

Carbon in the Southern Ocean: Known knowns and known unknowns

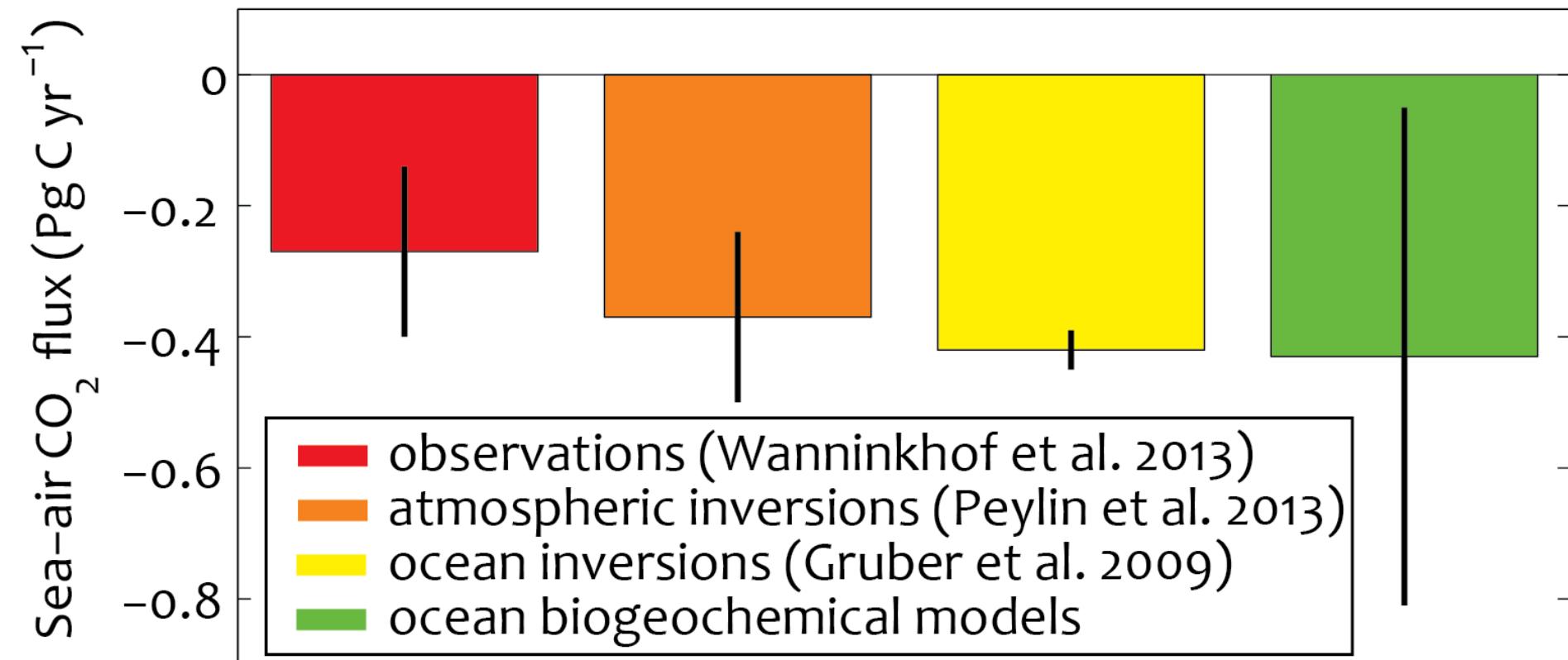
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Part I:

Known knowns

Southern Ocean is a sink for atmospheric CO₂

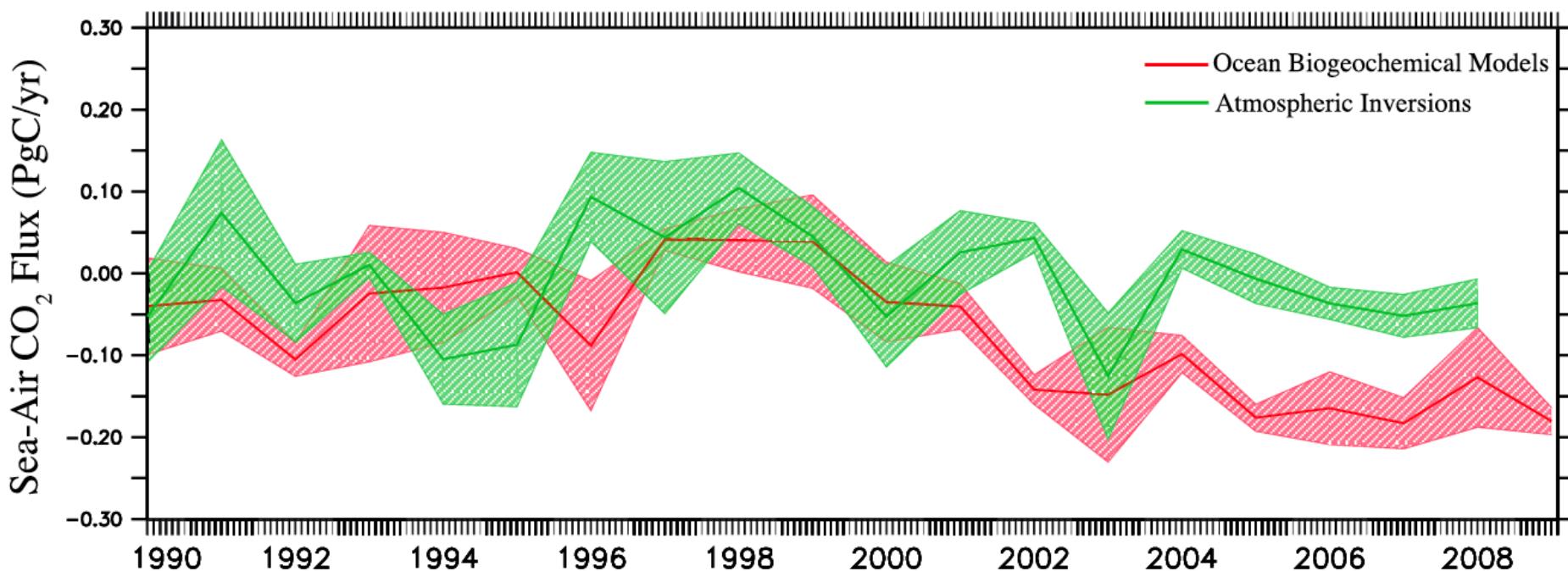
Median annual sea-air CO₂ flux, 1990-2009, 44°S-75°S



data from Lenton et al. (2013)

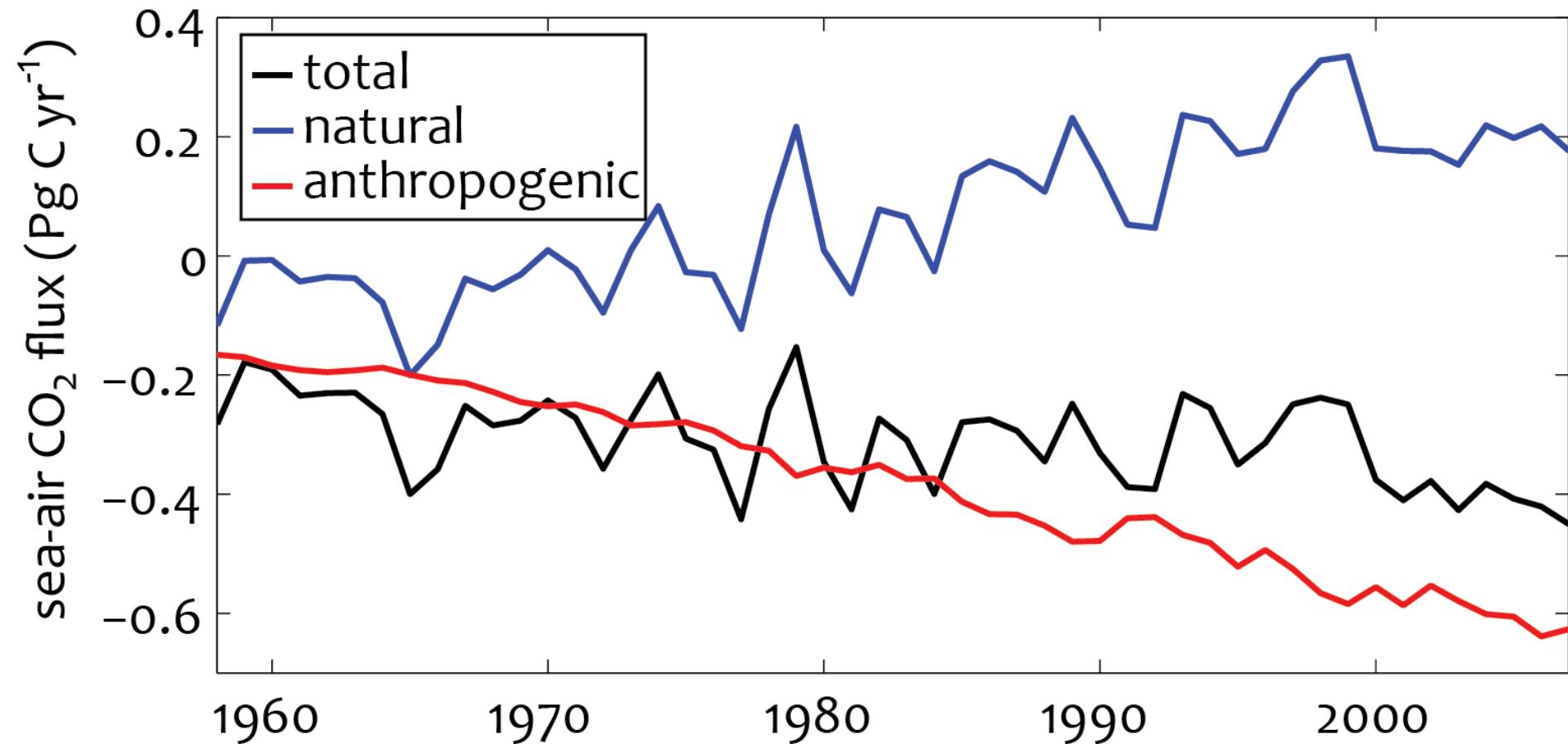
Southern Ocean has large CO₂ flux variability

Integrated sea-air CO₂ flux, 44°S-75°S

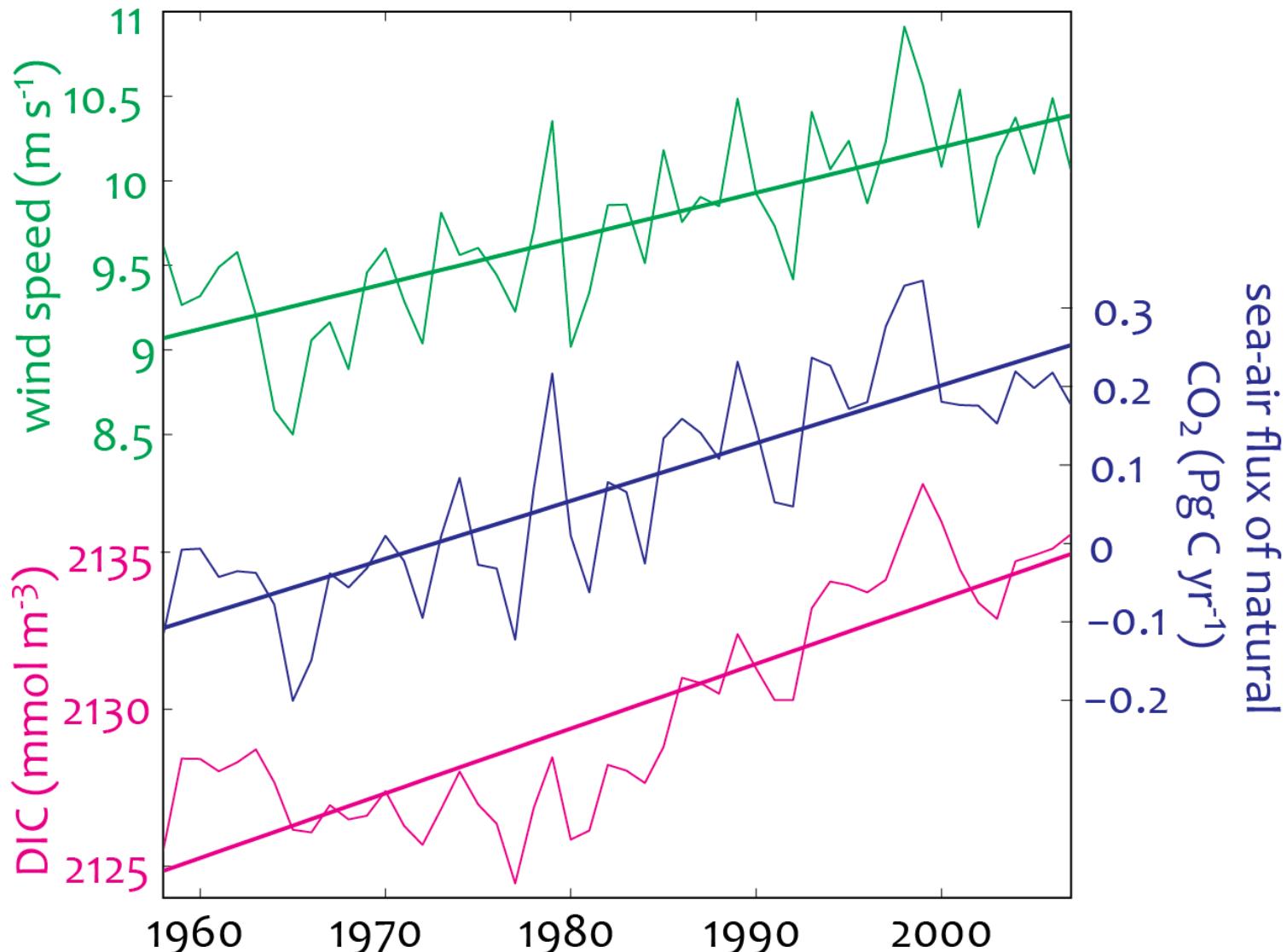


Total CO₂ flux variance ≈ Natural CO₂ flux variance

Integrated sea-air CO₂ flux, south of 44°S



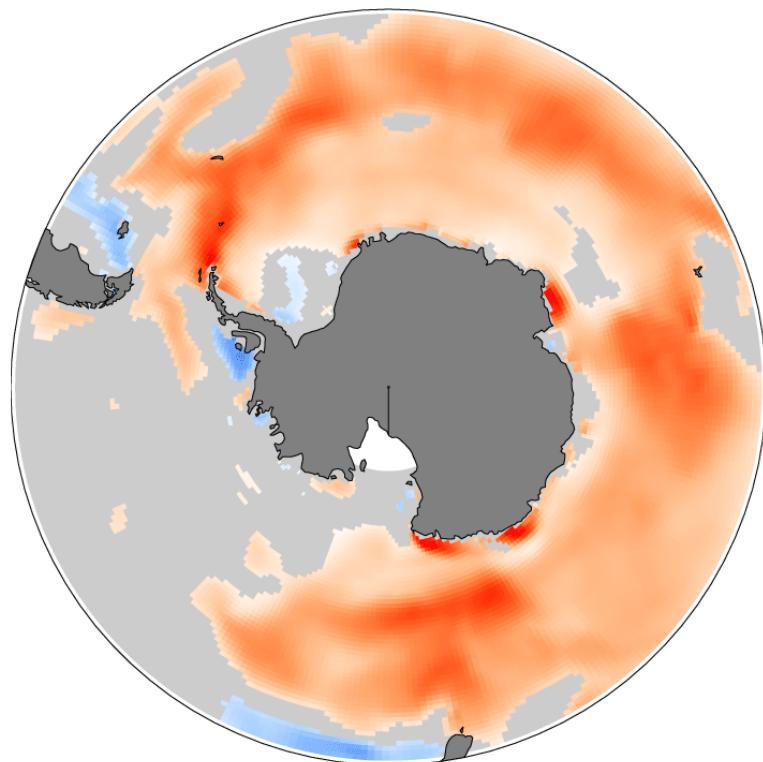
Wind drives natural CO₂ flux variability



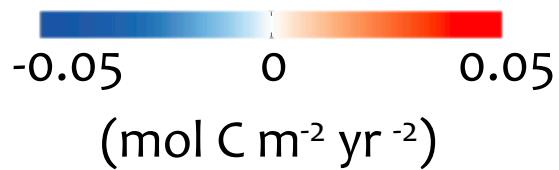
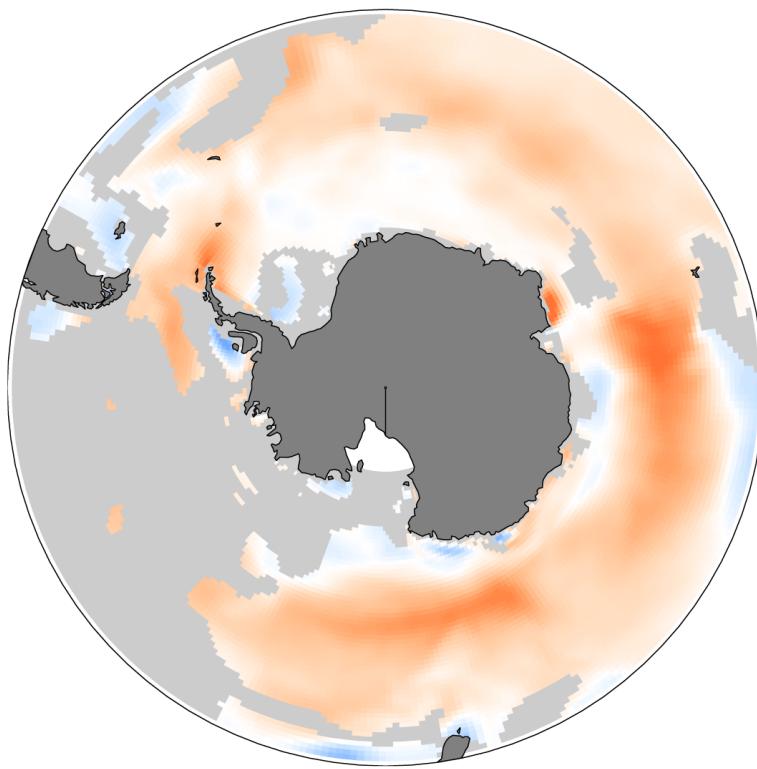
Lovenduski et al. (2013)

Wind drives natural CO₂ flux trend

Linear trend
1958-2007

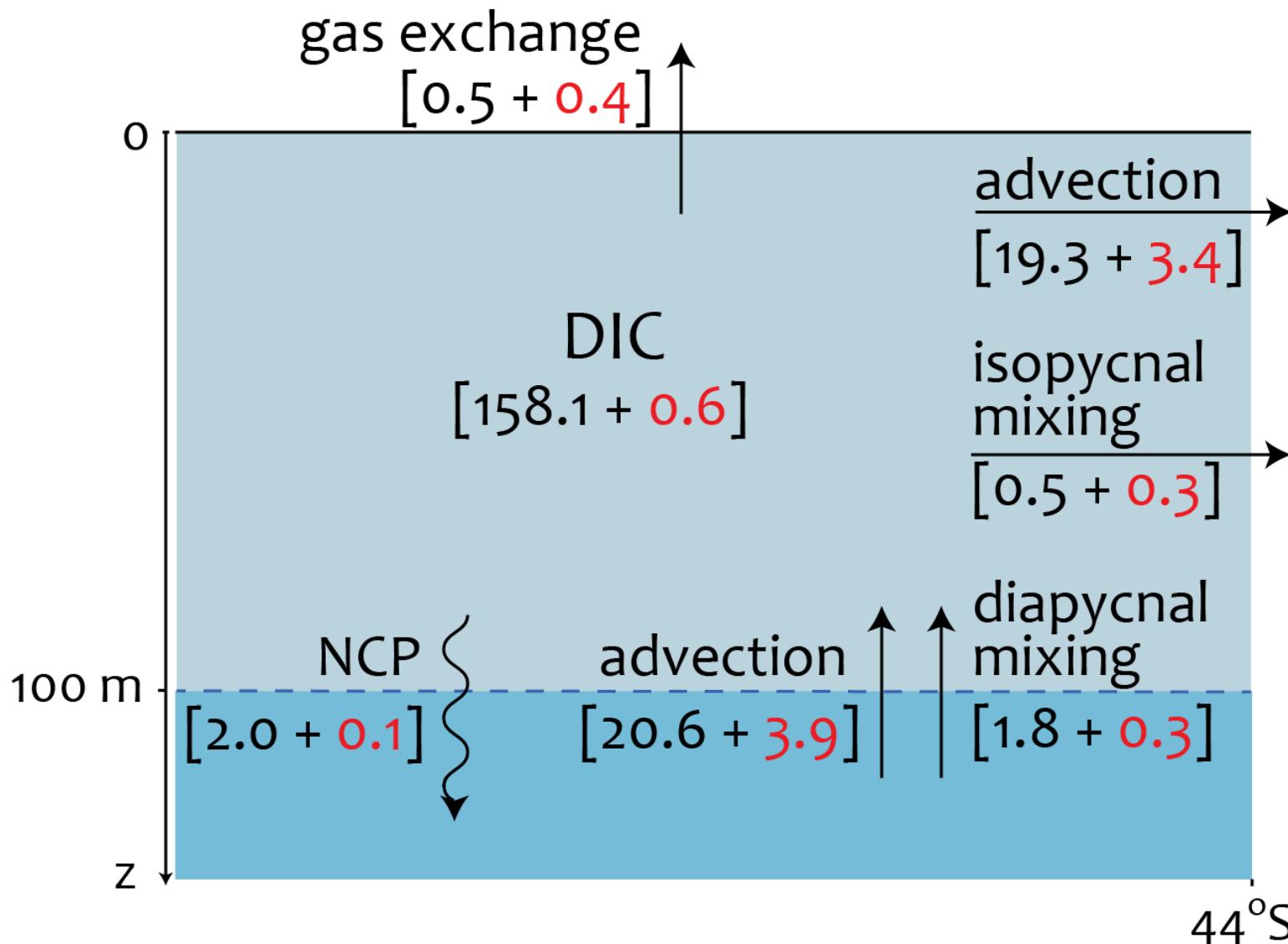


Trend congruent
with wind

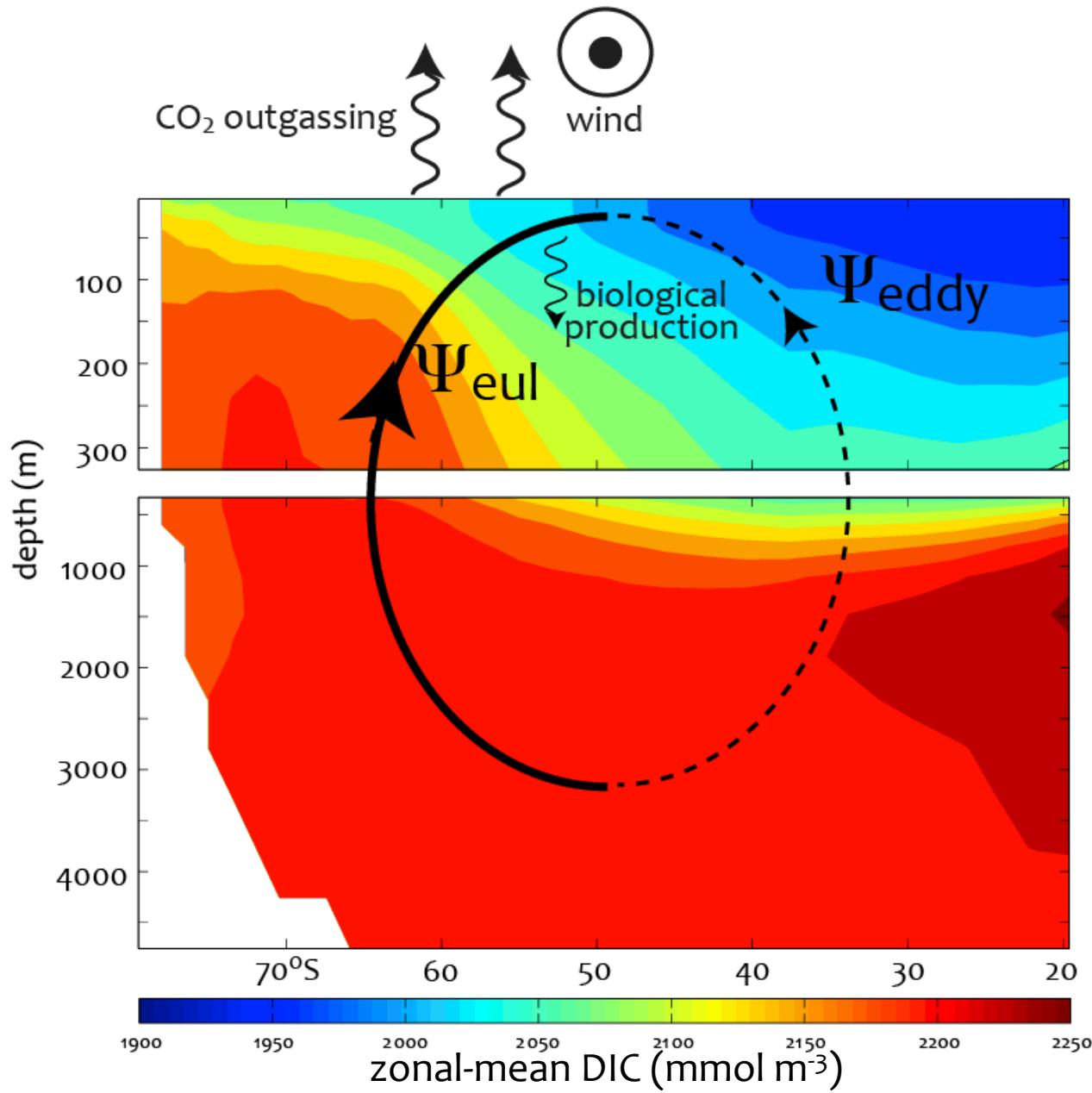


Lovenduski et al. (2013)

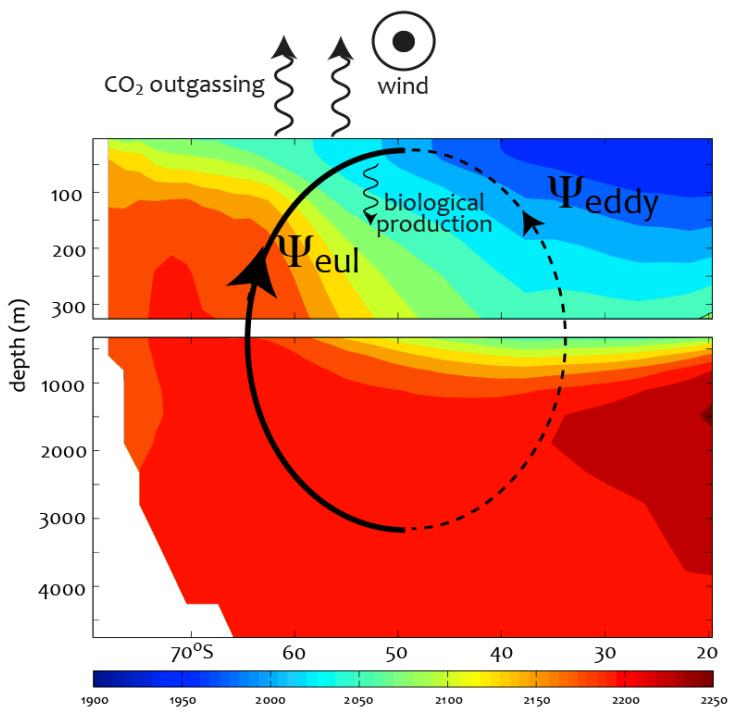
Stronger wind = higher surface DIC



Mechanism



Corroborating model results

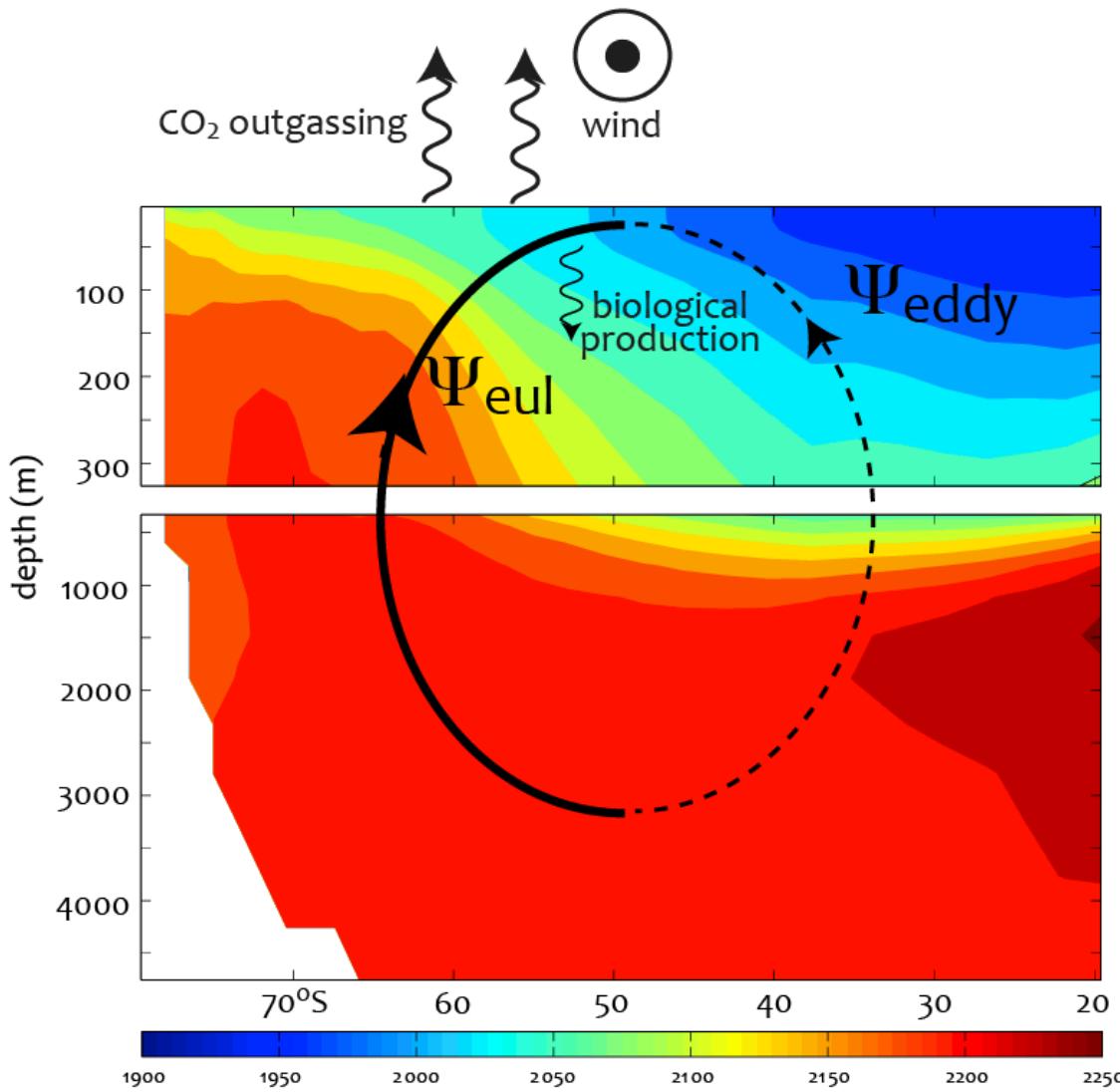


Model	Reference
Bern3D	Tschumi et al. 2008
CCSM/CESM	Lovenduski et al. 2007 Wang and Moore 2012 Lovenduski et al. 2013
CSIRO	Lenton et al. 2007
IPSL	LeQuéré et al. 2007 Lenton et al. 2009
LOVECLIM	Men viel et al. 2008
MITgcm	Lovenduski and Ito 2009
NASA GISS	Romanou et al. 2013
UVic	Zickfeld et al. 2007

Part II:

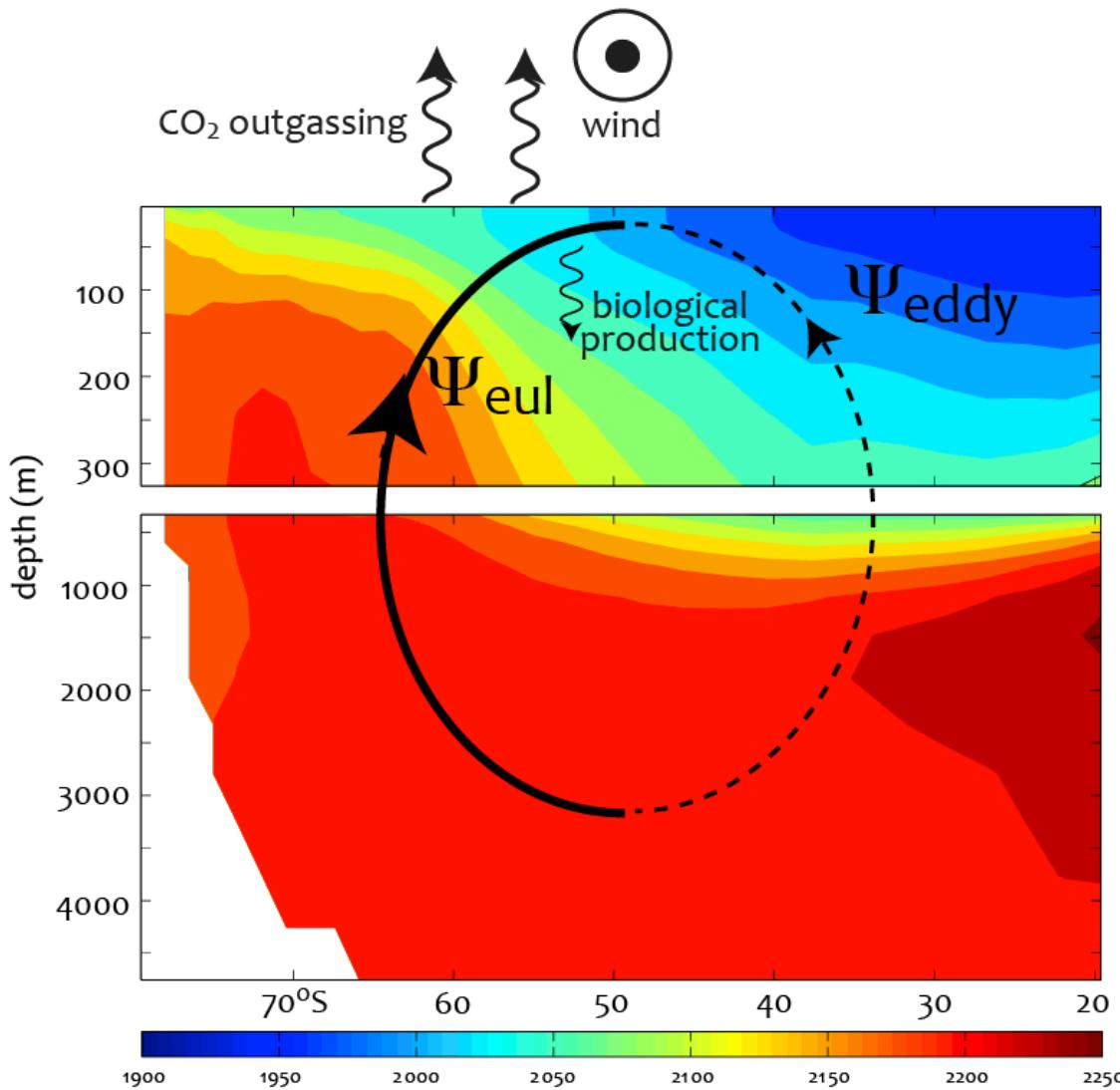
Known unknowns

Observing the mechanism



1. Is the model-predicted CO₂ flux trend real?
2. Has meridional overturning increased?
3. Has biological production changed?

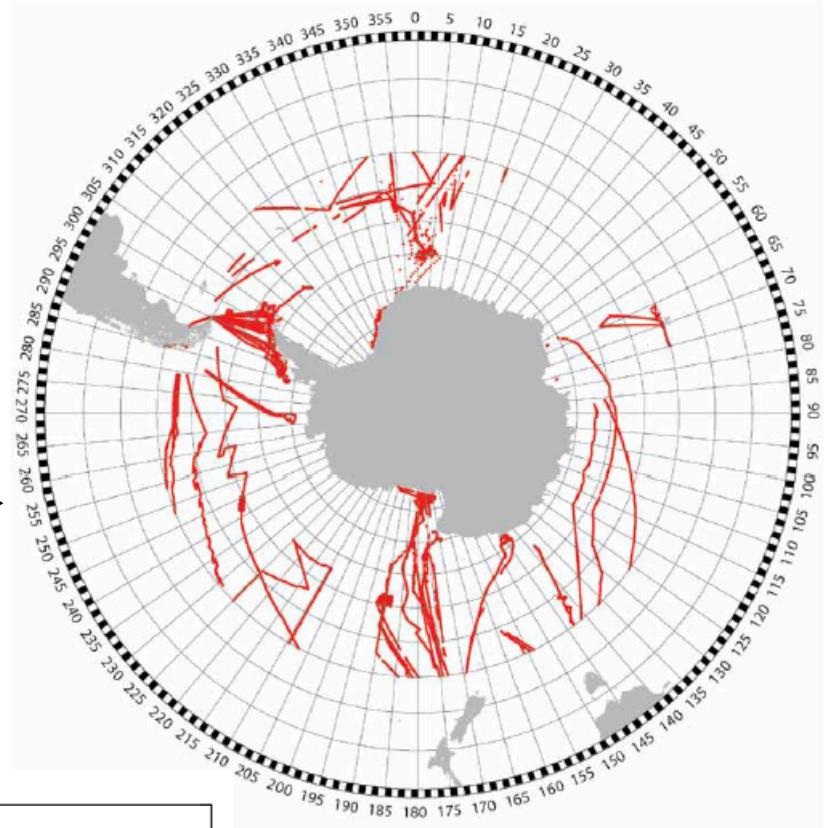
Observing the mechanism



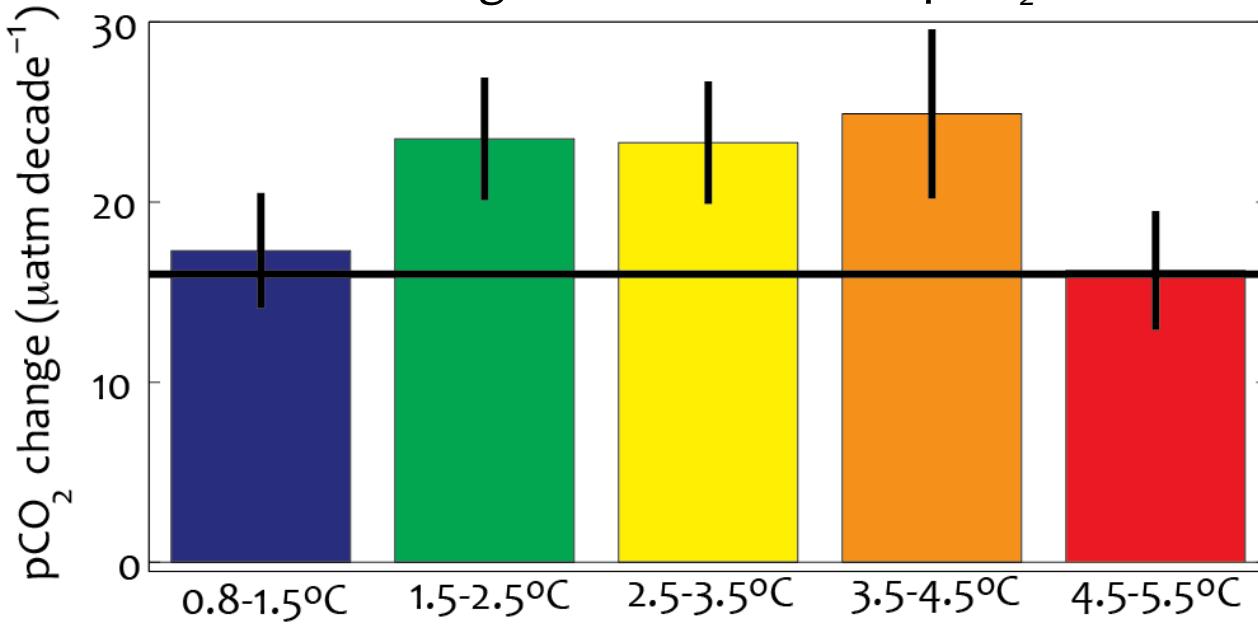
1. Is the model-predicted CO₂ flux trend real?
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Observed wintertime pCO₂ changes 1986-2010

Wintertime data locations →



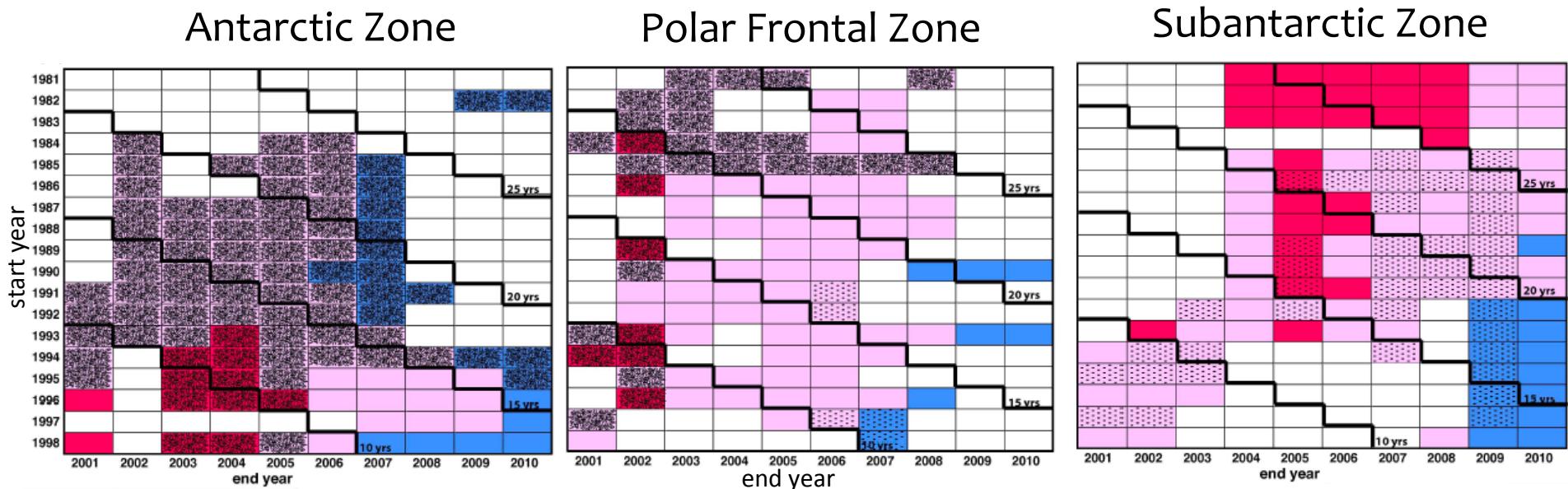
Change in surface ocean pCO₂



Change in atmospheric pCO₂

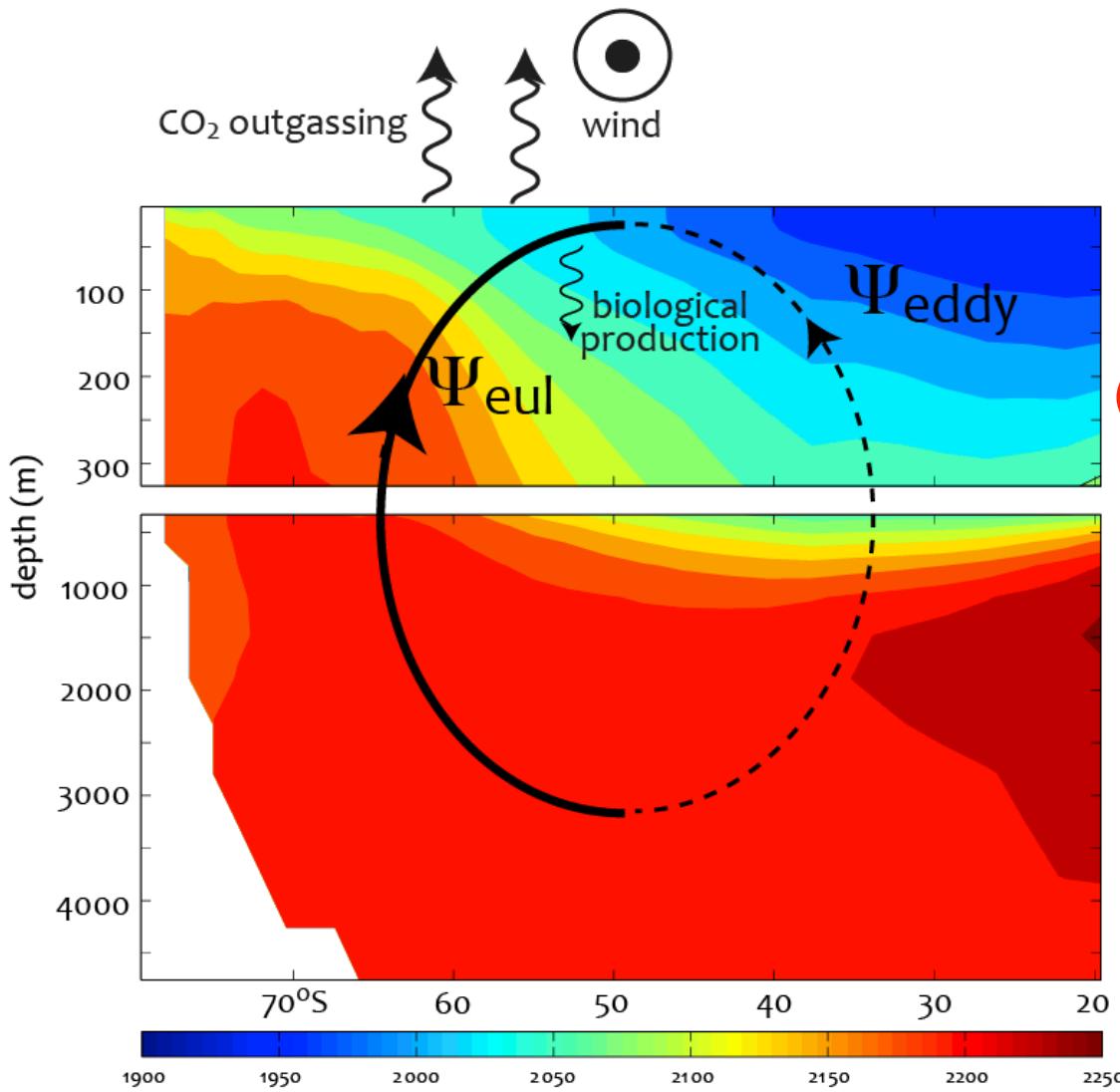
data from
Takahashi et al. (2012)

Trend in pCO_2^{oc} vs. pCO_2^{atm} trend



$\frac{dpCO_2^{oc}}{dt} < \frac{dpCO_2^{atm}}{dt}$	$\frac{dpCO_2^{oc}}{dt} \sim \frac{dpCO_2^{atm}}{dt}$	$\frac{dpCO_2^{oc}}{dt} > \frac{dpCO_2^{atm}}{dt}$
$\frac{dpCO_2 - T}{dt} > 0$		$\frac{dpCO_2 - T}{dt} < 0$

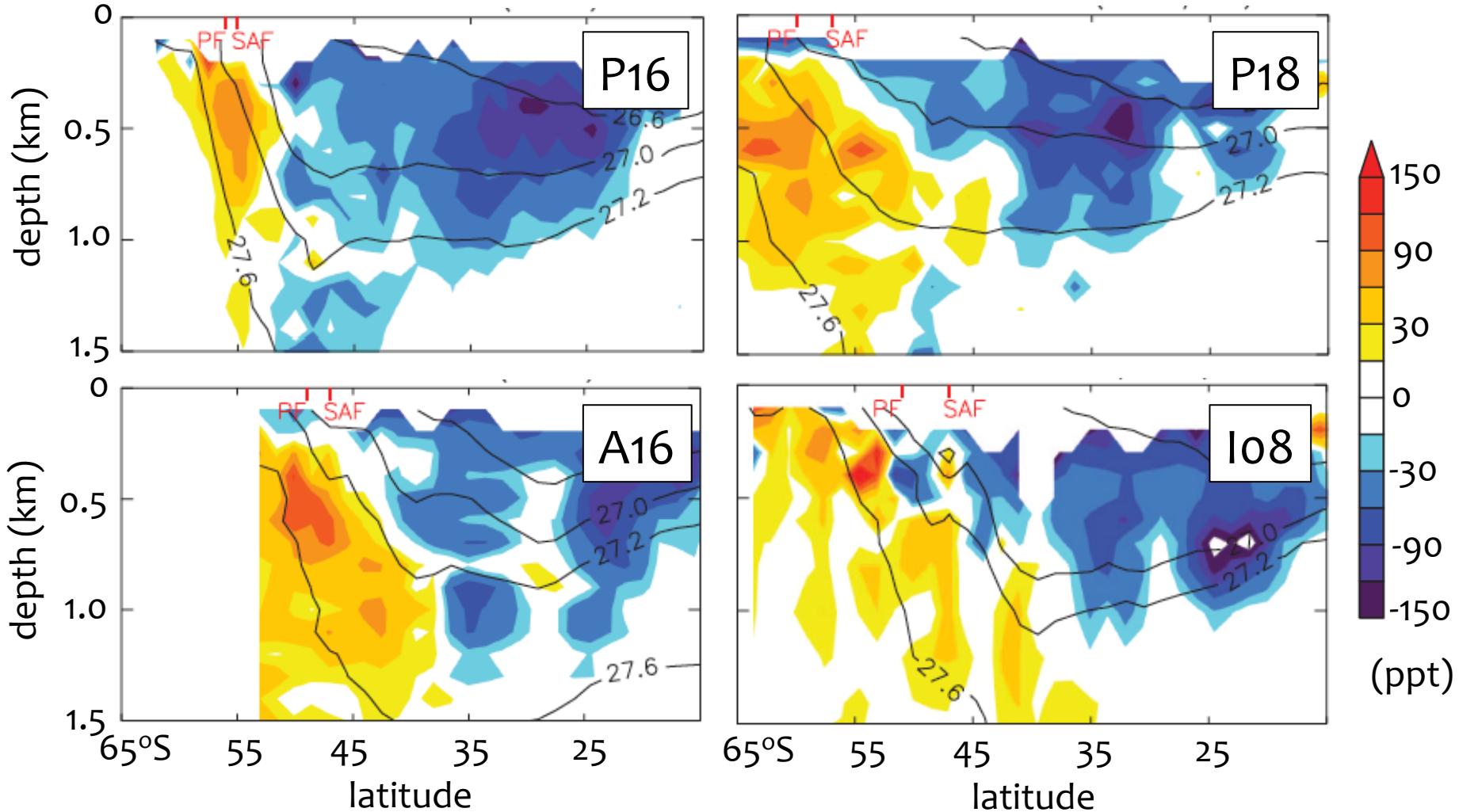
Observing the mechanism



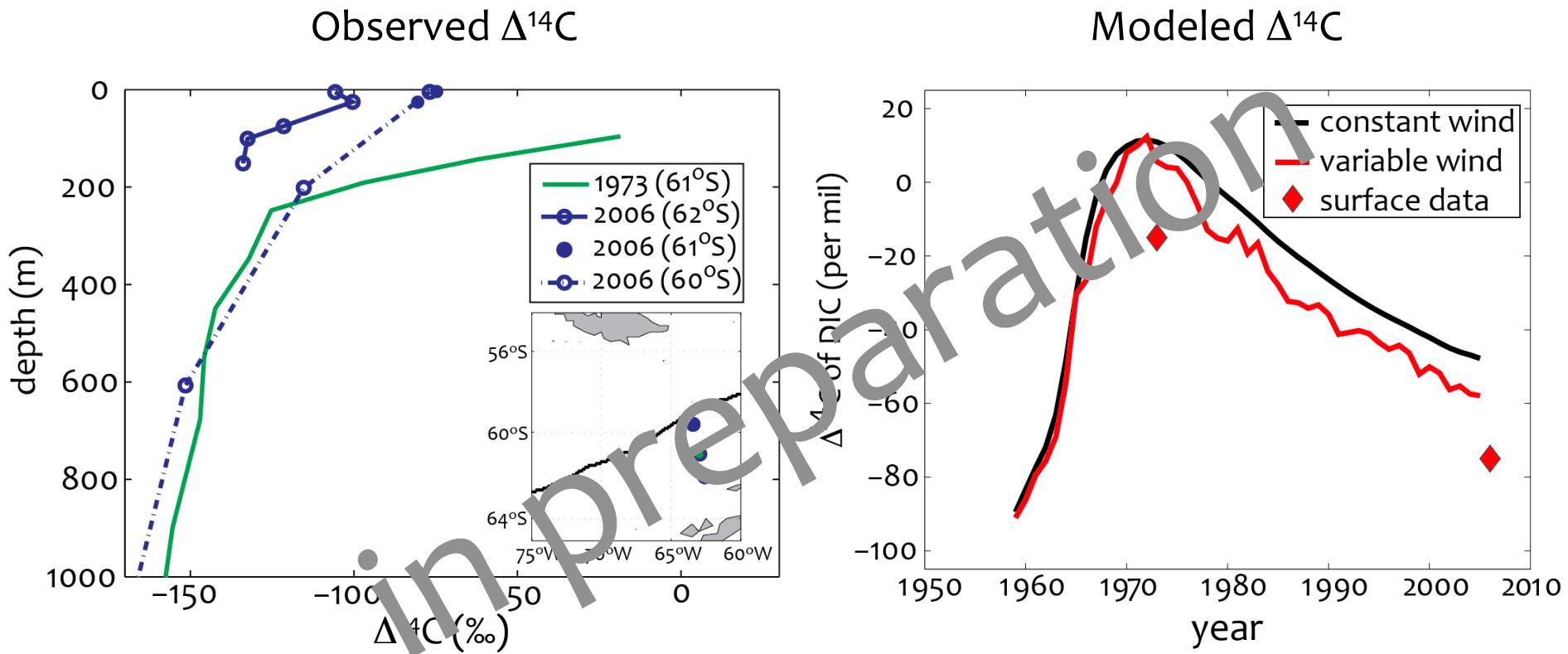
1. Is the model-predicted CO₂ flux trend real?
2. Has meridional overturning increased?
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CFC-12 changes

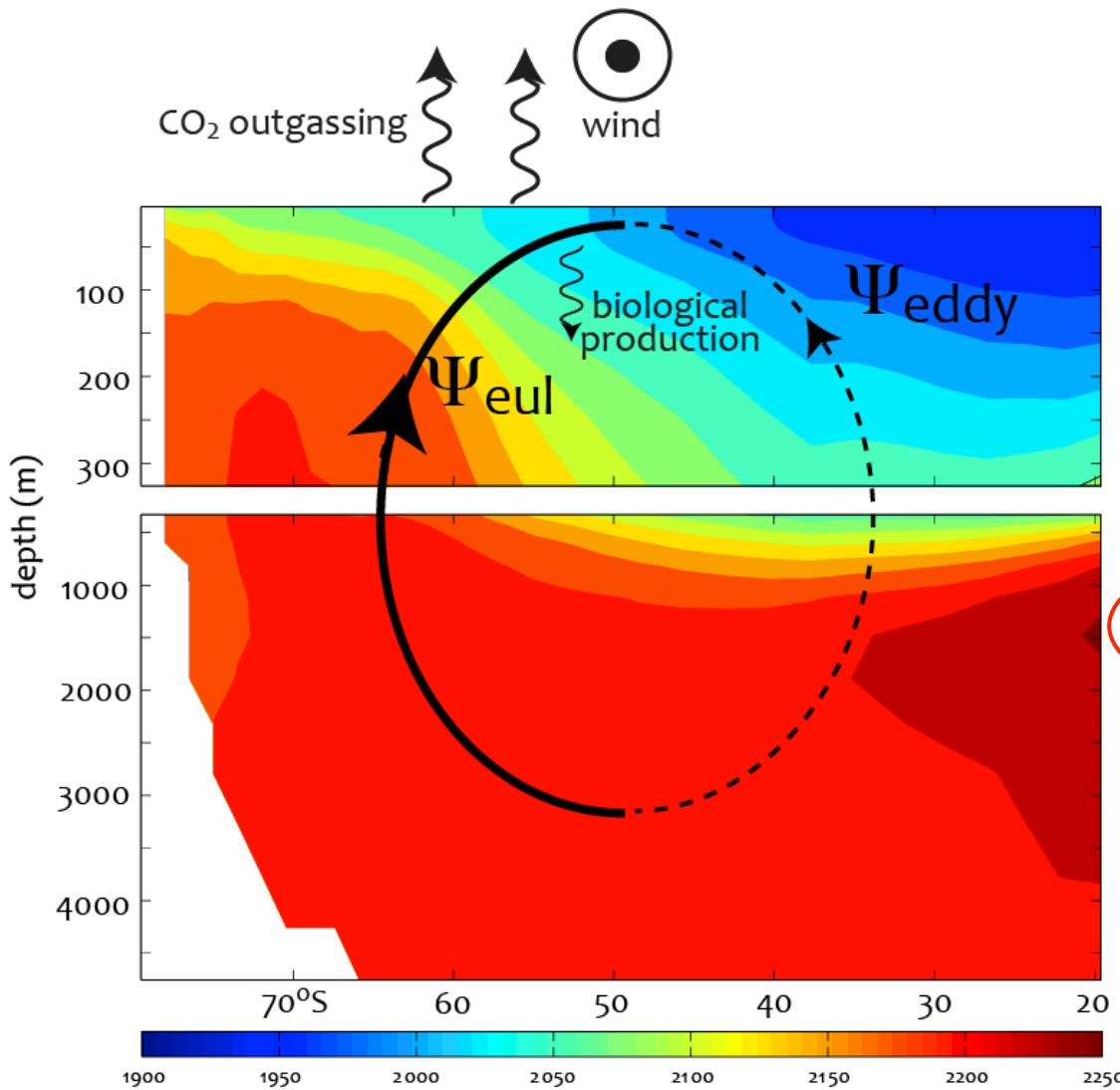
Change due to changing circulation, early 1990's to late 2000's



$\Delta^{14}\text{C}$ changes in Drake Passage



Observing the mechanism

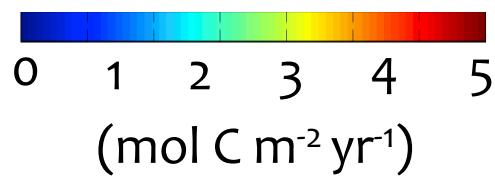
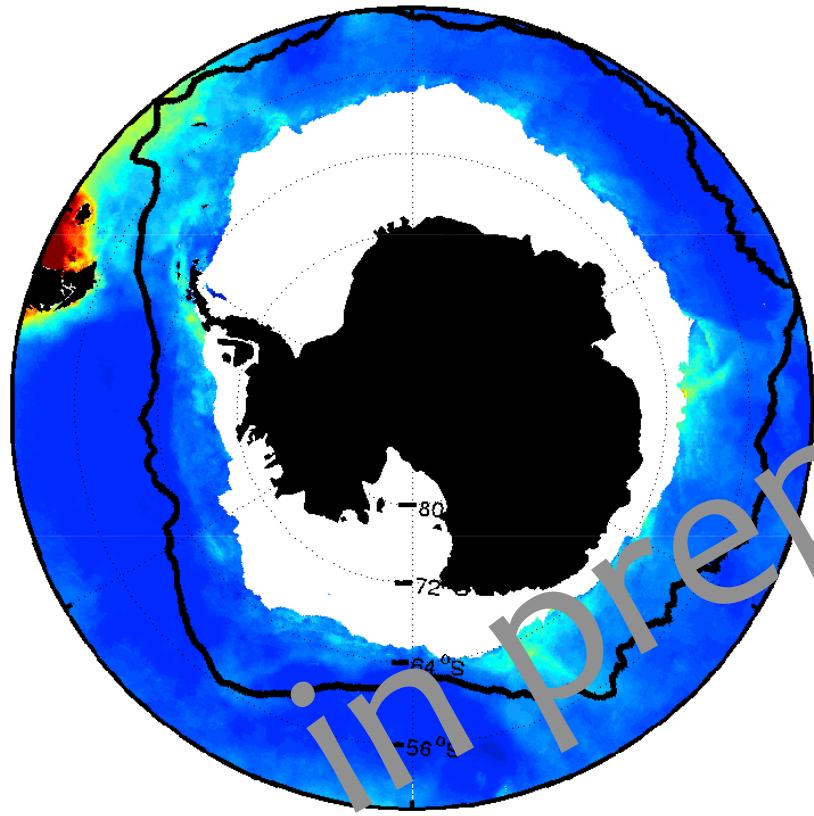


1. Is the model-predicted CO₂ flux trend real?
2. Has meridional overturning increased?
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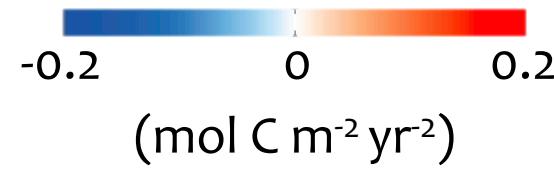
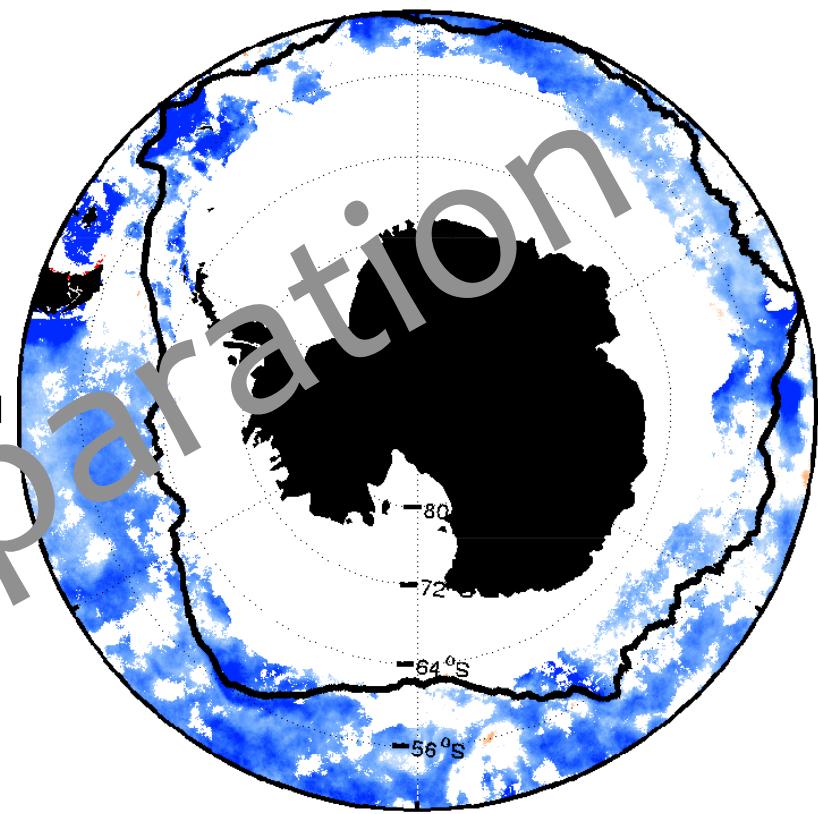
Net community production

2003 - 2011

annual mean

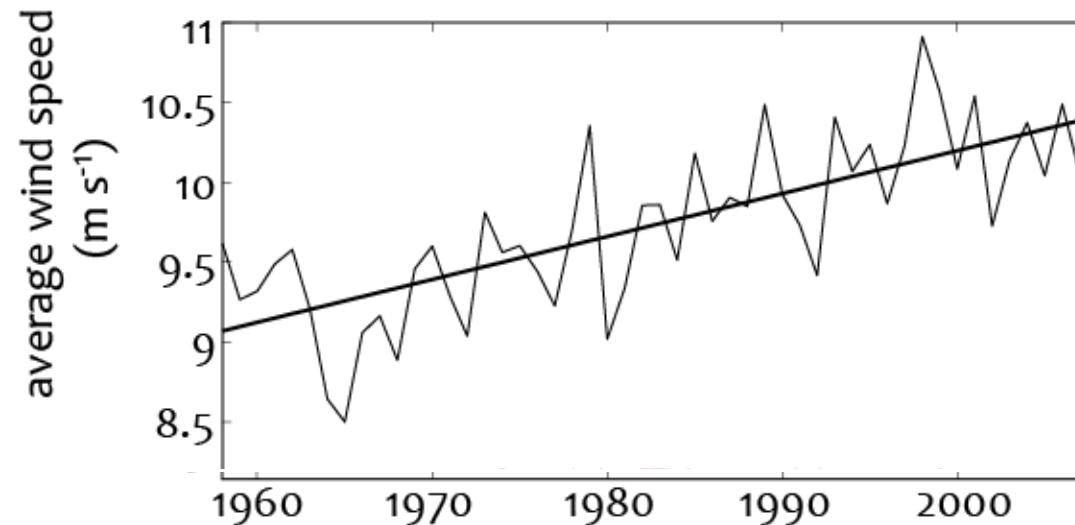


trend



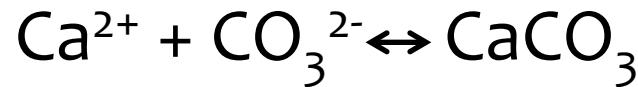
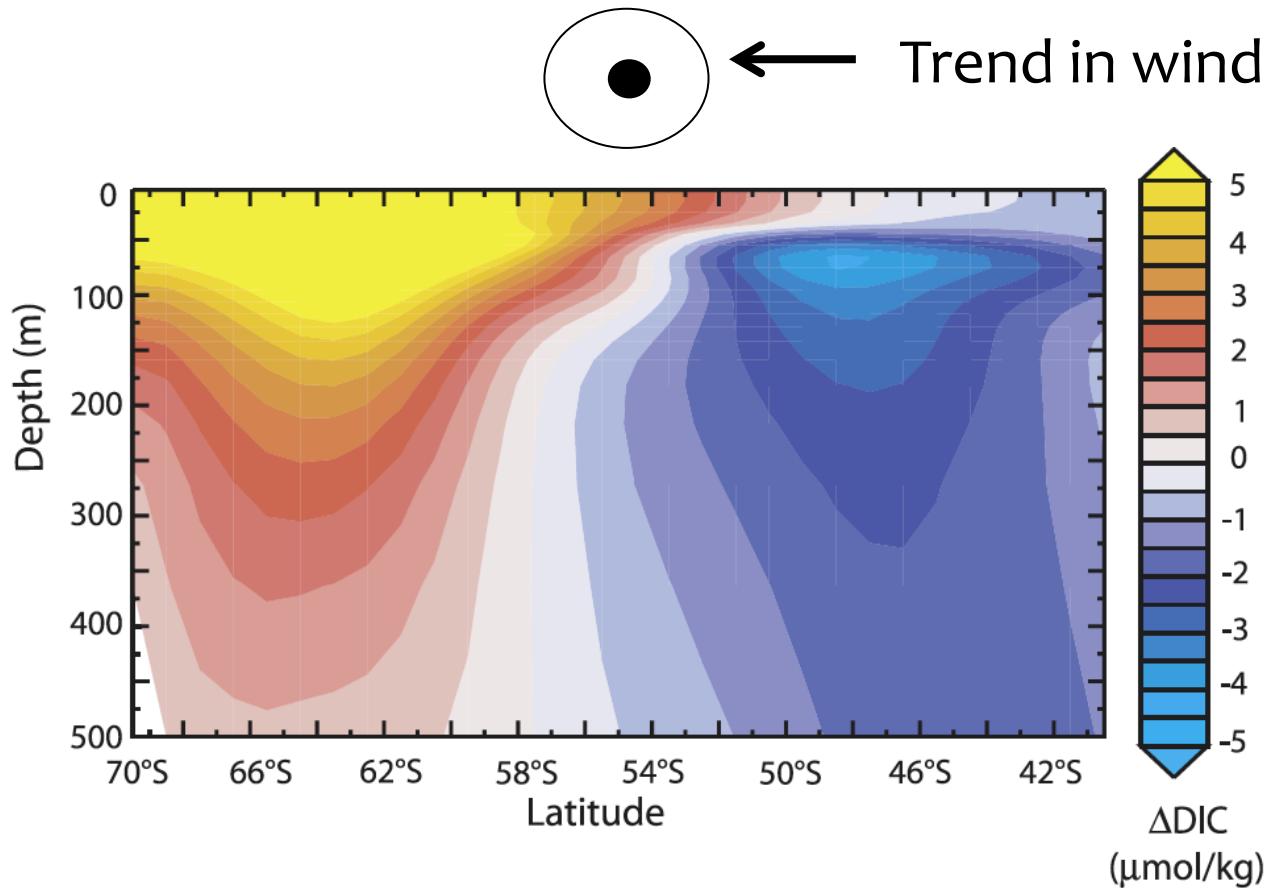
Munro et al. (in prep.)

If the wind is increasing....



1. What impact will this have on surface ocean carbonate chemistry and the rate of acidification?
2. Will this affect the rate of biological calcification?

Modeled changes in CaCO_3 saturation

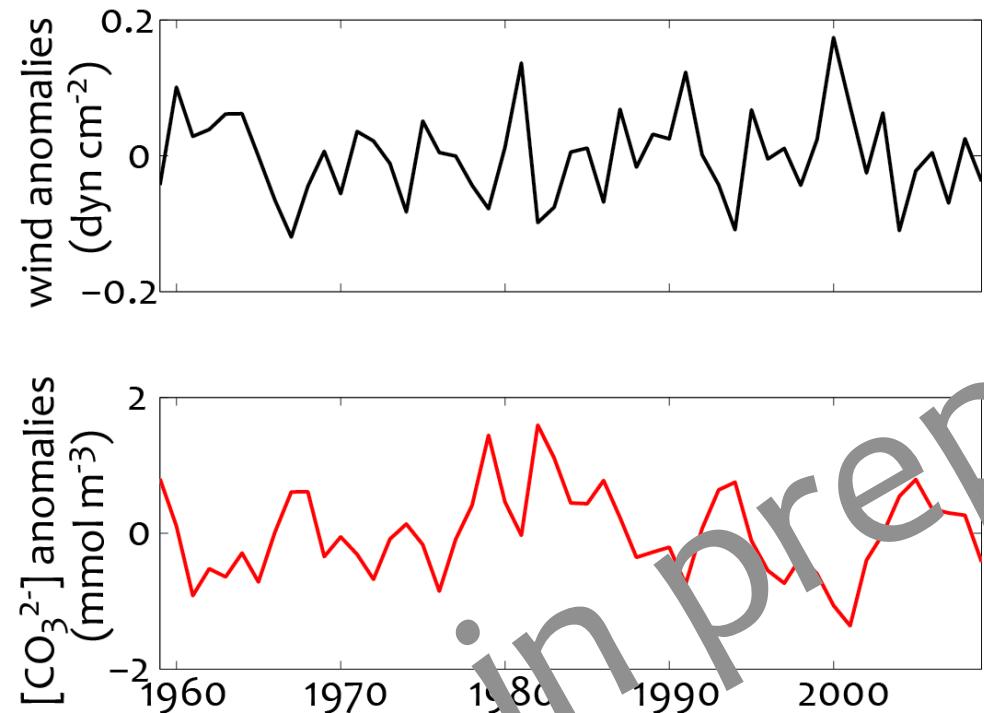


$$[\text{CO}_3^{2-}] \approx \text{Alk} - \text{DIC}$$

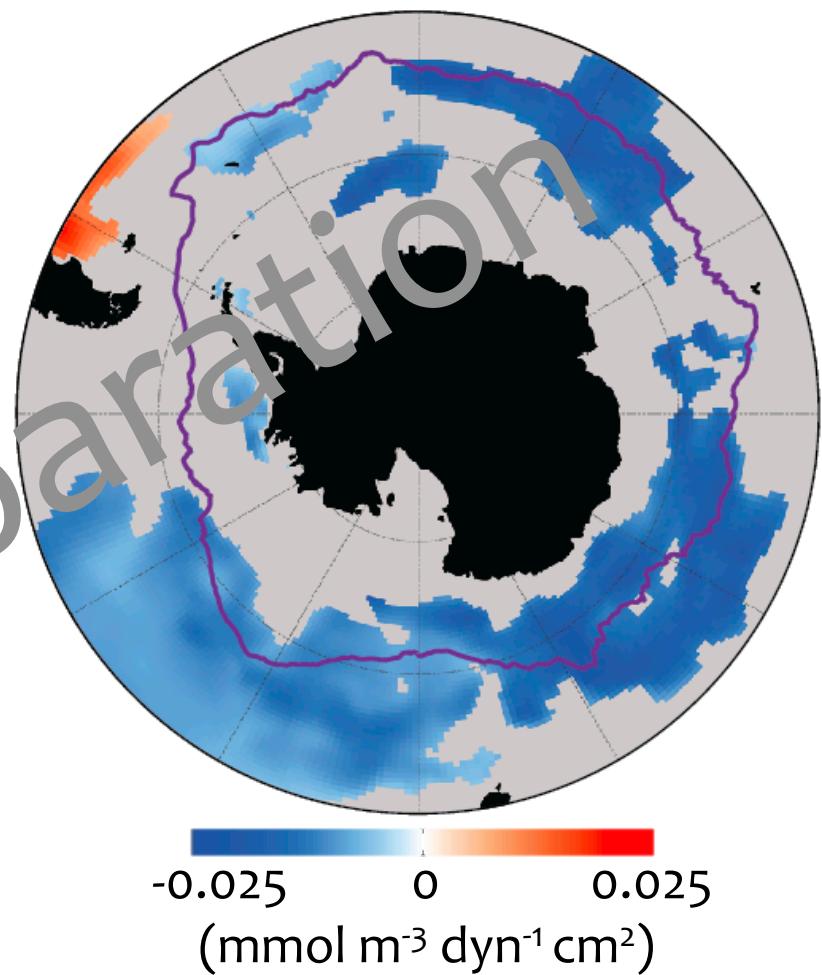
Lenton et al. (2009)

Wind variability and surface $[CO_3^{2-}]$

Southern Ocean averaged
wind and $[CO_3^{2-}]$

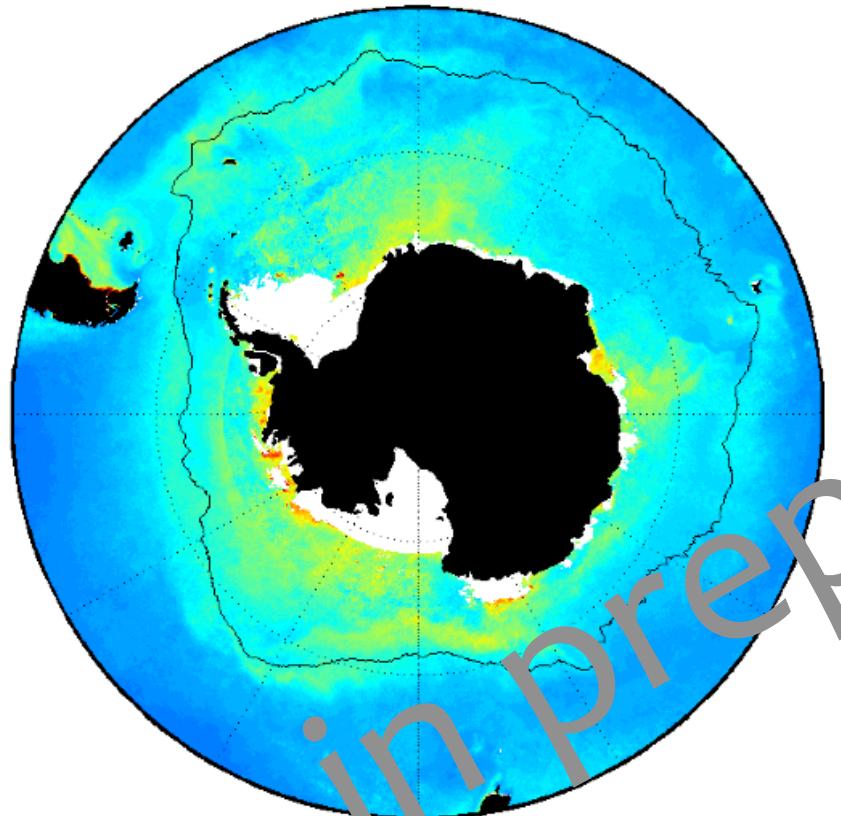


Wind – $[CO_3^{2-}]$ regression

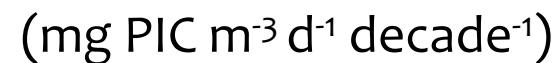
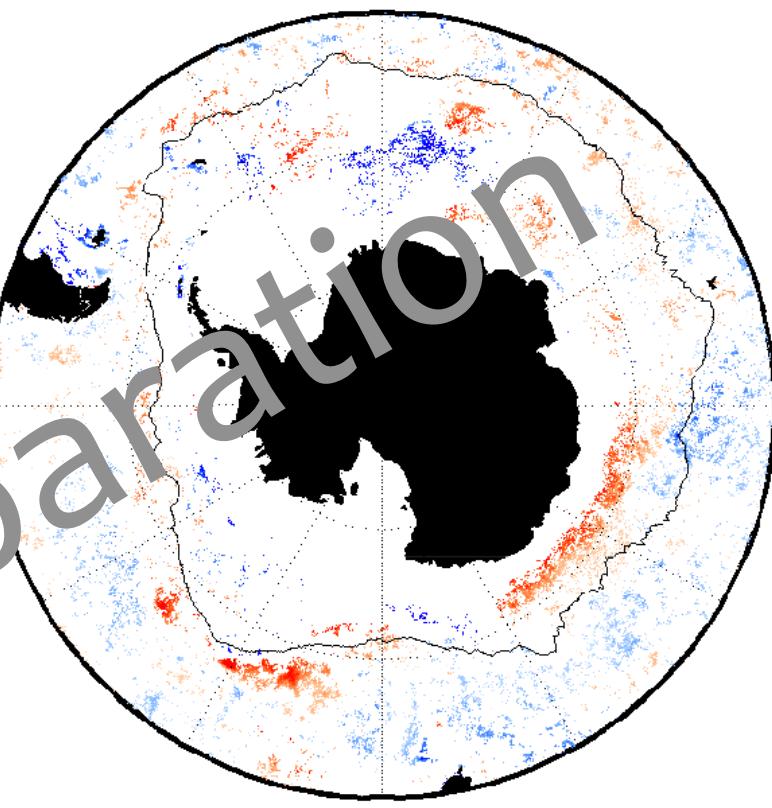


Calcification rate, 2003-2013

Summertime mean



Summertime trend



Conclusions

Known knowns:

- Southern Ocean is a sink for atmospheric CO₂
- Models indicate high variability and significant trends in sea-air flux of natural CO₂ from the Southern Ocean
- Models indicate that wind drives variability and trends in CO₂ flux, via changes in circulation and surface DIC

Known unknowns:

- Observed CO₂ flux trends?
- Observed trends in meridional overturning?
- Observed trends in biological production?
- Wind-driven changes in ocean acidification and biological calcification?

The End!