A new framework for quantifying the drivers of Southern Ocean air-sea carbon fluxes

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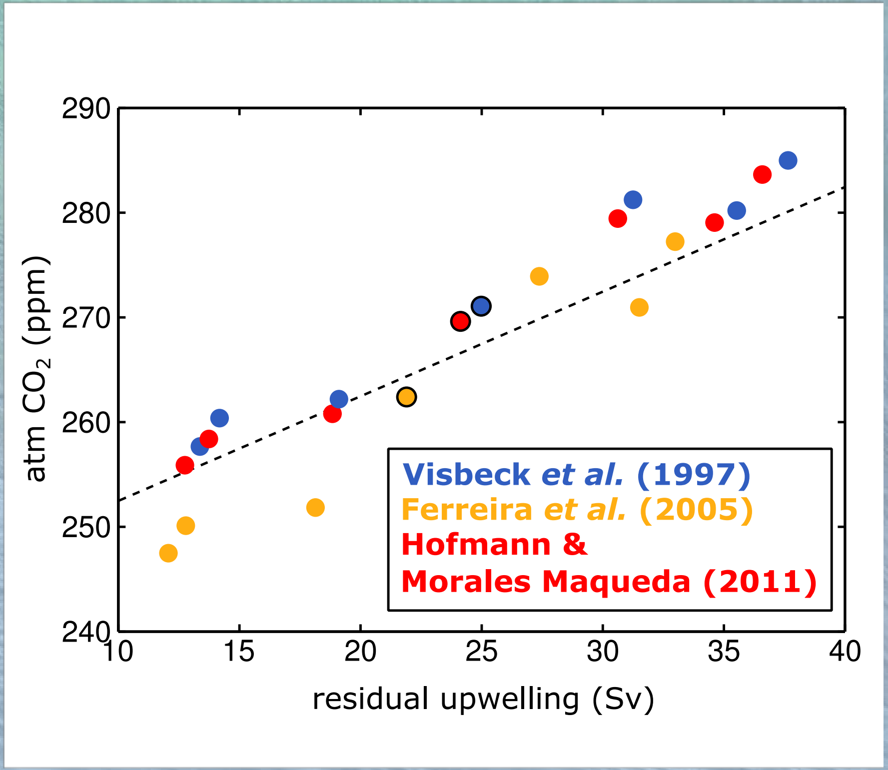
What influences CO_2 fluxes?

- Surface flux proportional to ocean pCO_2, which responds to a variety of factors.
- Can the key processes be separated (e.g. Murnane et al., 1999; Takahashi et al., 2002; 2009; and others)?
- Can we mechanistically map these drivers of the carbon flux?



Southern Ocean upwelling vs atm pCO_2
[Lauderdale, Williams, Munday and Marshall, 2016; Climate Dynamics]

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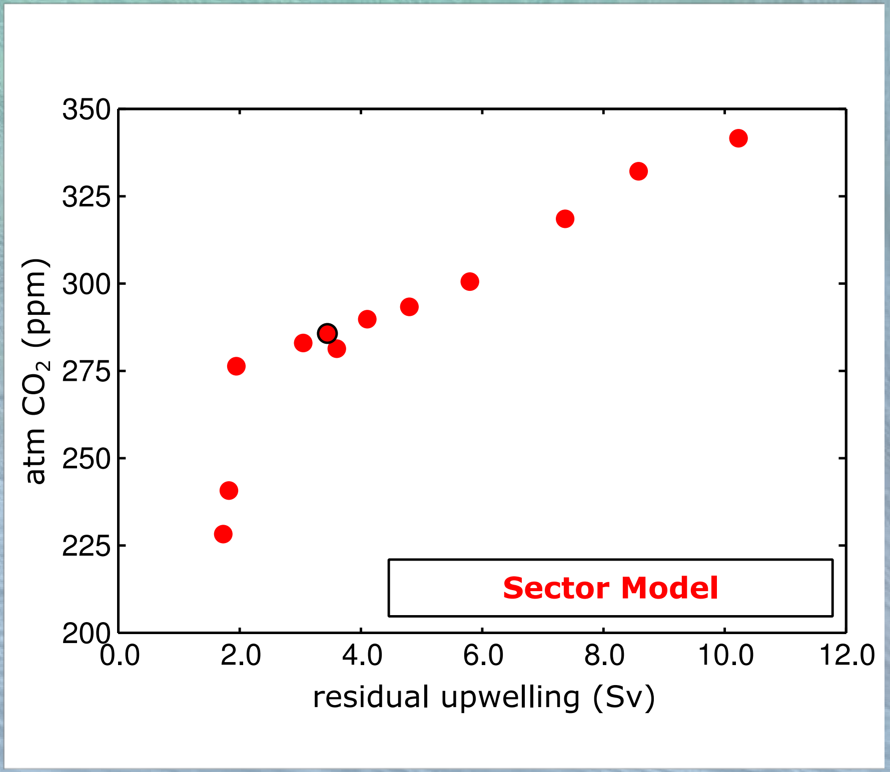

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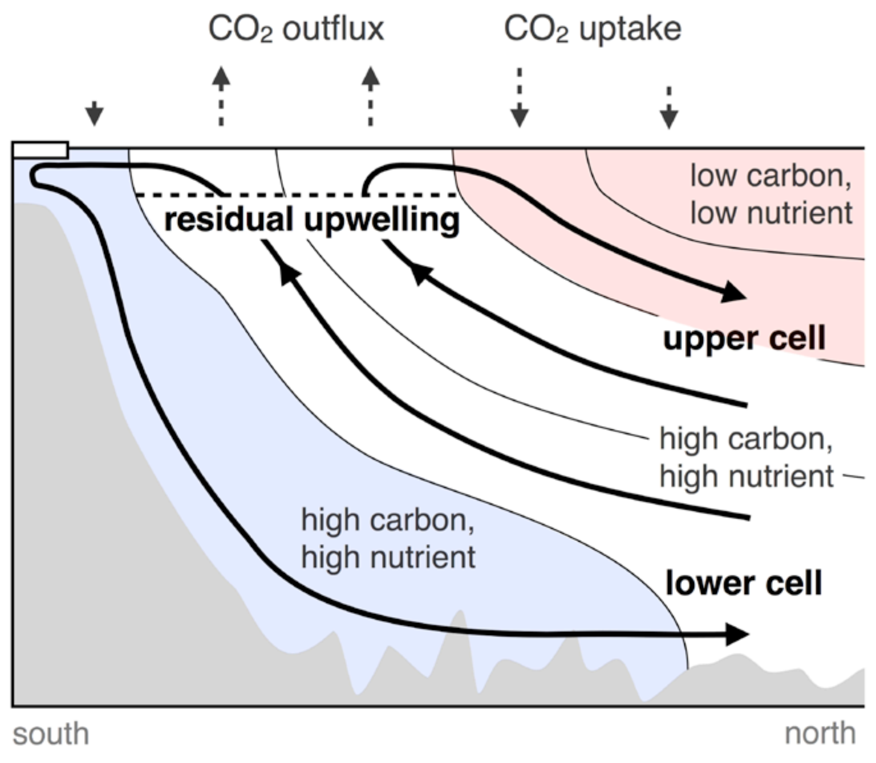


Southern Ocean schematic
[Lauderdale, Williams, Munday and Marshall, 2016; Climate Dynamics]

Start from a DIC budget…

$$\frac{\partial C}{\partial t} = -\nabla \cdot (\vec{u}C) + \nabla \cdot (\kappa \nabla C) - F_C - C_o F_{FW} - R_{C:P} S_{bioP} - S_{CaCO_3}$$

Change of DIC conc.	DIC Advection	DIC Diffusion	Air-sea exchange	FW Dilution	Biological Activity

…assume steady state over a seasonal cycle.

$$F_C = -\nabla \cdot (\vec{u}C) + \nabla \cdot (\kappa \nabla C) - C_o F_{FW} - R_{C:P} S_{bioP} - S_{CaCO_3}$$

Further break down into effects of temperature, salinity and alkalinity	Surface FW flux	Nutrient fields

Biological Activity

- Biological activity related to changes in DIC concentration via nutrient field changes.
- Carbonate cycling related to S_{bioP} through constant rain ratio.

$$S_{bioP} = -\nabla \cdot (\vec{u}P) + \nabla \cdot (\kappa \nabla P)$$

Carbon Partitioning Scheme

- DIC in the mixed layer can be separated into different components after Williams & Follows (2011) :

$$C = C^{sat} + C^{res}$$

- C^{sat} depends on temperature, salinity and alkalinity (e.g. Goodwin & Lenton, 2009; Lauderdale et al., 2013; 2016).
- The influence of salinity is negligible (… but it is included).

$$\delta C^{sat} = \delta T \frac{\partial C}{\partial T} + \delta A \frac{\partial C}{\partial A} + \delta S \frac{\partial C}{\partial S}$$

Carbon Partitioning Scheme

- Defining relationships for δT and δA (and δS) based on advection, diffusion and surface fluxes:

$$-\nabla \cdot (\vec{u}T) + \nabla \cdot (\kappa \nabla T) = F_{Heat}$$

$$-\nabla \cdot (\vec{u}A) + \nabla \cdot (\kappa \nabla A) = A_o F_{FW}$$

- We leverage the tight relationship between A and S in the surface ocean. Any (small) biogenic effects are collected in C^{res}.
- C^{res} is the residual, but represents two key processes of upwelling and solubility changes.

$$C = C^{sat} + C^{res}$$

Carbon flux framework

$$F_{CO_2} = \gamma_\theta \frac{F_{heat}}{\rho C_p}$$

CO_2 flux driven by surface heating.

$$+ \frac{F_W}{\rho_{fw}} \left(\gamma_S \overline{S} + \gamma_{A_T} \overline{A_T} - \overline{C_T}\right)$$

Net CO_2 flux driven by freshwater fluxes.

$$- R_{C_T:P} \big(-\nabla \cdot (\vec{u}P) + \nabla \cdot (\kappa \nabla P)\big)\ h$$

CO_2 flux driven by biological activity.

$$- \frac{1}{2} R_{CaCO_3} R_{C_T:P} \big(-\nabla \cdot (\vec{u}P) + \nabla \cdot (\kappa \nabla P)\big)\ h$$

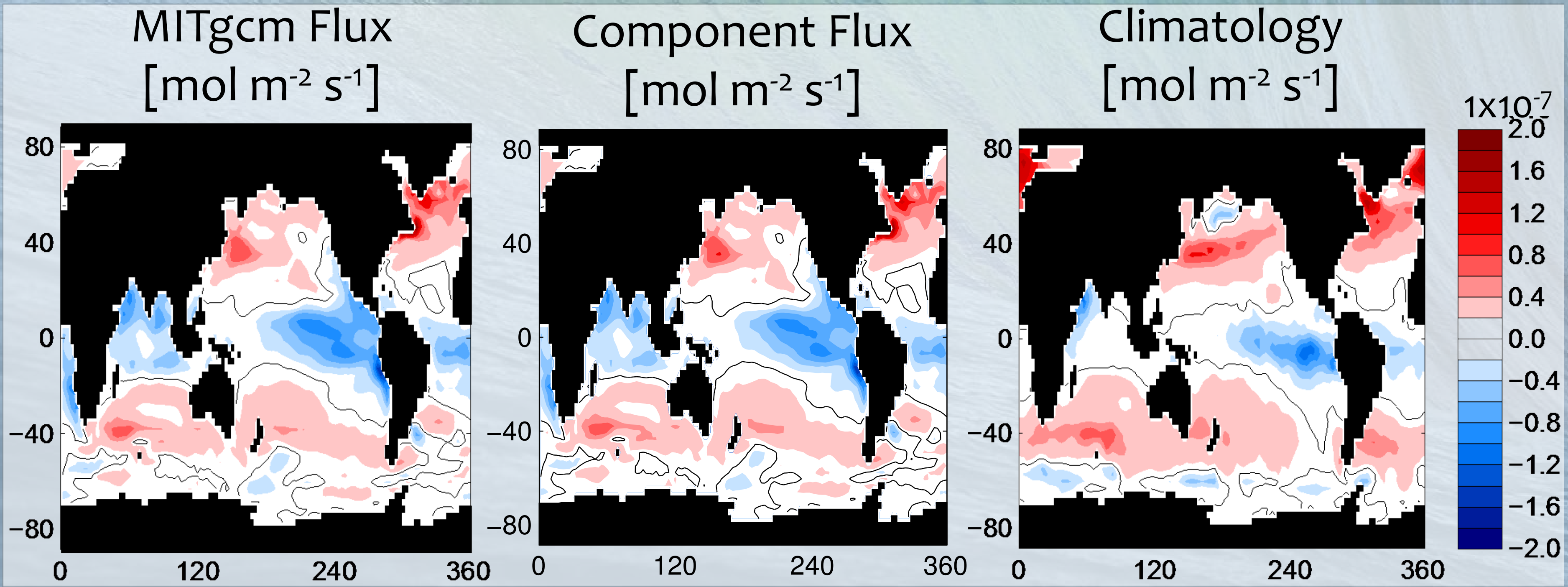
$$+ \big(-\nabla \cdot (\vec{u}C_{res}) + \nabla \cdot (\kappa \nabla C_{res})\big)\ h$$

CO_2 flux driven by disequilibrium.

See: Lauderdale, Dutkiewicz, Williams & Follows (2016), Quantifying the drivers of ocean-atmosphere CO_2 fluxes, GBC, accepted yesterday!

Carbon Fluxes in the Model World

- Coarse resolution MITgcm w/biogeochemistry model (Dutkiewicz et al., 2006).
- Substitute in the fluxes for the diagnostic equation and sum all components.



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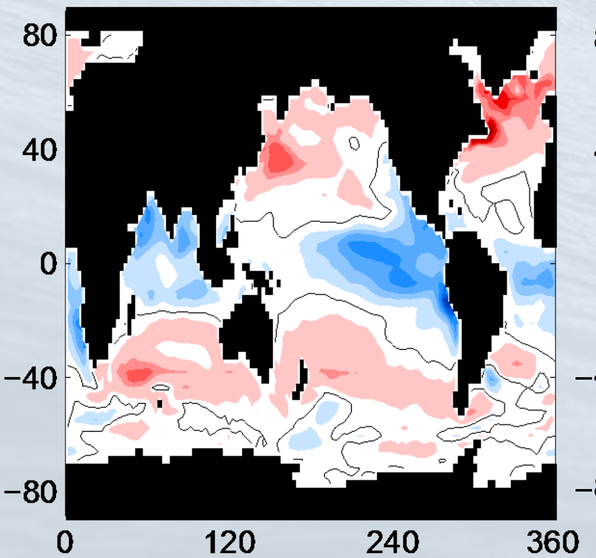
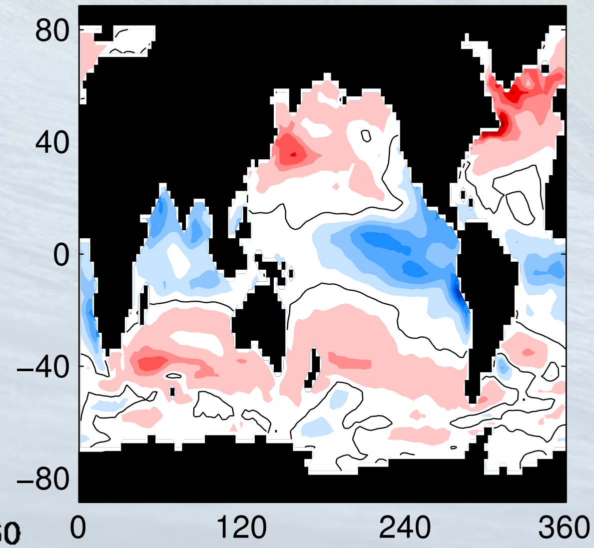
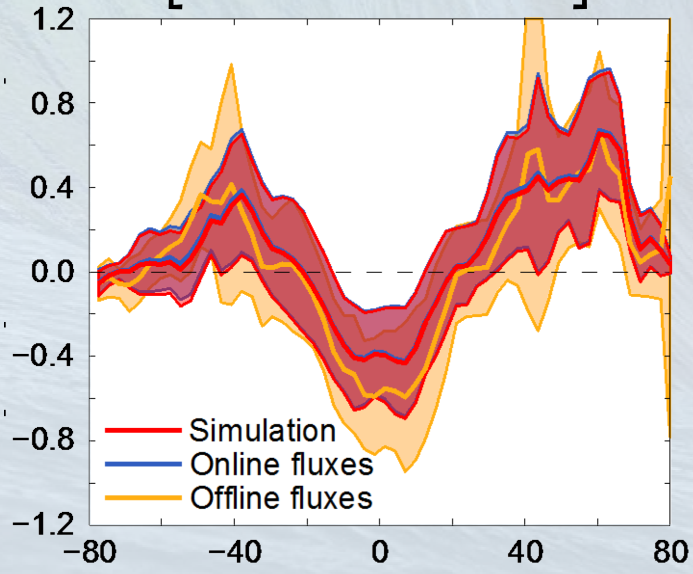
MITgcm Flux [mol m^{-2} s^{-1}]



Component Flux [mol m^{-2} s^{-1}]



Zonal-average fluxes [1x10^{-7} mol m^{-2} s^{-1}]

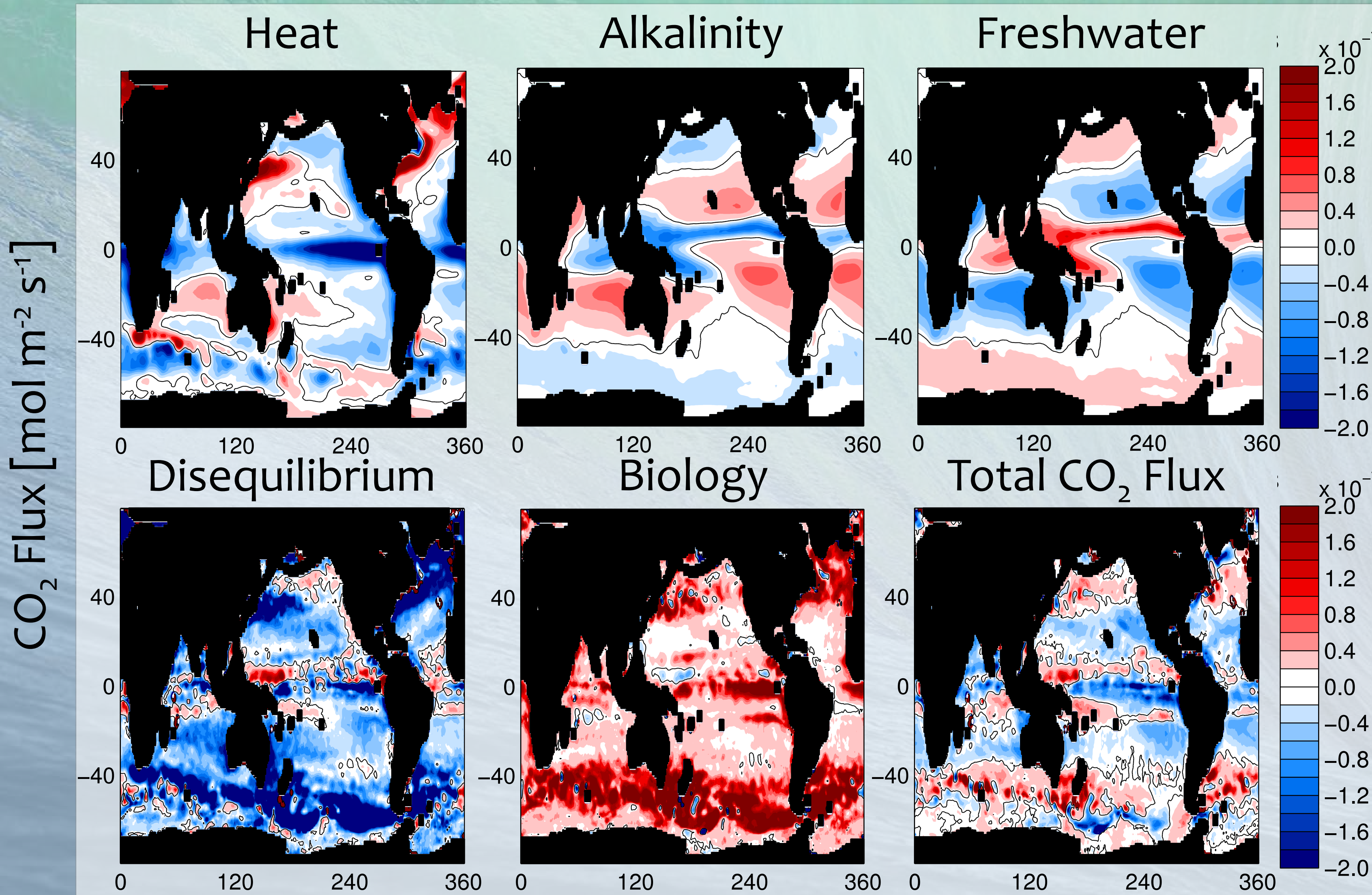


Carbon Fluxes in the “Real” World

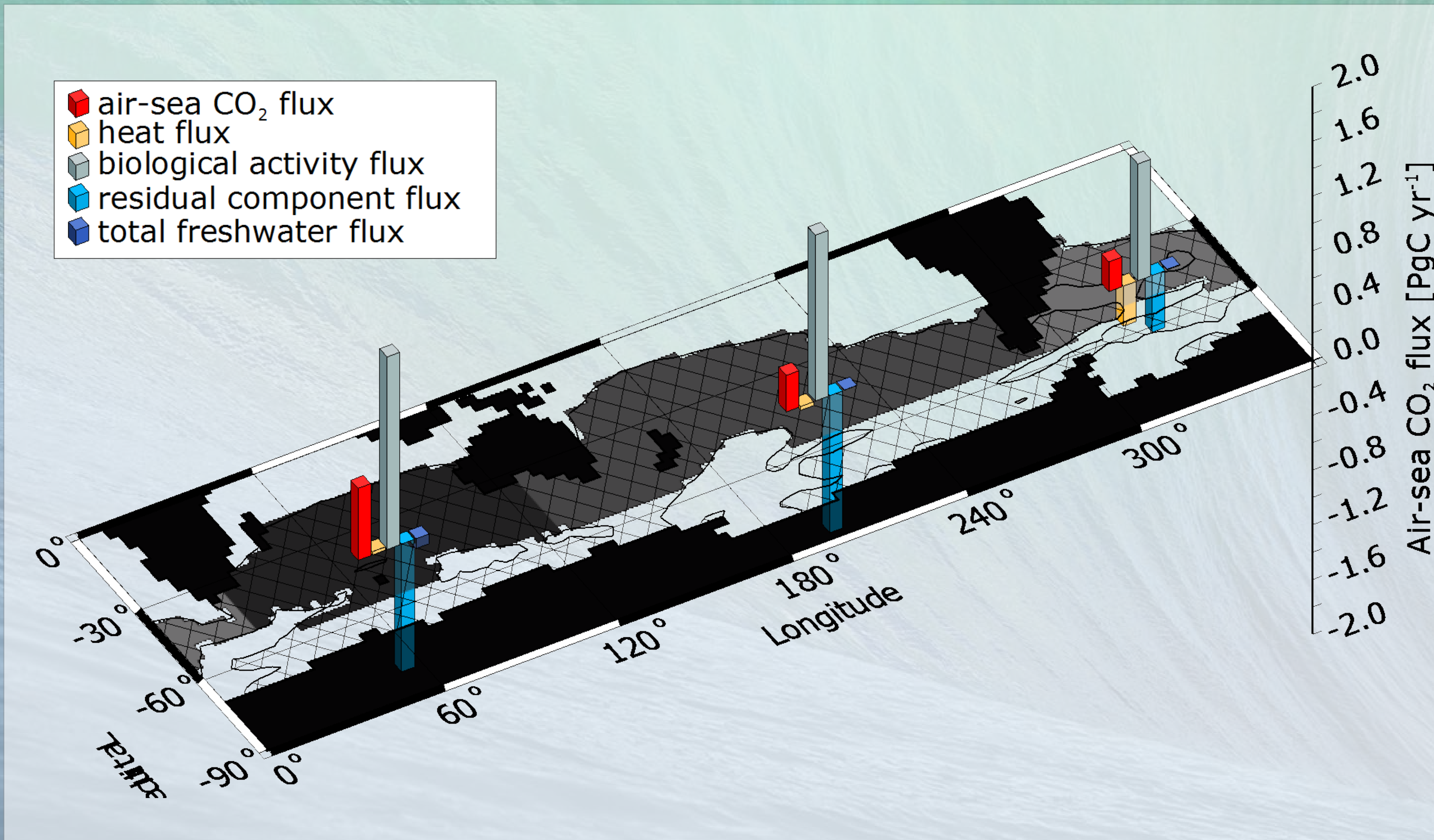
Variable	Product	Reference
12x U, V, W, Kz, Kh	Ocean Comprehensible Atlas (OCCAv2)	Forget et al., 2010
12x T, S, P	World Ocean Atlas 2013 (WOA13)	Locarnini et al., 2013; Zweng et al., 2013; 2xGarcia et al., 2013
12x Q, FW	ERA-Interim	Dee et al., 2011
1x DIC, ALK	GLODAPv2	Key et al., 2015; Olsen et al., 2016; Lauvset et al., 2016

- Monthly values for DIC and ALK reconstructed from GLODAPv2 single temporal snapshot using mixed layer depth (after Williams & Follows, 1998).

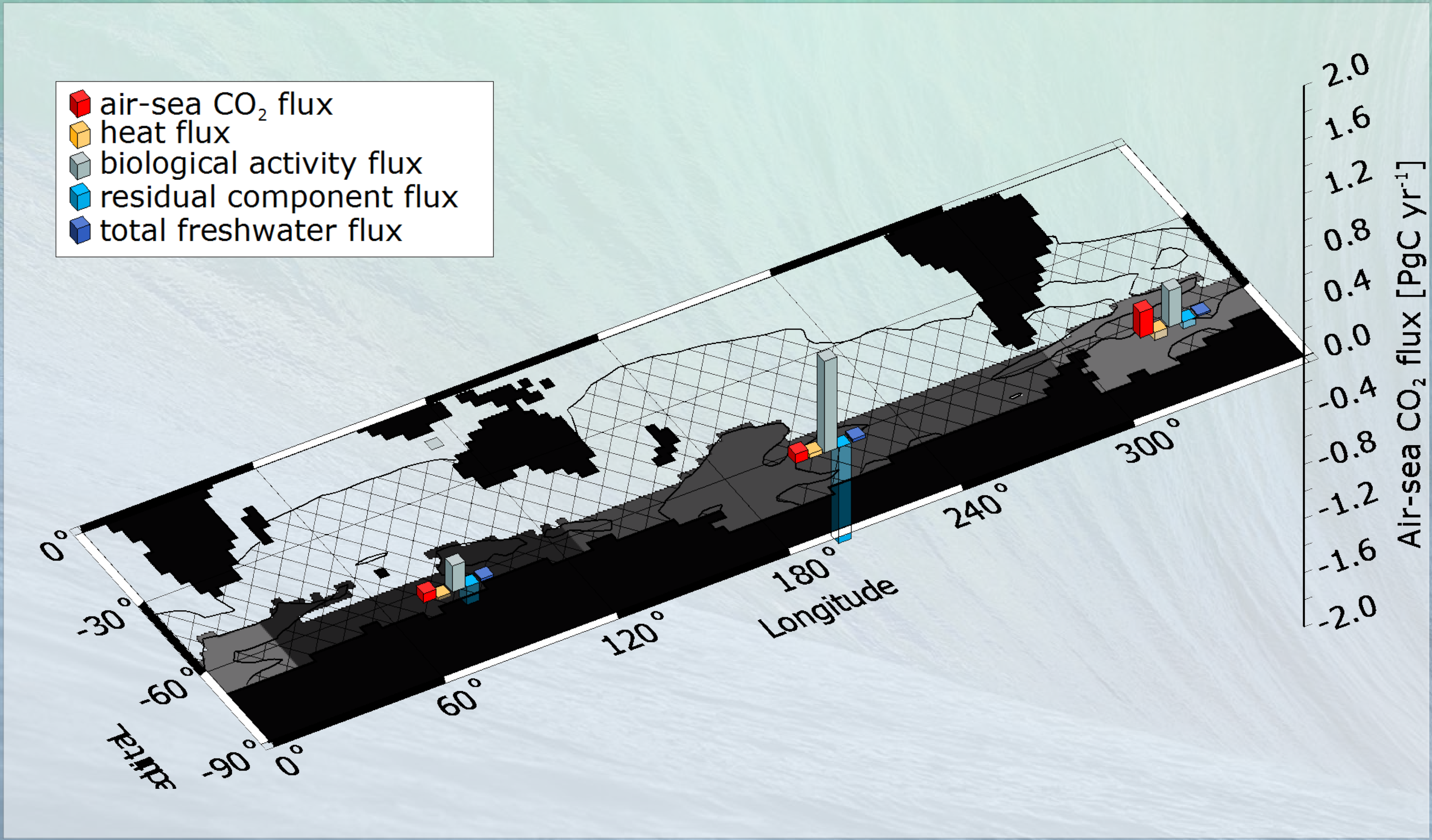
Carbon Fluxes in the "Real" World



Midlatitude Southern Ocean Carbon Fluxes



Southern Ocean Carbon Fluxes



Conclusions

- Mechanistic framework to interpret local drivers of air-sea CO_2 fluxes developed.
- Dominant drivers are the heat flux-driven component and opposing combination of biological activity and disequilibrium.
- Net freshwater effect is actually small because dilution of Alkalinity (in C^{sat}) and DIC mostly cancel.
- Framework readily extendable to:
  - Cover non-steady state solutions natural.
  - Handle anthropogenic CO_2 perturbations.

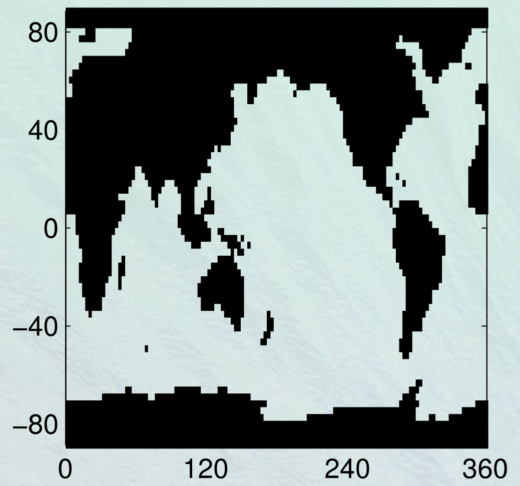
See: Lauderdale, Dutkiewicz, Williams & Follows (2016), Quantifying the drivers of ocean-atmosphere CO_2 fluxes, GBC, accepted yesterday!

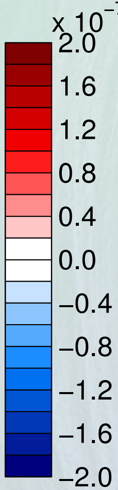
Carbon Fluxes in the Model World

Heat

Alkalinity

Freshwater





CO_2 Flux [mol m^{-2} s^{-1}]

Disequilibrium

Biology