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

Victoria N Vasys<sup>1</sup>, Ankur R Desai<sup>1,4</sup>, Galen A McKinley<sup>1</sup>,  
Val Bennington<sup>1</sup>, Anna M Michalak<sup>2</sup> and Arlyn E Andrews<sup>3</sup>

<sup>1</sup> Center for Climatic Research, Nelson Institute for Environmental Studies, University of Wisconsin, Madison, WI, USA

<sup>2</sup> Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA

<sup>3</sup> Earth Systems Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO, USA

E-mail: [desai@aos.wisc.edu](mailto:desai@aos.wisc.edu)

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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<sub>2</sub> flux from the atmospheric concentration typically assume that the influence from large lakes is negligible. CO<sub>2</sub> observations from a tall tower in Wisconsin segregated by wind direction suggested a CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>.

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

 Online supplementary data available from [stacks.iop.org/ERL/6/034016/mmedia](http://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

<sup>4</sup> Address for correspondence: Department of Atmospheric and Oceanic Sciences, University of Wisconsin—Madison, AOSS 1549, 1225 W Dayton Street, Madison, WI 53706, USA.

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.

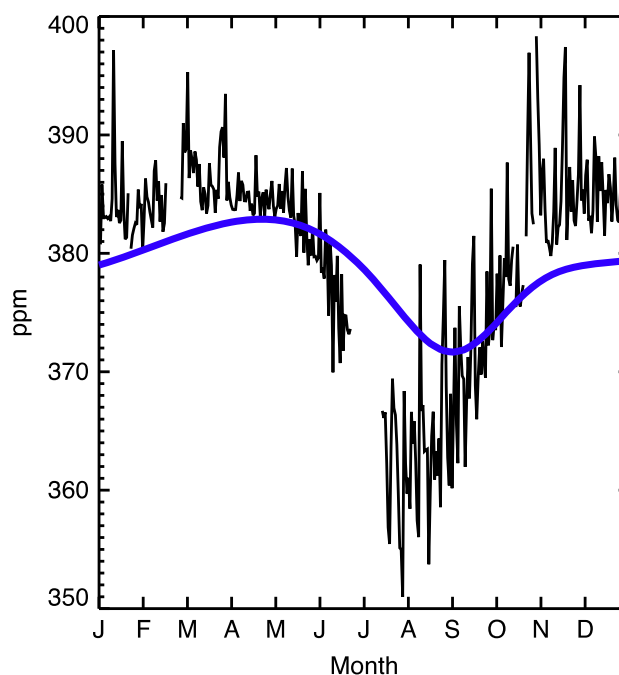
Discrepancies in the Lake Superior carbon budget (Kelly *et al* 2001, Cotner *et al* 2004, Urban *et al* 2004, 2005, Alin and Johnson 2007) prompted a recent investigation of the partial-pressure CO<sub>2</sub> (*p*CO<sub>2</sub>), computed from pH and alkalinity observations from the US Environmental Protection Agency (EPA) biannual survey. Atilla *et al* (2011) found large seasonal variability in surface *p*CO<sub>2</sub>, 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<sub>2</sub> observation sites near lakes may be useful for quantifying over-lake CO<sub>2</sub> fluxes (Urban and Desai 2009, Urban *et al* 2011). Lake CO<sub>2</sub> fluxes impart a signature on atmospheric CO<sub>2</sub>, 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<sub>2</sub> observations from the very tall WLEF tower situated near Lake Superior (Bakwin *et al* 1998). First, we examined the nature of CO<sub>2</sub> variability with lake transit by analyzing CO<sub>2</sub> 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](http://stacks.iop.org/ERL/6/034016/mmedia)). These influence functions were then convolved with CO<sub>2</sub> 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<sub>2</sub> fluxes are discussed. No published study has quantified the impact of large lakes on atmospheric CO<sub>2</sub> 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<sub>2</sub> data.

## 2. Large lake influence on tall tower air masses

The difference between tower and marine boundary layer (MBL) CO<sub>2</sub> is a simple way to represent the effect of continental surface fluxes, regional meteorology, and boundary layer dynamics on atmospheric CO<sub>2</sub> as it is advected across North America by prevailing westerly winds (figure 1). The large variability in daily averaged CO<sub>2</sub> at the tall tower, which ranged ±20 ppm from MBL CO<sub>2</sub>, at least partly reflects the

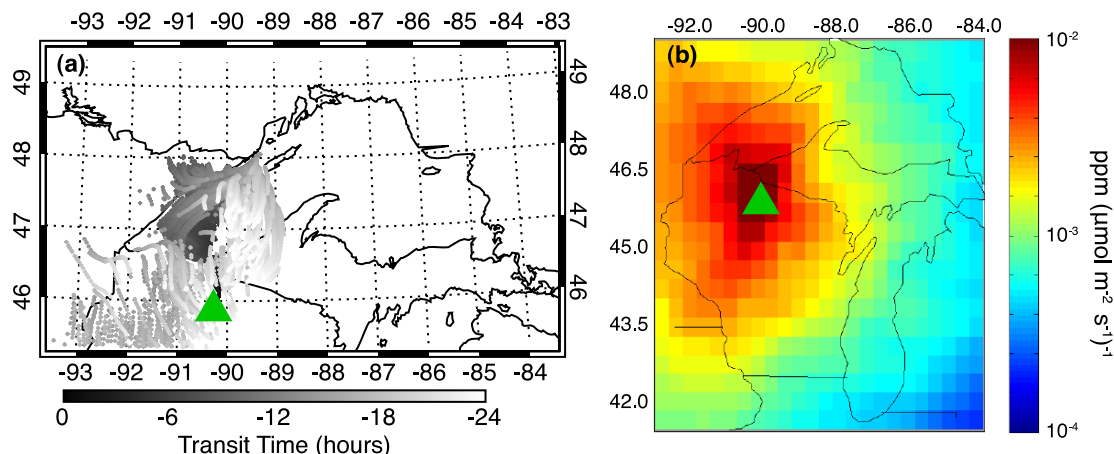


**Figure 1.** Daytime (9:00–15:00 LT) averaged daily CO<sub>2</sub> concentration (black) compared to interpolated flask marine boundary layer CO<sub>2</sub> (blue) by season.

varying contribution of lake fluxes on CO<sub>2</sub>. 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<sub>2</sub> 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).

Still, given the large daily variability of CO<sub>2</sub> 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<sub>2</sub>, these functions are in units of ppm ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )<sup>-1</sup>. 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<sub>2</sub> (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<sub>2</sub>.

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<sup>2</sup> s<sup>-1</sup>)<sup>-1</sup>) 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<sub>2</sub>

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<sub>2</sub> 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<sub>2</sub>. As the lake warmed again in spring, overturning, warming, and respiration of carbon supplied during the spring melt caused the lake to flux CO<sub>2</sub> 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<sub>2</sub> (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  $0.31 \mu\text{mol m}^{-2} \text{s}^{-1}$ , 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  $\pm 4 \mu\text{mol m}^{-2} \text{s}^{-1}$  and represent a footprint of forest and wetland (Davis *et al* 2003).

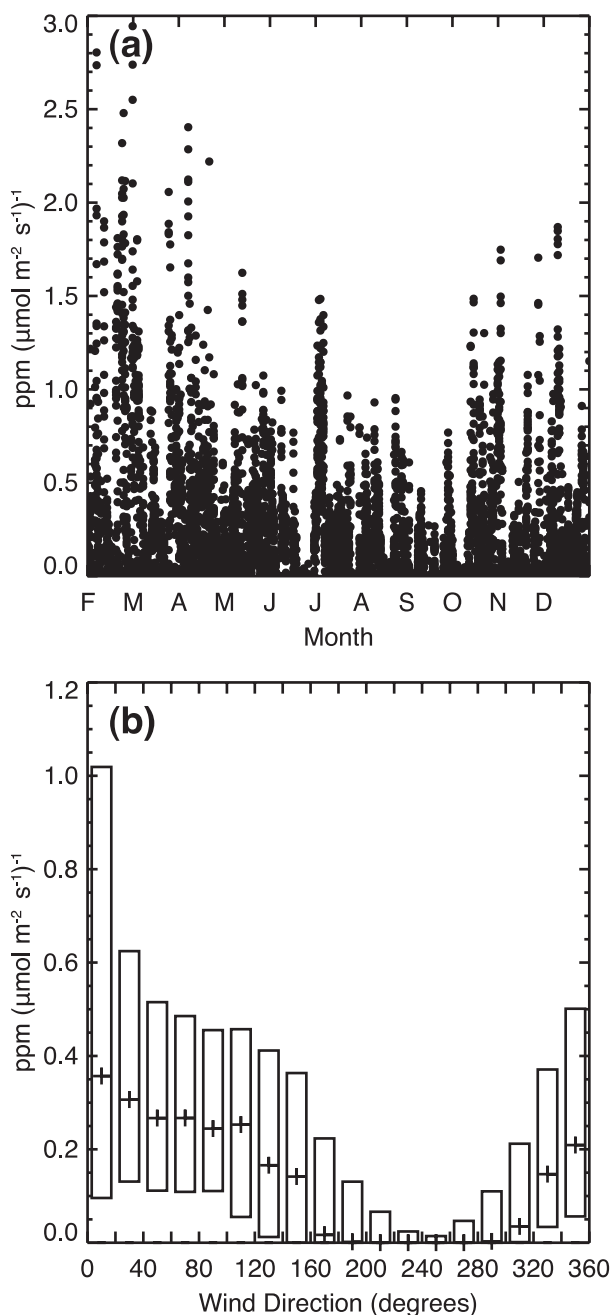
Consequently, at the daily scale, the absolute magnitude of contribution of lake fluxes to tower CO<sub>2</sub> was found to be quite small (figure 4(c), blue line) and unlikely detectable at the tower, whereas the contribution of land in the area around Lake Superior (figure 4(c), green line) was large ( $>0.2$  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<sub>2</sub> (gray shading, figure 4(c)). These potential fluxes were derived by assuming a  $\pm 1 \mu\text{mol m}^{-2} \text{s}^{-1}$  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<sub>2</sub> 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<sub>2</sub> and we conclude here that Lake Superior carbon exchange generally has a negligible impact on the tower measurements.

### 4. Implications for inverse modeling

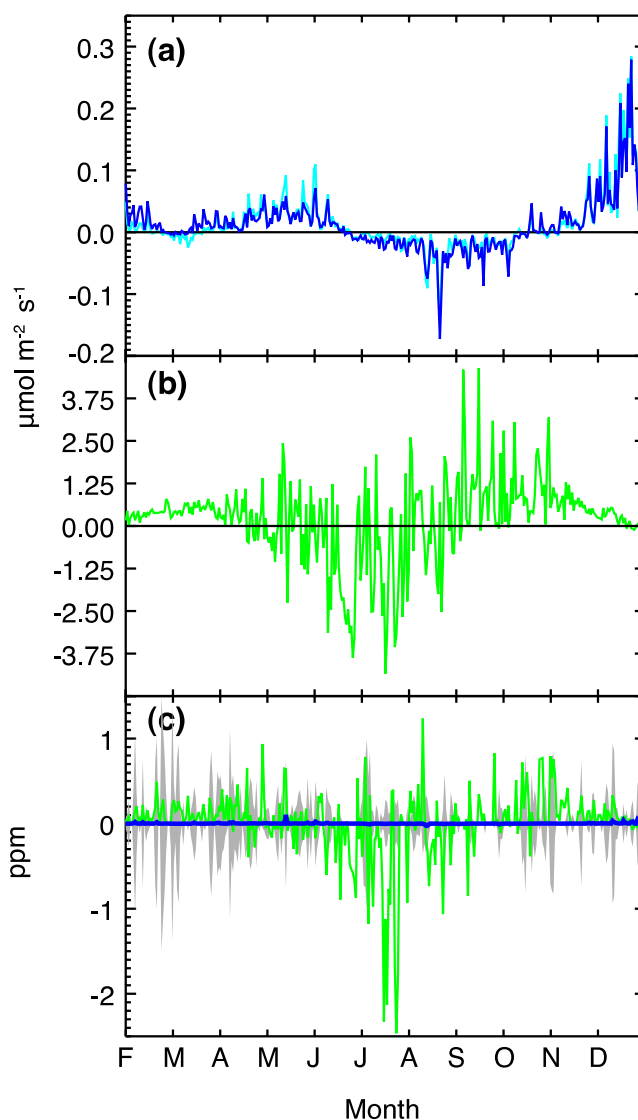
Influence functions revealed that the WLEF tall tower regularly sampled air masses from L. Superior, principally its western arm, and especially in winter and spring, with most lake-boundary layer transit occurring within the previous 24 h. Although the small CO<sub>2</sub> fluxes predicted by the numerical model of lake circulation and biogeochemistry produced a negligible CO<sub>2</sub> 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<sub>2</sub> 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 ( $\text{ppm}(\mu\text{mol m}^{-2} \text{s}^{-1})^{-1}$ ) of Lake Superior on WLEF tall tower  $\text{CO}_2$  from February to December, 2004; (b) Feb–Dec 2004 median (plus) and interquartile range (box) influence ( $\text{ppm}(\mu\text{mol m}^{-2} \text{s}^{-1})^{-1}$ ) as a function of  $20^\circ$  wind direction bins where  $0^\circ$  represents winds approaching from due North.

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  $\text{CO}_2$  observation from tall towers near large lakes, there are time periods when the lake contribution to tower  $\text{CO}_2$  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-



**Figure 4.** (a) Model-based estimates of daily total  $\text{CO}_2$  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  $\text{CO}_2$  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  $\text{CO}_2$  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  $\text{CO}_2$  flux similar to that plotted in figure 4(b). Land contribution to tower  $\text{CO}_2$  generally dominated potential lake contribution except from Nov–Apr.

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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