FluxLetter

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Tall Towers special Issue

Climate change mitigation opportunities: Relevance for multiple greenhouse gas species and need for emissions inventory validation by Marc Fischer

With the goal of limiting the potentially destructive effects of greenhouse gas induced (GHG) climate disruption, society is (albeit slowly) initiating action toward sustainable resource use. To gauge the success of these actions, accurate quantification of current GHG emissions and validation of future emissions reductions is essential (CRC 2010). The validation problem is scientifically challenging. For CO_2 emissions, one must distinguish direct and indirect anthropogenic emissions (e.g., fossil fuel combustion and land cover/use change) from quasi-natural sources and sinks (agriculture and forestry) which are both highly heterogeneous temporally and spatially, and typically an order of magnitude larger than the fossil fuel emissions on diurnal to synoptic time scales. FLUXNET plays a crucial role in this effort by improving mechanistic understanding of terrestrial ecosystem CO_2 exchange through integration of local measurements across sites with biogeochemical models.

The problem of estimating non-CO_2 GHG sources is similarly important and challenging because non-CO_2 greenhouse gases play a significant role in

Figure 1. LBNL and NOAA instruments measure CH_4, N_2O, and other greenhouse gases at a 600 m tower near Walnut Grove, California.

Looking to the future, we can expect significant progress on non-CO_2 emissions ...

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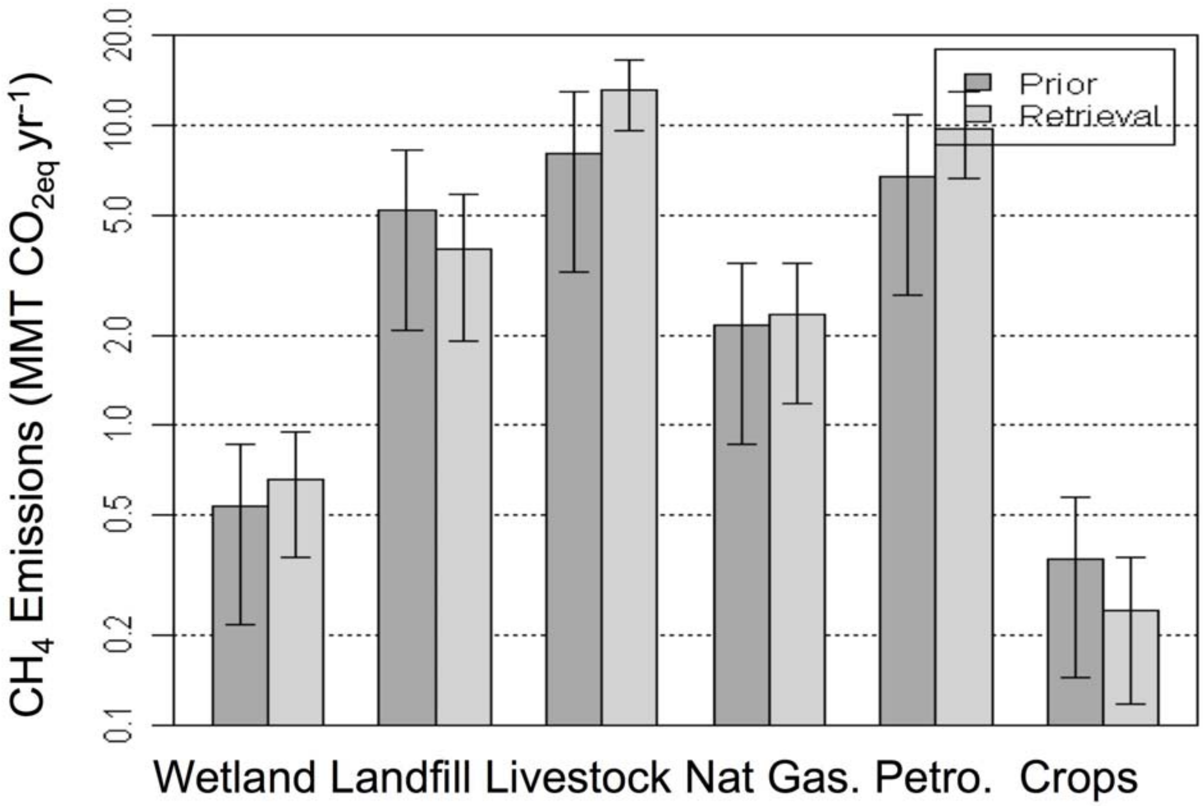

Figure 4. Prior and posterior CH_4 emissions estimates for California in October-December, 2007 (Zhao et al., 2009).

climate warming, are generally only weakly dependent on a readily metered quantities (e.g., fuel use), and are sensitive to climate and management (e.g, agriculture, waste management). For example, the mole-weighted forcing from methane and nitrous oxide emissions are on order 10 and 300 times stronger than CO_2 respectively on 100 yr time scales. Because emissions are intimately tied to land surface processes, particularly through management, there is a genuine opportunity for GHG emissions mitigation provided a sufficiently robust understanding of the processes can be developed. Hence, this is a case where the combination of direct (e.g., eddy covariance) flux measurements can inform development of "bottom-up" mechanistic biogeochemical land surface models which will also require regional synthesis and validation using the combination of atmospheric mixing ratio measurements and "top-down" inverse modeling.

To evaluate inter-annual variations in regional non-CO_2 GHG emissions, a collaborative team from the Atmospheric Science Department in Lawrence Berkeley National Laboratory's Environmental Energy Technologies Division (EETD) and the Carbon Cycle Group in the National Ocean and Atmospheric Administration's Earth System Research Laboratory are conducting "top-down" a study combining mixing ratio measurements from tall-towers in Central California, mesocale meteorology, and inverse modeling. Seeing the need for emissions validation as a component of long-term efforts to provide sustainable solutions to the tightly coupled problems of energy use and environmental quality, California Energy Commission's Public Interest Energy Research Program turned to EETD for a 2003 study evaluating the feasibility of quantifying California's GHG emissions, and in 2006 began the California Greenhouse Gas Emissions (CALGEM) project to quantify non-carbon dioxide (CO_2) greenhouse gas emissions at the regional scale.

For CALGEM project, the LBNL-NOAA team began continuous measurements of CH_4, CO_2, and CO at a tall-tower near Walnut Grove, CA, and collects daily mid-afternoon

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flask samples for analysis of all major main greenhouse gases at both the Walnut Grove and the Sutro Tower above San Francisco. The study then uses the mixing ratio measurements to evaluate the *a priori* emission inventories to provide the best statistical match between the measured atmospheric mixing ratios and the mixing ratios predicted as a product of an *a priori* inventory for different emission sources and surface influence functions (mixing ratio footprints) derived from high-resolution atmospheric transport simulations. For example, results for a fall-winter period have shown that while *a priori* CH_4 emissions from several sources are consistent with the inverse model evaluation but other sources (e.g., livestock) are likely underestimated (Zhao et al., 2009).

Quantitatively evaluating the uncertainties in estimated emissions is a crucial component of this work. Approximately half the project effort goes into quantifying errors in each component of measurements and modeling and then propagating those errors through the inversion process to derive uncertainties in the emission estimates. With the advent of extremely accurate GHG measurement instrumentation, and careful inter-comparison with measurements from the network-standard flasks, the dominant sources of uncertainty in the inverse model are errors in the meteorological model (e.g., boundary layer depth, and wind velocity), and errors in the assumed spatial distribution of *a priori* emissions. Hence, current work is focusing on improving the meteorological model by evaluating the model results with measurements from wind profilers and additional trace gas species including ^{222}Radon, incorporation of better *a priori* emission models. This presents a challenge to the Fluxnet community for non-CO_2 flux measurements in representative ecosystems that can improve the a priori models or be synthesized directly into the inverse optimization, perhaps with spatially flexible *a priori* models for the distribution of GHG emissions.

Looking to the future, we can expect regional, national, and international efforts to make significant progress quantifying non-CO2 emissions in tropical, temperate, and arctic ecosystems using the combination of direct flux measurements, biogeochemical and economic/ sociological models, and inverse modeling driven by mixing ratio measurements. Examples include growing efforts by groups in Asia, Canada, Europe, and the United States, to name a few. Together, this suggests there may be a valuable future role for Fluxnet to conduct non-co2 flux measurement syntheses similar to the ongoing work with carbon dioxide. In California alone, several coupled and independent activities are underway. With the passage of the California Global Warming Solutions Act of 2006 (AB32), the California Air Resources Board (CARB) is implementing a state-wide network of CH_4, CO_2, and CO mixing ratio measurements. A large collaboration including CARB, NOAA, DOE, USDA, and multiple California Universities recently conducted the CalNex 2010 field campaign on air quality and climate. Particularly relevant to Fluxnet, a collaboration including the US Geological Survey and the University of California, together with other partners, will be evaluating eddy covariance flux measurements and modeling to evaluate the climate change mitigation potential of wetland restoration. The National Institute of Standards and Technology is sponsoring a collaborative study including UC San Diego and Lawrence Livermore Laboratory to quantify California's high global warming potential GHG emissions (e.g., SF6, and halo carbons). From space, the SCIAMACHY and new GOSAT missions provide near global coverage of column-mean CH_4. Ideally, this wealth of measurements and models could be harnessed to provide a testbed for a national network to measure non-CO_2 GHG emissions, and eventually be incorporated with CO_2 measurements from ground, airborne and space platforms to evaluate GHG exchanges at multiple ecosystem and geopolitically relevant scales.

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Editorial

Rodrigo Vargas and Dennis Baldocchi

FLUXNET is a network of networks to study the "breathing of the biosphere". However, this task goes beyond the original goals of FLUXNET to embrace new challenges at different temporal and spatial scales. This issue of FluxLetter is dedicated to "Tall Towers" and highlights the important role they play to study the atmospheric boundary layer for understanding the "breathing of the biosphere".

This issue highlights research conducted using tall towers and the potential for future research. This research goes beyond CO_2 fluxes and has the potential to incorporate other non-CO_2 green house gases. Furthermore, the contributions presented in this issue show examples about the synergistic effort between measurements collected among FLUXNET sites to validate and upscale tall tower flux estimates. Finally, as we are moving into a data rich era where synthesis studies explore multiple spatial and temporal scales, there is a need for a better interaction between scientists, networks and platforms. As Ken Davis writes: "We must move …and embrace the notion of the flux tower network as no just a collection of sites, but as a spatial network" (See page 10 in this issue). We look forward for future contributions to debate and propose potential interactions between flux towers, tall flux towers, remote sensing and modeling approaches to better understand the "breathing of the biosphere".


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Györgyi Gelybó

My name is Györgyi Gelybó, a PhD student from Hungary. I have always been fascinated by science, at least since I became interested in things other than the color of my new toys. In the beginning, astronomy caught my attention and originally I wanted to be an astronomer. This was necessarily accompanied by interest in atmospheric processes which led me to meteorology, so I finally graduated in meteorology. I chose satellite remote sensing as the topic of my master's thesis at the Eötvös Loránd University in Budapest, Hungary still being attracted by the space. This research was focused on purely meteorological issues (raw data processing of the ATOVS atmospheric sounder onboard NOAA satellites), half-way between space and the Earth.

After graduation, I enrolled for a PhD at the School of Earth Sciences at the Eötvös Loránd University, (Budapest, Hungary) where I was involved in regional climatology research. My participation in this research made me increasingly more interested in impact studies and ecosystem processes. I consider myself lucky, since I had access to data from a unique tall flux tower located over a heterogeneous cropland. The tower is operated by the Department of Meteorology, Eötvös Loránd University together with the Hungarian Meteorological Service near Hegyhátsál, Hungary (46° 57'21"N, 16°39'08"E 248 m.a.s.l, Fig. 2). For more information about the site, please see Haszpra et al. 2005 or visit the website of the measurements (http://nimbus.elte.hu/hhs/), where measurements were set up based on experiences gained at the WLEF tall tower (Desai, this issue) and data processing was elaborated in collaboration with Ken Davis (Penn State) and his group. As a result, we explored possibilities on how we could both profit from my background in satellite remote sensing and climatology. With Dr. Zoltán Barcza (Dept. of Meteorology, Eötvös Loránd University), who operates the eddy covariance system at the tall tower site, we decided to use the MOD17 model to estimate GPP of the region (Gelybó et al. 2009), and possibly to use the remotely sensed measurements to constrain the Hungarian carbon balance estimations.

Figure 1: Györgyi Gelybó

The unusual tall measurement height (82 m) somewhat complicates the situation due to the influence of footprint changes on the measured flux. This is a challenge that many tall towers face. At our site, there are several crop types grown in the region and the measured fluxes cannot be easily attributed to individual crop types. It is possible, however, to attribute fluxes to plant categories by using a footprint model to determine the source region, and use remotely sensed data to determine crop type (simply summer or winter crops in our case) in the given pixel (Barcza et al. 2009). The crop-specific GPP can be used to validate and calibrate the MOD17 model for different crop types. At our site, typically maize (C4) is grown in summer and winter wheat (C3) is the winter crop. This contrast in plant physiology makes it possible to separate crops according to photosynthetic pathways in the model calibration.

In order to determine if these parameter sets can be used at larger spatial scales, we initiated a multi-site analysis involving several sites across Europe and the United States. Only short towers were included in this study over fields of typical C3 and C4 crop types including planting rotations. The Hungarian State Eötvös Fellowship supported this complex, tall tower and multi-site research to be partially carried out in the

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Figure 2: Tall flux tower near Hegyhátsál, Hungary . Photo credit Anikó Kern (Eötvös Loránd University).

United States. Currently, I am finalizing the research fellowship at the University of Illinois at Chicago the group led by Prof. Miguel Gonzalez-Meler. Meanwhile, I have had the opportunity to contribute to a book project (Haszpra 2010) concerned with research on Hungarian greenhouse gases (GHG), including estimation of the GHG balance of Hungary. The book was edited by Dr. László Haszpra (Hungarian Meteorological Service) and entitled "Atmospheric greenhouse gases: The Hungarian Perspective". Hopefully, this synthesis of tall tower and multi-site approach will result in improved methods for upscaling agricultural CO_2 fluxes using remote sensing based modeling.

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Further Reading

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Help put the flux back in tall towers

Ankur R. Desai

A tower is a tower is a tower. Unless it's tall. Really tall. "Tall towers", some of the tallest manmade structures on Earth, can become powerful tools for probing the atmospheric boundary layer. Unlike shorter, canopy towers, which are used to survey the atmospheric surface layer (first 50-100m of the atmosphere), tall towers can sample multiple heights through the lower boundary layer. The eddy covariance flux and carbon cycle communities have used these towers for that purpose for quite some time, but the total number of sites has always been limited given the logistics of finding and operating towers. The value they provide by sampling "regional" flux footprints and for investigating the larger atmospheric boundary layer, including convective, residual, and stable boundary layers, is immense, but the results have been limited to a handful of eco-regions.

Today, a larger number of tall towers currently in use are focused not on eddy flux, but on greenhouse and trace gas monitoring. The expansion of continuous tall-tower monitoring of greenhouse gases beyond some of the original sites, such as the WLEF-TV 447-m tower in Park Falls, WI tower (Bakwin *et al*., 1998), as is currently underway by the National Oceanic and Atmospheric Administration (NOAA) in the U.S., is and will continue to be a great boon to the atmospheric biogeosciences and tracer-transport inverse modeling communities. At these towers, high precision, high accuracy, real-time monitoring of the vertical profile of atmospheric mole fractions of CO_2 and other greenhouse gases, along with automated flask sampling of a large suite of trace gases, provides some of the most crucial observations used in modern, regional, inverse carbon cycle modeling and evaluation of satellite and airborne greenhouse gas observations.

Only a few of the recently initiated tall towers, though, have also included eddy covariance observations (e.g., US-KCM in Minnesota; Hegyhatsal in Hungary). Tall flux towers, in conjunction with well-calibrated trace gas observations, generate unique insights into interactions between regional landscapes and the lower atmosphere, in ways not easily done with shorter flux towers or tall greenhouse gas observatories without flux observations. For example, at the WLEF tower, where eddy fluxes of CO_2, H_2O, energy, and momentum have been made regularly since mid-1996 (Berger *et al*., 2001; Davis *et al*., 2003), a wealth of micrometeorological, ecological, and biogeochemical findings have been made by judicious combination of high-precision trace gas and eddy flux observations. Examples of unique research activities include:

—-Estimating sign and magnitude of advection (Yi *et al*., 2000)

—-Developing relationships for the depth of the boundary layer, as derived from multi-height CO_2, surface energy balance observations, and remote sensing of boundary layer depth (Yi *et al*., 2001) and evaluating these with mesoscale ecosystem-atmosphere models (Denning *et al*., 2008).

—-Applying modified Bowen ratio techniques to infer fluxes of CH_4 from eddy fluxes CO_2 and concentration profiles of CH_4 and CO_2 (Werner *et al*., 2003)

—-Formulating and evaluating empirical relationships for the convective boundary layer (CBL) flux footprint (Wang *et al*., 2006a).

—-Using the aforementioned CBL footprints to decompose regional eddy covariance flux signals so as to estimate ecosystem fluxes from multiple biomes simultaneously (Wang *et al*., 2006b) and compare these to flux tower upscaling (Desai *et al*., 2008)

—-Examining the diurnal and seasonal covariances between carbon fluxes and boundary layer mixing depths (Yi *et al*., 2004), and evaluating the impact of

Figure 1. Tall t tower. Photo credit Bruce D. Cook (NASA GSFC)

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these on atmospheric CO_2 transport models in coupled ecosystem-mesoscale atmosphere models (Denning *et al*., 2003, 2008) and vertical diffusion models (Chen *et al*., 2007).

—-Describing the impact of frontal passages on boundary layer CO_2 using the combination of flux and mixing ratio data to distinguish synoptic-scale transport from local changes in fluxes (Hurwitz *et al*., 2004).

—-Testing gradient functions in the virtual tall tower approach, a way to infer mid-boundary layer mixing ratios of CO_2 from surface layer flux and concentration observations (Wang *et al*., 2007a)

—-Comparing boundary layer budget and flux tower based regional net ecosystem exchange (Bakwin *et al*., 2004; Desai *et al*., 2010; Helliker *et al*., 2004; Wang *et al*., 2007b)

None of these findings would have been possible without multi-year observations from the unique combination of tall tower flux and greenhouse gas profiling. While many findings have been made at WLEF, there has been limited opportunity to tests similar findings in other biomes, climate zones, and across networks of tall towers, perhaps as an alternative method for estimating continental carbon fluxes. With tall towers now stretching in the U.S. from California to Maine and similarly in other parts of the world, we should not let the opportunity go to waste to push the frontiers of observation for regional ecosystem ecology and boundary layer meteorology.

I strongly urge flux tower investigators to consider coordinating with tall tower operators for future installation of eddy covariance observations at some of these sites.

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Tall towers, flux towers and diagnosis of regional scale carbon budgets

Kenneth J. Davis

Ankur Desai's article reviews studies that have been conducted using flux measurements on tall towers, and notes the potential for future research using observatories such as the 447m WLEF tower in northern Wisconsin, USA. Other sites that have similar instrumentation to the WLEF site include the Cabauw tower in The Netherlands, and the Hegyhatshal tower in Hungary.

When we first started presenting flux measurements from the WLEF tall tower (Yi et al., 2000; Berger et al., 2001; Davis et al., 2003), some observers thought that these towers would have such a large flux footprint that a network of tall towers might be the answer to mapping out terrestrial carbon fluxes across continents. Since turbulent fluxes are relatively rapidly mixed out by atmospheric turbulence, however (Weil and Horst, 1992), we knew that even for very tall towers the flux footprint, though much larger than that of a traditional surface layer tower, would be limited (Wang et al., 2006a). After a few eddy turnover times, turbulent fluctuations have been mixed out of the atmosphere and no flux signal remains. For the convective boundary layer (CBL), the eddy turnover time, t, is roughly z_i/w_*, or about 10^3 seconds (15 minutes). For a mean wind speed, U, of 5 m/s (perhaps a bit fast for the continental CBL), the advection time associated with the eddy turnover time is U times t, or about 5×10^3 m. Thus a few times 5 km, or roughly 20 km, is the upper limit for a turbulent flux footprint at any measurement altitude in the convective boundary layer. The ecology community sometimes uses the term "landscape scale." Perhaps this tall tower flux footprint upper limit is the micrometeorological complement to the "landscape scale."

So while we can use tall towers to conduct interesting studies of boundary layer meteorology (e.g. Yi et al., 2000), and construct challenging tests of landscape-scale flux aggregation (e.g. Desai et al., 2008) and disaggregation (e.g. Wang et al., 2006b) – any to pursue many other research topics described in Ankur's article – we cannot use tall towers to obtain terrestrial fluxes of CO_2 (or CH_4 or H_2O) mapped directly from coast to coast. Do tall towers play a role, then, in constructing accurate and precise diagnoses of the continental-scale carbon budget? Very likely. But how?

Fluxes can also be derived using atmospheric budgets, now known in the jargon of our field as atmospheric inversions. This approach has been extremely useful for global to zonal spatial scales and decadal temporal scales (e.g. Tans et al., 1990; Battle et al., 2000). Limited data, however, has limited its skill even at continental scales (e.g. Baker et al., 2006; Roedenbeck et al., 2003; Gurney et al., 2002). This leaves a gap in the scales at which we can diagnose fluxes (Davis, 2008). One proposed solution to this problem has been the creation of dense continental tower networks (e.g. Denning et al., 2005) necessary to construct accurate and precise regional to continental scale inversions. While advances have been made in constructing such regional to continental-scale inversions (e.g. Gerbig et al, 2003; Lauvaux et al., 2009; Schuh et al., 2010; Butler et al, in press), the pace of progress has been slow. As we know, it took a long time for eddy covariance to develop into a reliable and robust methodology, and it is still far from perfect, even for ideal sites. Regional atmospheric inversions are more complex. Issues that have limited progress include uncertainty in the atmospheric transport fields used to construct the inversions, uncertainty regarding how to represent the mismatch between model grids and point mixing ratio observations, limited atmospheric mixing ratio data, uncertainty in the initial flux estimates used in the inversions, and uncertainty regarding how

Figure 1. Tall tower (Photo credit: http://www.fluxnet.ornl.gov/fluxnet/Images/site_images/arm_sgp_main.jpg)

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to construct the solution to the inversion problem. The last three issues are particularly relevant to the flux measurement community, and spell out research needs that tie together the tall tower and flux tower research in ways that go beyond collocation of instrumentation.

Mixing ratio data: Regional atmospheric inversions require dense networks of well-calibrated atmospheric mixing ratio measurements. Tall towers have taught us that normal surface layer flux towers can be used to collect data suitable for inversions. This requires either carefully calibrated infrared gas analyzers (Bakwin et al., 1998) or more costly but more accurate and precise cavity ring-down spectrometers (Crosson, 2008). The data should be sub-sampled for well-mixed conditions before being used in the inversions (e.g. Schuh et al., 2010; Butler et al., in press) since large-scale transport models do not simulate the complex surface layer characteristic of the nocturnal boundary layer very well. And it might be necessary to correct for the small systematic bias that exists between the surface layer and the mixed layer, even under well-mixed conditions (Wyngaard and Brost, 1984; Wang et al., 2007), though some results suggest that this correction is small enough as to be relatively unimportant for inversions (Butler, 2010). Well-calibrated mixing ratio measurements are not necessary for good flux measurements, but these data greatly increase the utility of the flux tower network in diagnosing the carbon balance of continents.

Improved prior flux estimates: Atmospheric inversions are complex optimizations. Like most complex optimizations, they can be sensitive to initial conditions. A closer initial guess is more likely to lead to the correct solution. Ecosystem models are commonly used as the initial guesses for inversions. Networks of flux towers can be used to optimize these models using either informal (Lokupitiya et al., 2009) or formal (Braswell et al., 2005; Ricciuto et al., 2008) methods. There is currently a burst of publications making maps of fluxes using flux towers and optimization methods (e.g. Xiao et al., 2008). These maps should be incorporated into the priors of atmospheric inversions. Further, Bayesian inverse methods require that the prior flux estimates have uncertainties associated with them. Flux tower networks have great potential for improving the description of the error characteristics in the prior fluxes used in atmospheric inversions.

Structure of inverse solutions: Atmospheric inversions have made a wide range of assumptions in order to limit the number of unknowns to be constrained by atmospheric data. These assumptions range from solving for fluxes that barely resolve continents (Baker et al., 2006) to solving for fluxes at every transport model grid point (Roedenbeck et al., 2003). All of these are assumptions about the structure of the error in the prior flux. The structure of that error, in space and time, is not well known. Some initial work has been done with flux towers to investigate this topic (Chevallier et al., 2006), but a great deal remains to be learned. If atmospheric data were sufficiently dense this would not be a critical issue, but at present the required measurement density is uncertain, and will take time to establish and construct. Learning the structure of model errors is part of what will defined the required atmospheric measurement density. The global flux tower network can make significant contributions to this line of inquiry.

The flux tower community has now heartily embraced synthesis studies across sites. We must move more fully to embrace studies across platforms (tall towers and flux towers, for example), and embrace the notion of the flux tower network as not just a collection of sites, but as a spatial network. Tall towers and flux towers (and tall flux towers) will be needed in increasingly synthetic analyses to close regional carbon budgets.

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