, Office of Science and Technology Policy

Attachment A: Specifications of Spaceborne Instruments Capable of Measuring CO_2

Specification	OCO[a]	GOSAT[b]	SCIAMACHY[c]	AIRS[d]	IASI[e]
Tropospheric gases measured	CO_2, O_2	CO_2, CH_4, O_2, O_3, H_2O	O_3, O_4, N_2O, NO_2, CH_4, CO, CO_2, H_2O, SO_2, HCHO	CO_2, CH_4, O_3, CO, H_2O, SO_2	CO_2, CH_4, O_3, CO, H_2O, SO_2, N_2O
CO_2 sensitivity	Total column including near surface	Total column including near surface	Total column including near surface	Mid-troposphere	Mid-troposphere
Horizontal resolution (km)[f]	1.29 × 2.25/5.2	FTS: 10.5/80-790	30 × 60/960	15/1,650	12/2,200
CO_2 uncertainty (ppm)[g]	1-2	4	14	1.5	2
Instruments	3-Channel grating spectrometer	CAI, SWIR/TIR Fourier transform spectrometer	8-Channel grating spectrometer	Grating spectrometer	Fourier transform spectrometer
Viewing modes	Nadir, glint, target	Nadir, glint, target	Limb, nadir	Nadir	Nadir
Samples/day	500,000	18,700	8,600	2,916,000	1,296,000
Wavelength bandpass (µm)	0.757-0.772, 1.59-1.62, 2.04-2.08	0.758-0.775, 1.56-1.72, 1.92-2.08, 5.56-14.3	0.24-0.44, 0.4-1.0, 1.0-1.7, 1.94-2.04, 2.265-2.38	3.74-4.61, 6.20-8.22, 8.80-15.4	3.62-5.0, 5.0-8.26, 8.26-15.5
Signal/noise (nadir, 5% albedo)	>300 @ 1.59-1.62 µm, >240 @ 2.04-208 µm	~120 @ 1.56-1.72 µm, ~120 @ 1.92-2.08	<100 @ 1.57 µm	~2000 @ 4.2 µm, ~1400 @ 3.7-13.6 µm, ~800 @ 13.6-15.4 µm	~1000 @ 12 µm, ~500 @ 4.5 µm
Orbit altitude	705 km	666 km	790 km	705 km	820 km
Local time	13:30 ± 0:1.5	13:00 ± 0:15	10:00	13:30	21:30
Revisit time/orbits	16 days/233 orbits	3 days/72 orbits	35 days	16 days/233 orbits	72 days/1,037 orbits
Launch date	failed on launch	January 2009	March 2002	May 2002	October 2006
Nominal life	2 years	5 years	7+ years	7+ years	5 years

NOTES: AIRS = Atmospheric Infrared Sounder; CAI = Cloud and Aerosol Imager; FTS = Fourier transform spectrometer; GOSAT = Greenhouse gas Observing Satellite; IASI = Infrared Atmospheric Sounding Interferometer; OCO = Orbiting Carbon Observatory; SCIAMACHY = Scanning Imaging Absorption Spectrometer for Atmospheric Chartography; SWIR = short-wavelength infrared; TIR = thermal infrared.

[a] Crisp, D., C.E. Miller, and P.L. DeCola, 2008, NASA Orbiting Carbon Observatory: Measuring the column averaged carbon dioxide mole fraction from space, *Journal of Applied Remote Sensing*, **2**, 023508, doi:10.1117/1.2898457; Crisp, D., 2008, The Orbiting Carbon Observatory: NASA's first dedicated carbon dioxide mission, in *Sensors, Systems, and Next-Generation Satellites XII*, Proceedings of SPIE, **7106**, 710604.

[b] Shiomi, K., S. Kawakami, T. Kina, Y. Mitomi, M. Yoshida, N. Sekio, F. Kataoka, and R. Higuchi, 2007, Calibration of the GOSAT sensors, in *Sensors, Systems, and Next-Generation Satellites XI*, Proceedings of SPIE, **6744**, 67440G; Akihiko Kuze, Japan Aerospace Exploration Agency, Personal communication, 2009; Hamazaki, T., Y. Kaneko, A. Kuze, and H. Suto, 2007, Greenhouse gases observation from space with TANSO-FTS on GOSAT, in *Fourier Transform Spectroscopy/Hyperspectral Imaging and Sounding of the Environment*, Optical Society of America Technical Digest Series, paper FWB1.

[c] <http://envisat.esa.int/instruments/sciamachy/>; Burrows, J.P., E. Hölzle, A.P.H. Goede, H. Visser, and W. Fricke, 1995, "SCIAMACHY—Scanning Imaging Absorption Spectrometer for Atmospheric Chartography, *Acta Astronautica*, **35**, 445-451; Noël, S., H. Bovensmann, J.P. Burrows, J. Frerick, K.V. Chance, A.P.H. Goede, and C. Muller, 1998, The SCIAMACHY instrument on ENVISAT-1, in *Sensors, Systems, and Next-Generation Satellites II*, Proceedings of SPIE, **3498**, 94-104; Buchwitz, M., R. de Beek, S. Noël, J.P. Burrows, H. Bovensmann, H. Bremer, P. Bergamaschi, S. Körner, and M. Heimann, 2005, Carbon monoxide, methane and carbon dioxide columns retrieved from SCIAMACHY by WFM-DOAS: Year 2003 initial data set, *Atmospheric Chemistry and Physics*, **5**, 3313-3329.

[d] 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, and J. Susskind, 2003, AIRS/AMSU/HSB on the Aqua Mission: Design, science objectives, data products, and processing systems, *IEEE Transactions on Geoscience and Remote Sensing*, **41**, 253; Chahine, M.T., L. Chen, P. Dimotakis, X. Jiang, Q. Li, E.T. Olsen, T. Pagano, J. Randerson, and Y.L. Yung, 2008, Satellite remote sounding of mid-tropospheric CO_2, *Geophysical Research Letters*, **35**, L17807, doi:10.1029/2008GL035022.

[e] Phulpin, T., D. Blumstein, F. Prel, B. Tournier, P. Prunet, and P. Schlüssel, 2007, Applications of IASI on MetOp-A: First results and illustration of potential use for meteorology, climate monitoring, and atmospheric chemistry, in *Atmospheric and Environmental Remote Sensing Data Processing and Utilization III: Readiness for GEOSS*, Proceedings of SPIE, **6684**, 66840F; Crevoisier, C., A. Chedin, H. Matsueda, T. Machida, R. Armante, and N.A. Scott, 2009, First year of upper tropospheric integrated content of CO_2 from IASI hyperspectral infrared observations, Discussion, *Atmospheric Chemistry and Physics*, **9**, 8187-8222.

[f] Instantaneous field-of-view/Swath.

[g] The uncertainty represents the estimate of random errors (e.g., the effects of detector noise) and additional systematic errors (e.g., bias caused by cloud and aerosol effects) unaccounted for or otherwise eliminated from the total error. Bias is reduced by successful validation efforts.

The GOSAT uncertainty is dominated by the precision (random errors). For OCO, Crisp et al. (2004) and Miller et al. (2007) discuss the observational system simulation experiments, including modeling of the OCO instrument performance characteristics, that led to an instrument design that would meet a measurement requirement of 1 ppm. The as-built OCO instrument performance was verified during prelaunch tests, which included direct solar observations. The analysis of the latter gave the best confirmation that the as-built instrument performance exceeded its design requirements. See 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, 2004, The Orbiting Carbon Observatory (OCO) mission, *Advances in Space Research*, **34**, 700-709; 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, 2007, Precision requirements for space-based XCO2 data, *Journal of Geophysical Research*, **112**, D10314, doi:10.1029/2006JD007659.

The methods for bias reduction and validation are the same for GOSAT and OCO. Washenfelder et al. (2006) demonstrated the OCO validation concept and the essential role of ground-based measurements for meeting those objectives. Bösch et al. (2006) used these ground-based measurements to validate SCIAMACHY CO_2. The GOSAT team also plans to use the same validation sites and instruments. OCO planned to include and use Aeronet measurements. The OCO validation plan purposely located ground-based validation measurements at ARM sites to capitalize on the wealth of ancillary atmospheric and surface measurements. See Bösch, H., G.C. Toon, B. Sen, R.A. Washenfelder, P.O. Wennberg, M. Buchwitz, R. deBeek, J.P. Burrows, D. Crisp, M. Christi, B.J. Connor, V. Natraj, and Y.L. Yung, 2006, Space-based near-infrared CO_2 measurements: Testing the OCO retrieval algorithm and validation concept using SCIAMACHY observations over Park Falls, Wisconsin, *Journal of Geophysical Research*, **111**, D23302, doi:10.1029/2006JD007080;; 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, 2006, Carbon dioxide column abundances at the Wisconsin Tall Tower site, *Journal of Geophysical Research*, **111**, D22305, doi:10.1029/2006JD007154.

Attachment B: Committee Charge and Membership

COMMITTEE CHARGE

The study will review current methods and propose improved methods for estimating and verifying greenhouse gas emissions at different spatial (e.g., national, regional, global) and temporal (e.g., annual, decadal) scales. The greenhouse gases to be considered are carbon dioxide, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), nitrous oxide, methane, and perfluorinated hydrocarbons (PFCs). Emissions of soot and sulfur compounds along with precursors of tropospheric ozone may also be considered. The results would be useful for a variety of applications, including carbon trading, setting emissions reduction targets, and monitoring and verifying international treaties on climate change.

COMMITTEE MEMBERSHIP

Stephen W. Pacala, *Chair*, Princeton University, Princeton, New Jersey
Clare Breidenich, Independent Consultant, Seattle, Washington
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Steven C. Wofsy, Harvard University, Cambridge, Massachusetts

NRC Staff: Anne M. Linn

Attachment C: Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Steven J. Battel, Battel Engineering, Scotsdale, Arizona
Guy Brasseur, National Center for Atmospheric Research, Boulder, Colorado
Antonio Busalacchi, University of Maryland, College Park
William L. Chameides, Duke University, Durham, North Carolina
Robert A. Frosch, Harvard University, Cambridge, Massachusetts
Richard A. Houghton, Woods Hole Research Center, Woods Hole, Massachusetts
Paul Palmer, University of Edinburgh, United Kingdom

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J. Lanzerotti, New Jersey Institute of Technology, and Chris G. Whipple, ENVIRON. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

This study was supported by the United States intelligence community. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the intelligence community.