Lake Superior's carbon cycle and influence at the regional scale

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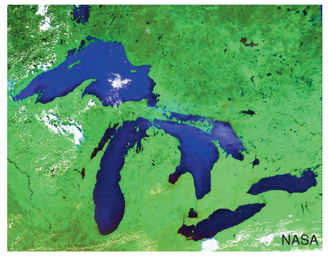
ABSTRACT

The Laurentian Great Lakes cover 25% of the land area of the 8 Great Lakes states, and, given comparable levels of primary production, their seasonal CO_2 emissions may be comparable to local terrestrial ecosystems. However, these fluxes are poorly quantified. Lake Superior is of particular interest because it is in close proximity to observations critical to quantification of the regional terrestrial carbon budget. The ongoing CyCLeS (Cycling of Carbon in Lake Superior) project is addressing these unknowns. We have used a coupled physical-ecosystem-carbon model for Lake Superior to estimate seasonal air-lake CO_2 fluxes. Coupling these fluxes to a back-trajectory analysis using an atmospheric transport model allows investigation of the impact of lake fluxes on CO_2 observations at the WLEF tall tower in Park Falls, WI. We ask:

- To what extent can we observe the contribution of lake-atmosphere CO_2 fluxes to tall tower CO_2 concentration observations?
- Is there a need to explicitly consider lake fluxes in priors for tracer-transport inversions?
- Is there an ability to resolve lake CO_2 fluxes by inverse methods?



THE GREAT LAKES ROLE IN GLOBAL AND REGIONAL CARBON CYCLING?

Recent studies have highlighted the importance of inland waters in the global carbon budget, concluding that they actively process terrestrial carbon and emit up to 1.4 PgC/yr (Tranvik et al. 2009; Cole et al. 2007). A systematic understanding of the global carbon cycle and its response to climate change requires improved quantification of carbon processes in inland waters.

Small temperate lakes are generally sources of carbon to the atmosphere (Hanson et al. 2004; Cardille et al. 2009). For large lakes, there is some evidence for a tendency of increasing carbon source with latitude due to respiration of allochthonous material (Alin and Johnson, 2007).

Where do the Great Lakes fall on a continuum between small lakes that return terrestrially-fixed carbon to the atmosphere and the global oceans that are the ultimate carbon sink?

THE CARBON BUDGET OF LAKE SUPERIOR

Previous data-based estimates for the carbon budget of Lake Superior have not been able to balance sources with sinks (Urban et al. 2005; Cotner et al. 2004; Figure 1). River sources are believed to be small, but estimates for respiration have been much larger than for primary productivity, which would suggest a significant allochthonous source. On the other hand, recent analysis of surface lake pCO_2 suggests the lake is not emitting large amounts of CO_2 (Atilla et al. 2011).

Lake Superior is a harsh environment for field study, and there are many gaps in the data. Most data, particularly for respiration, have been collected within 25km of shore and may not be representative of the open waters of the lake. Winter data is virtually non-existent.

We have built a coupled physical-biogeochemical model to allow further exploration of the carbon cycling in the lake.

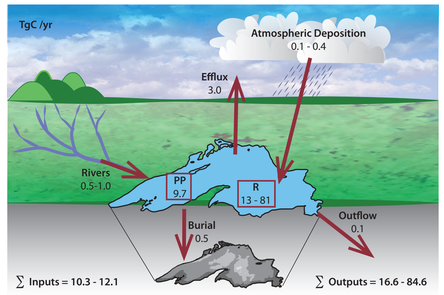


Figure 1: Lake Superior carbon cycle, sources and sinks.

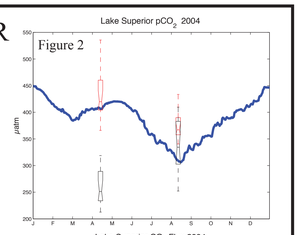
MODELED CIRCULATION AND CARBON CYCLE OF LAKE SUPERIOR

MODEL (MITgcm.Superior; Bennington et al. 2010, Bennington 2010)

- MIT General Circulation Model (Marshall et al, 1997) configured for Lake Superior bathymetry
- 3 hourly forcing of above lake wind, downward radiation, humidity and air temperature from the North American Regional Reanalysis Project (Mesinger et al., 2006)
- Phytoplankton growth limited by light and temperature (McDonald 2010, Sterner 2010)
- River flow data from USGS, Environment Canada, and Ontario Power Generation. River sampling from EPA STORET.

MODEL RESULTS

- Simulated pCO_2 compares reasonably well to EPA observations (Figure 2). However, springtime observations in 2004 are much lower than the long-term mean and the model does not capture this anomaly.
- CO_2 flux is from lake to atmosphere in fall and winter, and to the lake in summer, with total flux of 0.15 TgC/yr (Figure 3).
- Off-shore respiration is two orders of magnitude less than previously estimated based on extrapolation of near-shore measurement (not shown). This results in a significant downward revision of the lake-wide integrated respiration (to ~ 6 TgC/yr) and will allow for balancing of the lake's carbon budget (McKinley et al. 2010).



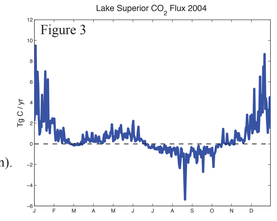


Figure 2
Figure 2: Lake Superior pCO_2 in 2004. Observed pCO_2 (Atilla et al. 2011) is in black (2004) and red (1996-2006 mean).

Figure 3: Lake-integrated CO_2 flux, 2004 (TgC/yr).

INFLUENCE OF LAKE SUPERIOR ON WLEF

Influence functions quantify the contribution of a unit flux over an area to atmospheric concentration at a specific location (ppm (μmol m^{-2} s^{-1})$^{-1}$). We used the WRF-STILT transport and trajectory model (Michalak et al 2004) to derive these functions.

Particle locations from a single release (Fig. 4a) show that air masses arriving at the WLEF tower can be sensitive to recent (< 24 hr) influence from L. Superior.

Yearly total influence on the WLEF tower of fluxes occurring over L. Superior (Fig. 4b) was comparable to the largest influences from the rest of the region. The strongest influence on the tower came from the western arm of the lake.

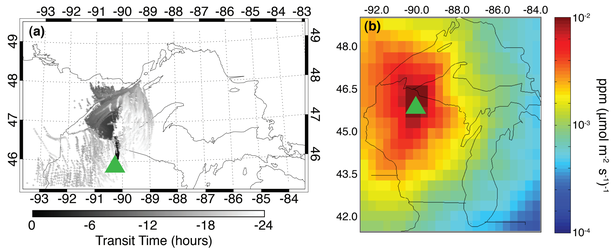


Figure 4: (a) Example of 24-hour particle trajectories, released from tower (green triangle) at 18 UTC 26 March 2004 using the STILT model, with shading representing time since release; (b) Annually-averaged influence (ppm (μmol m^2 s^{-1})$^{-1}$) of particles on the WLEF (green triangle) in the nearfield domain, showing that the strongest signal from Lake Superior is the western arm.

CO_2 FLUX IMPACTS AT WLEF

The lake-atmosphere CO_2 fluxes simulated by the physical and biogeochemical model were generally small in magnitude, over the lake as a whole (Fig. 5a, blue line), and over the western arm (Fig. 5a, cyan line). These fluxes were small especially when compared to tower eddy covariance fluxes (Fig. 5b). The tower flux footprint primarily samples forests and wetlands.

The absolute magnitude of contribution of lake fluxes to tower CO_2 was found to be minimal (Fig. 5c, blue line) and unlikely detectable at the tower, whereas contribution of land in the area around Lake Superior (Fig. 5c, green line) was large (> 0.2 ppm) in all seasons.

Gray bars in Fig. 5c indicate realm of potential lake contribution when lake fluxes were perturbed within ranges of observed values. Land contribution to tower CO_2 generally dominated potential lake contribution except from Nov-Apr.

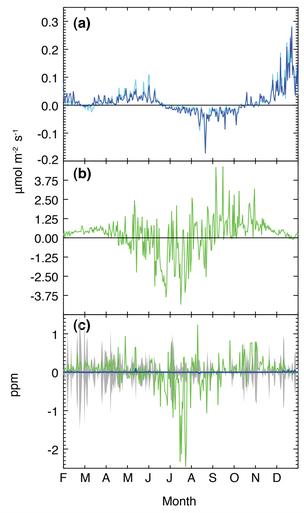


Figure 5: (a) February – December 2004 model-based estimates of daily total CO_2 fluxes from Lake Superior as a whole (dark blue) and from the western arm (light blue), with positive values indicating efflux to the atmosphere; (b) Time series of eddy covariance daily CO_2 flux over same time period showed 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 5(b). Land contribution to tower CO_2 generally dominated potential lake contribution except from Nov-Apr.

CONCLUSIONS AND FUTURE DIRECTIONS

- Numerical modeling allows for a downward revision in the basin-integrated respiration rate. With this, it should be possible to balance the carbon budget of Lake Superior.
- Tall towers near large lakes are regularly influenced by air masses that traverse the lake boundary layer.
- Typical assumptions to fix large lake carbon fluxes to a small value near zero in continental to global inverse models are justified for Lake Superior and possibly other large lakes.
- There are time periods when the lake contribution to tower CO_2 can be relatively large. 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. The ability to constrain lake fluxes by inversions appears to be limited.

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