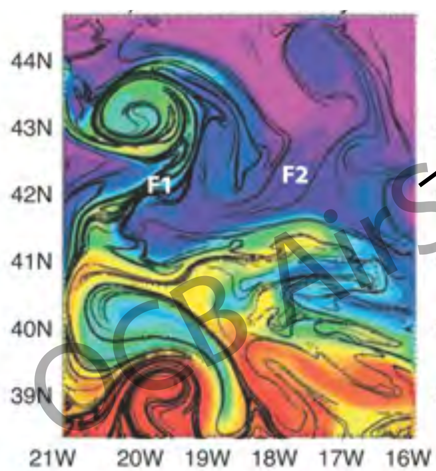
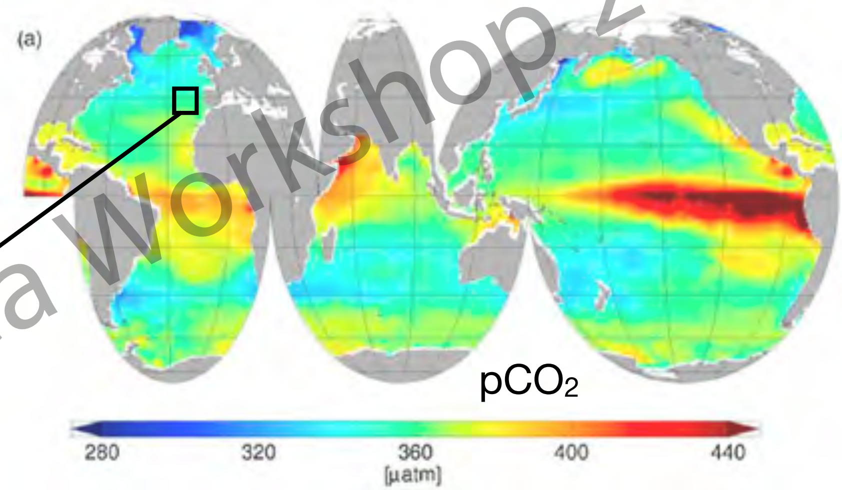
Greenhouse gases and the oceans

Small-scale
model 5 km



Resplandy et al. 2009

Global ocean

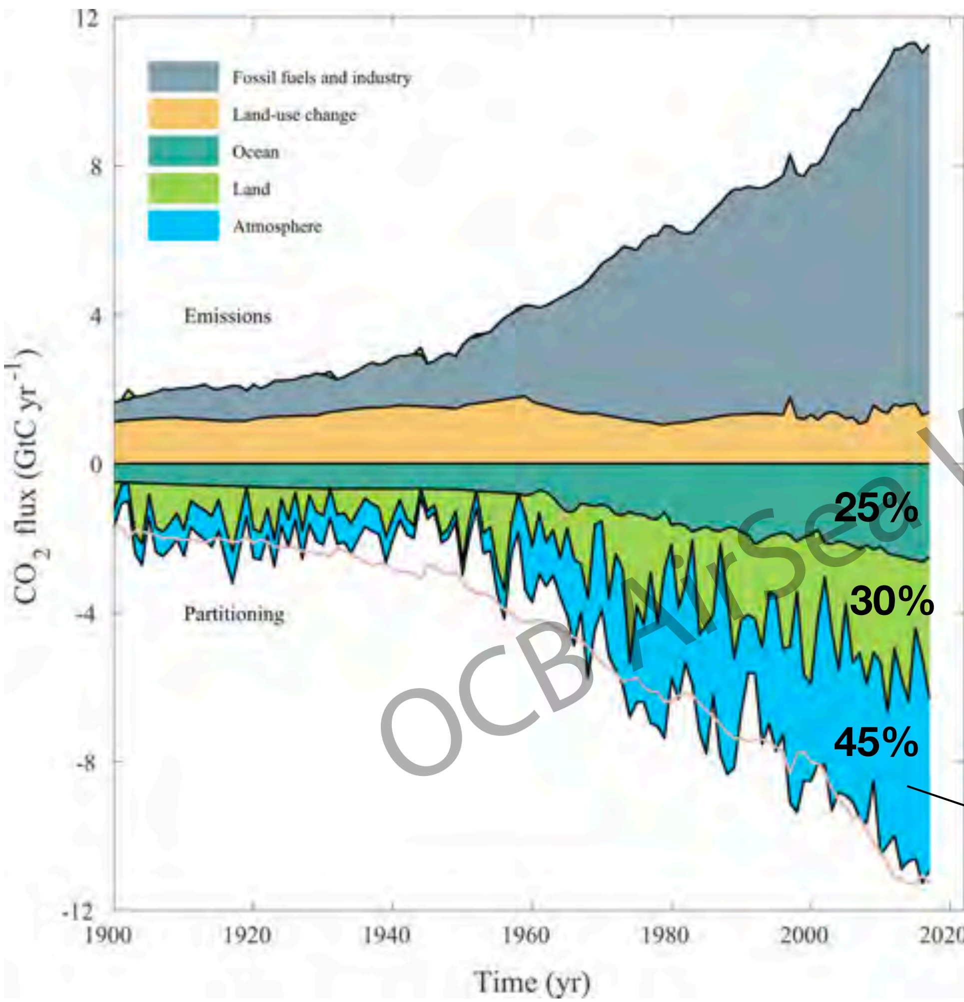


Landschützer et al. 2014

Princeton Environmental Institute

Laure Resplandy
Princeton University

Consensus on global carbon budget builds upon 6 decades of research



Le Quéré et al., 2018

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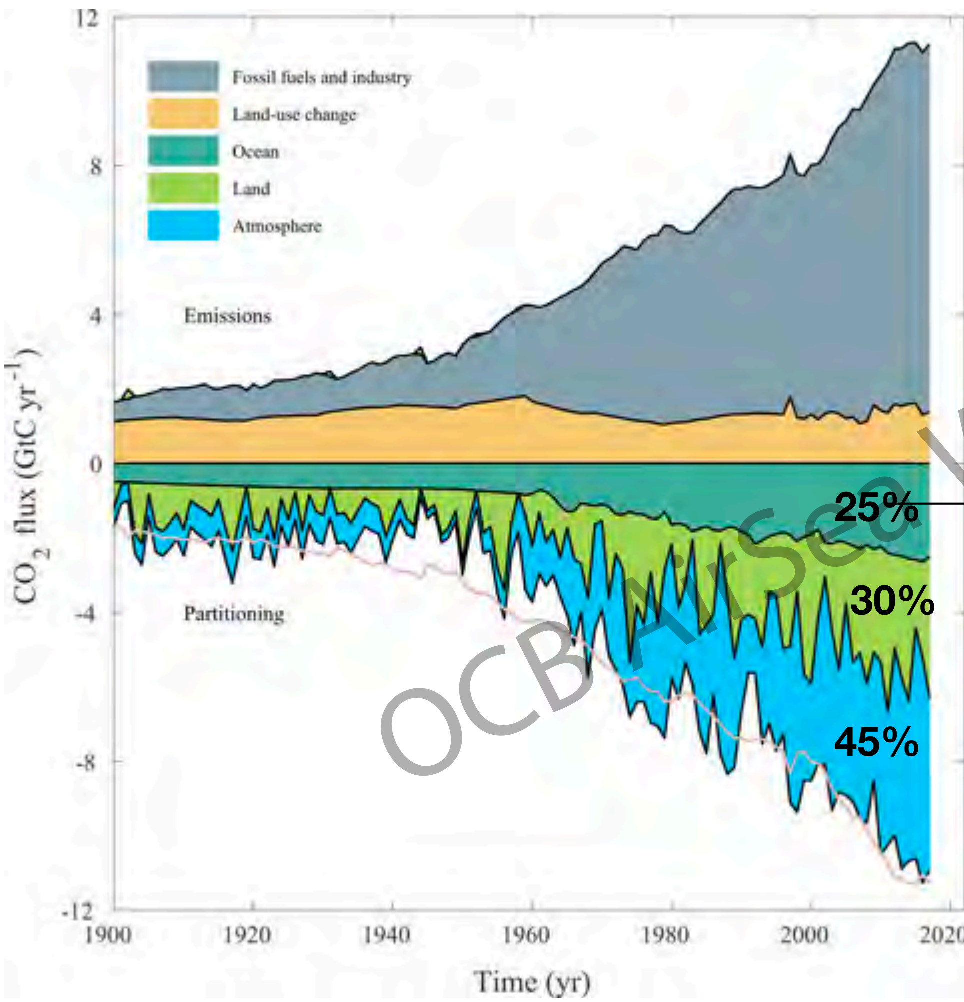

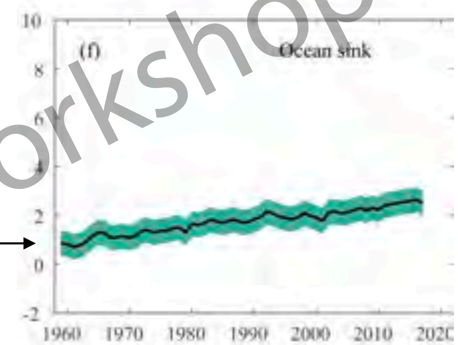

GLOBAL CARBON PROJECT

Le Quéré et al., 2018

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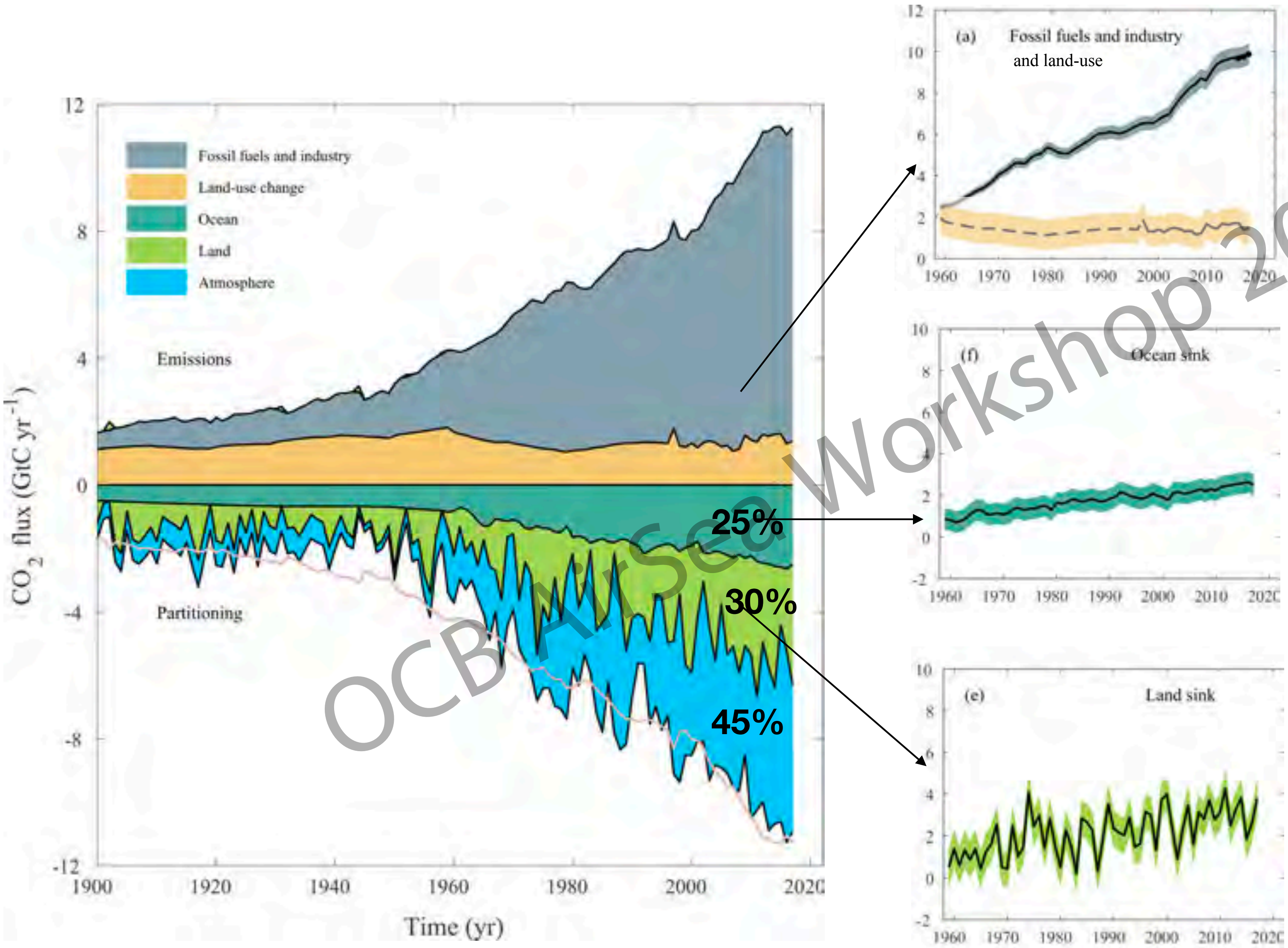
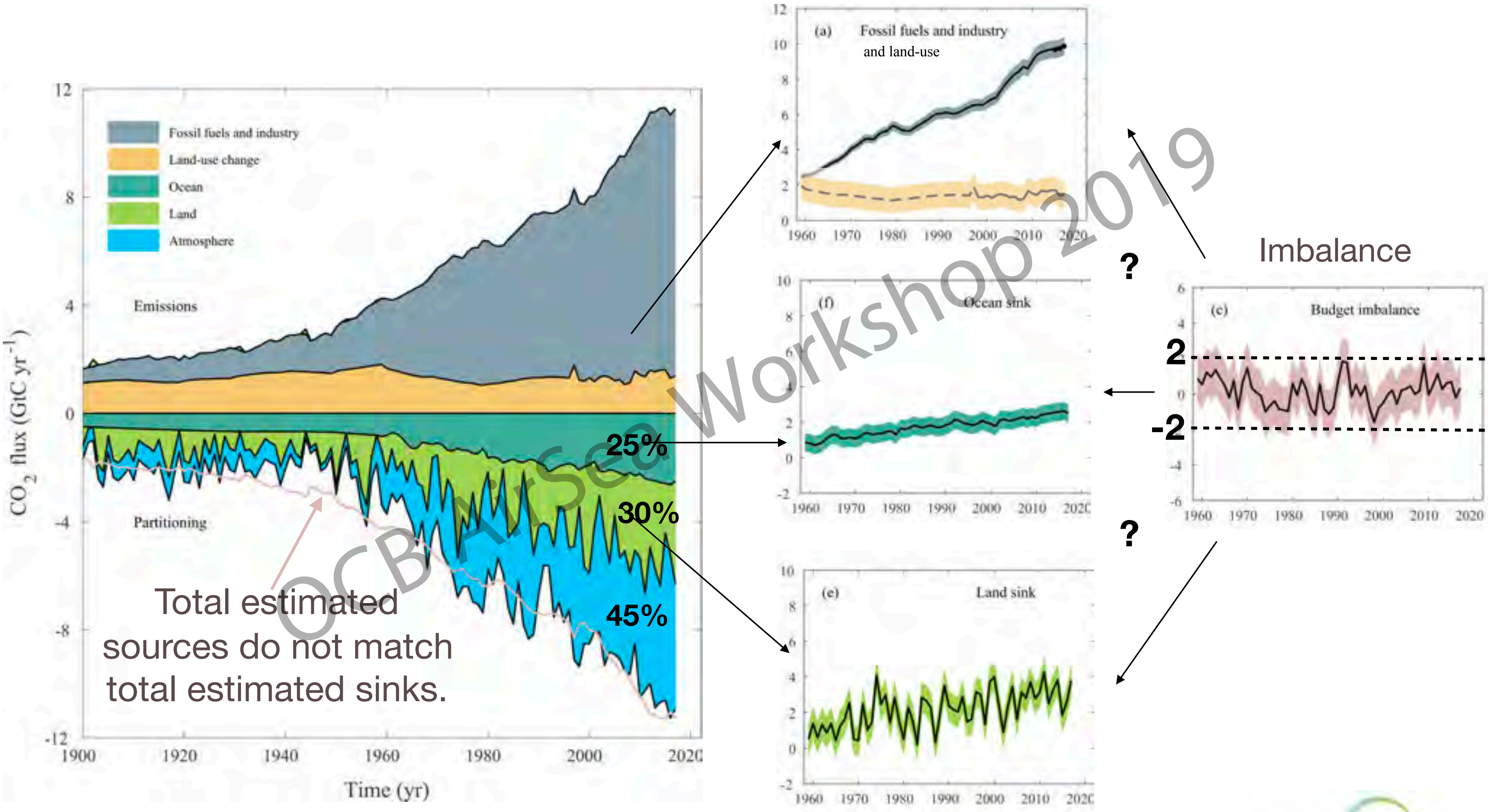


GLOBAL CARBON PROJECT

Le Quéré et al., 2018

Yet, imbalance reflects gaps in our understanding

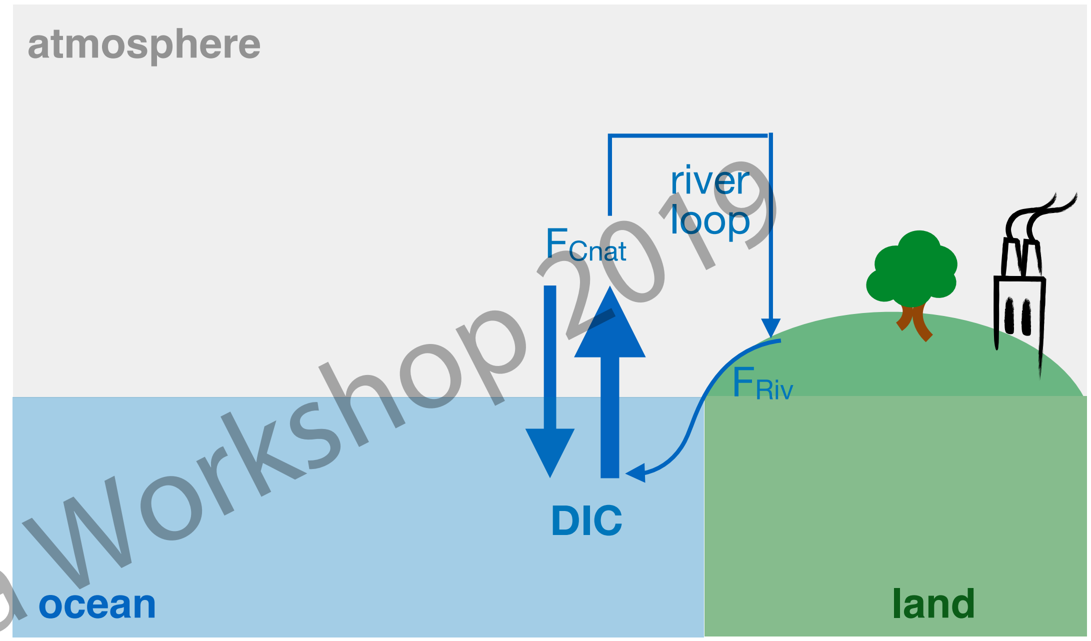


Le Quéré et al., 2018

Natural and anthropogenic flows of carbon

Natural cycle

$F_{Cnat} + F_{Riv} = 0$ (steady-state)



Natural and anthropogenic flows of carbon

Natural cycle

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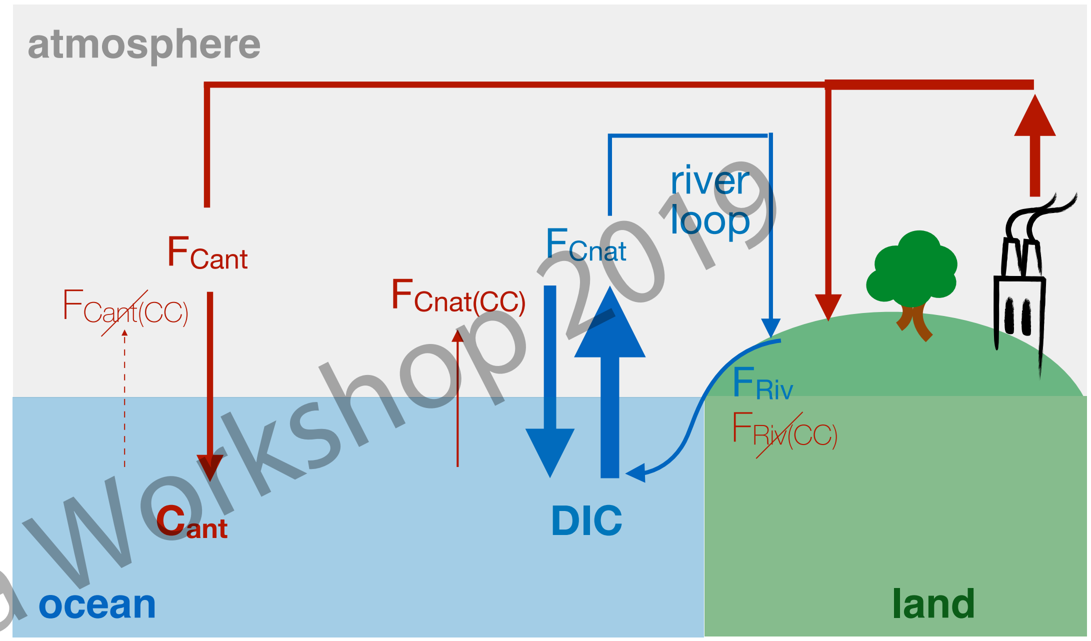
Anthropogenic perturbation

rising atmospheric CO_2
other changes: warming, fertilizers etc.



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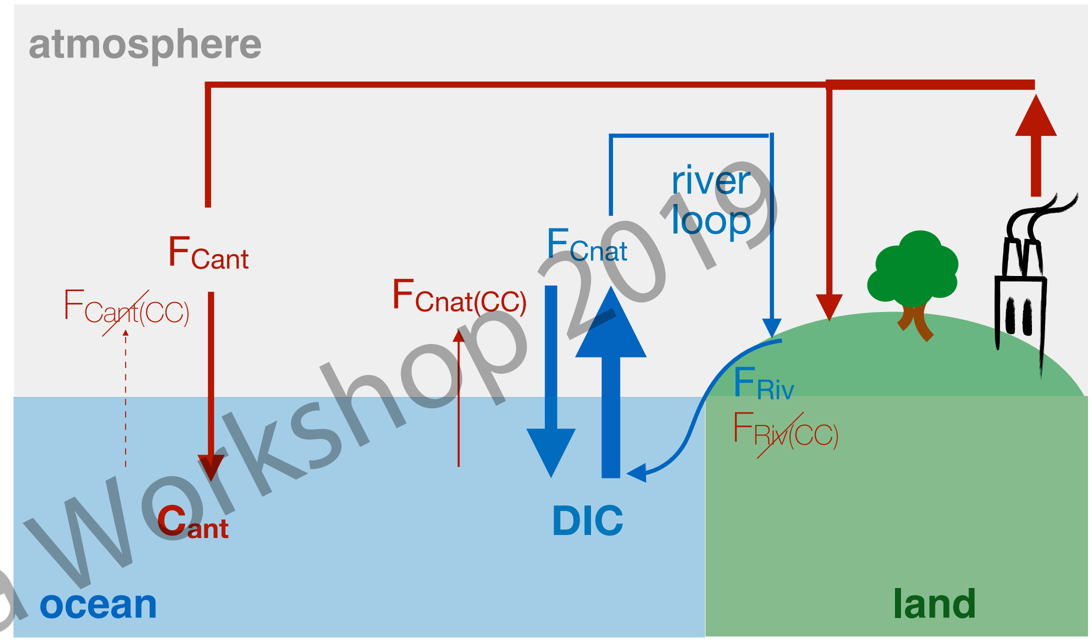
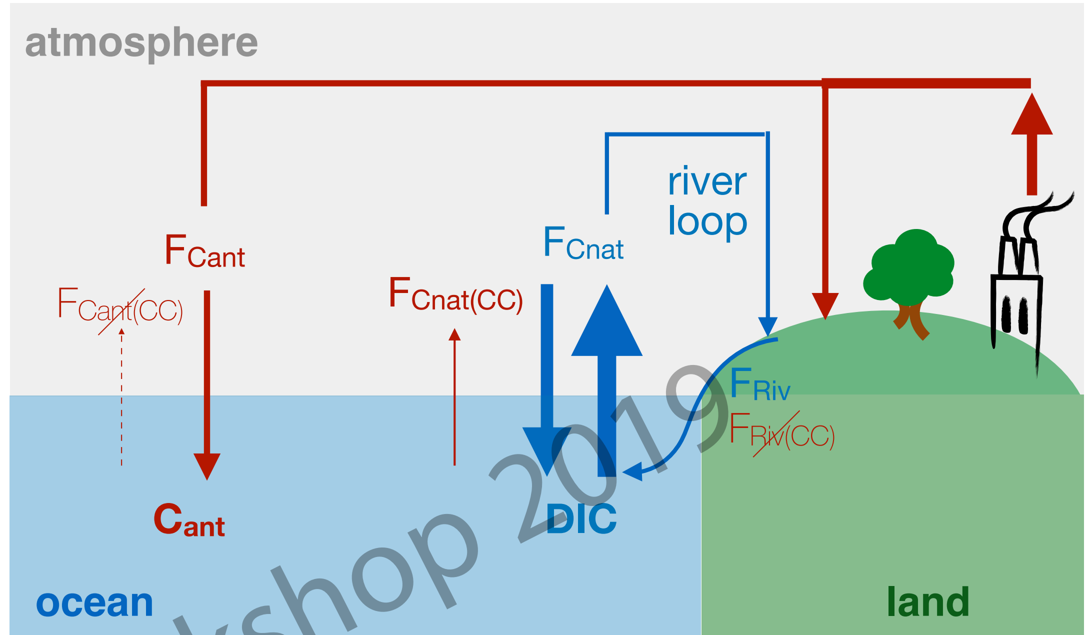


Net ocean uptake = $F_{Cnat} + F_{Riv} + F_{Cant} + F_{Cnat(CC)} = F_{Cant} + F_{Cnat(CC)}$

Air-sea flux = $F_{Cnat} + F_{Cant} + F_{Cnat(CC)}$

Flux of anthropogenic carbon into the ocean = F_{Cant}

Advances and challenges



Global ocean carbon budget and sink

Consensus and uncertainties

Natural carbon cycle

Poorly sampled southern hemisphere and rivers

Natural variability and carbon-climate feedbacks

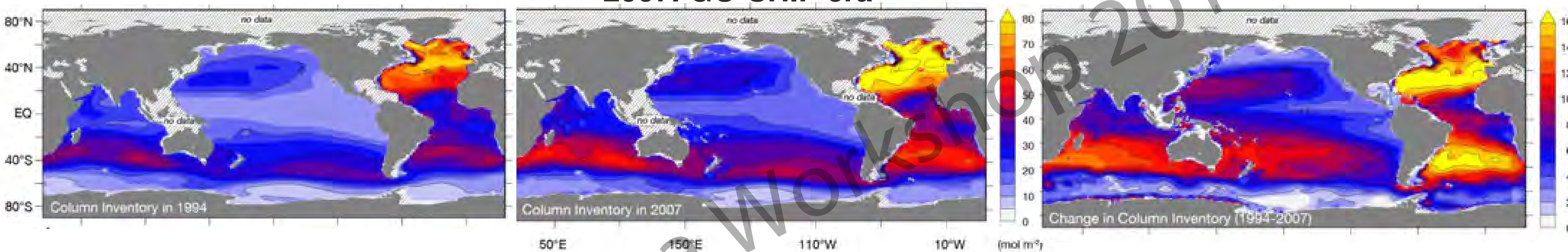
Southern Ocean vs. Tropics, seasonal amplification.

Consensus on global ocean carbon uptake at a rate expected from CO_2 rise

Global anthropogenic carbon flux from ocean interior accumulation

Repeat hydrography programs

1994. JGOFS–WOCE era **2007. GO-SHIP era** **C_{ant} accumulation 2007-1994**



Gruber et al, 2019 (figures courtesy of Bob Key)

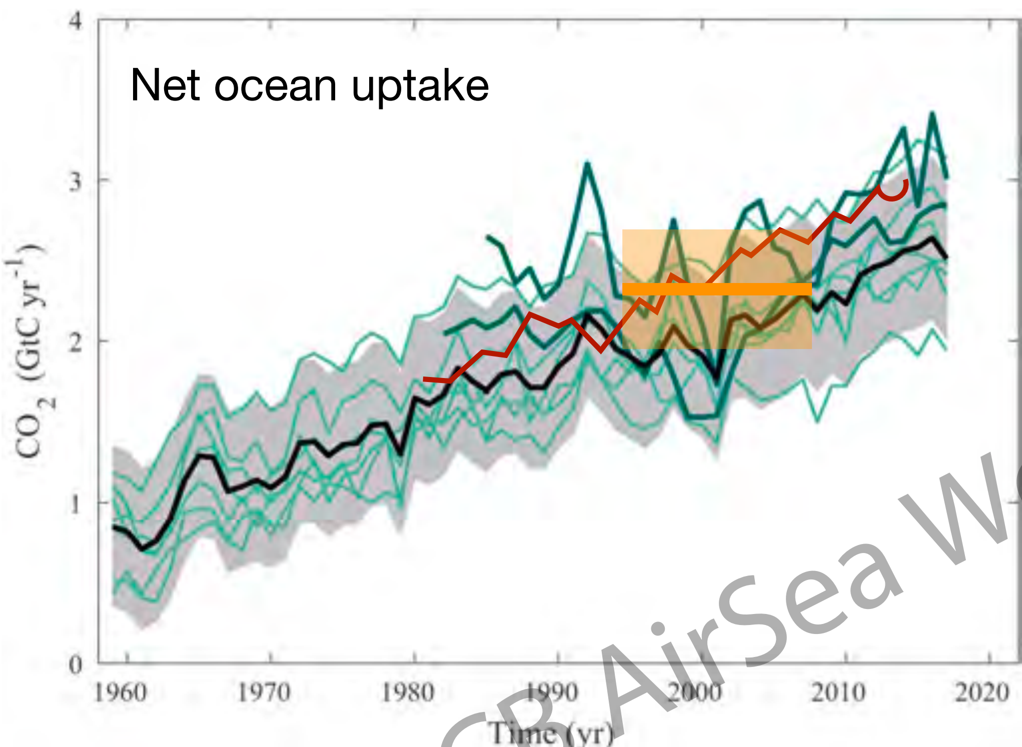
1994 to 2007. F_{Cant} = 2.6 ± 0.3 PgC/y

Net ocean uptake = F_{Cant} + $F_{Cnat(CC)}$ = 2.6 ± 0.3 - 0.3 ± 0.4 = **2.3 ± 0.4 PgC/y**

Matches expected uptake based on atmospheric CO_2 growth rate assuming steady-state circulation

Gruber et al, 2019

Consensus on global ocean carbon uptake at a rate expected from CO_2 rise



Global Carbon Budget 2018 (Le Quéré et al. 2018)

2 pCO2-based products

7 Ocean models

Repeat Hydrography (Gruber et al. 2019)

Ocean inversion assuming steady-state ocean circulation (DeVries et al., 2019)

1994-2007

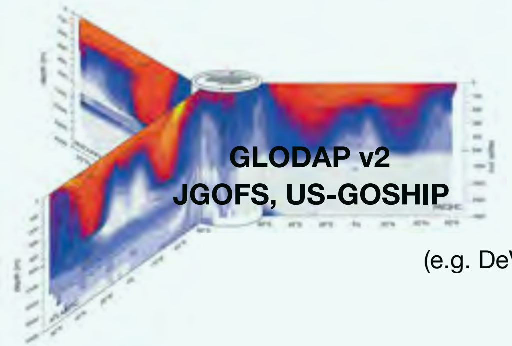
Net ocean uptake = F_{Cant} + $F_{Cnat(CC)}$ = **2.0 ± 0.3 PgC/y** (Le Quéré et al. 2018)

= **2.3 ± 0.4 PgC/y** (Gruber et al, 2019)

3 challenges and source of uncertainties …

1. Closing the ocean budget relies on assumptions for riverine flux & anthropogenic feedbacks

Ocean interior data



Linear Regressions
(e.g. Sabine et al. 2004; Gruber et al 2019)

→ **Flux of C_{ant}** F_{Cant}
$F_{Cnat(CC)}$ correction needed

Ocean inversions
(e.g. DeVries et al 2017, 2019; Gruber et al 2009)

→ **Net ocean uptake**
$F_{Cnat} + F_{Riv} + F_{Cant}$ (+ $F_{Cnat(CC)}$)
$F_{Cnat(CC)}$ correction needed

2. Connect open ocean and coastal ocean

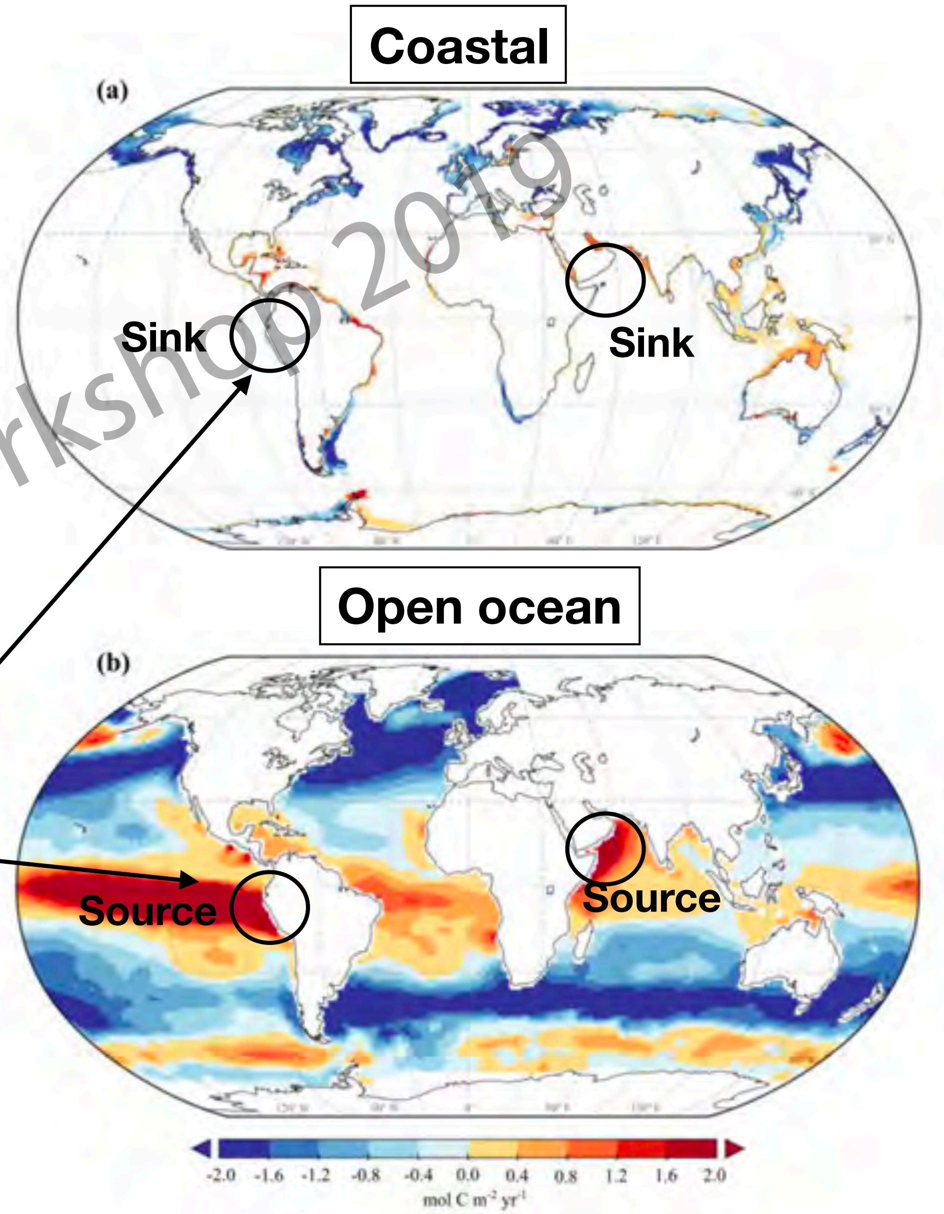
Mapping of Landschutzer
calibrated for coastal regions

Global pCO_2-based product

Coastal air-sea flux into ocean 0.2 PgC/y
(Roobaert et al, in revision)

Coastal areas behave similarly to adjacent open ocean regions (e.g. Wanninkhof et al., 2013)

Areal importance of shelves that take up carbon at northern high latitudes

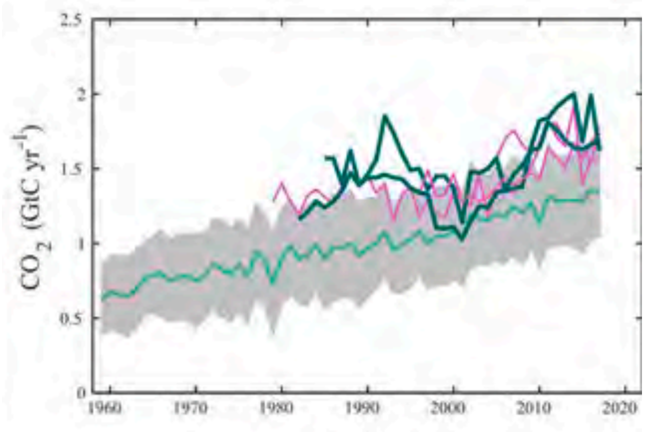


Insufficient observations in coastal upwelling regions to capture mean state and seasonal cycle

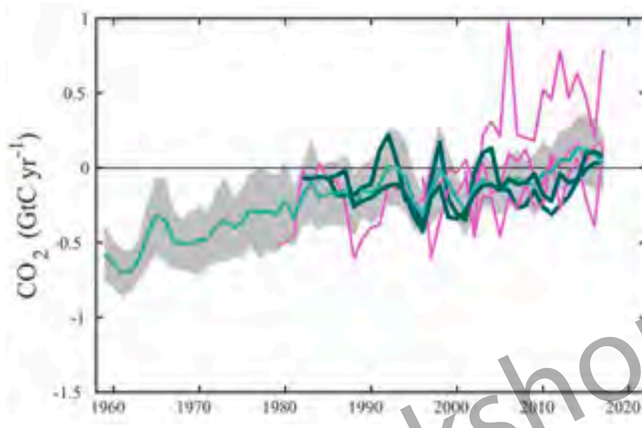
Laruelle et al., 2017
Roobaert et al, in revision

3. Uncertainties in regional fluxes & temporal variability

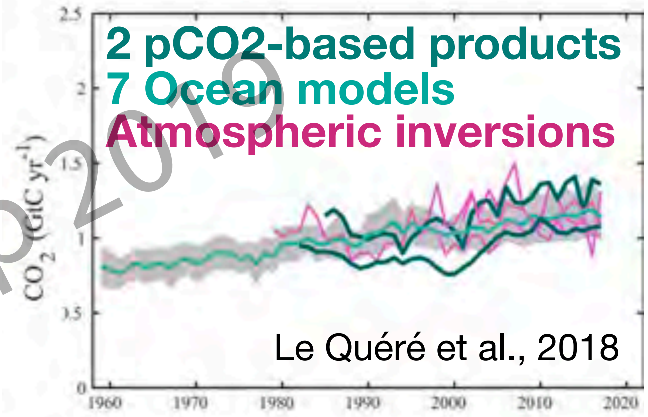
south



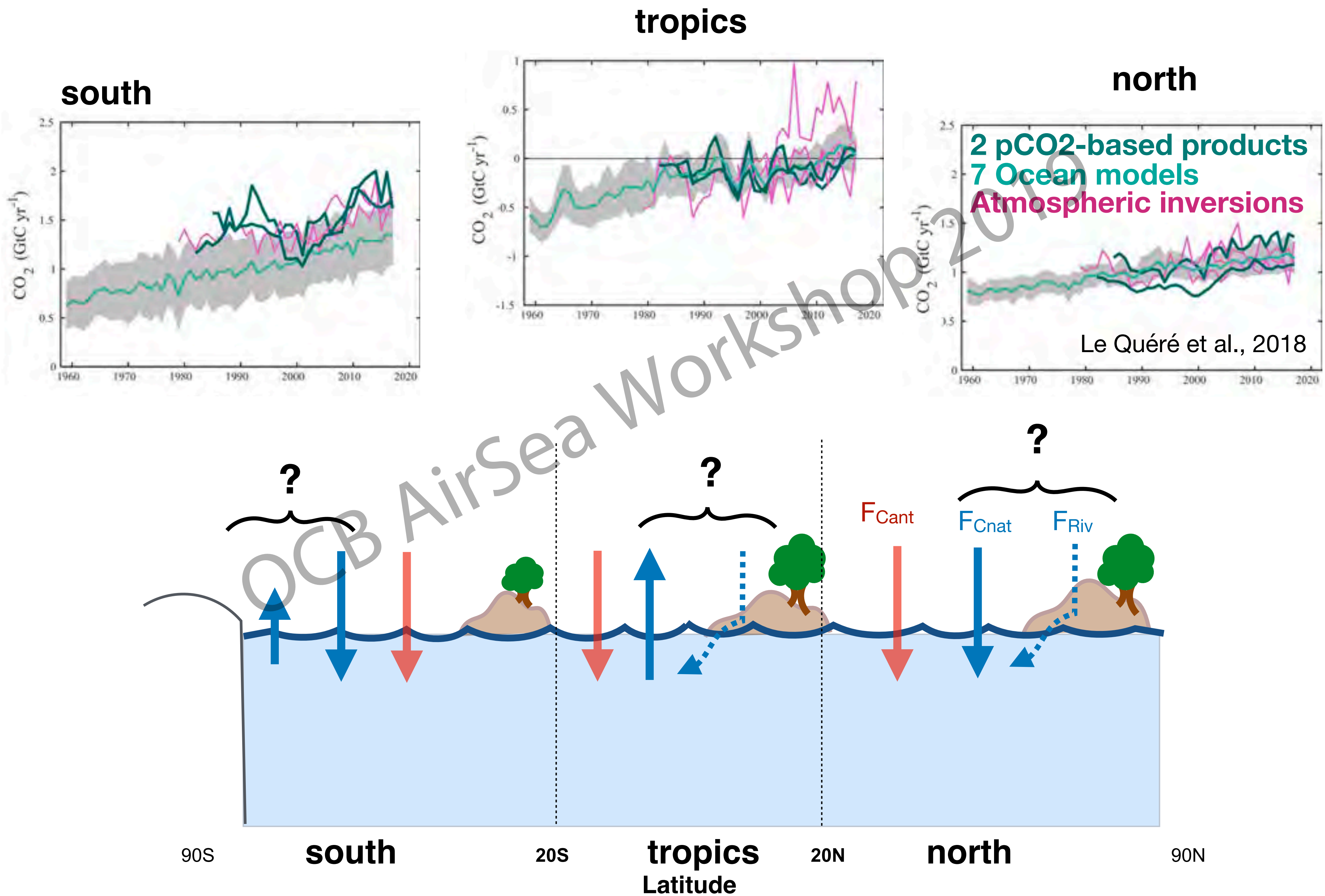
tropics



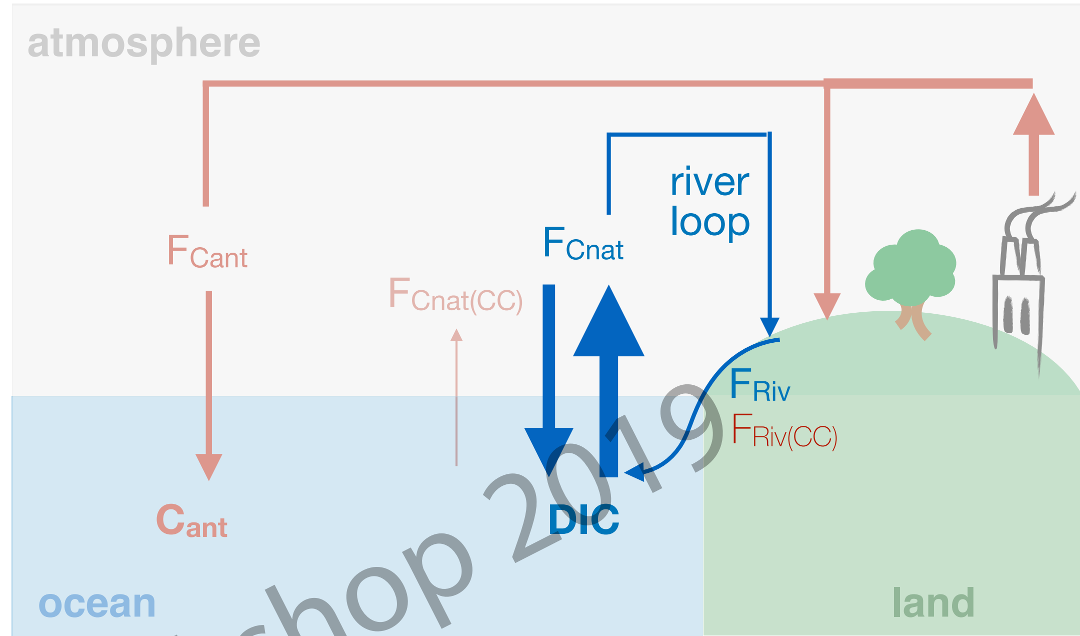
north



3. Uncertainties in regional fluxes & temporal variability



Advances and challenges

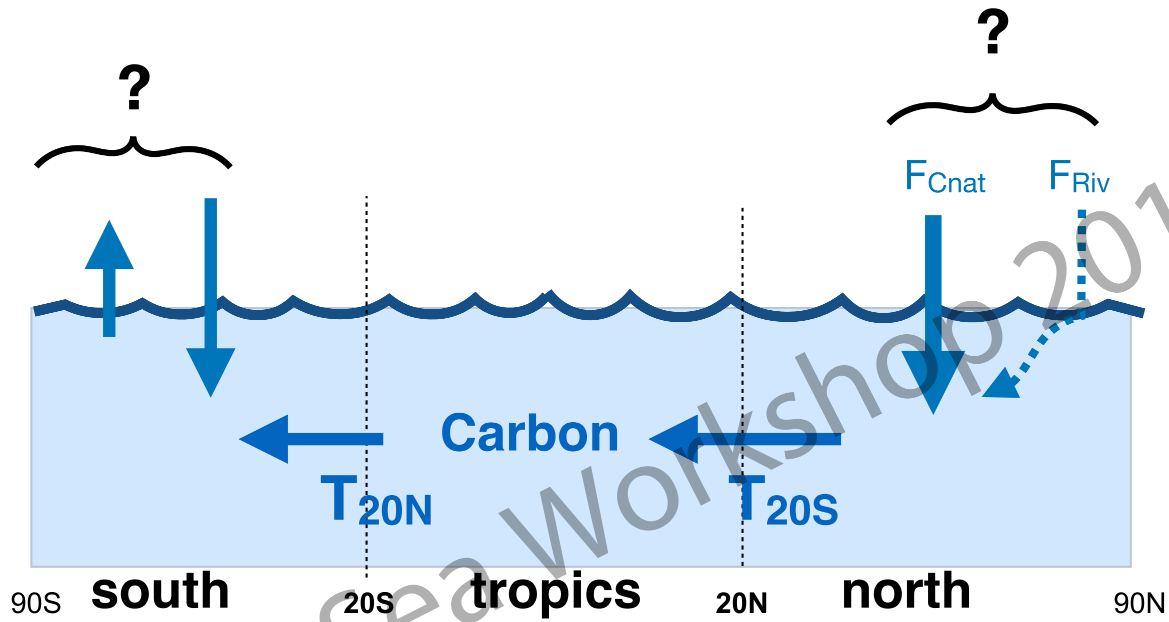


Global ocean carbon budget and sink
Consensus and uncertainties

Natural carbon cycle
Poorly sampled southern hemisphere and riverine flux

Natural variability and carbon-climate feedbacks
Southern Ocean vs. Tropics, seasonal amplification.

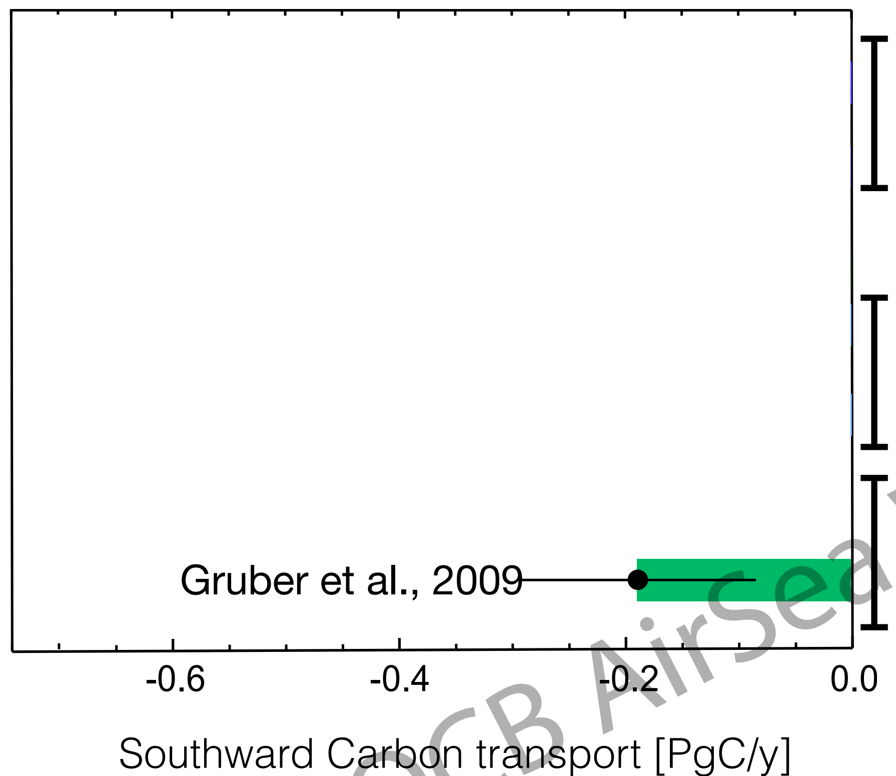
Constraint on the ocean/river carbon fluxes from hemispheric transport asymmetry



Hemispheric symmetry

$$A = (T_{20N} + T_{20S}) / 2$$

Do we know the ocean southward carbon transport?



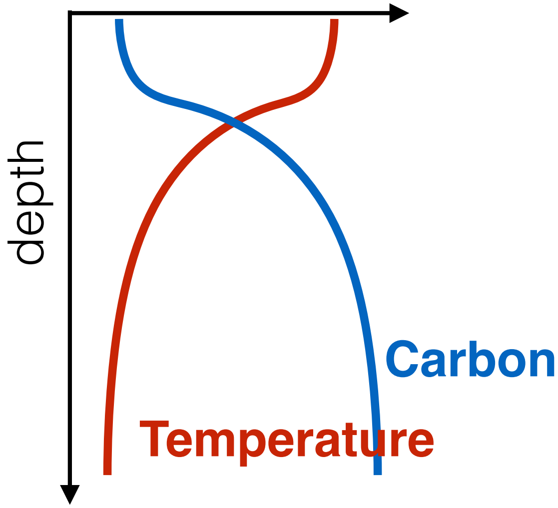
pCO_2-based corrected for C_{ant} using Khatiwala et al., 2012 **+ river loop = 0.78 PgC/y** (Resplandy et al., 2018)

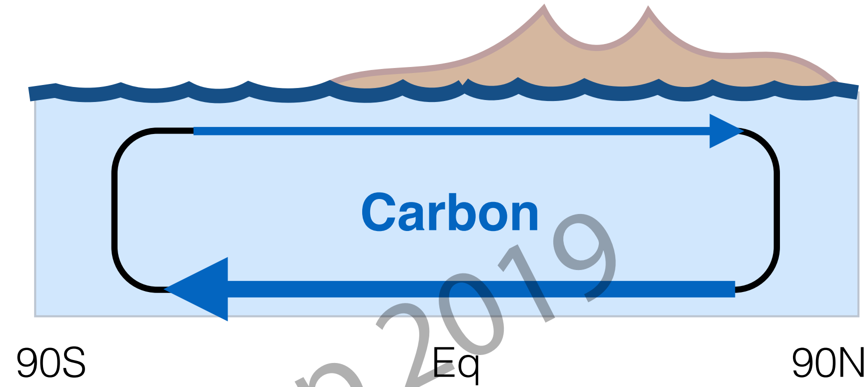
pCO_2-based corrected for C_{ant} using Khatiwala et al., 2012 **+ river loop = 0.45 PgC/y** (Jacobson et al., 2007)

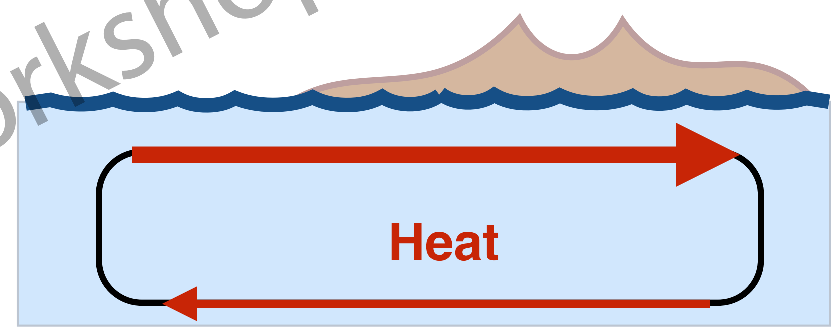
Ocean inversions incl. rivers

Resplandy et al., Nat Geo 2018

The ocean transports carbon southward & heat northward

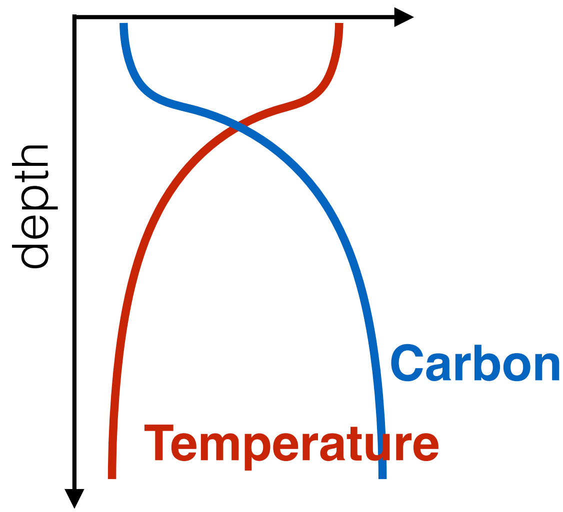


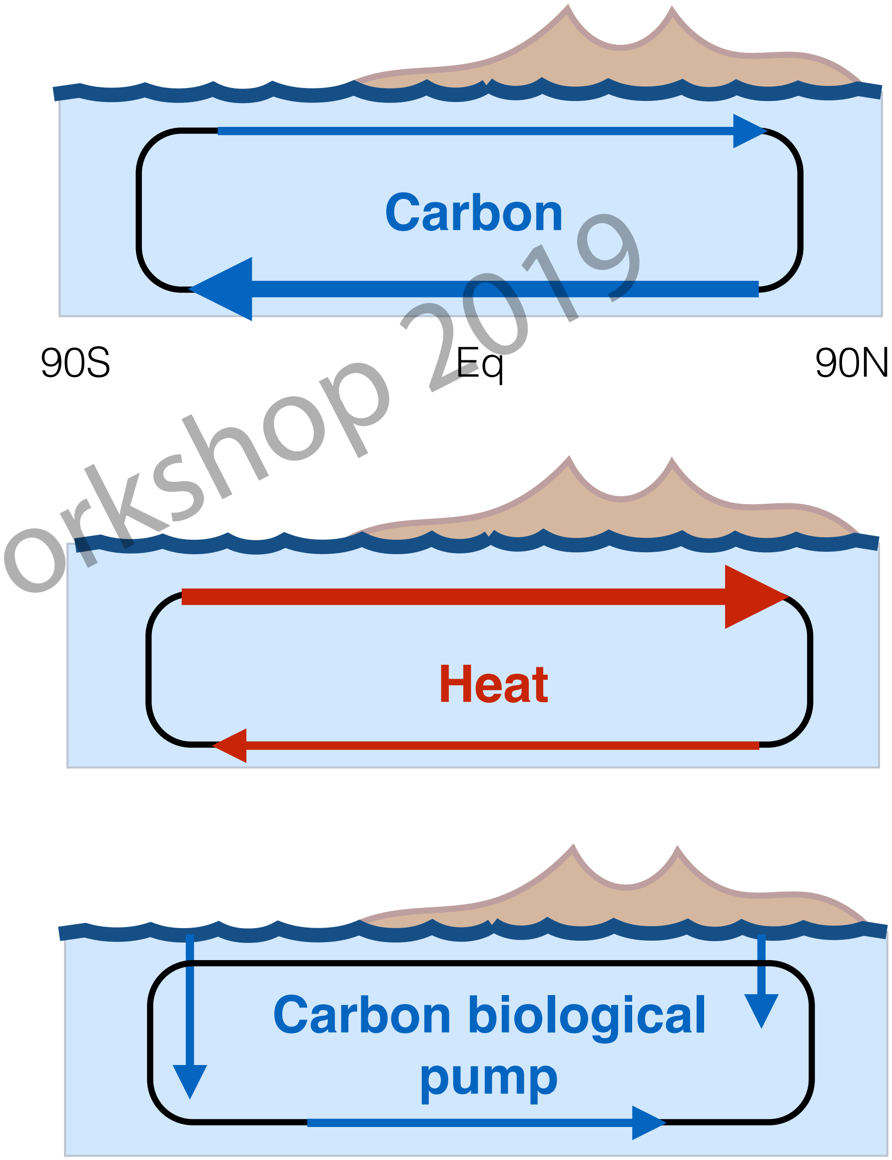




Tight carbon-temperature link arises from thermally driven fluxes (solubility) and biological pump (respired carbon)

The ocean transports carbon southward & heat northward



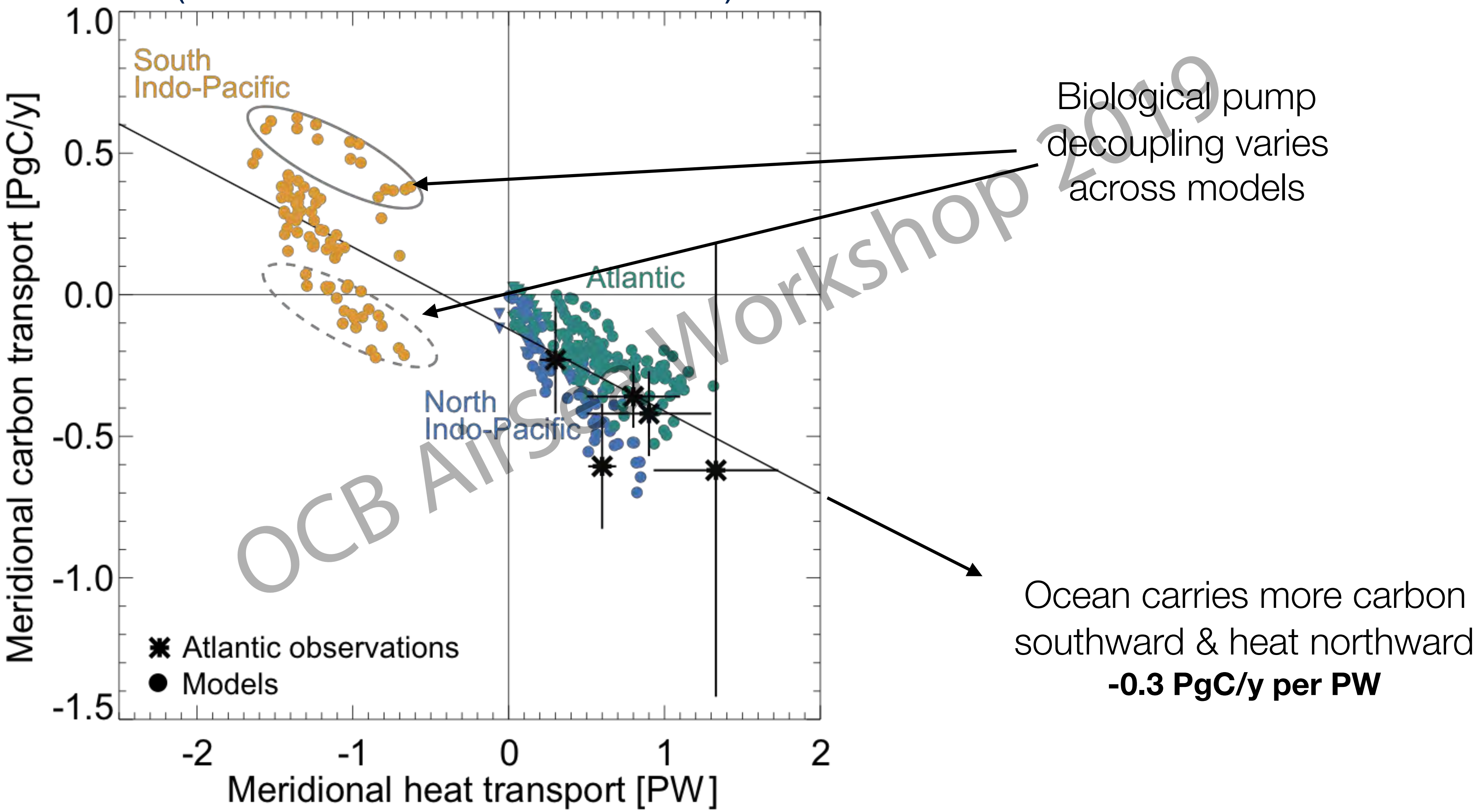


Tight carbon-temperature link arises from thermally driven fluxes (solubility) and biological pump (respired carbon)

Asymmetry in degree to which upwelled carbon is exported as sinking particles

Link between heat and carbon transport across sections

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

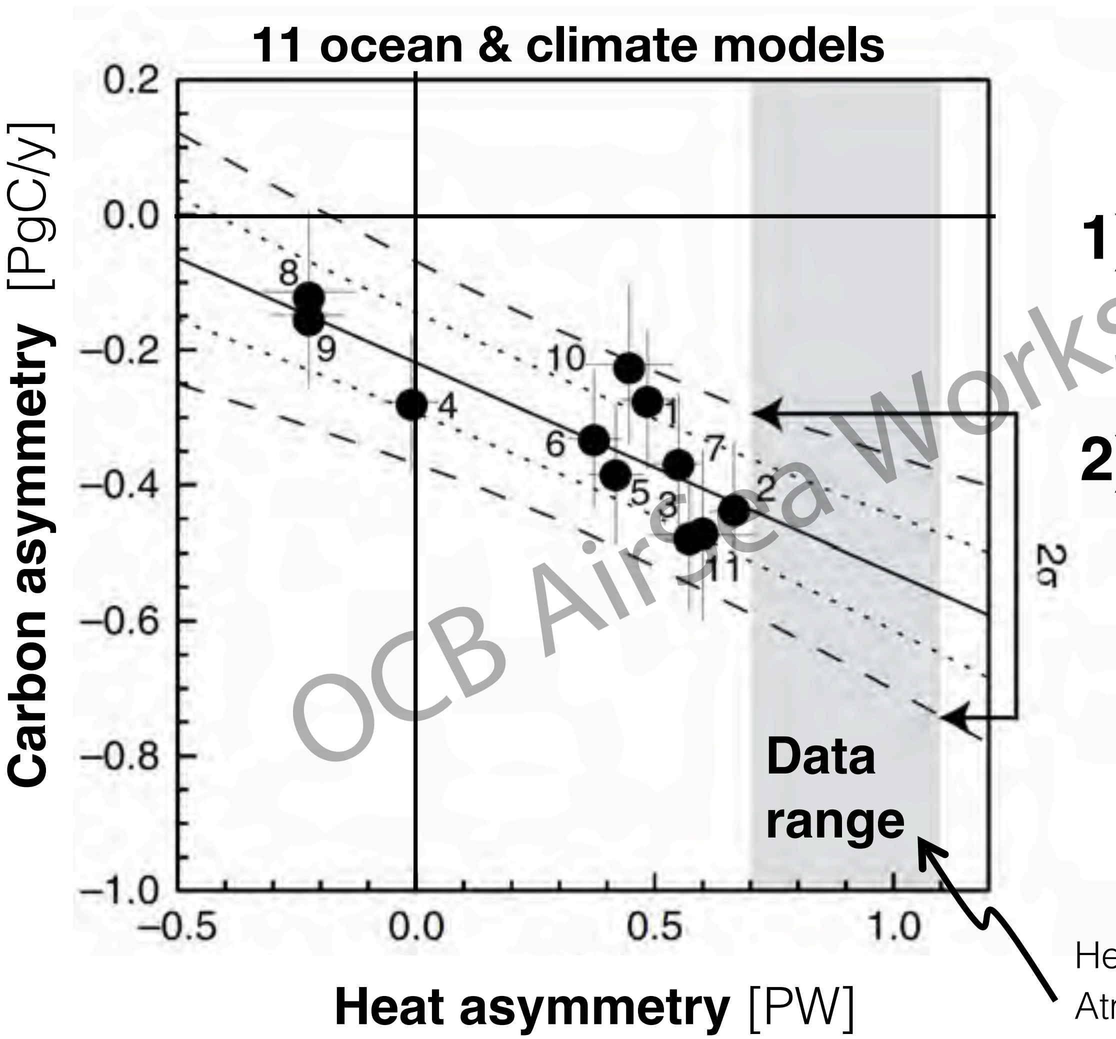


Resplandy et al., Nat Geo 2018

Data: Lundberg et al., 1996; Holfort et al., 1998; Alvarez et al., 2003; MacDonald et al. 2003, Ganachaud and Wunsch, 2003

Heat an indicator of interhemispheric carbon transport

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



1) Models **biased low in heat** and **carbon transports**

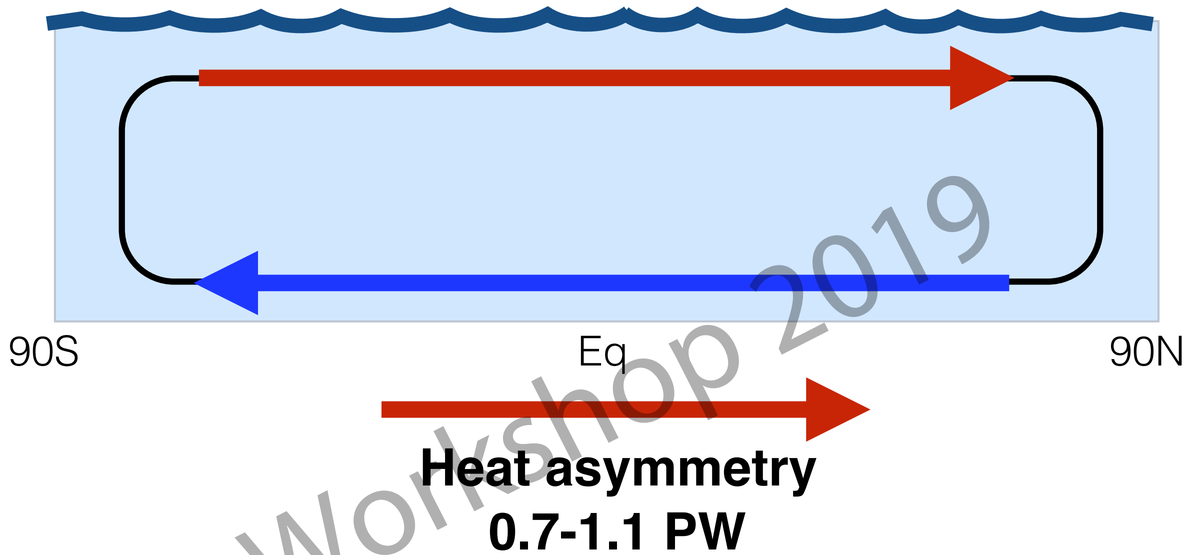
2) Southward carbon transport **= 0.30 to 0.75 PgC/y**

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

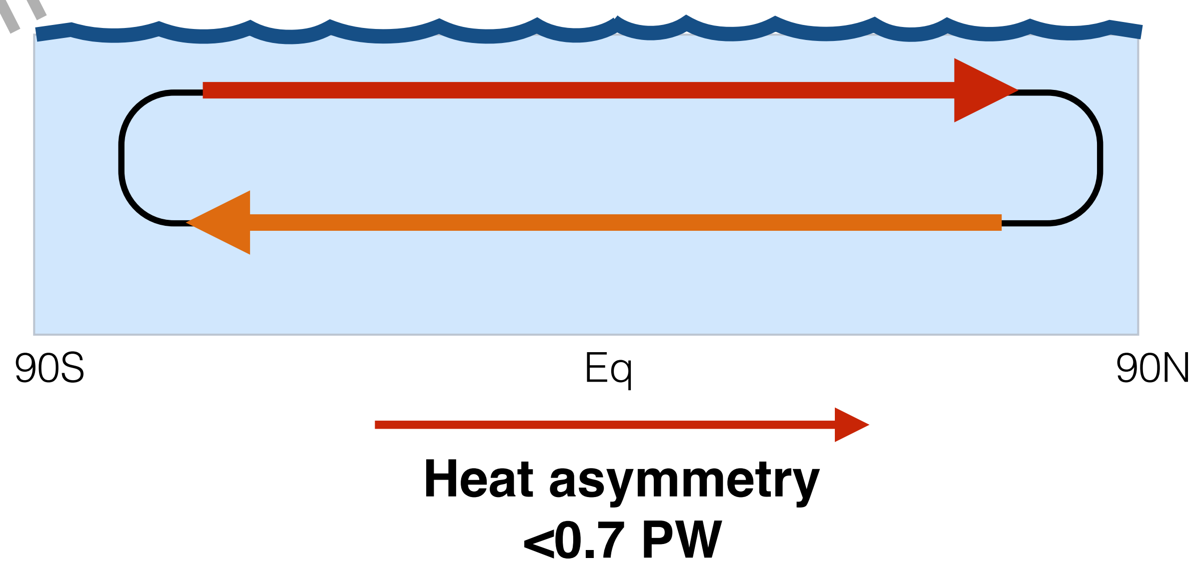
Resplandy et al., Nat Geo 2018

Too shallow overturning circulation in models…

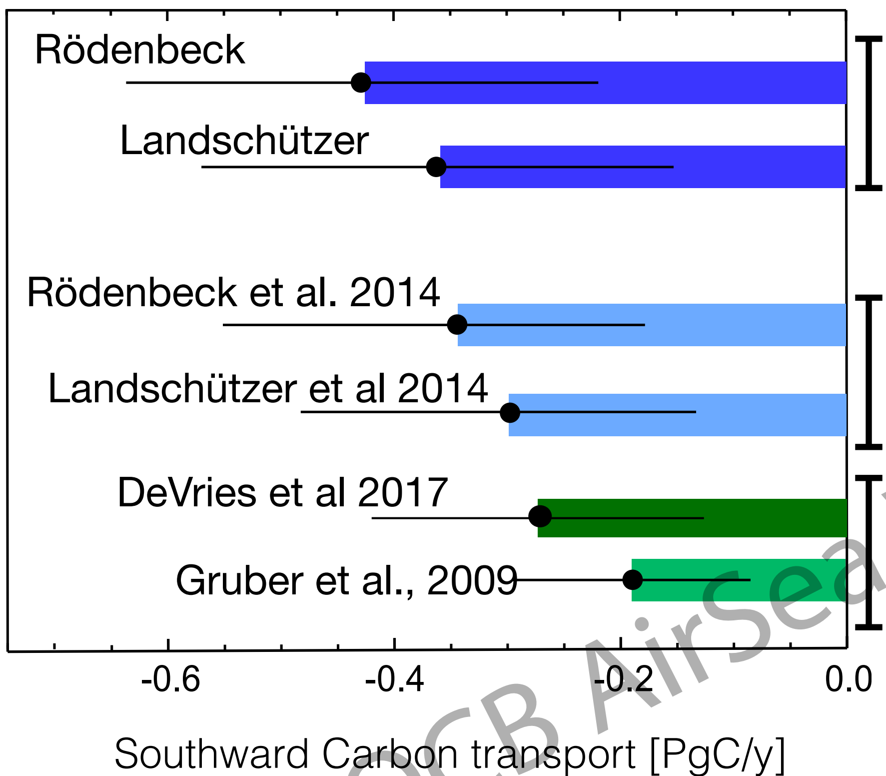
what we expect



in models



Heat constraint on carbon transport



pCO_2-based
+ river loop = 0.78 PgC/y (Resplandy et al., 2018)

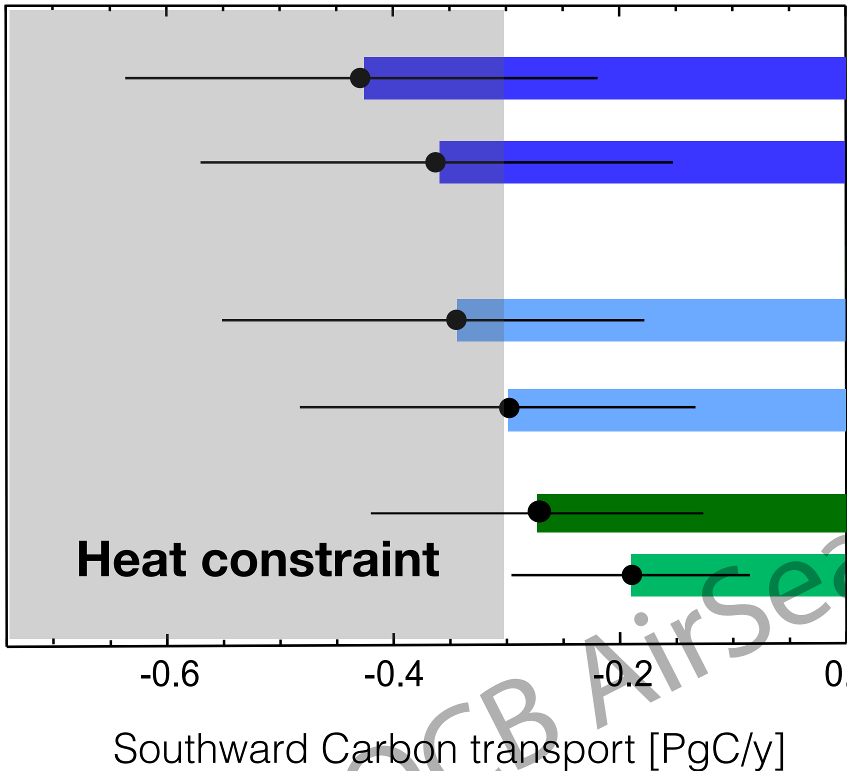
pCO_2-based
+ river loop = 0.45 PgC/y (Jacobson et al., 2007)

Ocean inversions incl. rivers

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

Resplandy et al., Nat Geo 2018

Heat constraint on carbon transport



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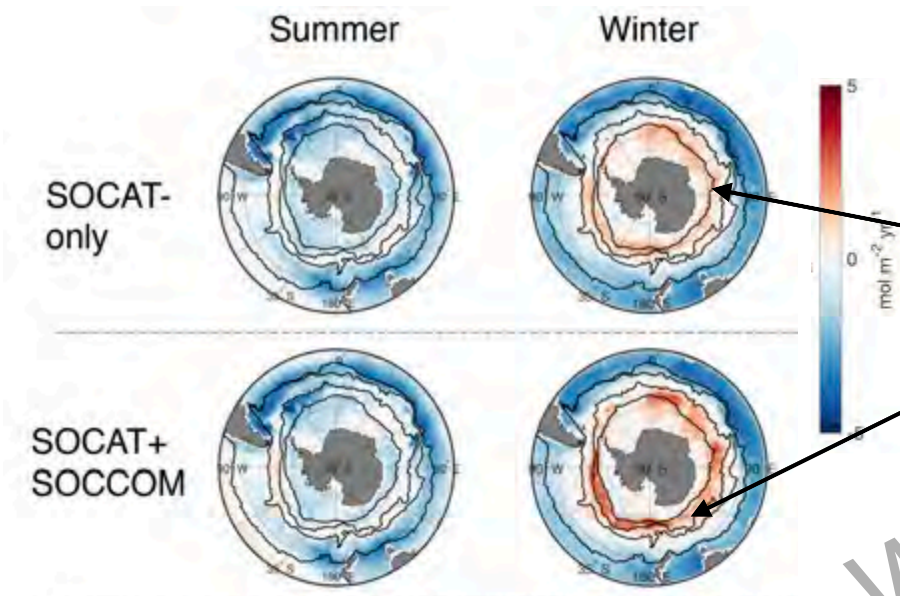
pCO_2-based
+ river loop = 0.45 PgC/y (Jacobson et al., 2007)

Ocean inversions incl. rivers

- Estimates agree within large uncertainties but …ocean inversions incompatible with heat constraint
- Strong asymmetry suggests
  - **strong river loop?**
  - **strong outgassing of natural CO_2 in South?**

Resplandy et al., Nat Geo 2018

Additional constraints on the southern carbon flux support the existence of stronger natural outgassing

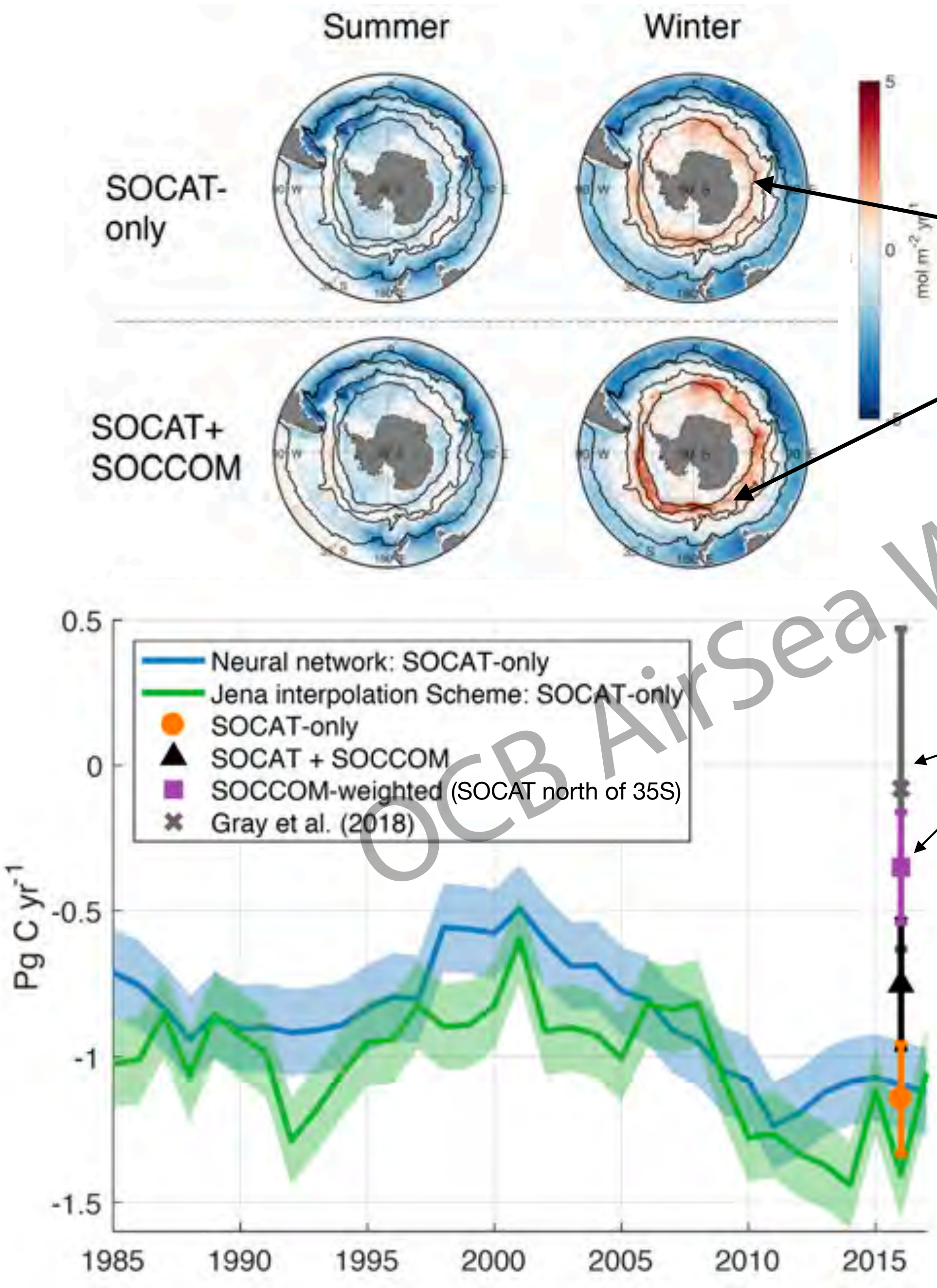


Adding BGC-Argo float data enhance wintertime CO_2 outgassing

SOCCOM

Bushinsky et al, in revision

Additional constraints on the southern carbon flux support the existence of stronger natural outgassing



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Floats alone insufficient to capture annual cycle

Adding SOCCOM floats to mapping models reduces annual CO_2 uptake by 0.4 PgC/y

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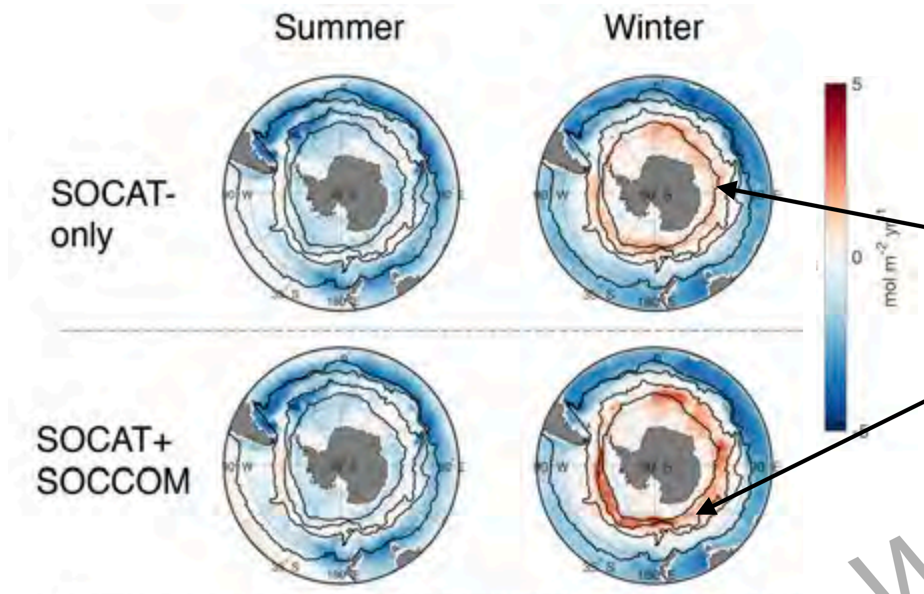

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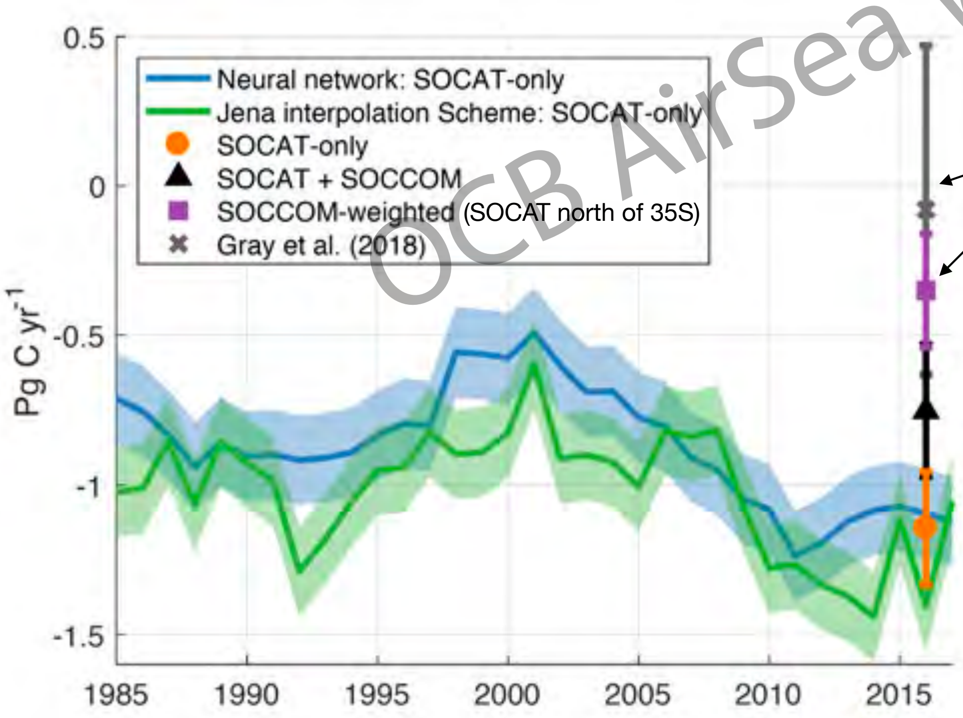


Floats alone insufficient to capture annual cycle

Adding SOCCOM floats to mapping models reduces annual CO_2 uptake by 0.4 PgC/y

Challenge to incorporate new float data into interpolation techniques

Bushinsky et al, in revision

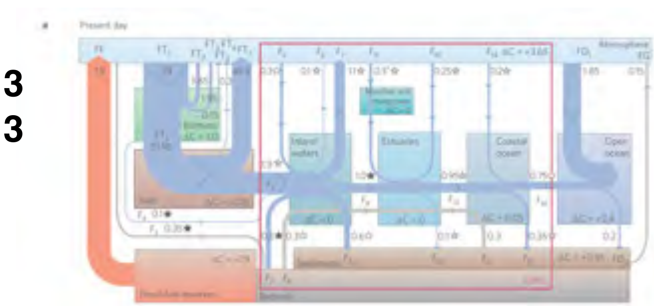
How well do we actually know the river carbon flux to the open ocean?

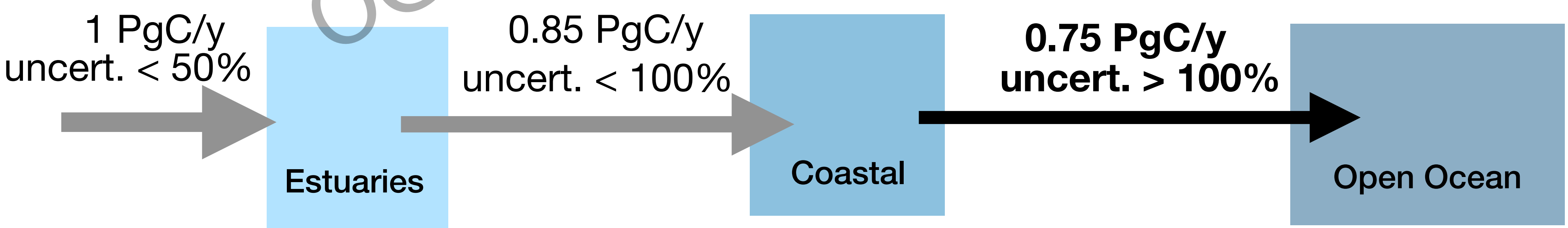
Ocean community has worked with systematically lower central values and uncertainties in river flux than the river/coastal community

0.55 ± 0.15 PgC/y (Sarmiento and Sunquist 1992)
0.45 ± 0.18 PgC/y (Jacobson et al 2007)

0.78 ± 0.41 PgC/y (Resplandy et al 2018)

Regnier et al., Nature Geosc. 2013
Bauer et al, Nature 2013



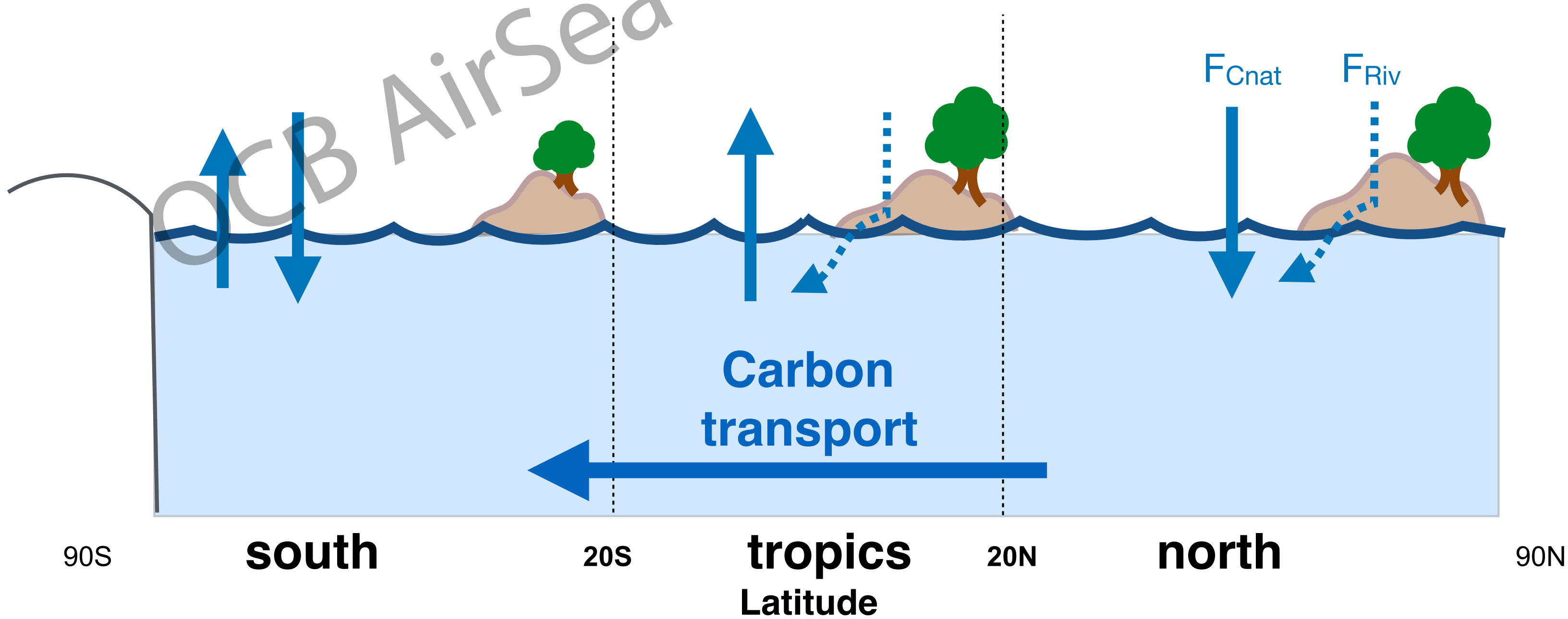


Uncertainties in land/estuaries + coastal processes and lateral transfer to open ocean

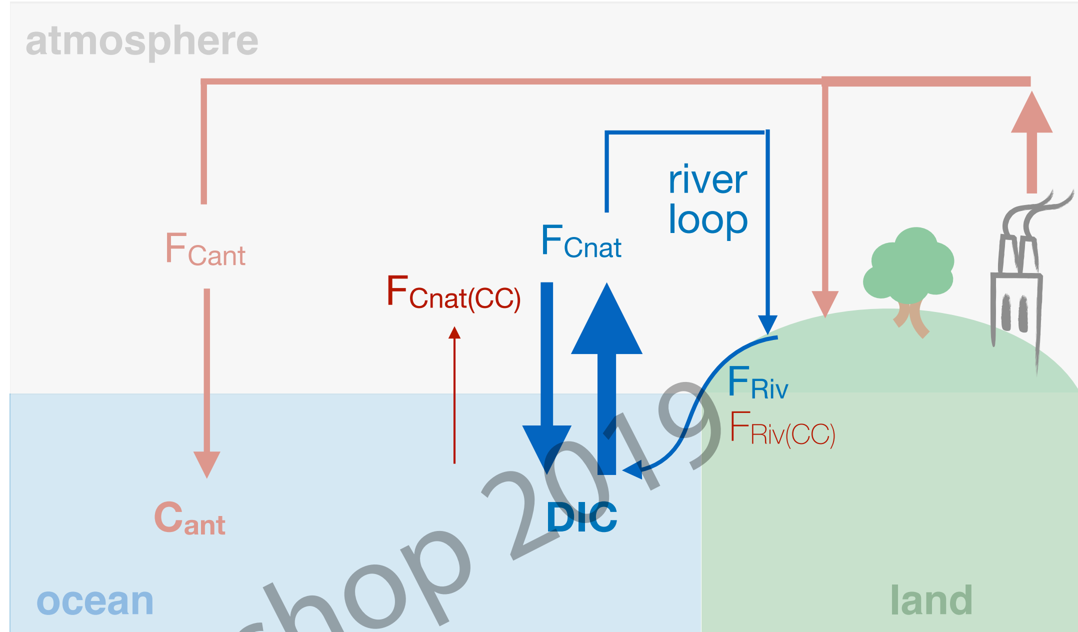
What have we learned?

Stronger winter outgassing in the Southern Ocean
Support for a stronger natural river loop

Challenge to include new float observations
Systematic low bias in heat and carbon transport in ocean models
Need to refine riverine input and transfer to open ocean



Advances and challenges



Global ocean carbon budget and sink
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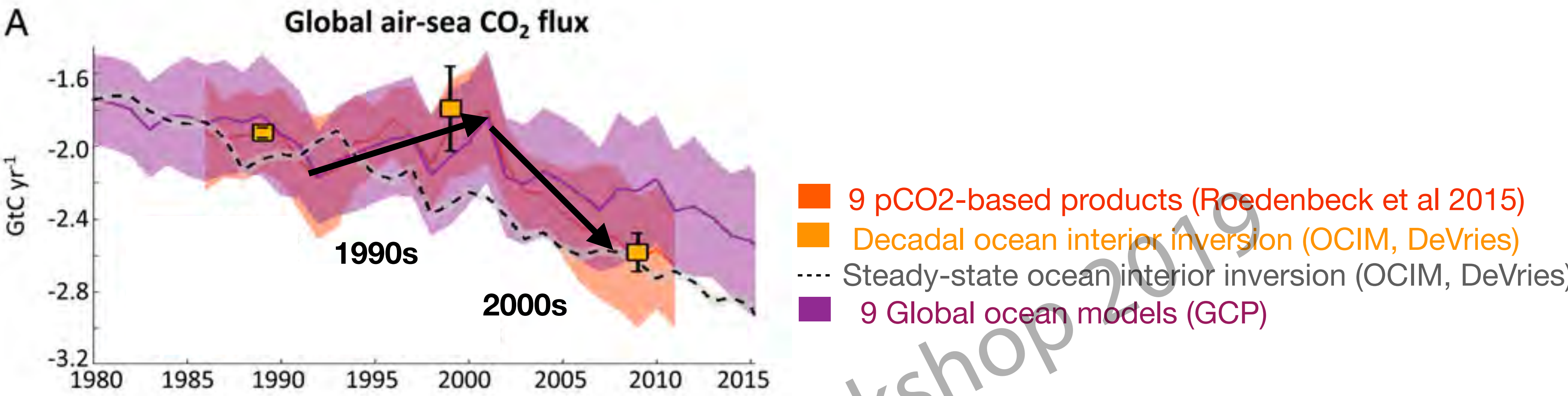
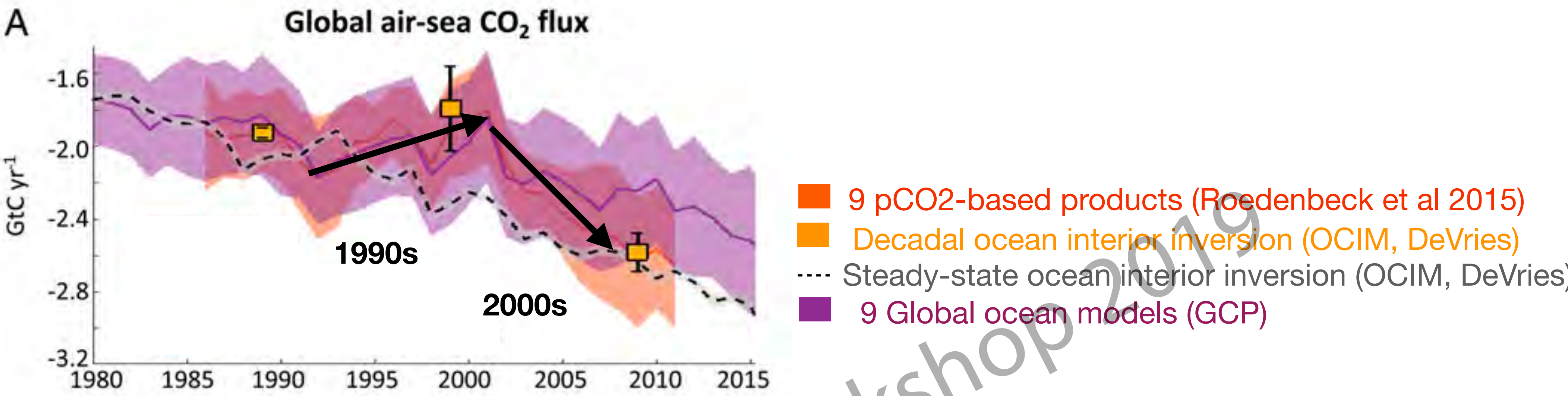
Reduced global ocean sink in the 1990s



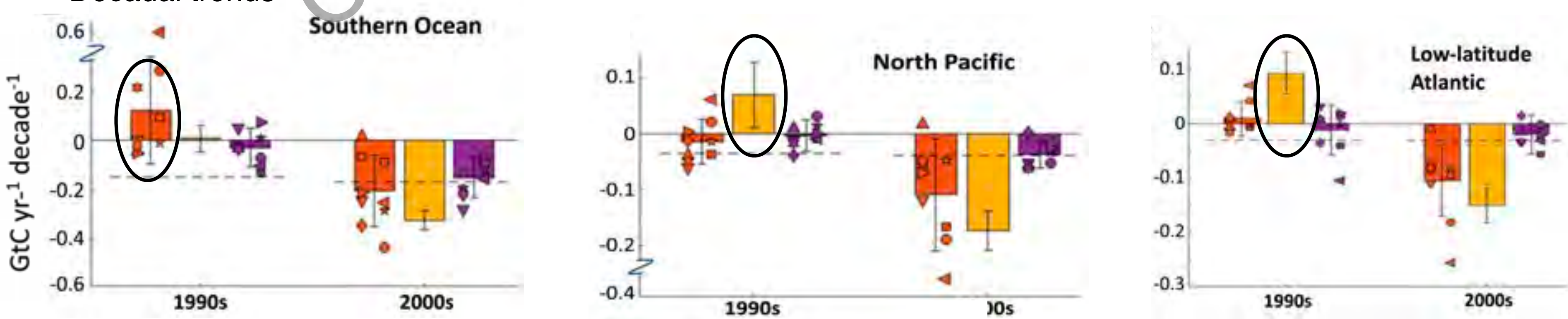
DeVries et al, 2019

Reduced global ocean sink in the 1990s



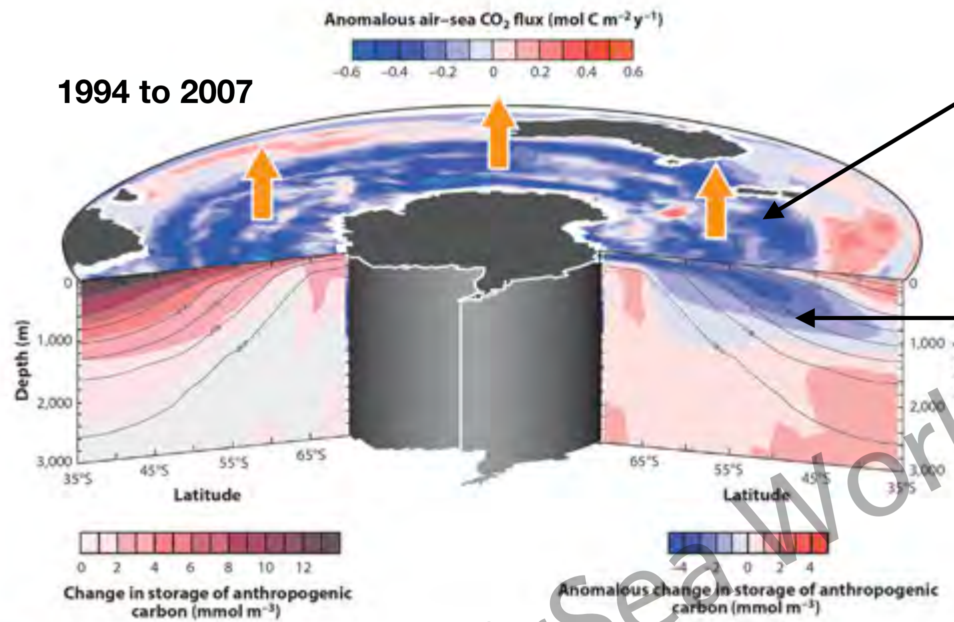
Discrepancies in the region/processes controlling this variability

Decadal trends



DeVries et al, 2019

Decadal variability in the Southern Ocean



Anomalous outgassing of CO2 of 3 Pg C (pCO2-based)
(net Flux - expected from transient)

C_{ant} storage anomaly accounts for 0.2 Pg C (repeat hydro)

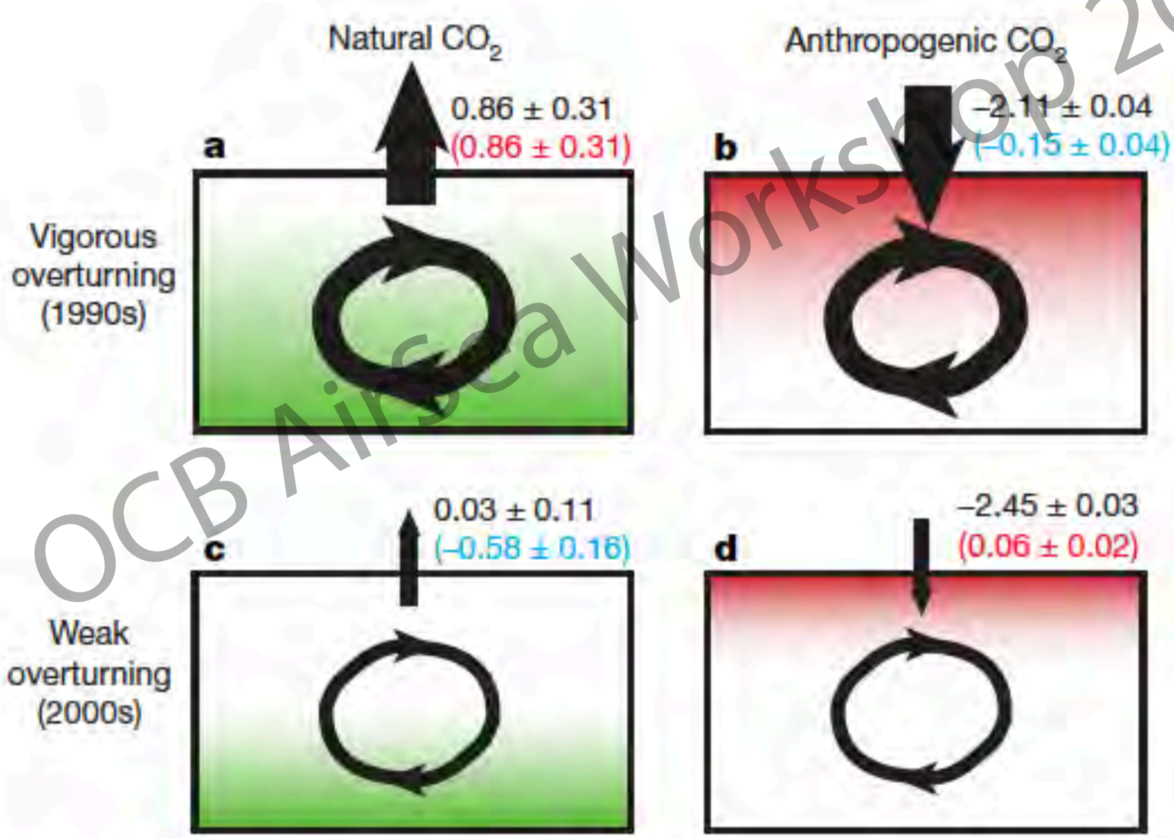
$$\Delta_t C_{ant}^{anom} = \Delta_t C_{ant} - \alpha \cdot C_{ant}(1994)$$

Natural flux must account for most of the anomaly

Gruber et al, Ann Rev. Mar. Sci 2019
Li and Illyna, 2018
Le Quéré et al 2007
Landschützer et al., 2015

Increased upper-ocean overturning during the 1990s?

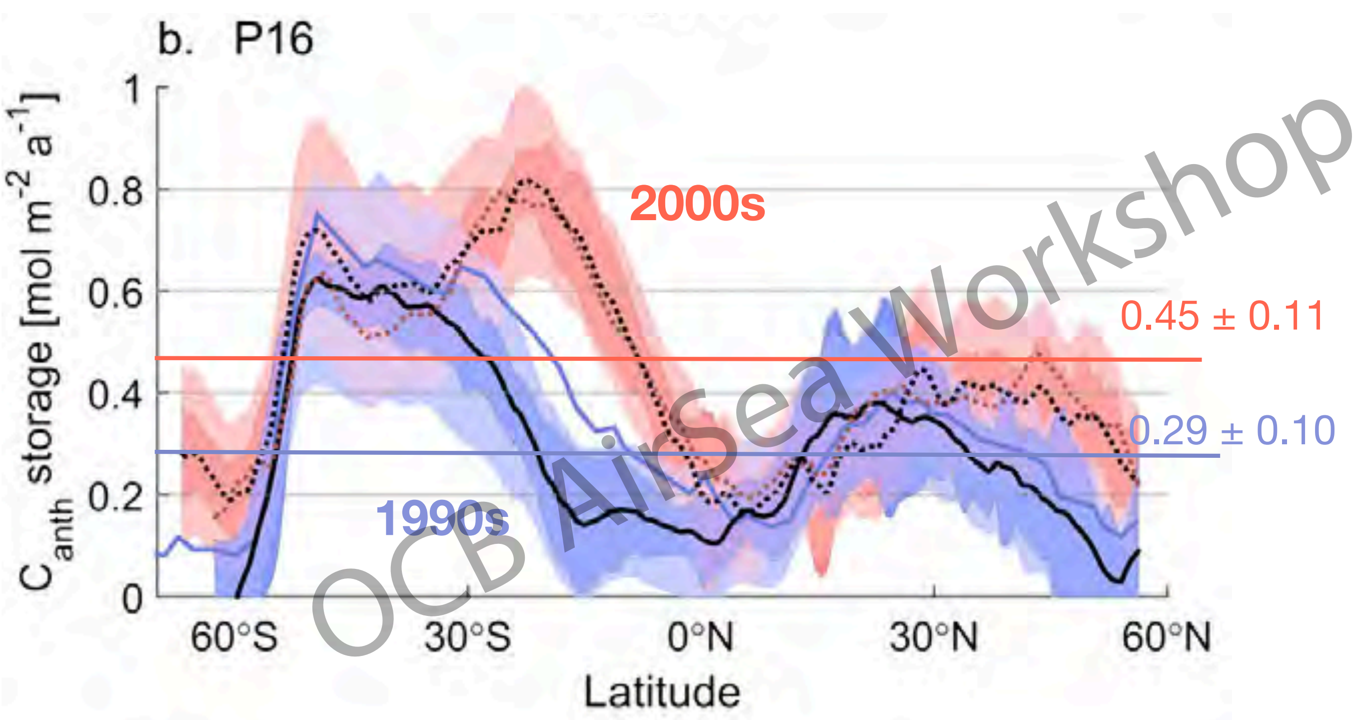
DeVries et al 2017 hypothesized that increased upper-ocean overturning in the 1990s could have increase natural CO_2 release (and anthropogenic CO_2 uptake)

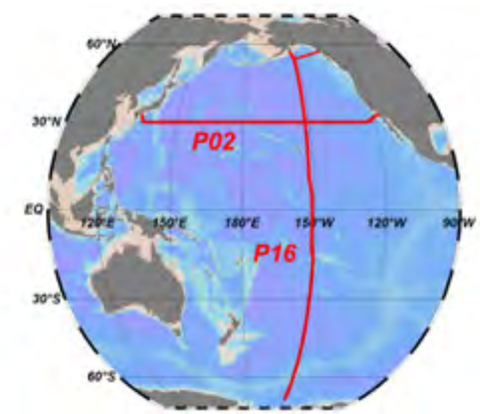


DeVries et al, 2017

Increased upper-ocean overturning during the 2000s?

In contrast, repeat hydrography in the Pacific suggest that the overturning increased during the 2000s yielding more anthropogenic carbon uptake



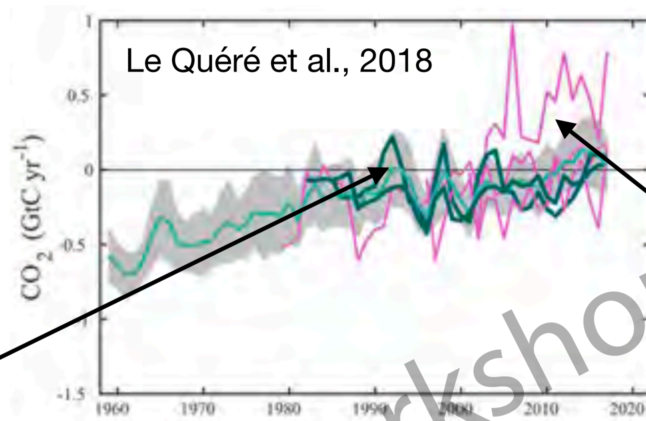


Carter et al., 2017

Unclear contribution of basin-scale natural variability

Magnitude and timing of ENSO-driven variability

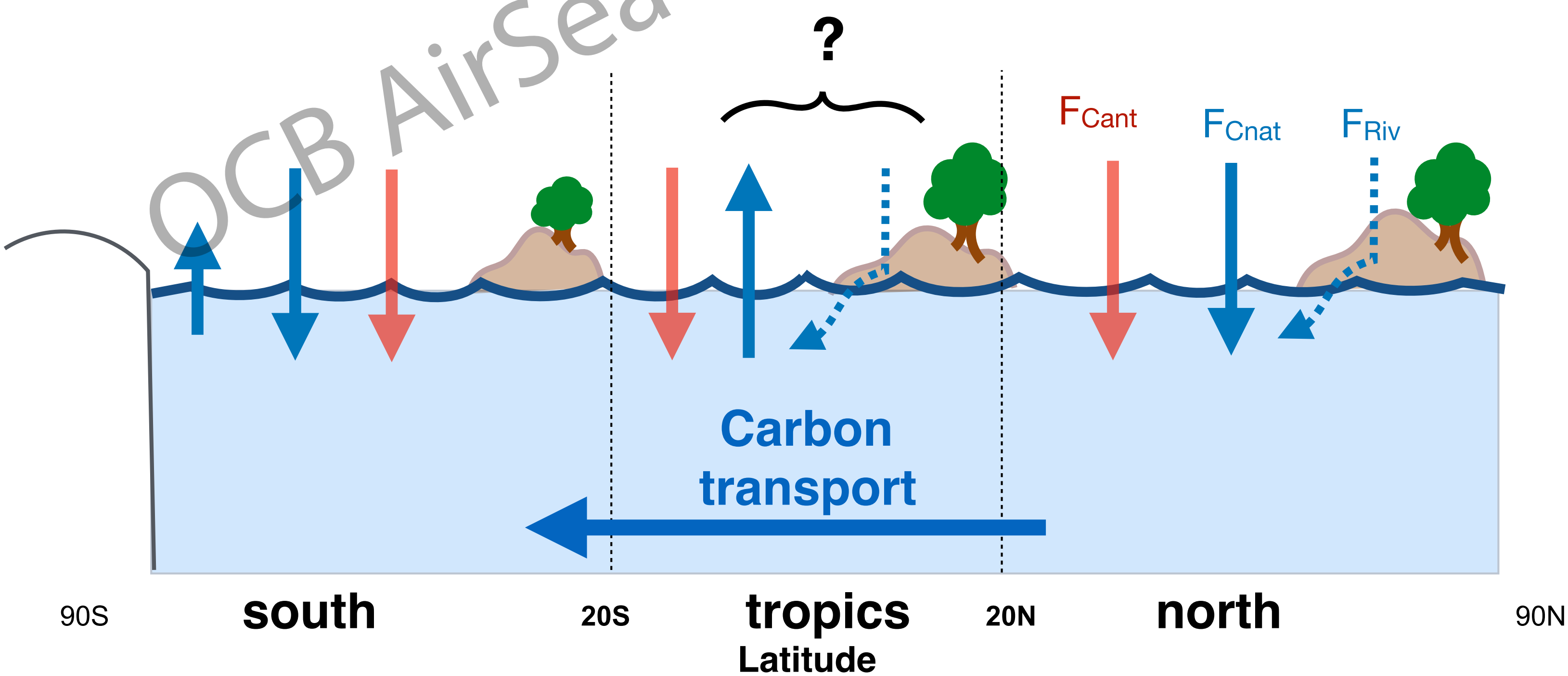
tropics



2 pCO2-based products
7 Ocean models
Atmospheric inversions

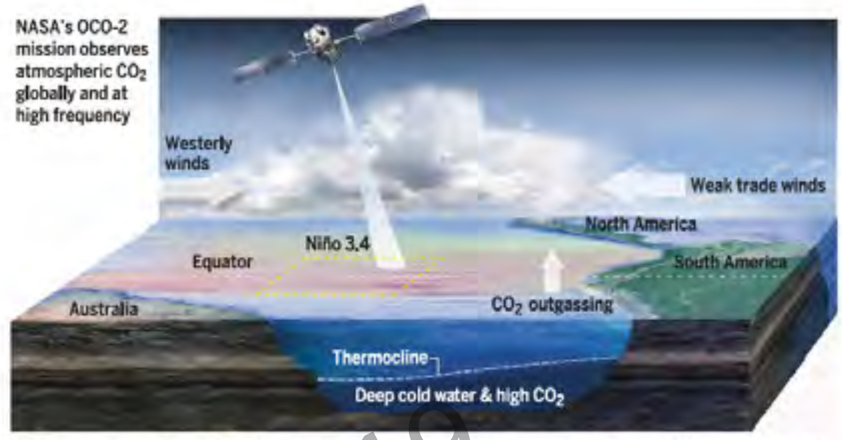
ocean/land partition?

Timing? magnitude?



El Niño reenforces the ocean sink

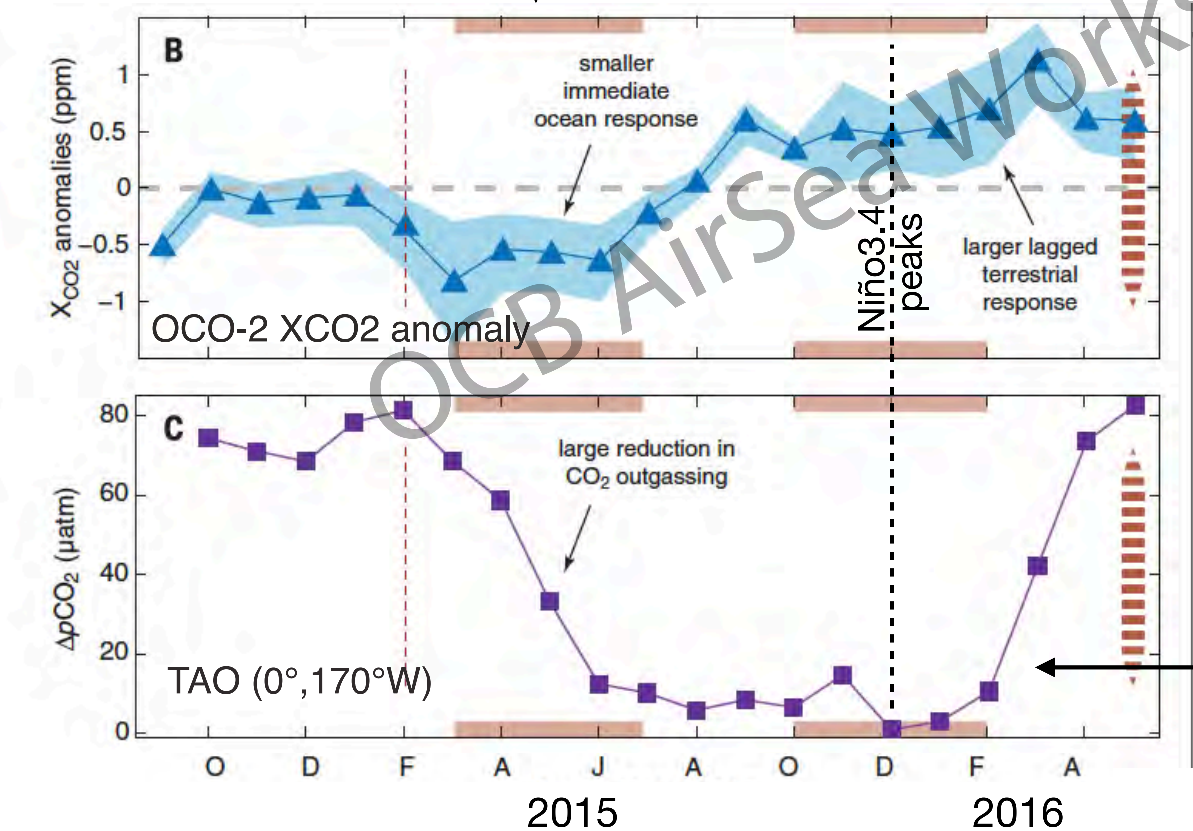
e.g. Murray et al 1994, Feely et al 1999, 2002 Sutton et al 2013, 2017



NASA-OCO2 ocean glint data

1. Ocean uptake controls atmospheric anomaly

2. Land release controls atmospheric anomaly

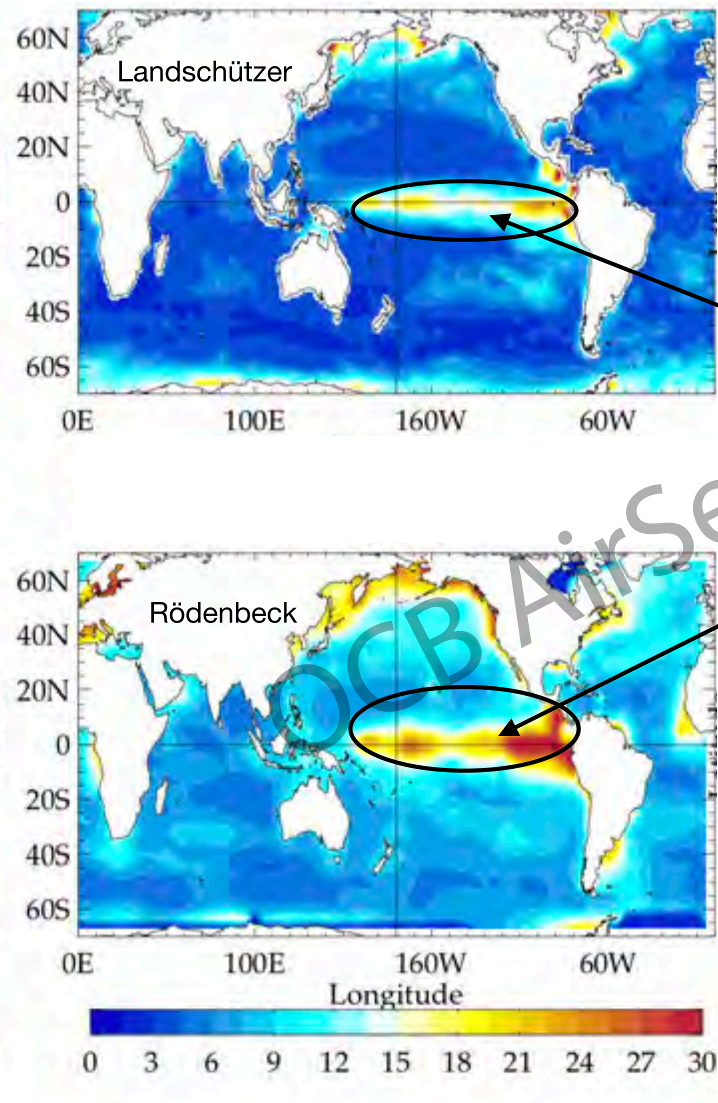


Ocean response terminated in Spring of year 2016

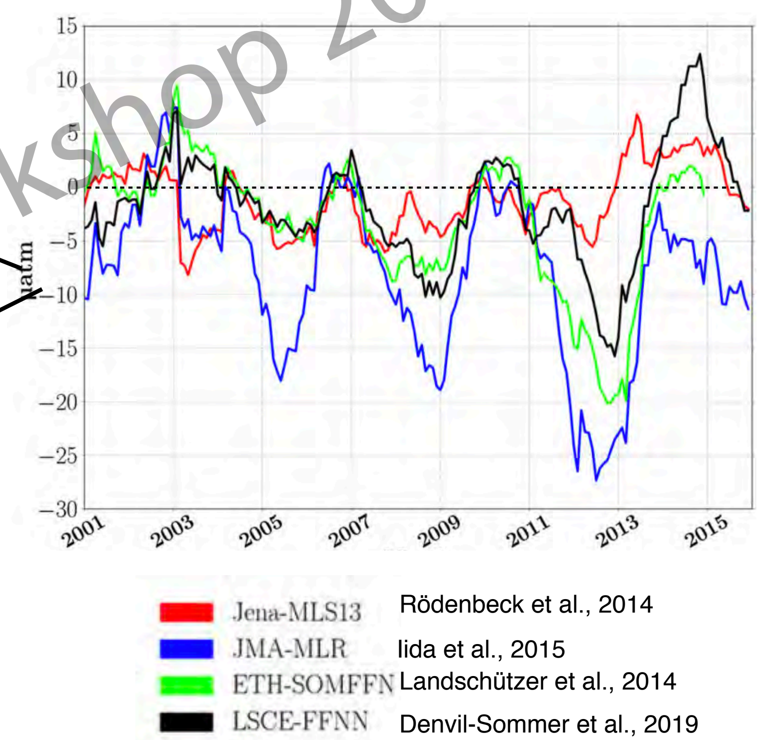
Chatterjee et al Science 2017

Uncertainties on the magnitude of ENSO-driven natural variability in Equatorial Pacific and global influence

Interannual variability
Ocean pCO_2

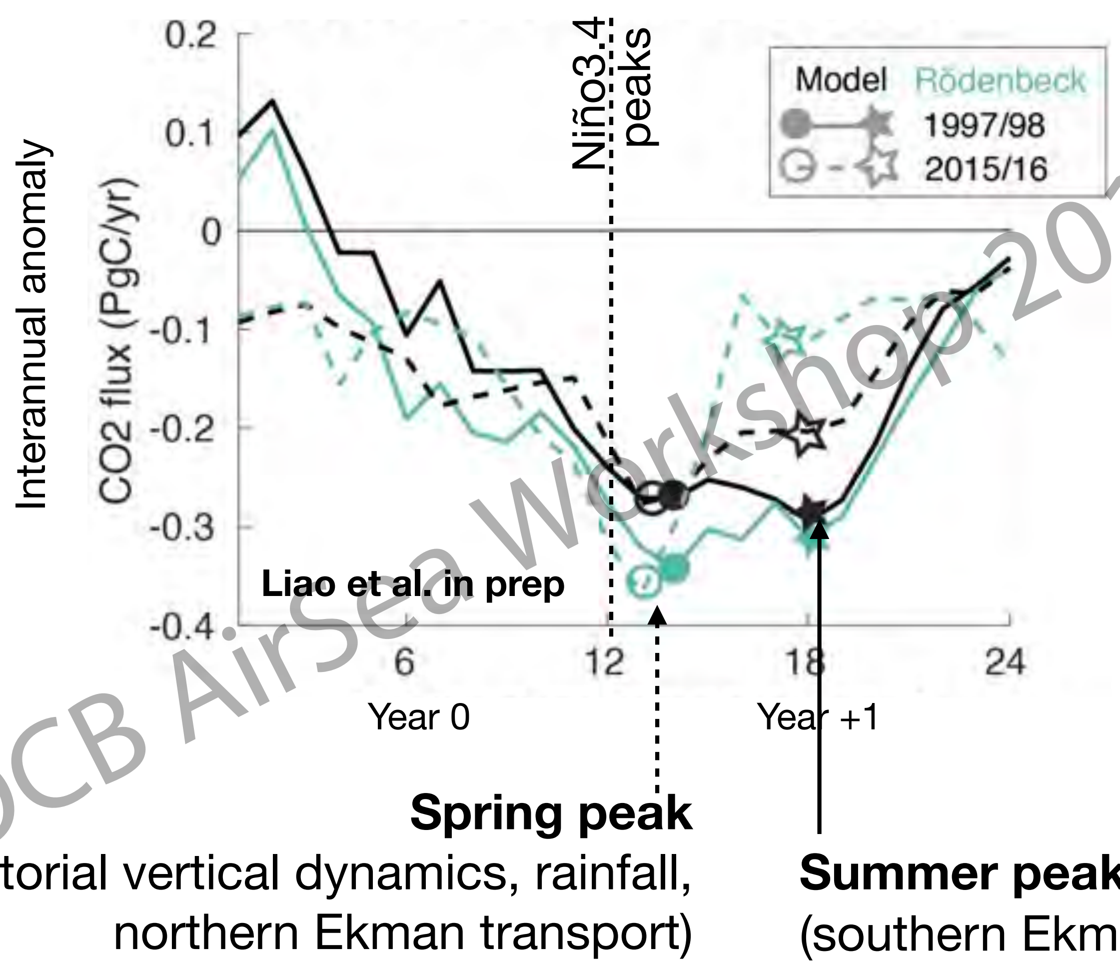


Mean pCO_2 mismatch in Equatorial Pacific (mapping - SOCAT raw data)



Denvil-Sommer et al. 2019
Rödenbeck et al 2015

Improve mechanistic understanding, a step towards reconciling different ocean estimates



Inform sampling / mapping technique / atmospheric inversions

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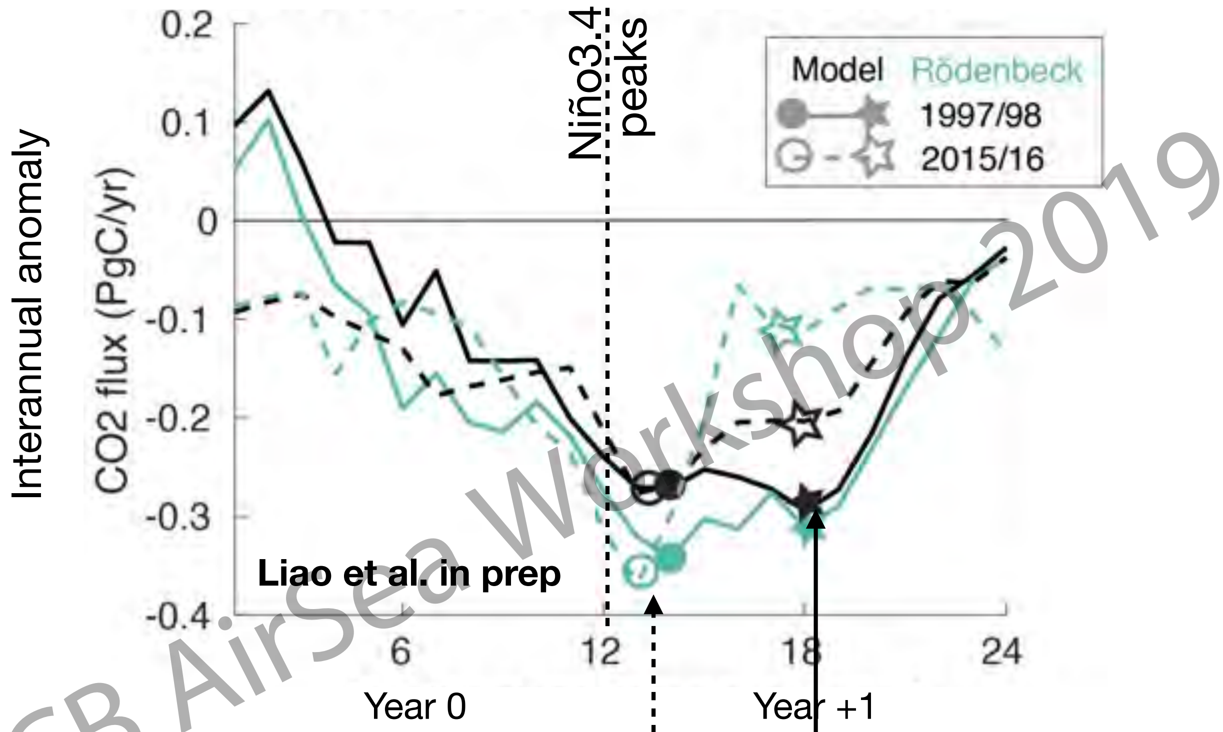


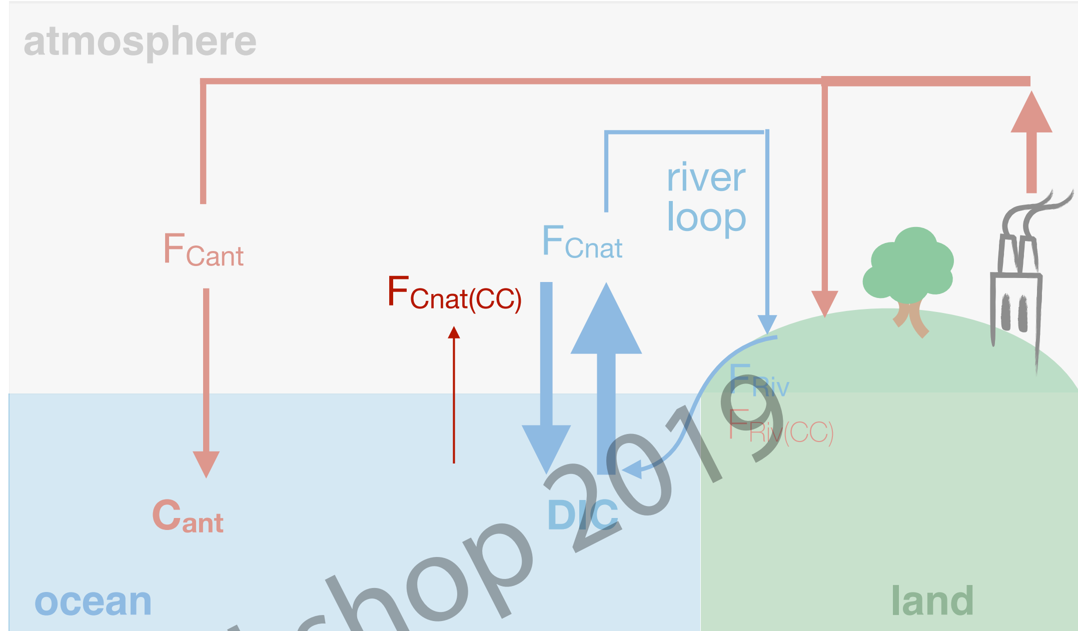
Spring peak
(Equatorial vertical dynamics, rainfall, northern Ekman transport)

Summer peak
(southern Ekman transport)

Inform sampling / mapping technique / atmospheric inversions

With implications for land sink and global budget

Carbon-climate feedbacks



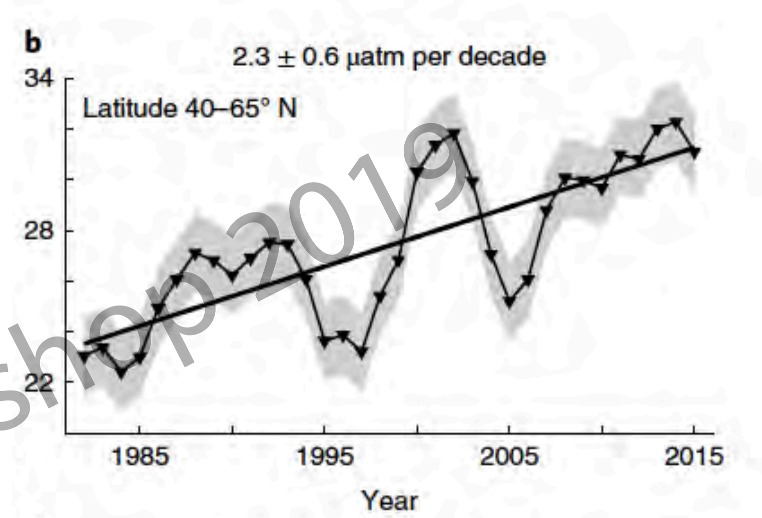
Warming
Anthropogenic nutrient (deposition, rivers)
Shifts in ecosystems
Chemical changes

Long-term increase in pCO_2 seasonal amplitude yields reduced sink/enhanced source

Seasonal asymmetry (seasonal max increases more than seasonal min decreases)

1. Long-term increase in ocean pCO_2 (seasonality acts on a larger pCO_2)

2. Stronger Revelle factor due to acidification at high latitude (pCO_2 becomes more sensitive)



Fassbender et al 2017
Landschutzer et al 2019

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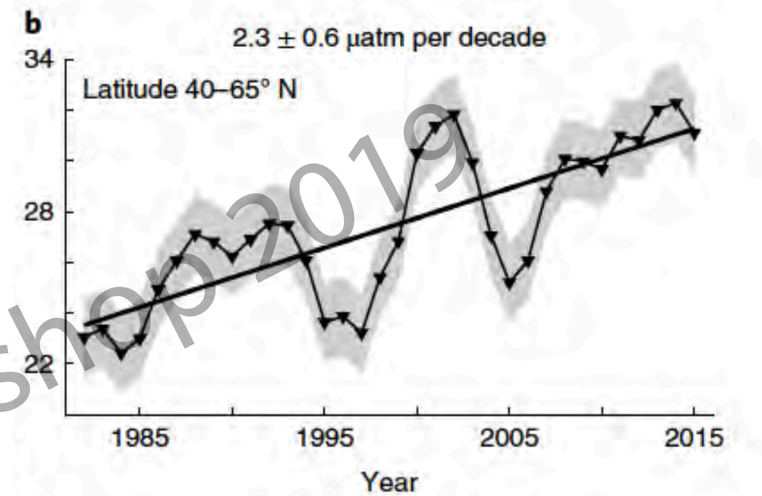
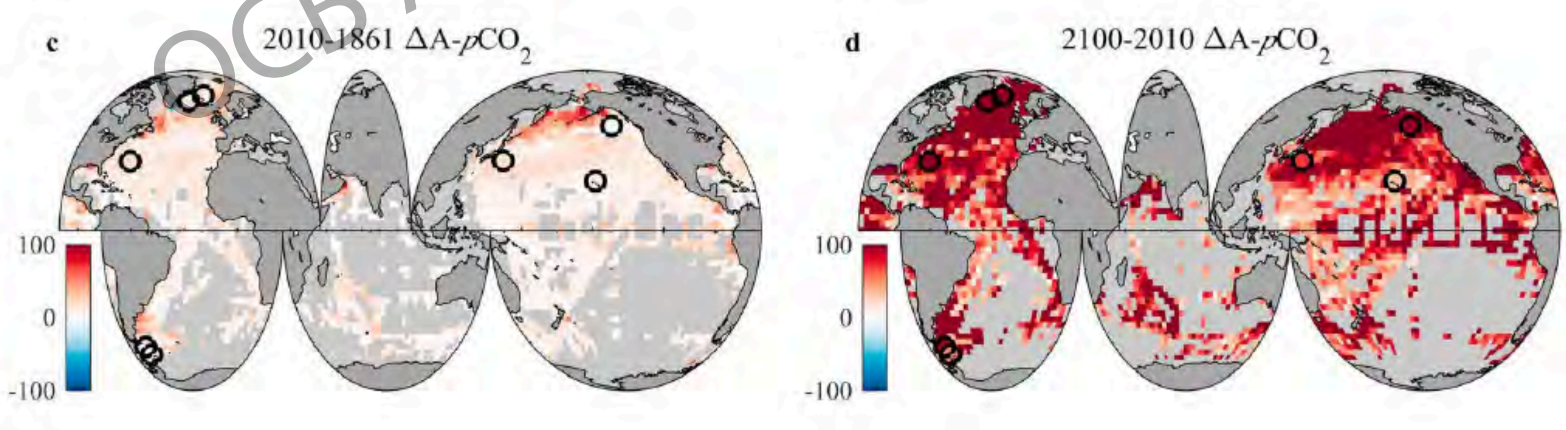


Seasonal amplification expected by 2100



Fassbender et al 2017
Landschutzer et al 2019

Advances

Consensus on global anthropogenic carbon budget

Tighter constraints on natural ocean/river carbon flux & seasonal cycle

Improved characterization of natural variability

Challenges - Efficient impact at policy level requires to reconcile estimates at regional and interannual time-scales.

Need for better quantification and mechanistic understanding of

- **land-ocean fluxes -** rivers + lateral fluxes between coastal and open ocean
- **basin-scale variability -** temporal and small-scale
- **carbon-climate feedbacks** - physical/biological response to perturbation (climate, nutrients etc.).

Observations still limited in polar oceans (ice, winter), tropical Pacific/ Indian (natural variability), coastal upwelling regions.

Include new data types (floats, satellite ocean glint etc.) into existing mapping method

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Other gases N_2O

2007-2016: largest uncertainty is in ocean flux

Top-down: 3.4-7.1 Tg N/y

Bottom-up: 2.6-4.4 Tg N/y

(Tian et al., in prep)

N_2O Budget 2019