Systematic deficiencies in ocean transport impact land and ocean carbon sinks

Laure Resplandy
Princeton University

R. Keeling (Scripps); B. Stephens, J. Bent, M. Long (NCAR)
K. Rodgers (AOS); L. Bopp (IPSL); C. Rödenbeck (MPI, Germany);
S. Khatiwala (Oxford, UK); P. Tans (NOAA)
Ocean carbon fluxes

- Into ocean
- To atmosphere

pCO$_2$-based SOCAT shipboard data
- Rödenbeck Jena mixed-layer scheme (update of Rödenbeck et al., 2014)
- Landchützer neural network (update of Landschützer et al., 2014)

Ocean Inversions (e.g. Mikaloff Fletcher et al, 2006 2007; Gruber et al, 2009)
Uncertainties in natural ocean fluxes
Uncertainties in natural ocean fluxes
Implications for the land sink
Implications for the land sink

Carbon transport

CO$_2$

Carbon transport
Hemispheric transport asymmetry

\[ A = \frac{(T_{20N} + T_{20S})}{2} \]

Carbon

air-sea + rivers

90S  20S  20N  90N
Do we know the ocean southward carbon transport?

Ocean inversions incl. rivers (e.g. Mikaloff Fletcher, 2007; Gruber et al., 2009)

pCO$_2$-based corrected for $C_{ant}$ using Khatiwala et al., 2012
+ river loop = 0.78 PgC/y (Resplandy et al., 2018)

pCO$_2$-based
+ river loop = 0.45 PgC/y (Jacobson et al., 2007)

Southward Carbon transport [PgC/y]
Do we know the ocean southward carbon transport?

- Estimates agree within large uncertainties but systematic differences in north-south balance

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Southward Carbon transport [PgC/y]

Resplandy et al., Nat Geo 2018
Heat an indicator of carbon transport?

Tight carbon-temperature link arises from thermally driven fluxes (solubility) and biological pump (vertical exchange of respired carbon).
Heat an indicator of carbon transport?

Not uniform biological pump still introduces decoupling between carbon and heat.
Carbon transport linked to heat transport

Hydrographic data + 11 models
(ESMs & ocean forward models)

Ocean carries more carbon southward & heat northward
-0.3 PgC/y per PW

Solubility effect (-0.9 PgC/y per PW) dampened by vertical exchange of respired carbon

Data: Lundberg et al., 1996; Holfort et al., 1998; Alvarez et al., 2003; MacDonald et al. 2003, Ganachaud and Wunsch, 2003
Carbon transport linked to heat transport

Hydrographic data + 11 models (ESMs & ocean forward models)

Biological pump decoupling varies across models

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Hemispheric transport asymmetry

\[ A = \frac{(T_{20N} + T_{20S})}{2} \]

- Carbon
- Heat

- air-sea + rivers
Heat an indicator of carbon transport?

Heat asymmetry explains 60% of carbon transport
Heat + Bio pump asymmetry explain 85% of carbon transport

Heat fluxes (Large and Yeager, 2009)
Atmospheric data (Resplandy et al., 2016)
Hydrography (Ganachaud and Wunsch, 2003)

Resplandy et al., Nat Geo 2018
Heat an indicator of carbon transport?

Heat asymmetry explains 60% of carbon transport
Heat + Bio pump asymmetry explain 85% of carbon transport

1) Models biased low in heat transport, expected biased low in carbon transport

2) Southward carbon transport = 0.30 to 0.75 PgC/y

Heat fluxes (Large and Yeager, 2009)
Atmospheric data (Resplandy et al., 2016)
Hydrography (Ganachaud and Wunsch, 2003)

Resplandy et al., Nat Geo 2018
Too shallow overturning circulation in models?

what we expect

Heat asymmetry 0.7-1.1 PW

in models

Heat asymmetry <0.7 PW
Do we know the ocean southward carbon transport?

- Estimates agree within large uncertainties but systematic differences in north-south balance

\[
\text{Southward Carbon transport [PgC/y]}
\]

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- \( + \text{ river loop} = 0.78 \text{ PgC/y} \) (Resplandy et al., 2018)
- \( \text{pCO}_2\)-based
- \( + \text{ river loop} = 0.45 \text{ PgC/y} \) (Jacobson et al., 2007)
- \( \text{Ocean inversions incl. rivers} \) (e.g. Mikaloff Fletcher, 2007; Gruber et al., 2009)
Heat constraint on ocean carbon flux estimates

- Estimates agree within large uncertainties but ...
- Ocean inversions incompatible with heat constraint
- “best estimate”: update of Rödenbeck + stronger river loop

- pCO$_2$-based corrected for $C_{ant}$ using Khatiwala et al., 2012
  + river loop = 0.78 PgC/y (Resplandy et al., 2018)

- pCO$_2$-based
  + river loop = 0.45 PgC/y (Jacobson et al., 2007)

Ocean inversions incl. rivers (e.g. Mikaloff Fletcher, 2007; Gruber et al., 2009)
Implications for land sink?

Ocean inversion
Gruber et al., 2009
(1990-2010 period)

Revised ocean
Roedenbeck
+ strong river loop
(1990-2010 period)

Atmospheric CO₂ inversion
Jena Carboscope - C. Roedenbeck
Same C<sub>ant</sub> from Khatiwala et al 2012

Resplandy et al., Nat Geo 2018
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Spurious southern land source

Strong northern sink

Get rid of unlikely southern land source

Weakens northern land sink

Ocean inversion

Revised ocean

Atmospheric CO₂ inversion
Jena Carboscope - C. Roedenbeck
Same C₅ from Khatiwala et al 2012

Resplandy et al., Nat Geo 2018
Implications for land sink?

Redistributes 40% of the land sink

Reduce gap between atmospheric inversions & ecosystem models/inventories

Revised ocean pCO$_2$-based + rivers (1990-2010 period)

Resplandy et al., Nat Geo 2018
Summary

Heat observational constraint on carbon budget

Rivers probably overlooked & underestimated in global carbon budgets

Models underestimate heat & carbon transport asymmetry

Implications for climate system

- ocean/land sinks magnitude and partition
- tropical precipitations, Arctic sea ice etc.
Carbon asymmetry consistent with pre-industrial hemispheric gradients in atmospheric CO$_2$

Scripps atmospheric data since 1959

South Pole

Mauna Loa

atmospheric CO$_2$ gradient

0.35 - 0.70 PgC/y
Carbon asymmetry consistent with pre-industrial hemispheric gradients in atmospheric CO$_2$

Scripps atmospheric data since 1959

Keeling et al. (1989); Keeling et al. (2011)