JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 1–8, doi:10.1002/jgrd.50135, 2013

Surface observations for monitoring urban fossil fuel CO_2 emissions: Minimum site location requirements for the Los Angeles megacity

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Received 28 August 2012; revised 19 November 2012; accepted 22 December 2012.

[1] The contemporary global carbon cycle is dominated by perturbations from anthropogenic CO_2 emissions. One approach to identify, quantify, and monitor anthropogenic emissions is to focus on intensely emitting urban areas. In this study, we compare the ability of different CO_2 observing systems to constrain anthropogenic flux estimates in the Los Angeles megacity. We consider different observing system configurations based on existing observations and realistic near-term extensions of the current ad hoc network. We use a high-resolution regional model (Stochastic Time-Inverted Lagrangian Transport-Weather Research and Forecasting) to simulate different observations and observational network designs within and downwind of the Los Angeles (LA) basin. A Bayesian inverse method is employed to quantify the relative ability of each network to improve constraints on flux estimates. Ground-based column CO_2 observations provide useful complementary information to surface observations due to lower sensitivity to localized dynamics, but column CO_2 observations from a single site do not appear to provide sensitivity to emissions from the entire LA megacity. Surface observations from remote, downwind sites contain weak, sporadic urban signals and are complicated by other source/sink impacts, limiting their usefulness for quantifying urban fluxes in LA. We find a network of eight optimally located in-city surface observation sites provides the minimum sampling required for accurate monitoring of CO_2 emissions in LA, and present a recommended baseline network design. We estimate that this network can distinguish fluxes on 8 week time scales and 10 km spatial scales to within ~12 g C m^{-2} d^{-1} (~10% of average peak fossil CO_2 flux in the LA domain).

Citation: Kort, E. A., W. M. Angevine, R. Duren, and C. E. Miller (2013), Surface observations for monitoring urban fossil fuel CO_2 emissions: Minimum site location requirements for the Los Angeles megacity, *J. Geophys. Res. Atmos.*, *118*, doi:10.1002/jgrd.50135.

1. Introduction

[2] Carbon dioxide (CO_2) is the single most important anthropogenic greenhouse gas [*Forster et al.*, 2007]. Atmospheric levels of CO_2 have increased from a preindustrial level of 280 ppm to nearly 400 ppm today, and anthropogenic emissions continue to rise [*Hofmann et al.*, 2009]. This 40% increase in CO_2 significantly perturbs the Earth's radiative balance, and provides potential incentive for a reduction in emissions. Atmospheric observations have the potential to provide independent validation for any future agreement on carbon emissions. However, to extract information on anthropogenic emissions from atmospheric observations, the role of transport and biospheric fluxes must be untangled. Current global assimilation frameworks are incapable of disentangling these components to the level required for monitoring of anthropogenic CO_2 at 300 km spatial scales [*Hungershoefer et al.*, 2010]. By developing a framework specifically focused on small area, large magnitude anthropogenic sources, we can potentially overcome transport and biospheric obfuscation. Improved observational constraints on anthropogenic emissions will also improve biospheric flux estimates.

[3] Megacities present an excellent target from both an atmospheric and policy perspective. Megacities concentrate large emissions in a small area, often producing an urban dome with significant anthropogenic enhancement of CO_2 [*Pacala et al.*, 2010]. Urban areas are estimated to be responsible for over 70% of global energy-related carbon emissions [*Rosenzweig et al.*, 2010]. Urban populations are expected to grow, with projections of global urban population almost doubling by 2050. Some megacities already have

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2169-897X/13/10.1002/jgrd.50135

climate plans in place, including aggressive greenhouse gas emissions reductions objectives (i.e., Los Angeles, *Villaraigosa et al.* [2007]).

[4] Many measurements of CO_2 in urban environments have been made, with a particular focus on the diurnal variation of CO_2 and its relation to boundary layer height and emissions [*Pataki et al.*, 2007; *Rigby et al.*, 2008; *Strong et al.*, 2011]. Recent examples have started to attempt to specifically attribute emissions [*Turnbull et al.*, 2011; *Newman et al.*, 2012] and perform trend detection over time [*McKain et al.*, 2012]. These studies suggest that attribution and trend detection with atmospheric observations are possible. However, although optimal global monitoring network design has been studied [*Gloor et al.*, 2000; *Suntharalingam et al.*, 2003; *Hungershoefer et al.*, 2010], optimal strategies for monitoring urban emissions have yet to be determined.

[5] *McKain et al.* [2012] posited that total column CO_2 observations may be preferable for urban monitoring. This notion, in concert with the excellent spatiotemporal coverage of satellite-based observations, suggests space-based observations would be an ideal manner in which to sample urban emissions. *Kort et al.* [2012] succeeded in detecting enhanced CO_2 over the Los Angeles and Mumbai megacities using observations from the Greenhouse gases Observing SATellite (GOSAT), but noted that current space-based urban CO_2 observing capabilities are quite limited, and still require as yet nonexistent ground-based validation. With long temporal averaging, SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) has exhibited sensitivity to persistent CO_2 emissions from industrial Germany [*Schneising et al.*, 2008], and future satellites with designs optimized for urban studies may significantly improve space-based studies [*Bovensmann et al.*, 2010].

[6] In this study, we use a high-resolution regional model to study the ability of different CO_2 observing systems to constrain anthropogenic flux estimates in the Los Angeles megacity. We consider different observing system configurations based on existing observations and realistic near-term extensions of the current ad hoc network. We evaluate the difference between in-city surface observations and more remote, downwind observing sites. We compare the information gained from surface and ground-based total column observations. We then assess the current observing network's sensitivity to emissions, and compare with proposed network enhancements.

[7] The remainder of the paper is structured as follows. Section 2 presents the inversion scheme and transport model employed. Section 3 outlines the different observing systems considered in our study. Section 4 discusses model results, comparing and contrasting different individual observations, urban observational networks, and identifies the minimum sampling required for accurate monitoring of CO_2 emissions in Los Angeles (LA), and recommends a baseline network design.

2. Methods

[8] Monitoring of urban greenhouse gas emissions is a burgeoning area of research, and there are many open questions about the best approach to take. There will be different optimal observing strategies depending on whether questions focus on bulk anthropogenic flux changes with time, or the evolving contribution from specific source sectors. In this analysis, we are interested in (1) determining the sensitivity of different observations to LA anthropogenic emissions, and (2) quantifying the relative ability of different observations (and networks) to constrain anthropogenic CO_2 emissions estimates for the Los Angeles megacity using average fluxes for ~8 week time windows.

2.1. Inversion Method

[9] To probe observations sensitivity to emissions at a fine spatial scale, we employed the Stochastic Time-Inverted Lagrangian Transport (STILT) model [*Lin et al.*, 2003], driven by wind fields generated with the Weather Research and Forecasting (WRF) model (as in *Nehrkorn et al.* [2010]). STILT and STILT-WRF have been described and used extensively in regional inversions of various trace gases [*Gerbig et al.*, 2003; *Kort et al.*, 2008; *Miller et al.*, 2012] as well as in urban studies [*McKain et al.*, 2012]. Key to the work here is the ability of this model to produce a footprint for any hypothetical observation. The footprint represents the sensitivity of the observation to surface emissions (units ppm m^2 s μmol^{-1}), and can be used to construct the Jacobian matrix (**H**). Once **H** has been calculated for an observation or set of observations, a Bayesian framework can be used to solve for optimized fluxes by minimizing the cost function

$$J(f) = \frac{1}{2}\left[(z - \mathbf{H}f)^T \mathbf{R}^{-1}(z - \mathbf{H}f) + \left(f - f_{\text{prior}}\right)^T \mathbf{C}_{\text{prior}}^{-1}\left(f - f_{\text{prior}}\right)\right] \tag{1}$$

[10] Here z is an $n \times 1$ vector of observations, **H** is an $n \times m$ Jacobian, f is an $m \times 1$ vector of fluxes in the domain, f_{prior} is an $m \times 1$ vector of a priori fluxes, **R** is an $n \times n$ model-data mismatch covariance matrix, and $\mathbf{C}_{\text{prior}}$ is an $m \times m$ a priori error covariance matrix representative of uncertainty in the prior flux field. An analytical solution to the minimization of (1) exists, yielding the optimized flux field (f_{post}), as well as the posterior error covariance matrix ($\mathbf{C}_{\text{post}}$), representative of the error in the optimized flux field

$$\mathbf{C}_{\text{post}} = \left[\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H} + \mathbf{C}_{\text{prior}}^{-1}\right]^{-1} \tag{2}$$

[11] The posterior error covariance matrix $\mathbf{C}_{\text{post}}$ calculated using this analytical approach provides a powerful tool for evaluating different hypothetical observing systems. By simply calculating **H** for a hypothetical observing system, and defining model-data mismatch and prior flux uncertainty (**R** and $\mathbf{C}_{\text{prior}}$, respectively), we can calculate the percentage error reduction due to this set of hypothetical observations. Because the framework is analytic and the calculations rapid, many different observing systems can be quantitatively assessed and compared for their ability to constrain urban CO_2 emissions. This same analytical technique has been exploited to study global observing systems [*Hungershoefer et al.*, 2010].

2.2. Transport Model Details

[12] The simulations in this study were all performed using the WRF meteorological fields developed by *Angevine*

et al. [2012] for California during the CALNEX campaign (May–June 2010). Many configurations were tested and optimized for this time frame. We focused on the configuration referred to by Angevine et al. as GM4, which was found to have optimum representation of Los Angeles basin dynamics (note that usage of the EM4N runs, with different initialization fields and land surface model, produces nearly equivalent results). The GM4 simulation has a horizontal grid spacing of 4 km within the Los Angeles basin, with initial and boundary conditions from the U.S. National Centers for Environmental Prediction Global Forecast System analyses. The extensive evaluation performed with these wind fields [*Angevine et al.*, 2012] indicates considerable systematic and random uncertainties. For much of the analysis presented here, our findings should be relatively insensitive to these errors—particularly as we consider relative performance of different observations. These errors will have a larger impact when we consider absolute flux reductions.

[13] A Jacobian (of 0.1° × 0.1° spatial resolution, domain delineated in Figure 1) was generated for each potential observing site for a midday observation (2 P.M. local time) each day for ~2 months (7 May to 30 June 2010). Simulations were focused on midday observations for two major reasons: (1) the model best captures the atmospheric dynamics at this time of day due to the well-developed boundary layer, and (2) radiocarbon measurements indicate midday observations within the LA basin are ~100% fossil fuel derived [*Newman et al.*, 2012], meaning biospheric contributions can safely be neglected in this study. One hundred air parcels were released back in time 24 h for each potential observing site, with 10 m above ground level as the default release height for surface sites. For simulating column CO_2 observations at Caltech, 100 air parcels were released from 10 different heights above ground level of 10, 310, 610, 910, 1210, 1510, 1810, 2110, 2410, 2710 m. The column footprint was then generated as the weighted average (by pressure) of these receptors multiplied by the mass fraction of the atmosphere we have modeled (~30%). All site locations simulated are presented in Table 1.

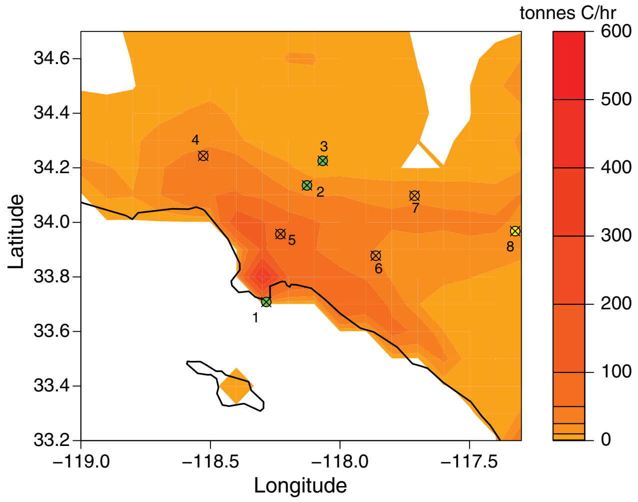

Figure 1. Vulcan emissions (average for May 2002). Targets indicate locations of observing sites, green sites currently exist, the yellow site is forthcoming, and hollow sites are proposed expansion locations.

Table 1. Surface Site Locations Used in Simulations

Identifier	Latitude	Longitude
1. Palos Verdes	33.708	–118.285
2. Caltech	34.200	–118.180
3. Mt. Wilson	34.226	–118.067
4. Northridge	34.244	–118.528
5. Downtown	33.957	–118.230
6. Anaheim	33.878	–117.862
7. Claremont	34.098	–117.713
8. Riverside	33.968	–117.324
9. Palm Springs	33.874	–116.506

[14] Comparison of modeled and observed winds at Los Angeles international airport indicates the land-sea breeze circulation is captured by the model [cf. *Angevine et al.*, 2012, Figure 4]. This suggests evening emissions that are pushed offshore and recirculated into the basin the next day are simulated. This feature of the LA basin dynamics indicates that midday observations exhibit some sensitivity to evening rush-hour emissions. It should be noted that this recirculation, and the model representation of it, is rather inefficient and uncertain. Future analyses using observations made throughout the full daily cycle would likely improve fossil-fuel emissions constraints, provided diurnal boundary layer features are captured by the model and validated by observations.

2.3. Error Covariance Matrices

[15] To reduce the influence of prior assumptions on our evaluated uncertainty reduction, we consider the simplest possible error covariance matrices. The model-data mismatch matrix (**R**) is defined as diagonal, with uncertainties (1σ) set at 5 ppm for surface observations, and 0.5 ppm for column observations. Note these values are representative of model-data mismatch, not observational uncertainty, and are approximations based largely on confidence in model representation. Thus, these values entrain uncertainty attributed to different processes including boundary condition and boundary layer height errors. The prior flux uncertainty ($\mathbf{C}_{\text{prior}}$) is based on the Vulcan CO_2 emissions inventory [*Gurney et al.*, 2009]. The average emissions for May is calculated, and uncertainty is defined as 66% of the emissions, with a floor of 3 μmol m^{-2} s^{-1}, where grid boxes with uncertainty less than this value are assigned this number. Usage of Vulcan enables us to account for the spatial heterogeneity of emissions throughout the basin, and defining an uncertainty floor enables the inversion to capture emissions from regions where Vulcan predicts negligible emissions.

[16] Note that bias errors are not included in this simple Bayesian formulism. This has a minimal impact on our relative comparison of different observations, but may impact absolute flux estimates, in particular through potential error in boundary layer height. We anticipate that the use of boundary layer observations to quantify and account for bias errors will be essential for accurate urban CO_2 flux estimates from inversions of actual observations.

3. Observing Systems

3.1. Single-Site Observations

[17] In this section we compare the information from different individual observing sites as well as from different measurement techniques. We first assess the benefits of

surface in situ observations from a site within the LA basin compared with a remote downwind site by analyzing observation at Caltech (where the actual measurement record extends back for more than a decade, *Newman et al.* [2012]) and Palm Springs, one of the LA basin's outflow regions. We also weigh the value of Caltech observations versus the near-remote site located on Mt. Wilson. We then explore whether urban CO_2 emissions can be monitored accurately with a single in-city site. Finally, we test the conclusion of *McKain et al.* [2012] that integrated column measurements are preferable for urban trend detection for Los Angeles by comparing whether surface in situ CO_2 measurements or ground-based measurements of column averaged CO_2 dry air mole fraction (XCO_2) from a single in-city location more accurately capture emissions in the LA urban CO_2 dome. Pasadena is selected for these simulations, as actual observations of each type are now being made (in situ: *Newman et al.* [2008, 2012]; column: observations began Spring 2012, similar to those in *Wunch et al.* [2009]).

3.2. Multisite Observations

[18] We consider three different observing system scenarios based on present and realistic near-term network expansions.

S1: Current observational capability in basin (Palos Verdes, Caltech, Mt. Wilson, Sites 1–3 in Table 1)
S2: S1 augmented by a downwind site in the Riverside area (Site 4, planned deployment)
S3: S2 augmented by 4 new sites (Sites 5–9, proposed deployment)

[19] The locations of existing and proposed sites are illustrated in Figure 1. Also plotted is the average anthropogenic CO_2 emissions predicted for May 2002 by the Vulcan inventory [*Gurney et al.*, 2009]. Notice the strategy proposed entails placing numerous sites in and around the high emissions concentrated in the LA basin. When actually deploying urban monitoring stations, site-specific selection details not accounted for here are critical. For this analysis we assume all sites sample air masses representative of the location on the ~1 km scale and are not dominated by "local" sampling effects. Thus, similar data would be observed for any location within ~1 km range of the sites in Table 1. From this perspective, ideal monitoring is performed from elevated height on towers, removed from very localized emission dynamics (i.e., individual roads or power plants) or submodel-scale meteorological dynamics (i.e., canyoning). Measurement accuracy, achieved though careful calibrations, is essential to prevent site-to-site biases (constant or evolving) from being falsely interpreted as atmospheric signatures from fluxes.

4. Results

4.1. Caltech

[20] Observations have been made discontinuously at Caltech since the early 1970s [*Newman et al.*, 2008]. Analysis of carbon isotopes from whole air flask samples has been performed to assess the observed CO_2 attributable to local emissions, and it was found that ~10 ppm more CO_2 was attributable to local emissions in the 1970s than the early 2000s, in seeming contrast to the known emissions increase in that time frame [*Newman et al.*, 2008]. This finding can possibly be explained by analysis of the footprint of the Caltech site, seen in Figure 2a. Observations at Caltech exhibit sensitivity to emissions in the historic downtown LA region. This downtown area was already well developed in the 1970s, and the increase in LA basins emissions in the past 40 years is more connected to urban sprawl, and an increase in emissions east in the basin. The center of LA has actually experienced a decrease in emissions, presumably largely attributable to improved transport efficiency (fuel economy) in this time frame. This highlights the value of an in-city site to track emissions trends, but emphasizes the limitations of such a site, which will only be sensitive to a portion of the regions emissions trends.

4.2. Caltech vs. Palm Springs

[21] Footprint analyses for individual observing sites explicitly show the sensitivity of observations at that site to CO_2 fluxes throughout the Los Angeles megacity. Figure 2 illustrates the average midday footprint for the previous 24 h—a good metric for a site's ability to constrain flux estimates in an inversion. Included are the footprints for surface observing sites at Caltech and Palm Springs (Figure 2a), Mt. Wilson (Figure 2b), and a total column CO_2 observation at Caltech (Figure 2c). Predominant midday wind patterns exhibit onshore flow into the basin. The Caltech surface observation footprint clearly illustrates this pattern, because the footprint is strongest southwest of the site. Wind patterns outside the basin exhibit more variability, and this is clearly exhibited in the Palm Springs footprint, showing sensitivity to emissions both to the west and southeast. Although Palm Springs has sensitivity to the LA basin on some days, many days there is little to no influence from the basin. The average footprint from Palm Springs is relatively weak in the basin compared to the site at Caltech, indicating it will not provide the same level of constraint on CO_2 emissions as the Caltech site can provide. Although a remote downwind site such as Palm Springs has days where it sees an integrated LA signal, this signal is diluted and mixed with other upwind fluxes, and is only sampled intermittently. For urban emissions monitoring, observations within the urban environment with daily sensitivity to emissions, larger signals, and fewer confounding fluxes appear superior.

4.3. Caltech vs. Mt Wilson

[22] Midday surface observations made on Mt. Wilson are thought to provide an integrated picture of the greater Los Angeles basin [*Hsu et al.*, 2010]. Mt. Wilson is located in the San Gabriel Mountains along the northern edge of the Los Angeles basin at an elevation of ~1700 m above sea level. Surface observations from Mt. Wilson sample the free troposphere in the evening, night, and morning. Midmorning upslope flow from the basin can start to reach the site. By midday, the well-established boundary layer of the LA basin can rise above the Mt. Wilson site. Therefore, the midday footprint from Mt. Wilson shows sensitivity within the LA basin (Figure 2b). Although the footprint is a bit more distributed throughout the basin than the Caltech footprint, the Mt. Wilson footprint still only exhibits sensitivity to a portion of the basin, and therefore does not contain information on the integrated basin's activities. The sensitivity to the

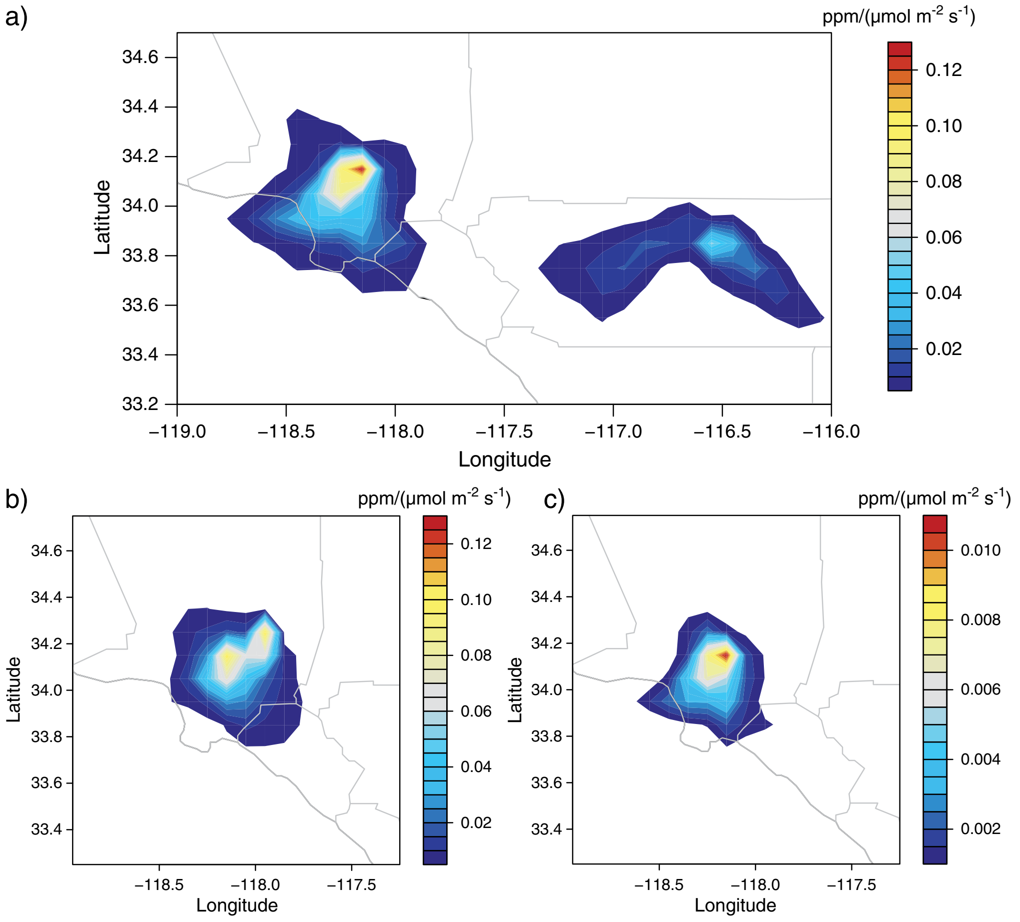

Figure 2. Average midday footprint for (a) Caltech surface site and Palm Springs surface site, (b) Mt. Wilson surface site, (c) and Caltech total column observation. Note all are shown on linear scale, where values less than 0.005 (0.001 for Figure 2c) are left white.

basin is also weaker than the in-city Caltech site, as illustrated in Figure 3, which displays the uncertainty reduction. An observation at Caltech has the ability to reduce flux uncertainty to more than 50%, while the site on Mt. Wilson can only achieve a reduction of up to 15%. Mt. Wilson is potentially a useful site for urban monitoring, particularly to define boundary conditions, as the free troposphere values sampled in evening, night, and morning, provide nice constraints on boundary CO_2 values entering the basin, but is does not provide tight constraints on emissions nor an integrated picture of the entire basin.

4.4. Caltech: Surface vs. Total Column

[23] It has recently been suggested that total column observations may be ideal for urban CO_2 emissions trend detection [*McKain et al.*, 2012]. This suggestion arises from

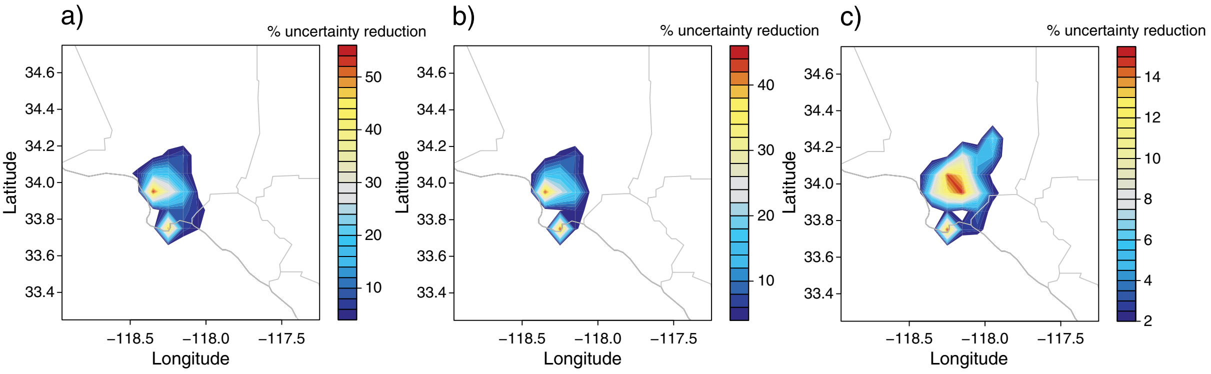

Figure 3. Uncertainty reduction in fluxes using (a) midday observations at the surface site at Caltech, (b) with a total column observation at Caltech, (c) and for observations on Mt. Wilson. Note that each panel uses a different uncertainty scale.

the notion that total column observations have lower sensitivity to small-scale emissions and meteorological dynamics, while simultaneously having sensitivity to the entire urban region. Though this may be true in a small city such as Salt Lake City, this does not hold in Los Angeles. The observation still has lower sensitivity to small-scale dynamics, but no longer is sensitive to the entire urban area. In fact, the near-field footprint of the total column observation is extremely similar to that of a surface observation in the same location (Figure 2). Interestingly, the uncertainty reduction attributable to total column versus surface observations are also very similar. This result is a product of the total column seeing smaller signals (and having a smaller **H**) but also being easier to model (having a smaller model-data mismatch error, largely attributed to reduced sensitivity to planetary boundary layer dynamics, **R**). Hence, although the total column observation will provide valuable information, and facilitate any linkage to space based observations, it does not solve the problem of having a network sensitive to the entire urban region.

4.5. Networks

[24] The current CO_2 observing network for Los Angeles is anchored by the long-term observation record at Caltech (Figure 1, Site 2). Observations at Mt. Wilson (Figure 1, Site 3) and Palos Verdes (Figure 1, Site 1) contribute boundary condition constraints and some additional sensitivity to portion of the LA megacity poorly sampled by the Caltech site. We designate this three-site network S1. As seen in Figure 4a, S1 shows good sensitivity to the urban core of the LA megacity. An inversion using observations from this network would significantly reduce CO_2 flux uncertainties over much of the megacity (>50% from prior uncertainty, Figure 5a). However, S1 lacks sensitivity to much of the megacity, especially the San Fernando and San Gabriel Valleys where much of the recent emission growth has occurred.

[25] The California Air Resources Board plans to place a new CO_2 observing site in the Riverside area (Figure 1, Site 8). Adding the Riverside site to S1 creates the four-site network we designate S2. The Riverside site will add sensitivity in the eastern section of the basin (Figure 4b). However, S2 only reduces flux uncertainty within the basin modestly compared to S1 (Figure 5b), and still lacks sensitivity to the entire basin.

[26] Following numerous trial analyses, we find that the eight-site network S3 represents a minimum design that provides sensitivity to emission throughout the basin (Figure 4c). Figure 1 shows the full S3 network, S2 augmented by in-city sites at Northridge (Figure 1, Site 4), Downtown (Figure 1, Site 5), Anaheim (Figure 1, Site 6), and Claremont (Figure 1, Site 7). Predicted uncertainty reductions now reach throughout much of the basin (Figure 5c). There are still regions of the LA megacity with weaker flux sensitivity (notably in Riverside and Northridge), but note these regions coincide with lower emissions as well. In fact, the suggested

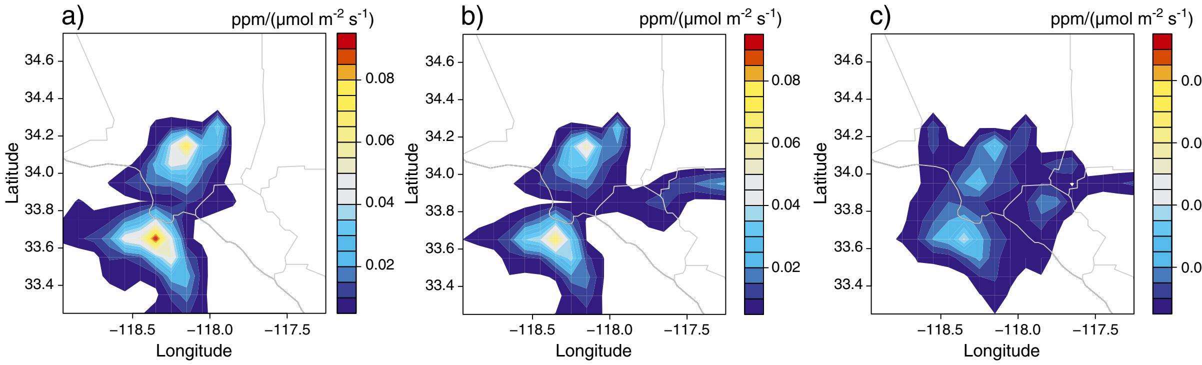

Figure 4. Average midday footprint for scenarios (a) S1, (b) S2, and (c) S3.

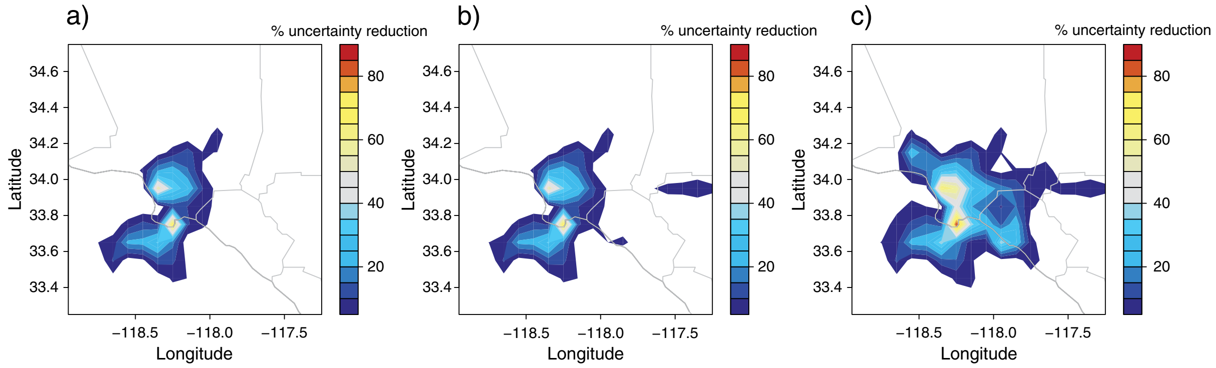

Figure 5. Uncertainty reduction in fluxes using midday observations for scenario (a) S1, (b) S2, and (c) S3.

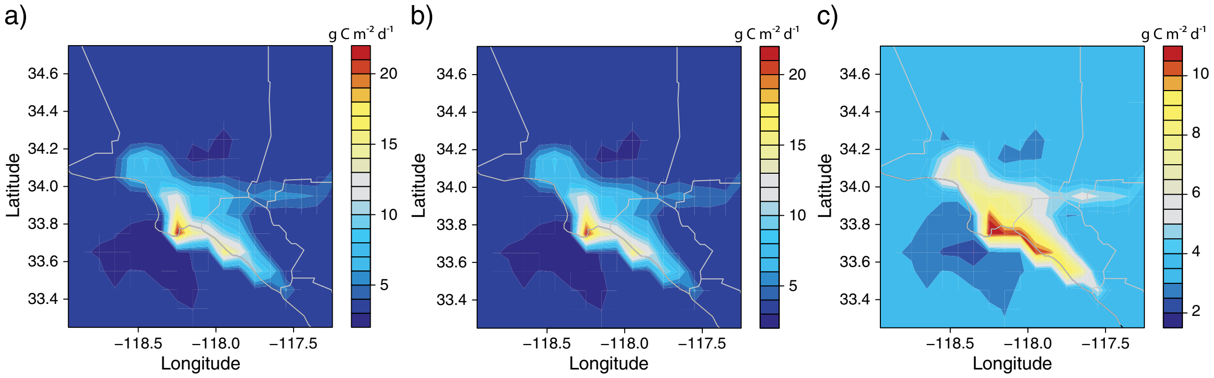

Figure 6. Posterior uncertainties for scenario (a) S1, (b) S2, and (c) S3. Note the reduced uncertainty scale for panel C.

network exhibits high sensitivity to almost the entirety of the high intensity emissions area (>10 tons C/h), suggesting this properly sited network would be able to provide observational constraints on the LA basin's emissions behavior.

4.6. Target Flux Requirements

[27] The inversion method applied is this work provides a robust answer for comparing the relative uncertainty reductions of different observing network strategies. We can also use this approach to evaluate absolute flux error reductions; however, absolute flux uncertainty estimates are highly dependent on the construction of the inversion. Even small changes to the prior error covariance matrices can significantly impact the results, whereas changes to the error covariance matrices have comparatively little impact on comparisons of relative uncertainty reductions.

[28] We consider two quantitative requirements: (1) Ability to distinguish fluxes on ~8 week time frames and ~10 km spatial scales to within 12 g C m^{-2} d^{-1}, equivalent to 10% of average peak fossil CO_2 flux in the LA domain for May 2002. Being able to reduce flux uncertainty in peak emitting areas to 10%, and be able to spatially attribute fluxes at 10 km scales begins to reach potential policy relevance. (2) Ability to distinguish 10% of average ~ monthly flux for the entire LA domain. For both policy and regional carbon balance questions, constraining the net flux of the domain is of primary importance.

[29] Figure 6 shows the spatial distribution of posterior uncertainties; demonstrating that only scenario S3 meets our requirement for high spatial resolution uncertainty. This indicates that such a network should be able to significantly reduce uncertainty of large emission regions, and be able to spatially identify the location of large emissions. None of the proposed networks with the inversion framework as constructed meet the requirement of reducing net flux uncertainty to 10%. This result is largely driven by the large uncertainty defined in the prior error covariance matrix—leading to prior net uncertainty of the high emission region (>65% of net flux) of ~100%. Scenario S3 does substantially reduce this net uncertainty of the higher emitting region to less than 50%. This inversion finding does not mean that the evaluated observing systems could not constrain fluxes at the 10% level—because inversion methods are not necessarily even required for constraining fluxes to the ~15% level [*McKain et al.*, 2012].

5. Conclusions

[30] In this study, a high-resolution regional model was used to study the minimal observational requirements to track anthropogenic CO_2 emissions trends for the Los Angeles megacity. We find that no single fixed-site CO_2 observation (surface in situ or total column) or within or downwind of the LA basin are sufficient for capturing the behavior of the entire megacity emissions trends. A minimum network of sites distributed optimally across the basin is needed to ensure sensitivity to emissions behavior throughout the LA basin. Although the present study was optimized for Los Angeles CO_2 emissions patterns and meteorology, the framework presented here can readily be applied to designing observing networks for other megacities. Additionally, because observational sensitivity to CO_2 emissions falls off exponentially with distance from the observing site, our conclusion that robust monitoring of megacity CO_2 emissions requires multiple in-city sites with location carefully selected based on local meteorology is completely general. Our proposed network here identifies the minimum sites required to detect emissions behaviors throughout the basin. We find the network proposed for Los Angeles, S3, can distinguish fluxes on 8 week time scales and 10 km spatial scales to within ~12 g C m^{-2} d^{-1}. If higher-resolution inversions are planned, and the intention is to also identify varying source locations, an even higher density network of sites with overlapping footprints would be required. We have also only focused on CO_2 observations. Use of other tracers, such as CO_2 isotopes or carbon monoxide, would facilitate in looking at specific questions relating to attribution.

[31] **Acknowledgments.** E.A.K. thanks the W. M. Keck Institute for Space Studies for support. Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. The author's would also like to thank the Megacity Carbon project team for useful discussion and feedback.

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