The carbon cycle of Lake Superior: Balancing the budget with spatial heterogeneity

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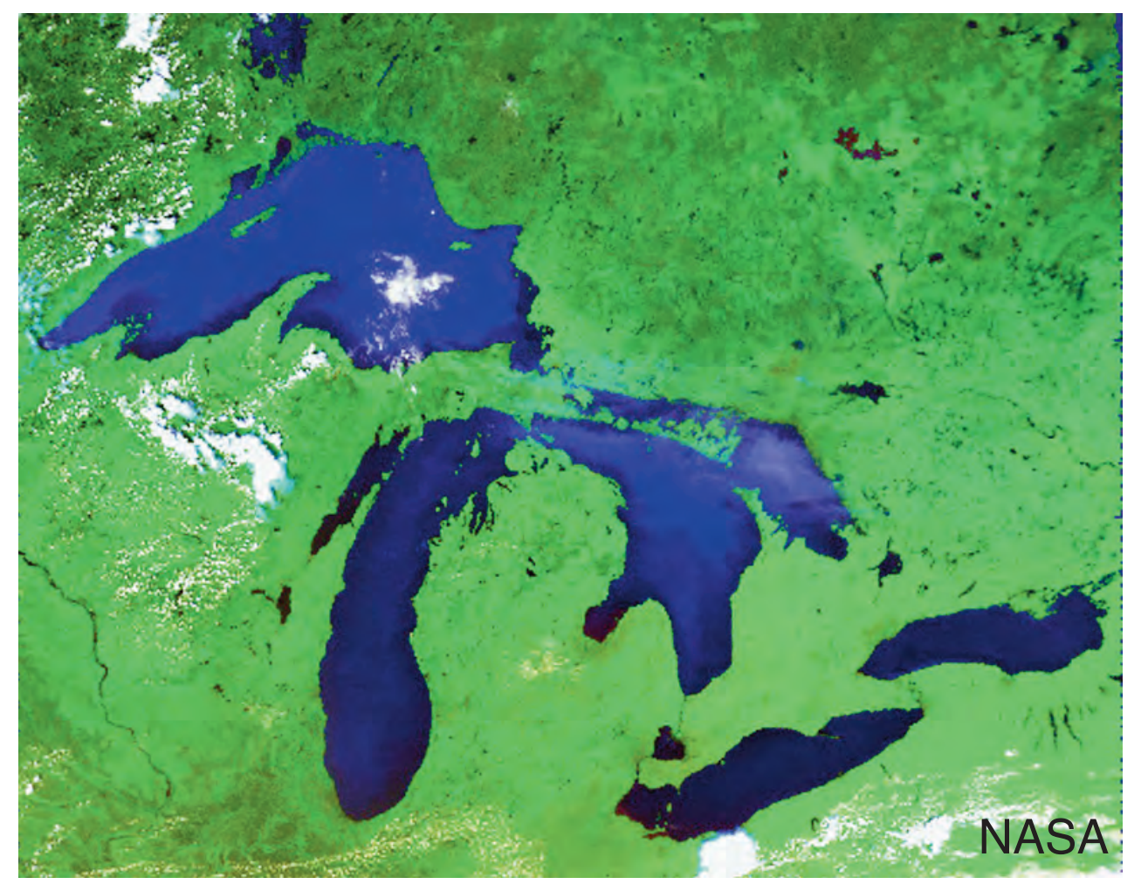
ABSTRACT

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 not quantitatively understood. The ongoing CyCLeS (Cycling of Carbon in Lake Superior) project is working to quantify carbon cycling in the lake and associated air-lake carbon fluxes and to place them in the context of regional carbon budgeting efforts by the North American Carbon Program (NACP). As part of CyCLeS, we have configured a three-dimensional hydrodynamic model with an ecosystem-carbon module for the Lake. The model is able to capture observed open-lake pCO_2, primary productivity (PP), and respiration rates (R). Here, we use this model and other evidence to revise the previously unbalanced carbon budget.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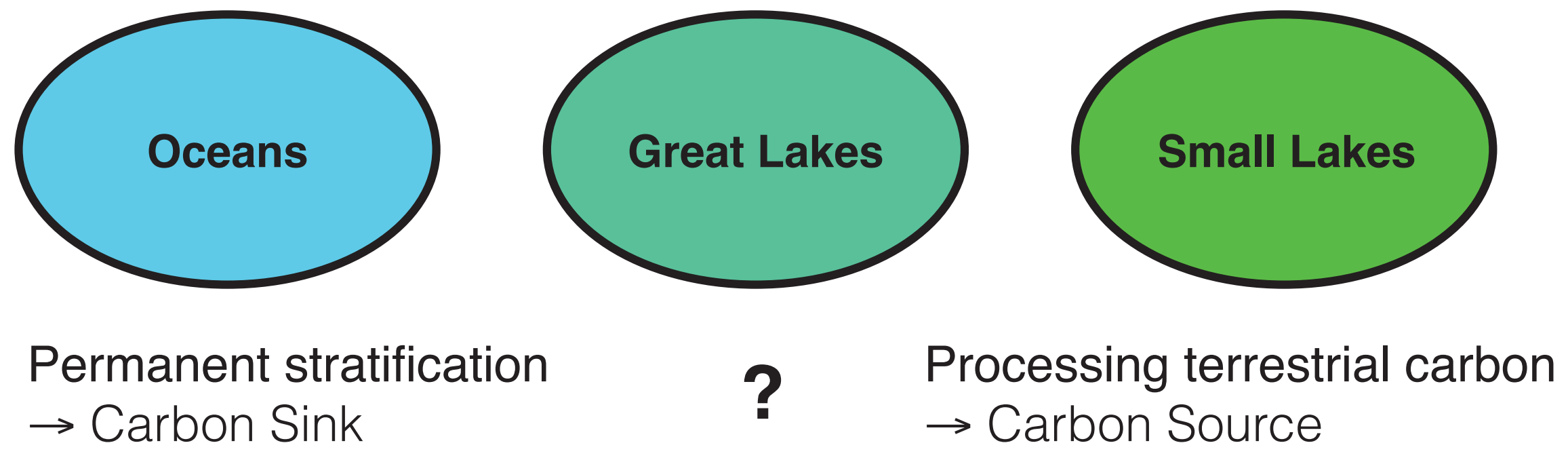
THE GREAT LAKES ROLE IN GLOBAL AND REGIONAL CARBON CYCLING?

Recent studies have highlighted the importance of inland waters in the global carbon budget, concluding that they actively process terrestrial carbon 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?


Oceans

Great Lakes

Small Lakes

Permanent stratification
→ Carbon Sink

?

Processing terrestrial carbon
→ Carbon Source

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. 2010).

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.

Can spatio-temporal variability explain the apparent mismatch between observed carbon inputs and ouputs in Lake Superior? We have built and applied a coupled physical-biogeochemical model to this question.

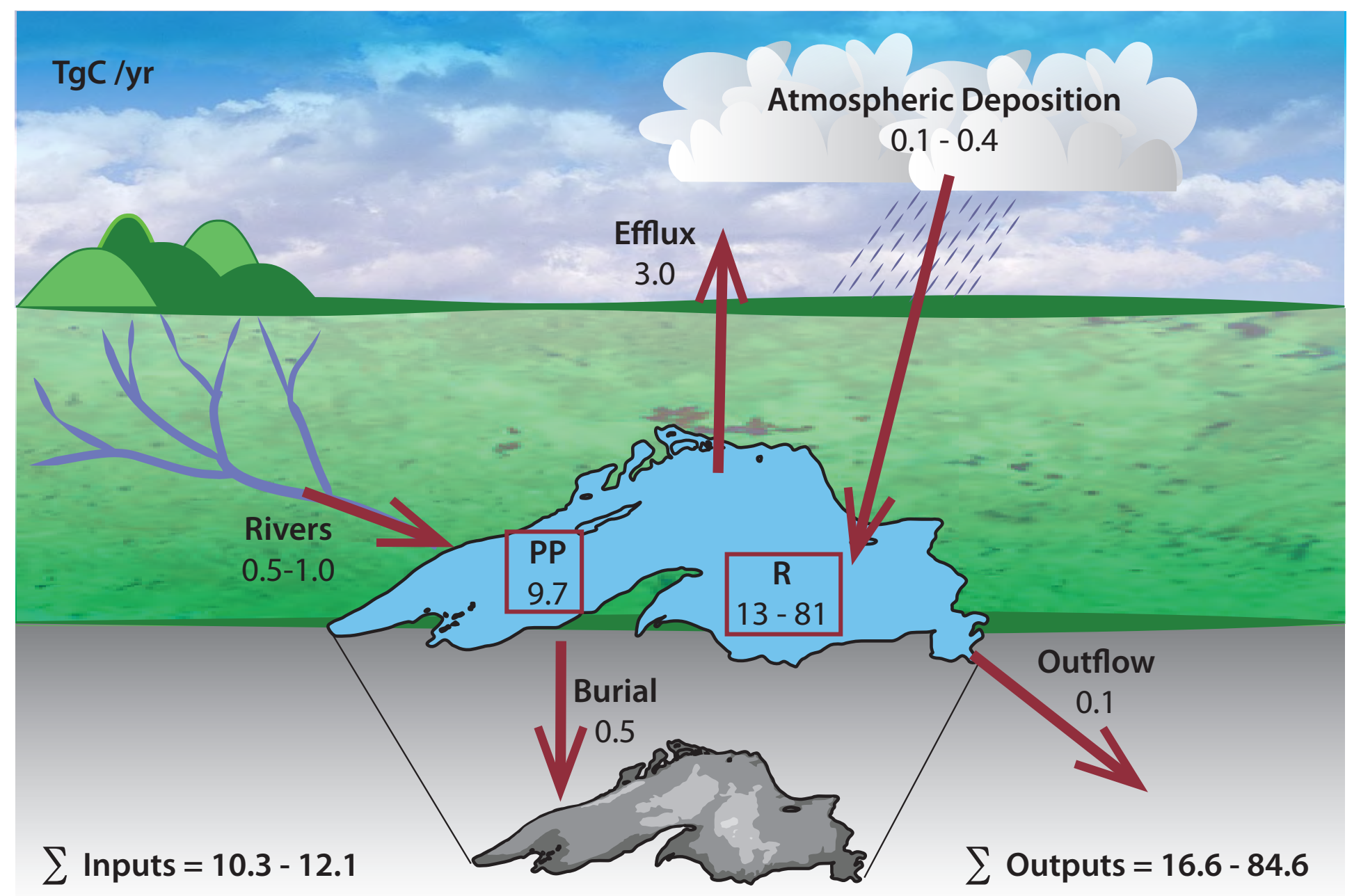


Figure 1. Lake Superior carbon cycle, sources and sinks.

MODELING THE CIRCULATION AND CARBON CYCLE OF LAKE SUPERIOR

PHYSICAL MODEL (MITgcm.Superior; Bennington et al. 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)
- Horizontal resolution of 10 km or 2 km
- 29 vertical levels ranging in resolution from 5m at surface to 31 m at depth
- Ice mask interpolated from NOAA data (Assel, 1993)

BIOGEOCHEMICAL MODEL (Bennington 2010)

- Ecosystem model adapted from Dutkiewicz et al. (2005)
- Phytoplankton growth limited by light and temperature (McDonald 2010, Sterner 2010)
- Cycling of carbon, oxygen, and alkalinity and explicit DOM and POM.
- Surface carbonate chemistry for freshwater [CO_2SYS]
- Air-sea exchange of carbon dioxide and oxygen following Wanninkhof (1992)
- Daily riverine supply of DOC, DIC, and alkalinity from nine largest rivers.
- Unique flow to DIC and flow to alkalinity relationships for each river derived using LOADEST (Runkel et al., 2004) created by USGS.
- River flow data from USGS, Environment Canada, and Ontario Power Generation. River sampling from EPA STORET.
- Constant DOC concentrations used for each river.

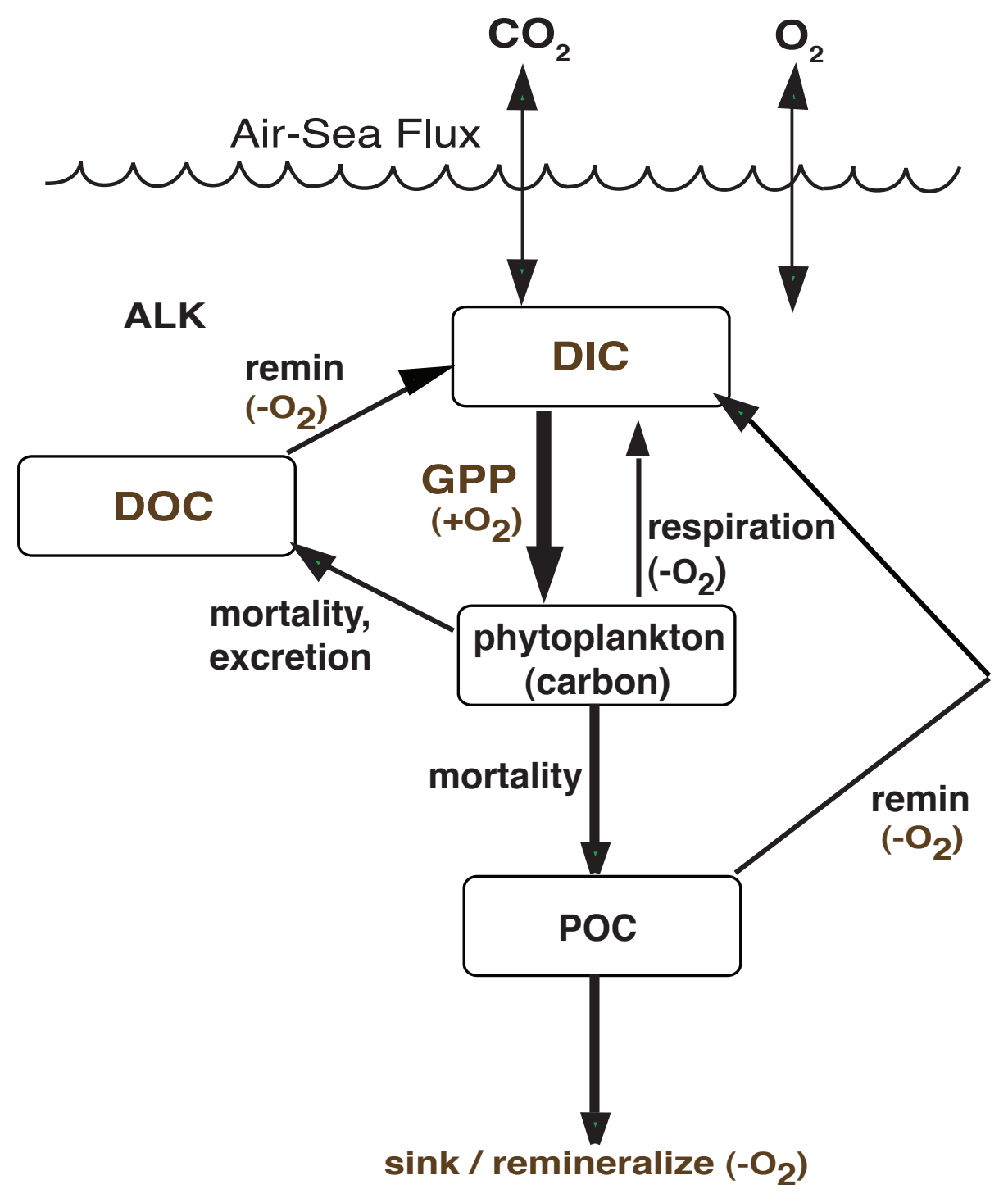


Figure 2. Ecosystem schematic.

PRODUCTIVITY AND RESPIRATION, 1999

Modeled GPP agrees with an estimate based on the empirical equation of Sterner (2010) (Figure 3); and with nearshore respiration observations at the mouth of the Ontonagon river (Figure 4).

On a water-column average volumetric basis, lake-wide productivity (Figure 3, inset) has a spatial pattern very similar to that of respiration (Figure 4, inset). This is consistent with both shallow depths and greater biological activity near to shore. Note the logarithmic scale, indicating variability in these column-average rates of two orders of magnitude.

When column-integrated rates are considered, however, quite a different pattern emerges. Productivity (Figure 5) has a much more homogenous pattern across the lake than respiration (Figure 6). Since productivity is confined to the euphotic zone (~30m), it has less sensitivity to water depth than respiration that occurs throughout the column.

Previous extrapolations of observed respiration in the nearshore have assumed that volumetric rates are lower in the open lake by only a factor of 2. We find 2 orders of magnitude difference. Our model-based estimate of basin-integrated R is 6.0 TgC/yr.

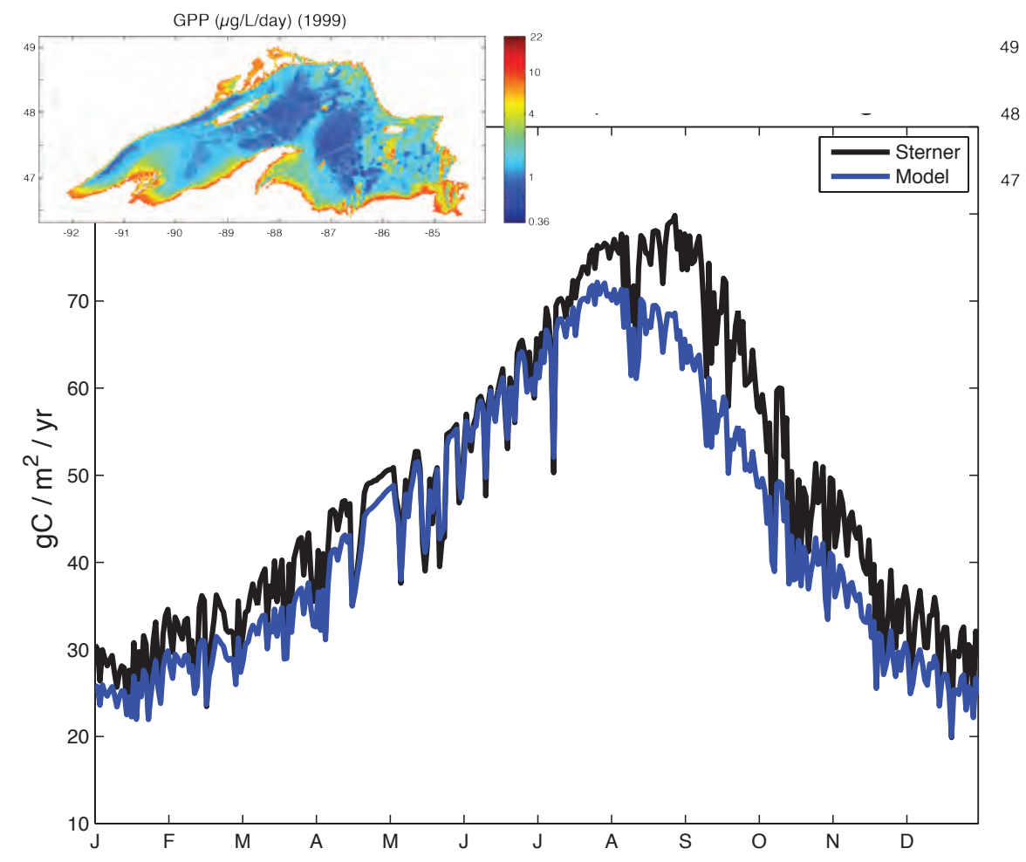


Figure 3. Primary productivity, 1999, modeled vs. empirical equation of Sterner (2010). Units on lake-wide annual average (inset) are ugC/L/d.

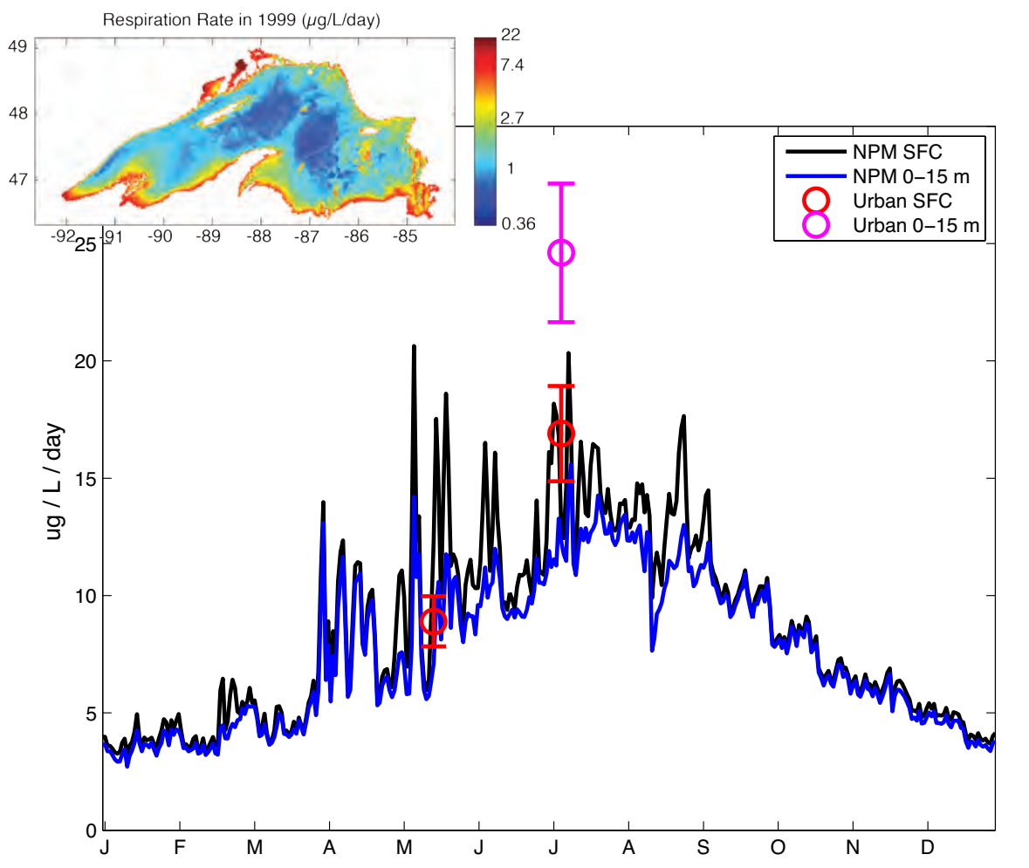


Figure 4: Respiration rates at the Ontonagon River mouth, 1999, at the base of the Keweenaw Peninsula, modeled (lines) and observed (circles).

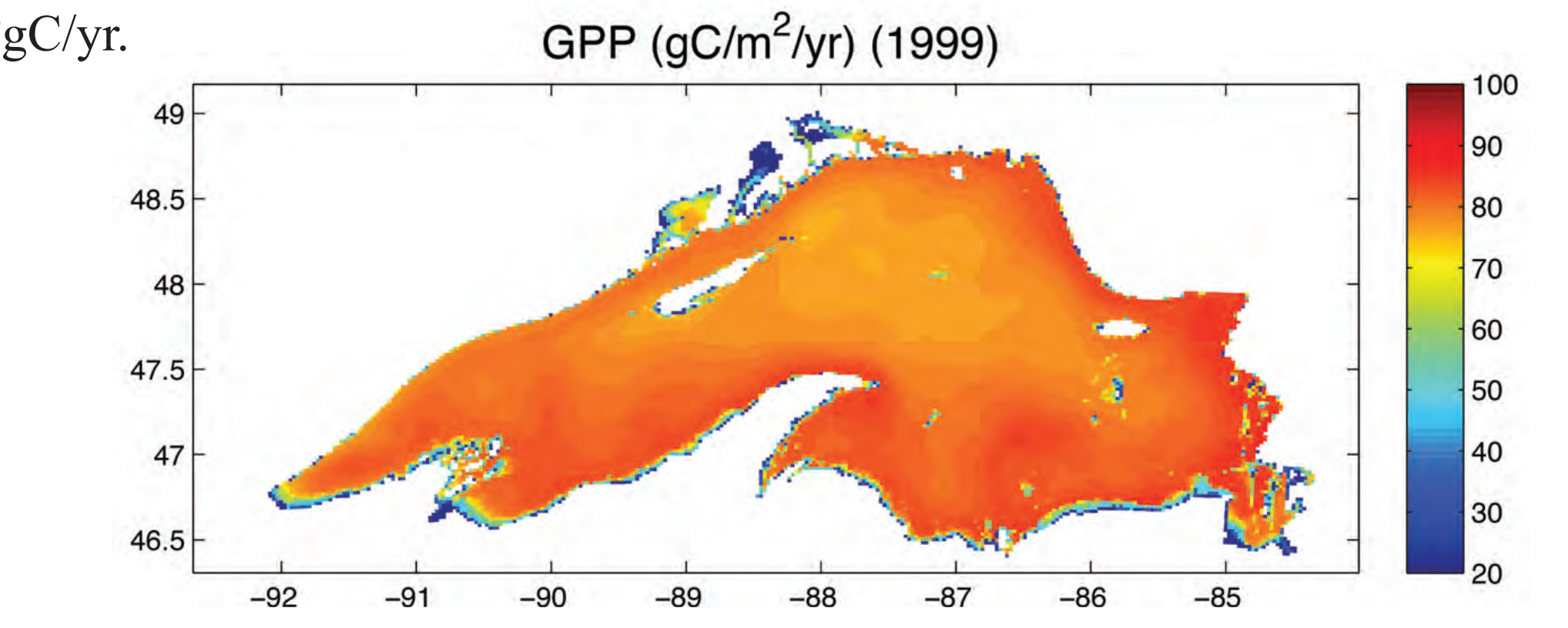


Figure 5: Column integrated gross primary productivity (GPP), modeled 1999 annual average.

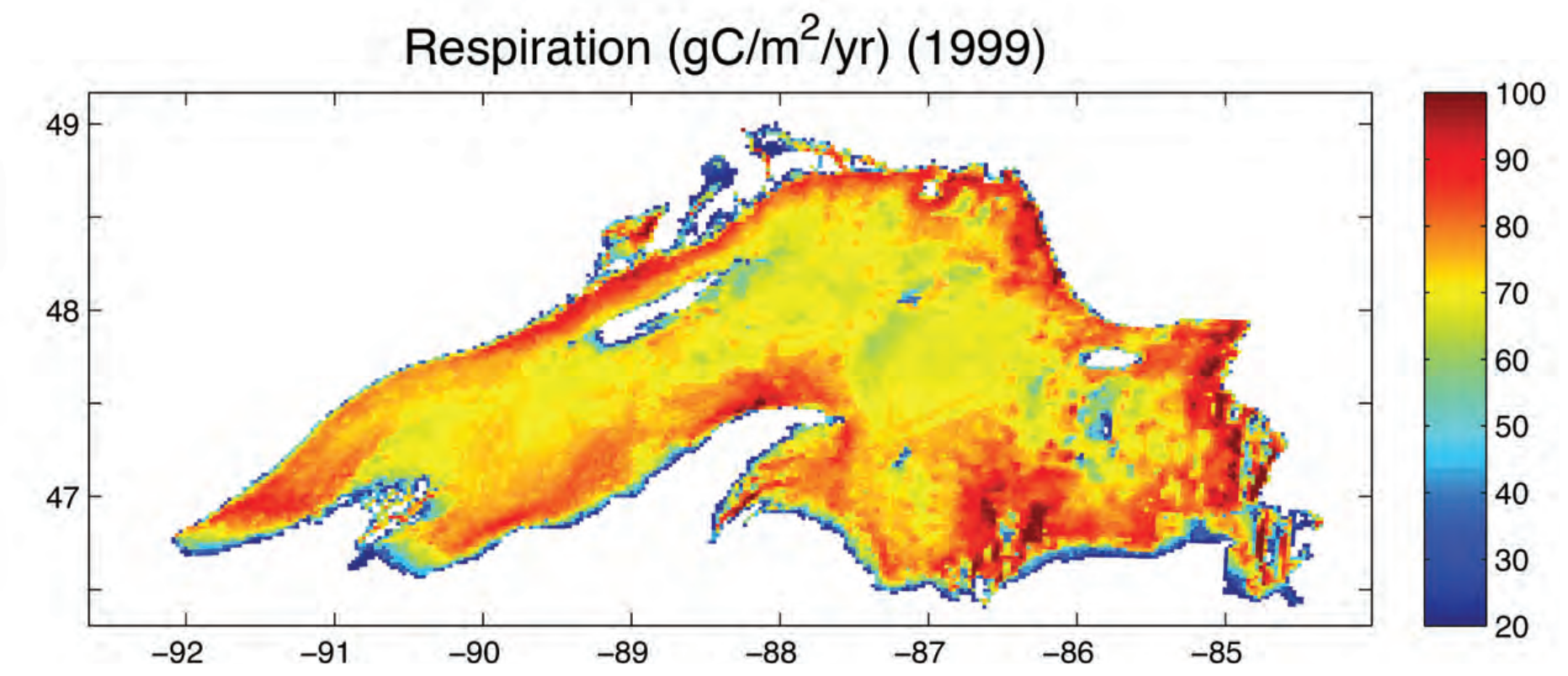


Figure 6: Column integrated respiration (R), modeled 1999 annual average.

EXPLAINING THE PATTERN OF RESPIRATION AND GPP/R

- The pattern of GPP/R (Figure 7) largely reflects the heterogeneity of respiration. The lake-wide mean is 0.98, indicating a slight heterotrophy; this is consistent with the relatively small amount of river-borne carbon being respired in the modeled lake, and a net carbon efflux of 0.15 TgC/yr.
- GPP/R (Figure 7) generally indicates net autotrophy near shore, then a band of net heterotrophy offshore, and then approximate balance in the open waters.
- Preliminary analysis suggests this pattern can be explained by the net divergence of the fluid motions (Figure 8). Specifically, regions of convergence are consistent with regions of low GPP/R and regions of divergence with high GPP/R. Thus, in regions where the products of photosynthesis, primarily DOC, are concentrated by the fluid motions (net convergence), there is net heterotrophy. Our next step is to explictly consider divergence of the DOC field.

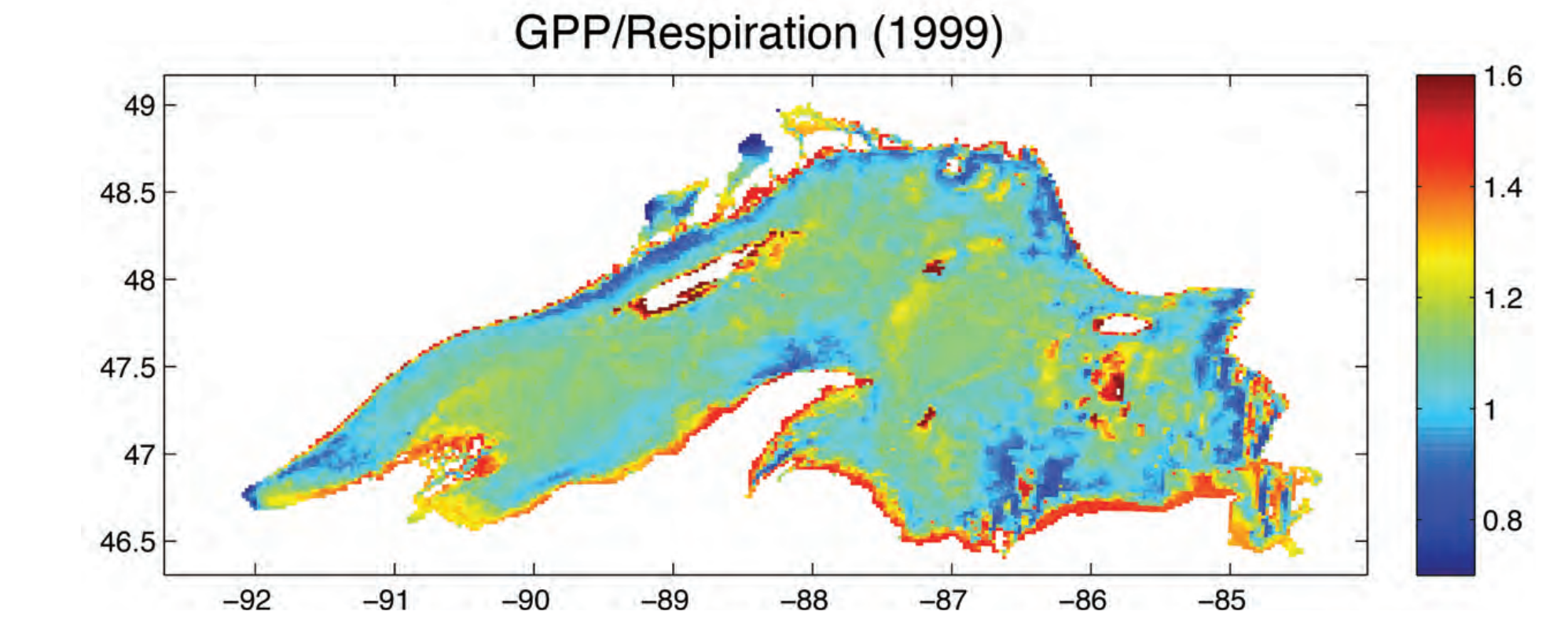


Figure 7: GPP/R, modeled 1999 annual average.

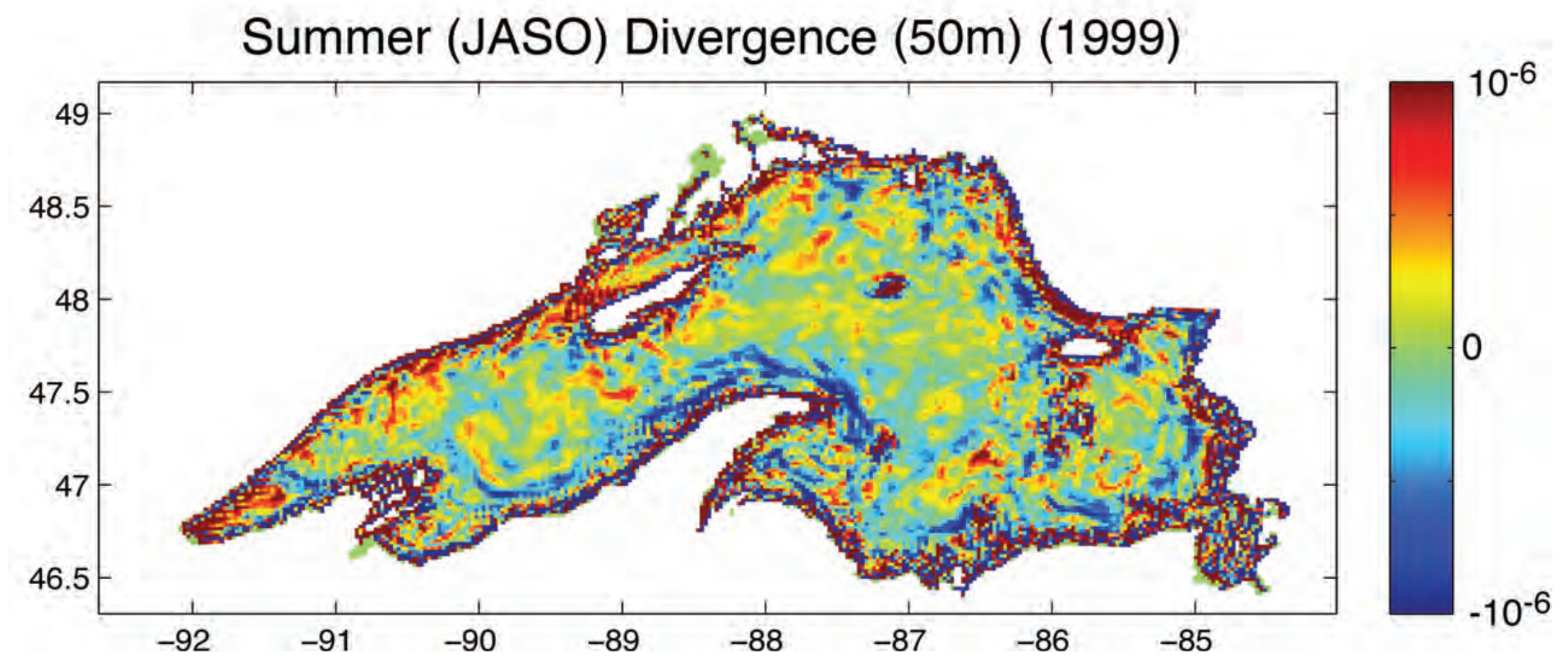


Figure 8: Flow divergence of top 50m (1/s), summer 1998. Annual mean is similar.

CONCLUSIONS AND FUTURE DIRECTIONS

- With a downward revision in the basin-integrated respiration rate to 6 TgC/yr, it should be possible to balance the carbon budget of Lake Superior.
    - We will combine observed rates with model-based information about spatial heterogeneity in respiration to revise the budget.
- Preliminary analysis suggests that fluid motions help to explain the spatial heterogeneity in column-integrated respiration that drives the GPP/R distribution. (Figs 5-8).
- This ecosystem model does not explicitly include phosphorus; a formal optimization procedure suggests that data are insufficient to support its inclusion (McDonald 2010). We are also working with an ecosystem that does include phosphorus (Bennington 2010) and find comparable results.

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