Space-based observations of megacity carbon dioxide

Eric A. Kort,[1,2] Christian Frankenberg,[2] Charles E. Miller,[2] and Tom Oda[3,4]

Received 14 June 2012; revised 25 July 2012; accepted 3 August 2012; published 14 September 2012.

[1] Urban areas now house more than half the world's population, and are estimated to contribute over 70% of global energy-related CO_2 emissions. Many cities have emission reduction policies in place, but lack objective, observation-based methods for verifying their outcomes. Here we demonstrate the potential of satellite-borne instruments to provide accurate global monitoring of megacity CO_2 emissions using GOSAT observations of column averaged CO_2 dry air mole fraction (X_{CO2}) collected over Los Angeles and Mumbai. By differencing observations over the megacity with those in nearby background, we observe robust, statistically significant X_{CO2} enhancements of 3.2 ± 1.5 ppm for Los Angeles and 2.4 ± 1.2 ppm for Mumbai, and find these enhancements can be exploited to track anthropogenic emission trends over time. We estimate that X_{CO2} changes as small as 0.7 ppm in Los Angeles, corresponding to a 22% change in emissions, could be detected with GOSAT at the 95% confidence level.

Citation: Kort, E. A., C. Frankenberg, C. E. Miller, and T. Oda (2012), Space-based observations of megacity carbon dioxide, *Geophys. Res. Lett.*, *39*, L17806, doi:10.1029/2012GL052738.

[2] Carbon dioxide (CO_2) holds a central role in the earth's climate system, acting as a potent greenhouse gas [*Forster et al.*, 2007]. It is the single most important human-influenced (anthropogenic) greenhouse gas, with atmospheric abundances increasing over the last 50 years from less than 320 ppm to present day values approaching 400 ppm, with a significant associated radiative forcing perturbation [*Forster et al.*, 2007]. Future agreements to abate and reduce emissions will require independent Measurement, Reporting, and Verifying (MRV) [*Duren and Miller*, 2011]. Atmospheric observations can provide independent MRV, as anthropogenic emissions are reflected in atmospheric CO_2 concentrations. However, other processes, including atmospheric transport, also influence atmospheric carbon dioxide levels, obfuscating source attribution, presenting a major challenge in using atmospheric observations for MRV. In particular, the exchange of carbon dioxide due to photosynthesis (uptake) and respiration (release) produces a large diurnal and seasonal impact on observed mixing ratios. Though land-based biospheric fluxes only represent a net sink of ~1/4 of annual anthropogenic emissions [*Pan et al.*, 2011], this represents the interplay between seasonally varying large uptake and release that greatly impact observed atmospheric CO_2. For MRV, we must disentangle the anthropogenic and biospheric signals.

[3] One approach is to exploit the spatial disaggregation of the fluxes [*Pacala et al.*, 2010]. Anthropogenic emissions are largely concentrated in urban areas. Net fluxes per unit area in urban regions greatly exceed that of forests (i.e., +20 kg CO_2 m^{-2} yr^{-1} for Los Angeles compared to −0.9 kg CO_2 m^{-2} yr^{-1} at Harvard Forest [*Pacala et al.*, 2010]). Megacities in particular are large anthropogenic emitters, with the ten largest greenhouse gas emitting cities having emissions comparable to those of Japan [*Hoornweg et al.*, 2010]. These emissions result in very large localized urban CO_2 domes that are easy to detect [*Pataki et al.*, 2007; *Rigby et al.*, 2008]. The large signal can often be attributed to fossil fuel emissions, which can overwhelm the influence of the urban biosphere [*Newman et al.*, 2012]. Fossil fuel signals in the total column have been estimated to range from ~0.5 to ~2.0 ppm for some representative large cities [*Pacala et al.*, 2010], though ground-based total column observations over Los Angeles indicate this signal ranges from 2–8 ppm [*Wunch et al.*, 2011]. Though megacities have been a research target for air quality, most recently by *Beirle et al.* [2011], the opportunity for monitoring anthropogenic greenhouse gas emissions is only beginning to be explored [*Pataki et al.*, 2007; *Rigby et al.*, 2008; *Mays et al.*, 2009; *Strong et al.*, 2011; *Newman et al.*, 2012]. The potential for space-based observation of point source emissions has been discussed for future satellite missions [*Bovensmann et al.*, 2010], and multi-year averaging of SCIAMACHY data has suggested enhancements of CO_2 over industrial Germany are observable [*Schneising et al.*, 2008]. A recent study highlights the potential of tracking urban emissions, and suggests column observations (such as those made from space) of urban CO_2 are likely the optimal method for tracking emissions trends [*McKain et al.*, 2012].

[4] Here we present and analyze column averaged CO_2 dry air mole fraction (X_{CO2}) derived from observations collected by the Greenhouse gases Observing Satellite (GOSAT) [*Morino et al.*, 2011] from June 2009 through 2011. GOSAT spectra, collected near midday, are fit using the ACOS v2.9 level 2 algorithm [*Wunch et al.*, 2011; *O'Dell et al.*, 2012; *Crisp et al.*, 2012]. In normal operations, GOSAT records three to five footprints, each ~10 km in diameter, across its 700 km swath with a revisit time of three days. Occasionally, GOSAT performs dedicated measurements over specific sites of interest, including some megacities as part of the GOSAT Research Announcement "Estimation of the anthropogenic CO_2 and CH_4 emissions from the spatial concentration distribution around large point sources" (http://www.gosat.nies.go.jp/eng/proposal/proposal.htm). Due to limitations of the GOSAT sampling coverage, we focus our study on Los Angeles and

---

[1] W. M. Keck Institute for Space Studies, California Institute of Technology, Pasadena, California, USA.
[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[3] Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado, USA.
[4] Earth System Research Laboratory, NOAA, Boulder, Colorado, USA.

Corresponding author: E. A. Kort, W. M. Keck Institute for Space Studies, California Institute of Technology, Pasadena, CA 91125, USA. (eric.a.kort@jpl.nasa.gov)

0094-8276/12/2012GL052738

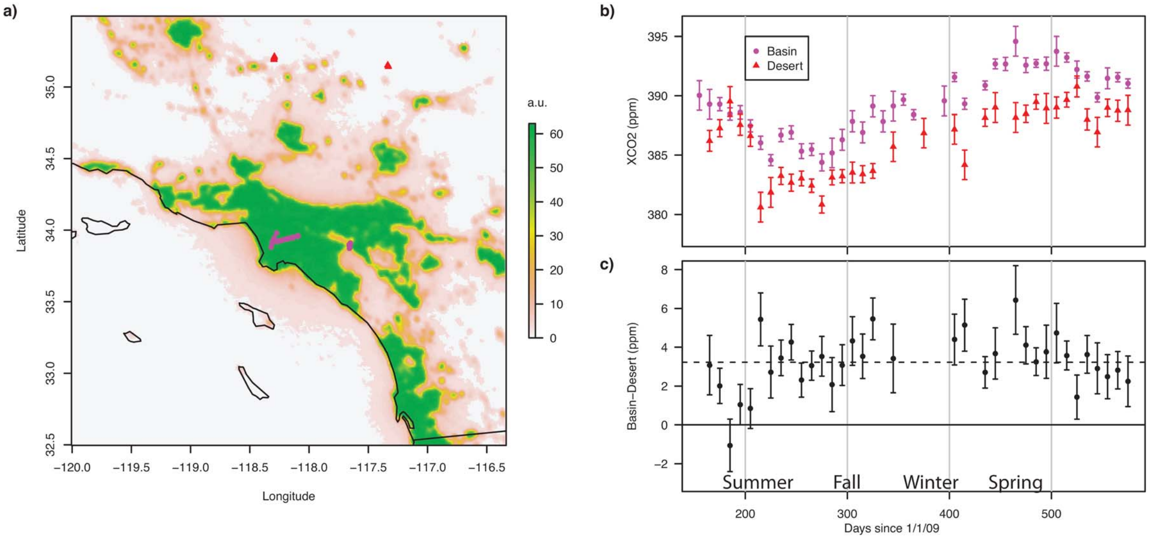

Figure 1. Observed X_{CO2} urban dome of Los Angeles from June 2009 to August 2010. (a) Nightlights map of the Los Angeles megacity and surroundings. Selected GOSAT observations within the basin (pink circles near 34°N, 118°W) and in the desert (red triangles near 35°N, 117–118°W). (b) Time-series for basin and desert observations averaged in 10-day bins. (c) The difference between 10-day block averages of basin and desert observations. The dashed black line shows the average difference (3.2 ± 1.5 ppm). All error bars plotted are one-sigma. Note Bakersfield is located near 35.4°N, 119.0°W.

Mumbai, where sufficient observations for our strategy exist. We find that statistically significant enhancements of X_{CO2} are observable throughout the year, and that these enhancements can be exploited to track anthropogenic emission trends in time.

[5] Key to our approach is the ability to differentiate X_{CO2} observations over the megacity with nearby 'clean' observations representative of background air. This relative difference isolates the CO_2 enhancement caused by megacity emissions. Relative differences are robust results that minimize sensitivity to global or zonal observational biases, and eliminate many sources of error in the satellite retrieval, as light path, viewing angle, and surface pressure are essentially identical for the megacity and clean scenes. Aerosols, surface albedo, and O_2 A-band radiance are potentially different between megacity and 'clean' observations [*Wunch et al.*, 2011].

[6] Though GOSAT has been recording operational science observations since June 2009, the need for observations both within the megacity and in a nearby background location limits the data we can use. For Los Angeles this requirement is met from June 2009 to August 2010. In August 2010 the GOSAT viewing strategy changed, resulting in a loss of the standard background desert observations. For the chosen time window, we select X_{CO2} observations within the basin, and in rural area north of the basin (termed desert). Figure 1a shows these 'basin' and 'desert' points over a nightlights map, delineating the extent of the LA megacity (nightlights image and data processing by NOAA's National Geophysical Data Center. DMSP data collected by US Air Force Weather Agency). Typical midday circulation exhibits on-shore winds with low wind-speeds [*Lu and Turco*, 1995]. This leads to large X_{CO2} enhancements where the basin observations are located, in downtown LA, and east towards Riverside. The desert observations typically sample a similar 'background' column without the anthropogenic influence (though outflow from Bakersfield and LA can influence these observations). Large-scale transport or fluxes would be expected to impact the desert and city observations similarly ('background' variability), whereas the desert observation point has little local fluxes to perturb the column. Since very few days have both basin and desert observations, we take 10-day block averages of basin and desert points. The column over this time frame clearly tracks a seasonal cycle, with basin observations systematically higher than the corresponding desert point (Figures 1b and 1c). This persistent enhancement is found to be 3.2 ± 1.5 (1σ) ppm. This enhancement is consistent with ground-based X_{CO2} observations made in Los Angeles in 2008, which observed column enhancements from 2–8 ppm attributed to anthropogenic emissions [*Wunch et al.*, 2009]. This agreement strongly supports the GOSAT observations, and validates that the differencing technique indeed produces the enhancement attributable to LA emissions. Furthermore, the value of 3.2 ± 1.5 ppm agrees well with the column enhancement predicted by a simple box model with an emissions inventory (~3.8 ppm [*Wunch et al.*, 2009]), again supporting the observations and differencing technique.

[7] Ideally we would difference basin and desert observations from the same day. Fortunately, changes in the X_{CO2} background occur on synoptic time scales, and the X_{CO2} enhancement in the basin is a robust daily feature of the Los Angeles urban dome [*Wunch et al.*, 2009; *Newman et al.*, 2012]. Daily transport variation will impact the magnitude of the enhanced CO_2 dome. This variation may in fact be responsible for some of the spread in the observed basin-desert difference. Interestingly, 20-day or 30-day block averages yield enhancements that are statistically equivalent to the 10-day block averages (Figure S1 in the auxiliary material).[1] This finding indicates the LA basin enhancement is a robust feature of the region attributable to anthropogenic emissions,

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL052738.

and not affected by seasonally varying changes in biospheric fluxes or transport patterns. We rule out aerosol, albedo, and radiance effects (see auxiliary material). Continuous in-situ observations of $CO_{2(excess)}/CO_{(excess)}$ validated by periodic comparison with $^{14}CO_2$ from whole air flask samples, indicate that up to 100% of the midday enhancement can be attributed to emissions from fossil fuel combustion [*Newman et al.*, 2012]. The lack of any seasonality in the basin-desert difference (Figure 1b) further suggests that no significant biospheric or oceanic CO_2 fluxes are impacting our retrieved difference, as either biospheric or coastal upwelling contributions would exhibit strong seasonality. This is expected for both the city and desert observation locations, as both exhibit relatively low photosynthetic activity, demonstrated by the very low chlorophyll fluorescence signal observed in the LA region [*Frankenberg et al.*, 2011].

[8] Local meteorological conditions explain the cases when the basin-desert difference drops to zero or becomes negative. During Santa Ana conditions, the circulation changes dramatically, with strong winds travelling from the desert into the LA basin. These events carry urban emissions out to sea, expelling the urban CO_2 dome and reducing the basin-desert difference to near zero. At times the desert observation is directly downwind of Bakersfield, and therefore influenced by anthropogenic emissions and not representative of background X_{CO2}. Back trajectory calculations (using HYSPLIT [*Draxler and Rolph*, 2012]) indicate that these two conditions explain observations near day 200 in Figure 1.

[9] The data in Figure 1 demonstrate conclusively that space-based observations can detect enhanced X_{CO2} over the LA basin. With such observations we ask: What is the smallest change in emissions that could be detected? We focus on the question of change rather than absolute fluxes for a number of reasons. Even with very dense surface observational networks, retrieval of accurate absolute fluxes is hampered by the presence of unaccounted for bias errors. This often is a product of transport error in the inverse method [*Lauvaux et al.*, 2012]. When looking for changes in fluxes rather than absolute values, many bias errors do not influence our assessment. Furthermore, by looking at the change in emissions, we are insensitive to potential biases present in the differencing technique (such as the background 'desert' site being offset from a truly representative background site). We are insensitive to daily CO_2 variations attributable to transport, as we consider the full year statistical aggregate. We assume on average the transport (most importantly the basin ventilation time), does not change annually.

[10] The basin-desert difference distribution is quite Gaussian (Figure S3), enabling the use of simple statistical tools. Assuming we have the same observation set (i.e., identical statistics) for a different ~1 year time frame, a simple t-test suggests we could detect a minimum change of 0.7 ppm (22% of the observed enhancement) in the basin-desert difference with 95% confidence using GOSAT observations. The basin-desert difference measures the additional CO_2 molecules within the basin due to local emissions. Assuming no trend in basin ventilation time, this difference value is therefore linearly dependent on the flux. Consequently, the t-test implies GOSAT-like space-based observations could detect emissions changes of 22% or greater. California has a goal to reduce greenhouse gas emissions back to 1990 levels by 2020 (30% below current trends [*Croes*, 2012]). By 2030 Los Angeles plans to cut greenhouse gas emissions 35% vs. 1990 levels [*Villaraigosa et al.*, 2007]. To achieve these goals, emissions reductions will need to exceed 22% from 2009/2010 levels. If these reductions were spatially heterogeneous through the LA basin, these reductions would appear to be observable and verifiable with appropriate sustained observations from space. Ground-based observations of CO_2 and meteorological variables would be necessary to support and validate such space-based verification.

[11] The question arises whether similar X_{CO2} enhancements can be observed over other megacities. Mumbai also exhibits a CO_2 urban dome observable from space. When appropriate GOSAT observations are available (e.g., during the dry season of 2011), we can apply the same technique used to analyze Los Angeles X_{CO2}. We identify city and rural observations, and find a robust X_{CO2} enhancement of 2.4 ± 1.2 (1σ) ppm in Mumbai (Figure S4). In fact, on specific observing days in March of 2011, GOSAT observations captured the city-rural X_{CO2} gradient (Figure 2). Further interpretation of the Mumbai observations is hampered by the limited data and the total lack of observations in the wet season. There is a potential biospheric influence on the background sites. The current observational capability over Mumbai would be challenged to detect robust emissions changes, but these observations do demonstrate that satellite observations of this precision can identify enhanced X_{CO2} due to megacity emissions as well as map their spatial extent and variability.

[12] The meteorology in both Los Angeles and Mumbai enables us to apply our simple technique. Both are coastal cities with consistent wind patterns that commonly form urban CO_2 domes. Nearby background locations with smaller anthropogenic and biogenic influence exist. Many megacities are near other major urban sources or strong biogenic influences. This leads to significant daily perturbations to the megacity CO_2 concentrations that are not attributable to local anthropogenic emissions. To monitor CO_2 concentrations under these conditions requires numerous observations in space and time both around and within the megacity. Additionally, atmospheric transport must be explicitly considered.

[13] Although our simple approach works for Los Angeles and Mumbai, the current GOSAT observing strategy limits its use for systematic monitoring and assessing global megacity emission trends. There are few observations directly over the small areas occupied by megacities, or in a nearby background location. Filtering of cloudy or other contaminated retrievals reduces the number of usable observations further. It is rare to have a day with observations both within the city and over a nearby rural/background location. In spite of the sparseness of megacity observations, care should be taken when using special observations in global inversion studies, as these are non-random samples in space, and are biased towards point-emitters poorly represented in global models.

[14] We suggest a program of "Special Observations" focused on megacities, with particular emphasis on rapidly growing population centers (e.g., Delhi, Dhaka, Karachi, Lagos, Shanghai). The program should include dense observations within each urban center combined with nearly simultaneous observations of appropriate nearby rural/background sites (see Figure 1a).

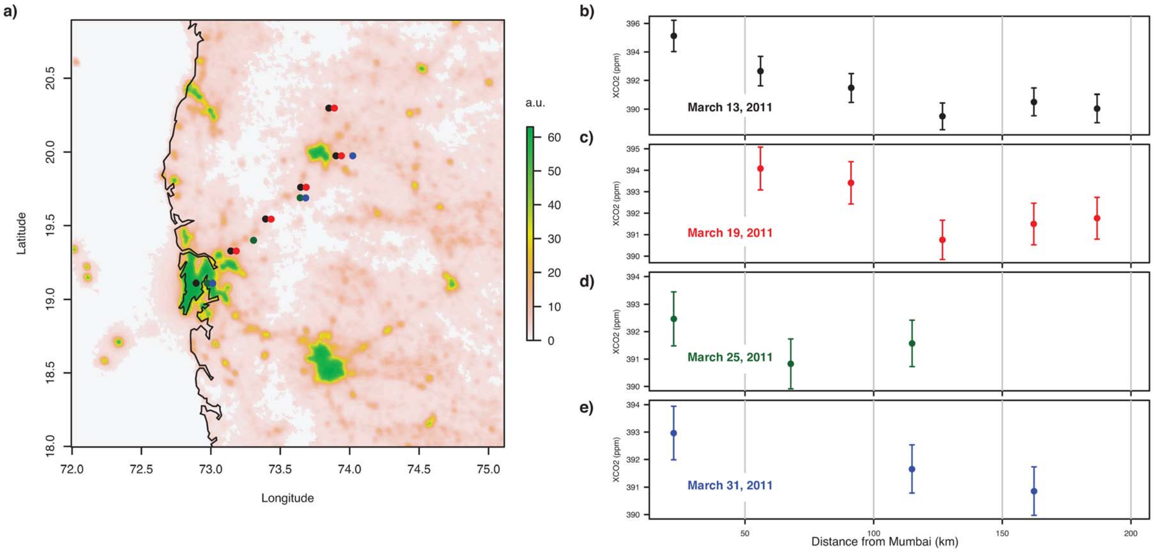

Figure 2. Spatial mapping of Mumbai X_{CO2} urban dome in March 2011. (a) Nightlights map of the Mumbai megacity and surroundings. Selected GOSAT observations, corresponding to days in Figures 2b–2e. Overlaying footprint locations are offset for visibility. (b–e) X_{CO2} urban dome gradient observed over Mumbai. Error bars are one-sigma retrieval error.

[15] Future satellites will offer new opportunities to monitor megacity CO_2 emissions. Improved spatiotemporal coverage with small footprints, such as offered by ‘mapping’ or geostationary observations are particularly attractive for megacity emissions studies.

[16] **Acknowledgments.** This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. EAK thanks the W. M. Keck Institute for Space Studies for support. GOSAT Level 1B products (spectral data) were provided by the GOSAT Project (JAXA, NIES, and Ministry of the Environment Japan) through its collaboration with NASA’s Atmospheric CO_2 Observations from Spaces (ACOS) team. The X_{CO2} data used in this work were processed by the ACOS team using software build 2.9. The authors thank the GOSAT and OCO/ACOS teams for continued collaboration and detailed technical discussions. The authors wish to thank Paul Wennberg, Yuk Yung, Michael Gunson, and Annmarie Eldering for insightful and constructive suggestions and comments.

[17] The Editor thanks Prabir K. Patra for assisting in the evaluation of this paper.

References

Beirle, S., K. F. Boersma, U. Platt, M. G. Lawrence, and T. Wagner (2011), Megacity emissions and lifetimes of nitrogen oxides probed from space, *Science*, *333*(6050), 1737–1739, doi:10.1126/science.1207824.

Bovensmann, H., M. Buchwitz, J. P. Burrows, M. Reuter, T. Krings, K. Gerilowski, O. Schneising, J. Heymann, A. Tretner, and J. Erzinger (2010), A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications, *Atmos. Meas. Tech.*, *3*(4), 781–811, doi:10.5194/amt-3-781-2010.

Crisp, D., et al. (2012), The ACOS XCO_2 retrieval algorithm, Part 2: Global XCO_2 data characterization, *Atmos. Meas. Tech. Discuss.*, *5*, 1–60, doi:10.5194/amtd-5-1-2012.

Croes, B. E. (2012), New Directions: California’s programs for improving air quality and minimizing greenhouse gas emissions, *Atmos. Environ.*, *47*, 562–563, doi:10.1016/j.atmosenv.2010.05.041.

Draxler, R. R., and G. D. Rolph (2012), HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory), report, Air Resour. Lab., NOAA, Silver Spring, Md. [Available at http://ready.arl.noaa.gov/HYSPLIT.php.]

Duren, R. M., and C. E. Miller (2011), Towards robust global greenhouse gas monitoring, *Greenhouse Gas Meas. Manage.*, *1*, 80–84.

Forster, P., et al. (2007), Changes in atmospheric constituents and in radiative forcing, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 129–234, Cambridge Univ. Press, Cambridge, U. K.

Frankenberg, C., et al. (2011), New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity, *Geophys. Res. Lett.*, *38*, L17706, doi:10.1029/2011GL048738.

Hoornweg, D., et al. (2010), *Cities and Climate Change: An Urgent Agenda*, The World Bank, Washington, D. C.

Lauvaux, T., et al. (2012), Constraining the CO_2 budget of the corn belt: Exploring uncertainties from the assumptions in a mesoscale inverse system, *Atmos. Chem. Phys.*, *12*, 337–354, doi:10.5194/acp-12-337-2012.

Lu, R., and R. P. Turco (1995), Air pollutant transport in a coastal environment. 2. 3-dimensional simulations over Los-Angeles basin, *Atmos. Environ.*, *29*(13), 1499–1518, doi:10.1016/1352-2310(95)00015-Q.

Mays, K. L., P. B. Shepson, B. H. Stirm, A. Karion, C. Sweeney, and K. R. Gurney (2009), Aircraft-based measurements of the carbon footprint of Indianapolis, *Environ. Sci. Technol.*, *43*(20), 7816–7823, doi:10.1021/es901326b.

McKain, K., S. C. Wofsy, T. Nehrkorn, J. Eluszkiewicz, J. R. Ehleringer, and B. B. Stephens (2012), Assessment of ground-based atmospheric observations for verification of greenhouse gas emissions from an urban region, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(22), 8423–8428, doi:10.1073/pnas.1116645109.

Morino, I., et al. (2011), Preliminary validation of column-averaged volume mixing ratios of carbon dioxide and methane retrieved from GOSAT short-wavelength infrared spectra, *Atmos. Meas. Tech.*, *4*(6), 1061–1076, doi:10.5194/amt-4-1061-2011.

Newman, S., et al. (2012), Diurnal tracking of anthropogenic CO_2 emissions in the Los Angeles basin mega-city during spring. 2010, *Atmos. Chem. Phys. Discuss.*, *12*, 5771–5801, doi:10.5194/acpd-12-5771-2012.

O’Dell, C. W., et al. (2012), The ACOS CO2 retrieval algorithm—Part 1: Description and validation against synthetic observations, *Atmos. Meas. Tech.*, *5*(1), 99–121, doi:10.5194/amt-5-99-2012.

Pacala, S. W., et al. (2010), *Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements*, Natl. Acad. Press, Washington, D. C.

Pan, Y. D., et al. (2011), A large and persistent carbon sink in the world’s forests, *Science*, *333*(6045), 988–993, doi:10.1126/science.1201609.

Pataki, D. E., T. Xu, Y. Q. Luo, and J. R. Ehleringer (2007), Inferring biogenic and anthropogenic carbon dioxide sources across an urban to rural gradient, *Oecologia*, *152*(2), 307–322, doi:10.1007/s00442-006-0656-0.

Rigby, M., R. Toumi, R. Fisher, D. Lowry, and E. G. Nisbet (2008), First continuous measurements of CO_2 mixing ratio in central London using a compact diffusion probe, *Atmos. Environ.*, *42*(39), 8943–8953, doi:10.1016/j.atmosenv.2008.06.040.

Schneising, O., M. Buchwitz, J. P. Burrows, H. Bovensmann, M. Reuter, J. Notholt, R. Macatangay, and T. Warneke (2008), Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite—Part 1: Carbon dioxide, *Atmos. Chem. Phys.*, *8*(14), 3827–3853, doi:10.5194/acp-8-3827-2008.

Strong, C., C. Stwertka, D. R. Bowling, B. B. Stephens, and J. R. Ehleringer (2011), Urban carbon dioxide cycles within the Salt Lake Valley: A multiple-box model validated by observations, *J. Geophys. Res.*, *116*, D15307, doi:10.1029/2011JD015693.

Villaraigosa, A. R., et al. (2007), *Green L.A.: An Action Plan to Lead the Nation in Fighting Global Warming*, City of Los Angeles, Los Angeles, Calif.

Wunch, D., P. O. Wennberg, G. C. Toon, G. Keppel-Aleks, and Y. G. Yavin (2009), Emissions of greenhouse gases from a North American megacity, *Geophys. Res. Lett.*, *36*, L15810, doi:10.1029/2009GL039825.

Wunch, D., et al. (2011), A method for evaluating bias in global measurements of CO_2 total columns from space, *Atmos. Chem. Phys.*, *11*(23), 12,317–12,337, doi:10.5194/acp-11-12317-2011.