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The influence of carbon exchange of a large lake on regional tracer-transport inversions: results from Lake Superior

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Abstract

Large lakes may constitute a significant component of regional surface–atmosphere fluxes, but few efforts have been made to quantify these fluxes. Tracer-transport inverse models that infer the CO_2 flux from the atmospheric concentration typically assume that the influence from large lakes is negligible. CO_2 observations from a tall tower in Wisconsin segregated by wind direction suggested a CO_2 signature from Lake Superior. To further investigate this difference, source–receptor influence functions derived using a mesoscale transport model were applied and results revealed that air masses sampled by the tower have a transit time over the lake, primarily in winter when the total lake influence on the tower can exceed 20% of the total influence of the regional domain. When the influence functions were convolved with air–lake fluxes estimated from a physical–biogeochemical lake model, the overall total contribution of lake fluxes to the tall tower CO_2 were mostly negligible, but potentially detectable in certain periods of fall and winter when lake carbon exchange can be strong and land carbon efflux weak. These findings suggest that large oligotrophic lakes would not significantly influence inverse models that incorporate tall tower CO_2.

Keywords: Lake Superior, tall tower, tracer transport, inverse modeling, STILT

S Online supplementary data available from stacks.iop.org/ERL/6/034016/mmedia

1. Motivation

Large lakes play a significant role in local atmospheric circulation and pollutant transport, and their ecology, biogeochemical cycles, and surface evaporation are in turn affected by a changing climate (Desai *et al* 2009). The carbon balance of large lakes is important to regional carbon cycling owing to their connectivity to both land and atmosphere and their capacity to cycle large amounts of carbon over long periods of time (Cole *et al* 2007, Quinn 1992). Large lake carbon cycles, however, are poorly understood and quantified, largely because carbon sources and sinks are spatially and temporally heterogeneous (Alin and Johnson 2007, Urban *et al* 2005). Additionally, direct measurement of lake–atmosphere carbon fluxes is difficult due to methodological limitations and

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sampling bias caused by limited accessibility during periods of strong storms or significant ice cover (Atilla *et al* 2011, Urban *et al* 2005). Lake Superior, the largest of the North American Laurentian Great Lakes, is no stranger to these issues.

Discrepancies in the Lake Superior carbon budget (Kelly *et al* 2001, Cotner *et al* 2004, Urban *et al* 2004, 2005, Alin and Johnson 2007) prompted a recent investigation of the partial-pressure CO_2 (pCO_2), computed from pH and alkalinity observations from the US Environmental Protection Agency (EPA) biannual survey. Atilla *et al* (2011) found large seasonal variability in surface pCO_2, with super-saturation in the spring and near-equilibrium values in the summer. Uncertainty remains when extrapolating these processes to the whole lake basin and over longer timescales, because scaling approaches have not been fully evaluated.

In situ CO_2 observation sites near lakes may be useful for quantifying over-lake CO_2 fluxes (Urban and Desai 2009, Urban *et al* 2011). Lake CO_2 fluxes impart a signature on atmospheric CO_2, and this signature could be extracted through an inverse modeling approach (e.g., Gurney *et al* 2002). However, most tracer-transport inverse models currently either prescribe a fixed flux for large lakes, or assume it to be zero (e.g. Gourdji *et al* 2010, Schuh *et al* 2010). This assumption begs the questions—could we potentially infer lake fluxes using an atmospheric inversion approach and are we biasing terrestrial flux estimates by assuming lake fluxes are either zero or known *a priori*?

In this study, the potential impact of lake fluxes on atmospheric inversions was investigated using an atmospheric transport model and long-term continuous CO_2 observations from the very tall WLEF tower situated near Lake Superior (Bakwin *et al* 1998). First, we examined the nature of CO_2 variability with lake transit by analyzing CO_2 concentration at the tower and comparing these to transport-model-derived influence functions (Lin *et al* 2003, see also detailed methods in online supplement available at stacks.iop.org/ERL/6/034016/mmedia). These influence functions were then convolved with CO_2 fluxes from a recently developed physical and biogeochemical model (Bennington *et al* 2010, 0000) to explore the potential atmospheric signatures imparted by carbon cycling in large lakes. Finally, the implications of these findings for tracer-transport inversion for land and over-lake CO_2 fluxes are discussed. No published study has quantified the impact of large lakes on atmospheric CO_2 and the consequent implications for inverse modeling, which are likely to exist as these models increase spatial and temporal resolution (i.e., regional inverse modeling) and assimilate more continuous CO_2 data.

2. Large lake influence on tall tower air masses

The difference between tower and marine boundary layer (MBL) CO_2 is a simple way to represent the effect of continental surface fluxes, regional meteorology, and boundary layer dynamics on atmospheric CO_2 as it is advected across North America by prevailing westerly winds (figure 1). The large variability in daily averaged CO_2 at the tall tower, which ranged ±20 ppm from MBL CO_2, at least partly reflects the varying contribution of lake fluxes on CO_2. However, most of this signal represents the influence of boundary layer mixing and advection of continental air masses that reflect larger-scale synoptic variability and fluxes over large regions (Bakwin *et al* 2004, Yi *et al* 2004). For example, summer tower CO_2 is dominated by contribution from the land carbon sink, given the dominance of southwesterly winds and the strong carbon sink found in regional terrestrial forests (Davis *et al* 2003, Desai *et al* 2010).

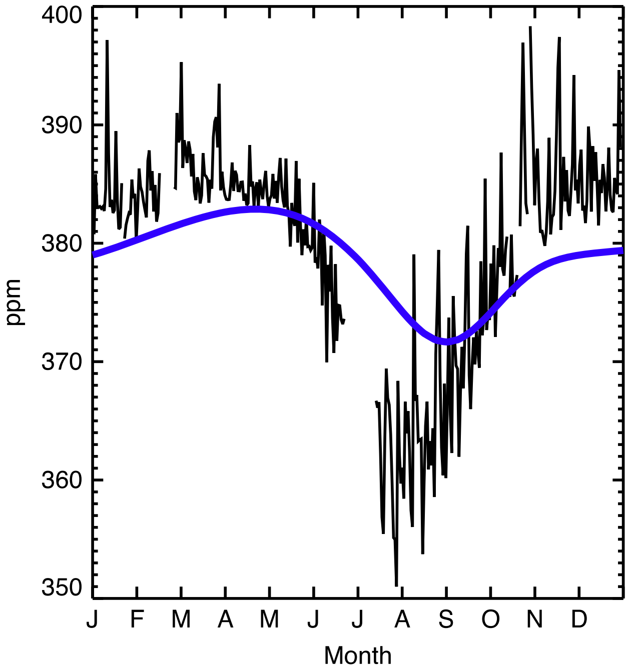

Figure 1. Daytime (9:00–15:00 LT) averaged daily CO_2 concentration (black) compared to interpolated flask marine boundary layer CO_2 (blue) by season.

Still, given the large daily variability of CO_2 at the tower, how much of this variability is possibly from Lake Superior? The particle model influence functions quantify the contribution of a unit flux over a given area to atmospheric concentration at a specific location; for CO_2, these functions are in units of ppm (μmol m^{-2} $s^{-1})^{-1}$. Particle trajectories and annual aggregated influence function of air masses arriving at the WLEF tower revealed that Lake Superior fluxes, especially within the previous 24 h, have the potential to influence tower CO_2 (figure 2). Particle locations from a single release (figure 2(a)) showed that air masses arriving at the WLEF tower from the near-field domain (WI, MI, MN) were sensitive to recent influence from L. Superior. Yearly total influence on the WLEF tower of fluxes occurring over L. Superior (figure 2(b)) was comparable to the largest influences from the rest of the domain as defined by the extent of figure 2(b). Lake Superior's shape and circulation (Bennington *et al* 2010) allow it to be divided into two 'arms', a western and eastern one. The strongest influence for the tower came from the western arm and implies that this portion of the lake has the highest likelihood of contributing to WLEF tall tower CO_2.

Seasonal and directional influence functions aggregated from the hourly influence functions can be used to identify

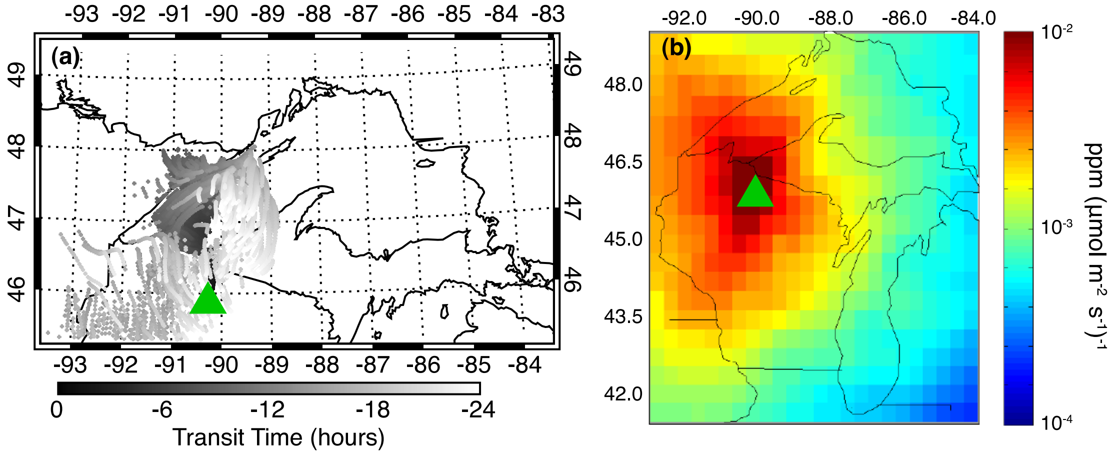

Figure 2. (a) Example of 24 h particle trajectories, released from tower (green triangle) at 18 UTC 26 March 2004 using the STILT model, with shading representing time since release; (b) annually averaged influence (ppm(μmol m^2 s^{-1})$^{-1}$) of particles on the WLEF (green triangle) in the near-field domain, showing that the strongest signal from Lake Superior is the western arm.

when the potential for lake contribution to the tower is highest (figure 3). The influence of the lake (figure 3(a)) was highly variable at the hourly scale. Largest sensitivities were found during the winter, and average sensitivity can approach 20% of the total influence of the domain identified in figure 2(b). As expected, observations taken during northeasterly, northerly, and northwesterly winds had greater influence from the lake (figure 3(b)), with a maximum for northerly winds (0°–10°).

3. Air–lake flux impact on tall tower CO_2

Given that lake influence is possible, we attempted to quantify this contribution by convolving a prognostic model of lake fluxes with the influence functions. Lake–atmosphere CO_2 fluxes predicted by the biogeochemical model (figure 4(a)) were driven by the seasonal cycle of vertical mixing and biological processes. Overturning during late fall and winter brought dissolved inorganic carbon (DIC) to the surface and caused the most intense efflux during 2004. At the end of winter (March), the lake had effluxed excess carbon but continued to cool, and thus, became a small sink of atmospheric CO_2. As the lake warmed again in spring, overturning, warming, and respiration of carbon supplied during the spring melt caused the lake to flux CO_2 to the atmosphere. As lake production increased throughout spring and summer, the biological drawdown of surface DIC in a stratified lake drove an influx of CO_2 (largest during August). Biological production decreased as the lake cools and mixes, and during fall, the lake began to emit carbon dioxide absorbed during the productive months.

The basin-averaged lake–atmosphere fluxes output by the model were generally small in magnitude, between -0.17 and 0.31 μmol m^{-2} s^{-1}, over the lake as a whole, and similarly over the western arm, whose fluxes dominate the lake contribution to the tower. These fluxes were small especially when compared to tower eddy covariance fluxes (figure 4(b)), which range in daily average flux by ± 4 μmol m^{-2} s^{-1} and represent a footprint of forest and wetland (Davis *et al* 2003). Consequently, at the daily scale, the absolute magnitude of contribution of lake fluxes to tower CO_2 was found to be quite small (figure 4(c), blue line) and unlikely detectable at the tower, whereas the contribution of land in the area around Lake Superior (figure 4(c), green line) was large (>0.2 ppm) in all seasons. This domain was defined as a 600 km × 300 km box around the lake, which comprised 53% land and 47% lake.

We also considered the maximum potential lake contribution on tower CO_2 (gray shading, figure 4(c)). These potential fluxes were derived by assuming a ± 1 μmol m^{-2} s^{-1} maximum potential daily flux. In this case, with fluxes 1–2 orders of magnitude larger than modeled, there are clearly periods in all seasons where a lake flux could be detected against the background of CO_2 variability and an observation accuracy of $\sim$0.2 ppm. From November to April, much of the land contribution is of the same order as this maximum potential lake contribution. Thus, it would take a lake with carbon fluxes 10–100 times modeled to significantly have a detectable signature on tall tower CO_2 and we conclude here that Lake Superior carbon exchange generally has a negligible impact on the tower measurements.

4. Implications for inverse modeling

Influence functions revealed that the WLEF tall tower regularly sampled air masses from L. Superior, principally its western arm, and especially in winter and spring, with most lake-boundary layer transit occurring within the previous 24 h. Although the small CO_2 fluxes predicted by the numerical model of lake circulation and biogeochemistry produced a negligible CO_2 contribution from the lake on the tower at daily scales, maximum reasonable bounds of this contribution may be detectable relative to tower sampling uncertainty ($\sim$0.2 ppm) and can be of the magnitude of regional land contribution to tower CO_2 primarily from late fall to early spring.

These results imply that typical assumptions to fix large lake carbon fluxes to a small value near zero in continental

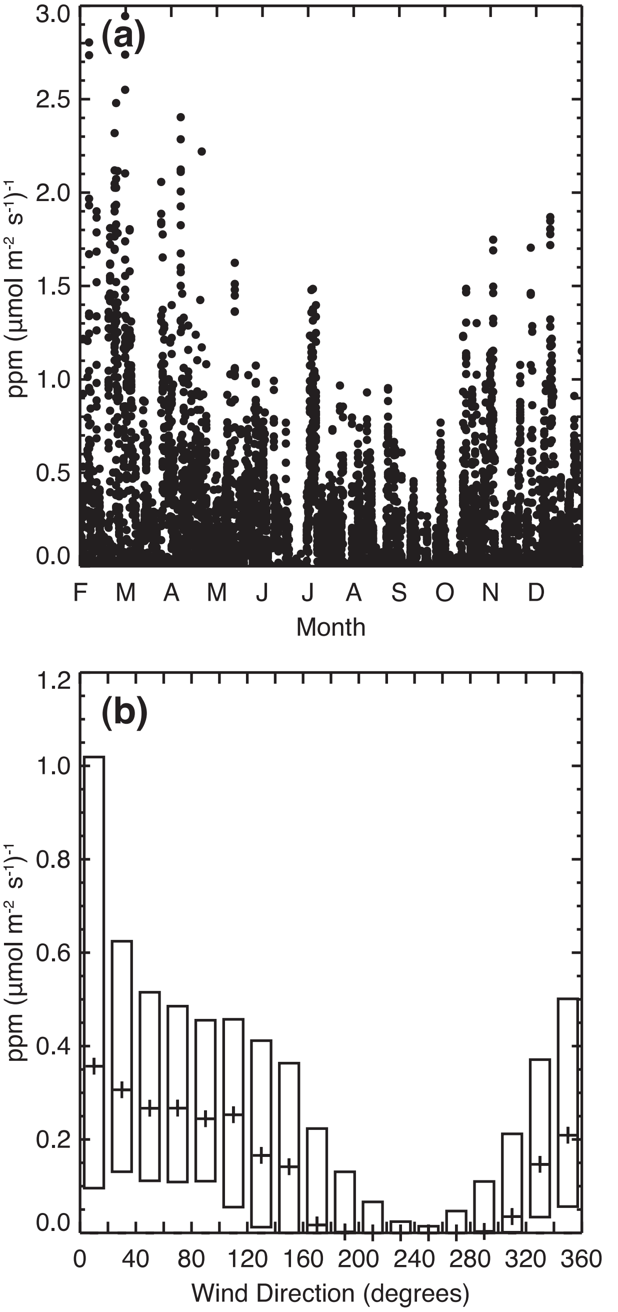

Figure 3. (a) Total influence (ppm(μmol m^2 s^{-1})$^{-1}$) of Lake Superior on WLEF tall tower CO_2 from February to December, 2004; (b) Feb–Dec 2004 median (plus) and interquartile range (box) influence (ppm(μmol m^2 s^{-1})$^{-1}$) as a function of 20° wind direction bins where 0° represents winds approaching from due North.

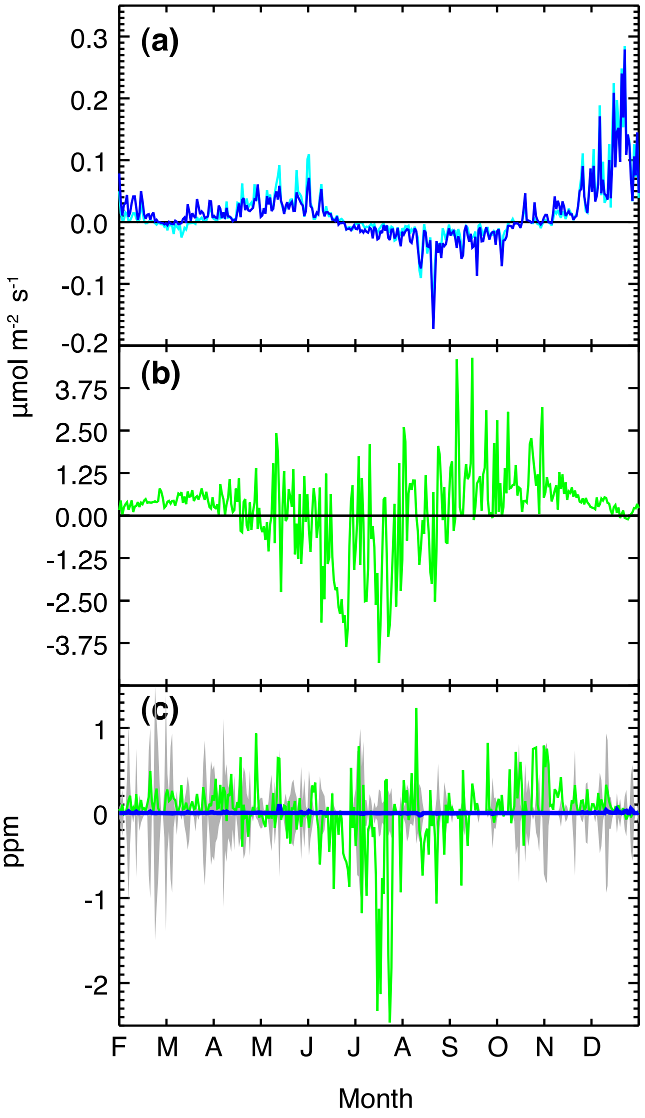

Figure 4. (a) Model-based estimates of daily total CO_2 fluxes from Lake Superior as a whole (dark blue) and from the western arm (light blue), with positive values indicating efflux to the atmosphere; (b) time series of eddy covariance daily CO_2 flux over same time period showed significantly larger fluxes than the lake model in the growing season; (c) fluxes convolved with influence functions produce a time series of daily contribution of lake (blue line) and land flux (green line) on tall tower CO_2 concentration. Gray bars indicate realm of potential lake contribution when lake fluxes were perturbed within ranges of observed values. Land contribution was derived by assuming domain around Lake Superior had CO_2 flux similar to that plotted in figure 4(b). Land contribution to tower CO_2 generally dominated potential lake contribution except from Nov–Apr.

to global inverse models are justified for Lake Superior and possibly other large oligotrophic lakes. However, we also show that in the case of continental continuous CO_2 observation from tall towers near large lakes, there are time periods when the lake contribution to tower CO_2 can be relatively large, and if the purpose of the inversion is to constrain regional terrestrial carbon fluxes, these time periods will need to either be filtered out of the measurements prior to assimilation or a model of lake emissions will need to be explicitly incorporated. Additional work to investigate large lakes in regional tracer-transport inverse modeling is warranted, both to constrain large lake fluxes, and to reduce biases of derived terrestrial carbon fluxes in lake-rich regions.

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Online Supporting Material – Supplementary Data

S.1 Methods

S.1.1 CO_2 observations

CO_2 concentrations at 396 m above ground were measured at the WLEF 447-m tall tower, located 14 km east of Park Falls, WI, USA (Bakwin *et al* 1998) using a non-dispersive infrared gas analyzer calibrated against known standard gases. These tower-observed CO_2 concentrations in units of ppm were compared to mid-latitude (45^o N) Pacific Ocean marine-boundary-layer (MBL) CO_2 concentrations to assess the relative influence of continental sources and sinks on tower CO_2 – MBL anomalies. MBL CO_2 was acquired from the NOAA ESRL Globalview dataset, which is interpolated from the global CO_2 flask observation network.

S.1.2 Influence functions and lake contribution

The well-tested Stochastic Time-Inverted Lagrangian Transport (STILT) particle tracking model (Gerbig *et al* 2003, Lin *et al* 2003, Michalak *et al* 2004) was used to compute influence functions for this study. STILT derives these functions by tracing ensembles of particles released in a model of wind fields. Wind fields used by STILT were provided by high-resolution mesoscale transport fields obtained using the National Center for Atmospheric Research (NCAR) Weather Research and Forecasting (WRF) model (Gourdji *et al* 2010).

Both models were run for Feb-Dec 2004. January was not included due to WRF model output not being available at the time of analysis, but the results from February and December should be comparable to January. The transport model was run in a nested grid with the highest resolution of 2 x 2 km in the region surrounding WLEF. WRF model output showed high fidelity in reproducing both large-scale transport fields and local transport near the tower. The STILT model released 500 virtual particles from the 396-m level of the tower every hour. Trajectories of these particles through the WRF wind fields were tracked for 10 days backward in time and locations of particles in latitude, longitude, and altitude were recorded every 15 minutes. To generate particle dispersion among the particles, positions of particles were randomly perturbed from the release location and a subgrid model of random fluctuations was applied to the wind fields. WRF-STILT output is available online at http://puorg.engin.umich.edu/. It is likely that there were transport model biases owing to the difficulty of modeling lake-land boundary layer transitions, internal boundary layers along coastlines, and step changes in mixing depths, and these require further investigation. Still, previous studies have shown the large-scale synoptic transport of trace gases is well simulated by this model (Lin *et al* 2003).

Gridded influence function maps were computed by summing mass-conservation corrected (Gerbig *et al* 2003) boundary-layer particle mass across both a regional 0.375° grid, and a lake-specific 10-km grid. A primary assumption here is that particles, in the modeled boundary layer were influenced by fluxes emitted at the surface over which they transited, though we also accounted for particle height in this calculation by scaling contribution of an individual particle by the height of the particle relative to modeled boundary layer depth. Total lake influence was subset from these maps by applying a water mask to the grid and summing influence over all pixels identified as water.

S.1.3 Lake modeling

A three-dimensional gridded hydrodynamic-ecosystem model of Lake Superior (Bennington *et al* 2010, Desai *et al* 2009, Bennington *et al* in prep.) was run for 2004. Net primary productivity (NPP), respiration, carbon cycling and lake-air fluxes were calculated on a 2-km x 2-km grid and output in units of μmol m^{-2} s^{-1}. The model included daily carbon loads from the lake's nine largest tributaries, and seasonal variations of pCO_2 compared well to observations (Atilla *et al* 2011). The contribution of the lake fluxes to tall-tower CO_2 was computed by convolving the previously-described influence functions (ppm/(μmol m^{-2} s^{-1})) with these gridded hourly fluxes (μmol m^{-2} s^{-1}), and summing those values across all lake grid cells and over each month of analysis to produce CO_2 influence at the tower in units of ppm.

To compare contributions of the lake to those of the surrounding terrestrial ecosystems, the contribution of regional land fluxes to tall-tower CO_2 was also approximated, over a domain defined by a 600 km by 300 km box circumscribing Lake Superior. A typical CO_2 flux was assumed across the based on eddy covariance observed fluxes at the WLEF tall tower (Davis *et al* 2003) and convolved with the influence functions in the same manner as for the lake. The tower footprint samples a representative forest-wetland landscape (Desai *et al* 2010), and so this is a reasonable first guess of typical land surface CO_2 flux.

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