Ocean controls on climate: challenging heat and carbon budgets

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The ocean buffers the anthropogenic perturbation

**Warming (1950-2000)**

- IPCC 2013

**Anthropogenic carbon (1994)**

- Khatiwala et al., Nature 2009

<table>
<thead>
<tr>
<th>Depth (m)</th>
</tr>
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<tbody>
<tr>
<td>0 - 200</td>
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<tr>
<td>200 - 1000</td>
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<tr>
<td>1000 - 2000</td>
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<td>2000 - 4000</td>
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  - 90%

- **Anthropogenic carbon (1994)**
  - 30%
Underlying natural ocean circulation and transport

Warming (1950-2000) 90%

IPCC 2013

Anthropogenic carbon (1994) 30%

Khatiwala et al., Nature 2009
How well do we know ocean natural transports of heat and carbon?

What are the implications for the Earth system?

1. Ocean heat transport

- ocean heat
- climate system
- atmospheric data

constraint
Ocean transports heat poleward - northward asymmetry

There is a close correspondence between tropical precipitation and wind stress convergence. Although there should be such a relationship, it is not guaranteed, because of the independent data. The precipitation maxima in the Atlantic and eastern Pacific are related to convergence of meridional stress, whereas in the western Pacific it is the zonal stress that matters most. The reduced precipitation farther north off West Africa is consistent with the cancellation of meridional convergence by zonal stress divergence in Fig. 6.

The CORE.v2 climatological mean air–sea heat flux \( f \) is shown in Fig. 8. All the expected features are evident, but their magnitudes may differ from unbalanced, or constrained climatologies. The near-zero global balance is attained through an area weighted cancellation of strong heating with strong cooling. The upwelling of colder water from depth leads to strong heating along the equator with a maximum of about 150 W/m\(^2\) in the east Pacific cold tongue, and along the eastern boundaries of the Pacific and Atlantic subtropical gyres. Poleward circulation of warm surface water results in strong cooling of the Nordic seas \(-Q_{as}[-100 W/m^2]\), the Labrador Sea and the western boundary currents \(-Q_{as}[-180 W/m^2]\) and their extensions, including the Agulhas retroflection \(-Q_{as}[-120 W/m^2]\).

The solar, longwave, and sensible, heat flux climatologies are shown in Fig. 9. The distribution of latent heat flux can easily be inferred from the evaporation of Fig. 7c, because from (3c), the 10 mg/m\(^2\) per second contour corresponds to a latent heat flux of 25 W/m\(^2\). Over most of the ocean the net heat flux (Fig. 8) is a balance between solar heating and cooling due to \( Q_E \) plus \( Q_L \). However, the sensible heat flux, \( f_0 Q_H \) is a significant contribution to the cooling where strong winds blow very cold continental air over western boundary currents and their extensions, the Nordic and Labrador seas and the marginal ice-zones. The relatively small cooling by a latent heat flux of between \(-50 \) and \(-75 \) W/m\(^2\) (Fig. 7c) is a major factor in the net heating (Fig. 8) of both the eastern equatorial Pacific, and along the eastern boundaries of the South Atlantic and South Pacific. Another influence along these boundaries is the relatively small cooling by a longwave flux of only about \(-30 \) W/m\(^2\).

The band of predominant heating in the south Atlantic and Indian Oceans along 50\(^\circ\)S appears to reflect topographic steering, especially east of Drake Passage, of cold polar waters to the north and underneath a more temperate atmosphere. This band is aligned with relative minima in Fig. 7.

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**Fig. 7b** Global distributions of the climatological CORE.v2 air–sea fluxes of a freshwater, b precipitation, c evaporation, colored at 10 mg/m\(^2\) per second intervals with a zero contour. Multiplication of the evaporation by a factor of 2.5 gives the latent heat flux in W/m\(^2\).
There is a close correspondence between tropical precipitation and wind stress convergence. Although there should be such a relationship, it is not guaranteed, because of the independent data. The precipitation maxima in the Atlantic and eastern Pacific are related to convergence of meridional stress, whereas in the western Pacific it is the zonal stress that matters most. The reduced precipitation farther north off West Africa is consistent with the cancellation of meridional convergence by zonal stress divergence in Fig. 6.

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Ocean transports heat poleward - northward asymmetry
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Northward heat transport controls tropical rainfall

Position of Intertropical Convergence Zone
McGee et al., EPSL 2014; Schneider et al., Nature 2014…)

Annual precipitation maximum

Marshall et al., 2014
Northward heat transport controls tropical rainfall
Northward heat transport controls Arctic sea ice

Models w/ strong northward heat transport

Models w/ weak northward heat transport

Mahlstein and Knutti, 2011

observations (HadISST) 1980-2008
Observations of heat transport asymmetry?

Heat asymmetry

\[ A = \frac{T_{20N} + T_{20S}}{2} \]
Observations of heat transport asymmetry?

Ocean sections
(Macdonald, 1998; Ganachaud and Wunsch, 2003; Talley, 2003 and Johns et al., 2011)

Surface flux climatology
(Large and Yeager, 2009)

Top of the atmosphere
(Trenberth and Caron, 2001; Fasullo and Trenberth, 2008)

Heat asymmetry
\[ A = \frac{T_{20N} + T_{20S}}{2} \]

between -0.1 to 1.1 PW
(PW = petawatt = \(10^{15}\) watt)
Inert gas flux in ocean scales with heat flux out

\[ F = -A \times Q \]

depends on gas solubility

Keeling and Shertz (1992)
Atmospheric fingerprint of the ocean heat transport

The atmosphere smoothes and integrates ocean processes

Hypothesis: northern deficit in atmosphere

Heat asymmetry
Potential oxygen to track ocean heat

Atmospheric Potential Oxygen
(Keeling and Manning, review Treatise on Geochem. 2014)

\[ \text{APO} = O_2 + 1.1 \text{CO}_2 \]
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\[ \text{APO} = O_2 + 1.1 \text{CO}_2 - \text{fossil fuel} \]
Potential oxygen to track ocean heat

Atmospheric Potential Oxygen

\[ \text{APO} = \text{O}_2 + 1.1 \text{CO}_2 - \text{fossil fuel} \]

Oceanic Potential Oxygen
(Keeling et al., Ann Rev Mar Sci 2010)

\[ \text{OPO} = \text{O}_2^* + 1.1 \text{C}^* - \text{C}_{\text{anthropogenic}} \]
Potential oxygen scales with ocean heat, like an inert gas

Oceanic Potential Oxygen

$$OPO = O_2^* + 1.1 \text{ C}^* - C_{\text{anthropogenic}}$$
Airborne atmospheric potential oxygen data

B. Stephens, J. Bent (NCAR)
1600 observations
~500 hours of flight

Resplandy et al., Clim. Dyn 2016
Airborne atmospheric potential oxygen data

B. Stephens, J. Bent (NCAR)
1600 observations
~500 hours of flight

northern deficit consistent with our hypothesis ~ 10.5 per meg

Airborne atmospheric potential oxygen data

Potential Oxygen (per meg)

Resplandy et al., Clim. Dyn 2016
Model suite to determine link between ocean heat transport & atmospheric potential oxygen

**DATA**
Atmospheric potential oxygen

**PREDICTION**
Atmospheric potential oxygen

Model suite with different northward heat transports

Resplandy et al., Clim. Dyn 2016
Atmospheric deficit scales with ocean heat transport

Atmospheric potential oxygen data

Heat transport asymmetry [PW]

APO north deficit (per meg)

7 Ocean inversions (GFDL/MIT models) + 6 Climate models

Resplandy et al., Clim. Dyn 2016
Atmospheric deficit scales with ocean heat transport

- Atmospheric potential oxygen data
- 7 Ocean inversions (GFDL/MIT models) + 6 Climate models
- Observational target 0.7-1.1 PW

Resplandy et al., Clim. Dyn 2016
Atmospheric deficit scales with ocean heat transport

Atmospheric potential oxygen data

7 Ocean inversions (GFDL/MIT models)
+ 6 Climate models

Previous data estimates
- Ocean sections
- Air-sea flux climatology
- Top of atmosphere budgets

observational target 0.7-1.1 PW

Resplandy et al., Clim. Dyn 2016
Shallow overturning circulation in models

what we expect

Heat asymmetry
0.7-1.1 PW
Shallow overturning circulation in models

what we expect

Heat asymmetry
0.7-1.1 PW

in models

Heat asymmetry
<0.7 PW
Implications for climate system and future predictions?

- **Intertropical convergence zone & precipitations**

- **Arctic sea ice** (Mahlstein and Knutti, 2011)

- **Regulation of glacial/interglacial transitions**
  (Crowley Paleoceanogr. 1992, Barker et al., Nature 2009 …)
Implications for climate system and future predictions?

• **Intertropical convergence zone & precipitations**  
  McGee et al., EPSL 2014; Schneider et al., Nature 2014…)

• **Arctic sea ice** (Mahlstein and Knutti, 2011)

• **Regulation of glacial/interglacial transitions**  
  (Crowley Paleoceanogr. 1992, Barker et al., Nature 2009 …)

• **Link to carbon cycle**
How well do we know ocean natural transports of heat and carbon?

What are the implications for the Earth system?

2. Carbon cycle
Where is the anthropogenic carbon going?

Global Carbon Project 2015
Where is the anthropogenic carbon going?

Global Carbon Project 2015
Where is the anthropogenic carbon going?

- Anthropogenic emissions inventory
- Observed atmospheric concentrations
- Ocean estimate, model & observation

Global Carbon Project 2015
Where is the anthropogenic carbon going?

- **Emissions**
  - Fossil fuels and industry
  - Land-use change
  - Land
  - Atmosphere
  - Ocean

- **Partitioning**
  - Residual: land biosphere
  - Observed atmospheric concentrations
  - Ocean estimate: model & observation

Global Carbon Project 2015
Why should we care?

CO₂

atmosphere

warming?

ocean

acidification?

land biosphere

vulnerable sink?
Challenges in latitudinal ocean/land carbon partition

Strong southern source bias
Peylin et al. (2013)

~ 0.5 PgC/y

90S south 20S tropics 20N north 90N

Northern sink magnitude?
Tans et al. (1990) ...

land CO₂

ocean/river CO₂
Uncertain partition between ocean and land sinks
Uncertain partition between ocean and land sinks

\[ \sum \]

\[ \sum \]

\[ \text{CO}_2 \]

south 20S tropics 20N north 90N
Can we constrain ocean carbon transport?
Two estimates of ocean carbon sink

**ocean inversions**
(carbon data + model)
Mikaloff Fletcher et al., 2006, Gruber et al., 2009

**pCO₂ data**
+ river estimate
Takahashi et al. 2009, Landchüzter et al. 2014, Roedenbeck et al., 2013; Jacobson et al., 2007

agree within their large uncertainties … but systematic bias with implications for global carbon budget
Systematic difference in carbon transport asymmetry

**Ocean inversions**
(carbon data + model)
Mikaloff Fletcher et al., 2006, Gruber et al., 2009

**pCO₂ data + river estimate**
Takahashi et al. 2009, Landchüzter et al. 2014, Roedenbeck et al., 2013; Jacobson et al., 2007

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

0.20 PgC/y

0.45 PgC/y

90S -> 20S -> tropics -> 20N -> north -> 90N
# Long standing controversy on carbon asymmetry

<table>
<thead>
<tr>
<th>Atmospheric CO₂ data</th>
<th>previous state-of-the-art</th>
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<tbody>
<tr>
<td>1 PgC/y (Keeling et al., 1989)</td>
<td></td>
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<tr>
<td>Models/Inversions</td>
<td>&lt; 0.3 PgC/y (Murnane et al., 1999; Aumont et al. 2001; Gloor et al., 2003; Mikaloff Fletcher et al., 2007…)...</td>
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<td>Heat-based constraint</td>
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Long standing controversy on carbon asymmetry
Heat an indicator of carbon transport?

Tight carbon-temperature link arises from thermally driven fluxes (solubility) and biological pump (respiration of organic matter at depth)
Heat an indicator of carbon transport?

Tight carbon-temperature link arises from thermally driven fluxes (solubility) and biological pump (respiration of organic matter at depth)
Heat an indicator of carbon transport?

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

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

\[ A_C \propto -0.31 \pm 0.15 \times A_Q + 0.19 \pm 0.10 \times A_{Bio} \]
Carbon transport linked to heat and biological pump

Carbon asymmetry $A_C$ [PgC/y]

Heat asymmetry $A_Q$ [PW]

Data range

heat northward transport
carbon southward transport

Heat fluxes (Large and Yeager, 2009)
Atmospheric data (Resplandy et al., 2016)
Hydrography (Ganachaud and Wunsch, 2003)
Carbon transport linked to heat and biological pump

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

2) Observational target 0.35 - 0.65 PgC/y southward

Heat fluxes (Large and Yeager, 2009)
Atmospheric data (Resplandy et al., 2016)
Hydrography (Ganachaud and Wunsch, 2003)
## New constraint on carbon asymmetry

<table>
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<th>This study</th>
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<tr>
<td>Atmospheric CO₂ data</td>
<td>1 PgC/y</td>
<td>55 years atmospheric CO₂</td>
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<tr>
<td></td>
<td>(Keeling et al., 1989)</td>
<td>recent generation</td>
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<tr>
<td>Models/Inversions</td>
<td>&lt; 0.3 PgC/y</td>
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Towards the reconciliation on carbon asymmetry...

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<td>Atmospheric CO$_2$ data</td>
<td>1 PgC/y</td>
<td>~0.5 PgC/y</td>
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pCO₂ data + river estimate
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0.35-0.65 PgC/y

0.20 PgC/y

0.45 PgC/y
Implications for land sink?

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

Revised ocean pCO₂-based + rivers
(1990-2010 period)

Resplandy et al., in rev

Atmospheric CO₂ inversion
Jena Carboscope - C. Roedenbeck
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Atmospheric CO2 inversion
Jena Carboscope - C. Roedenbeck

Spurious southern land source

Get rid of unlikely southern land source

Weaken northern land sink
Implications for land sink?

Redistributed 40% of the land sink

Reduce gap between atmospheric inversions & ecosystem models/inventories

Revised ocean pCO₂-based + rivers (1990-2010 period)

Resplandy et al., in rev

Atmospheric CO₂ inversion
Jena Carboscope - C. Roedenbeck
New observational constraints on heat/carbon budget

Rivers probably overlooked & underestimated in global carbon budgets

Models underestimate heat & carbon transport asymmetry

Implications

- tropical precipitations, Arctic sea ice etc.
- ocean/land sinks magnitude and partition, impacts on acidification, sink vulnerability etc.

Resplandy et al., Climate Dyn. 2016
Resplandy et al., in rev
Carbon asymmetry linked to heat and biological pump

Suite of 11 models

-0.31 PgC/y per PW

Heat asymmetry [PW]

+0.17 PgC/y per PgC/y

Biological pump asymmetry [PgC/y]

$A_C = -0.31 A_Q + 0.17 A_{Bio}$

Heat explains $60\%$ of carbon transport
Heat + Bio. pump explain $85\%$ of carbon transport
Controversy on carbon asymmetry

Atmospheric data: Keeling et al., 1989

- Atmospheric CO₂ steady-state: ~0.8 ppm
- South Pole: ~1 PgC/y
- Mauna Loa: ~1 PgC/y
Carbon asymmetry consistent with pre-industrial hemispheric gradients in atmospheric CO$_2$

observed CO$_2$ gradient
Mauna Loa to South Pole [ppm]

Fossil fuel emissions [GtC / y]

y-intercept
-0.55 ± 0.15 ppm

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