Carbon in the Southern Ocean: Known knowns and known unknowns

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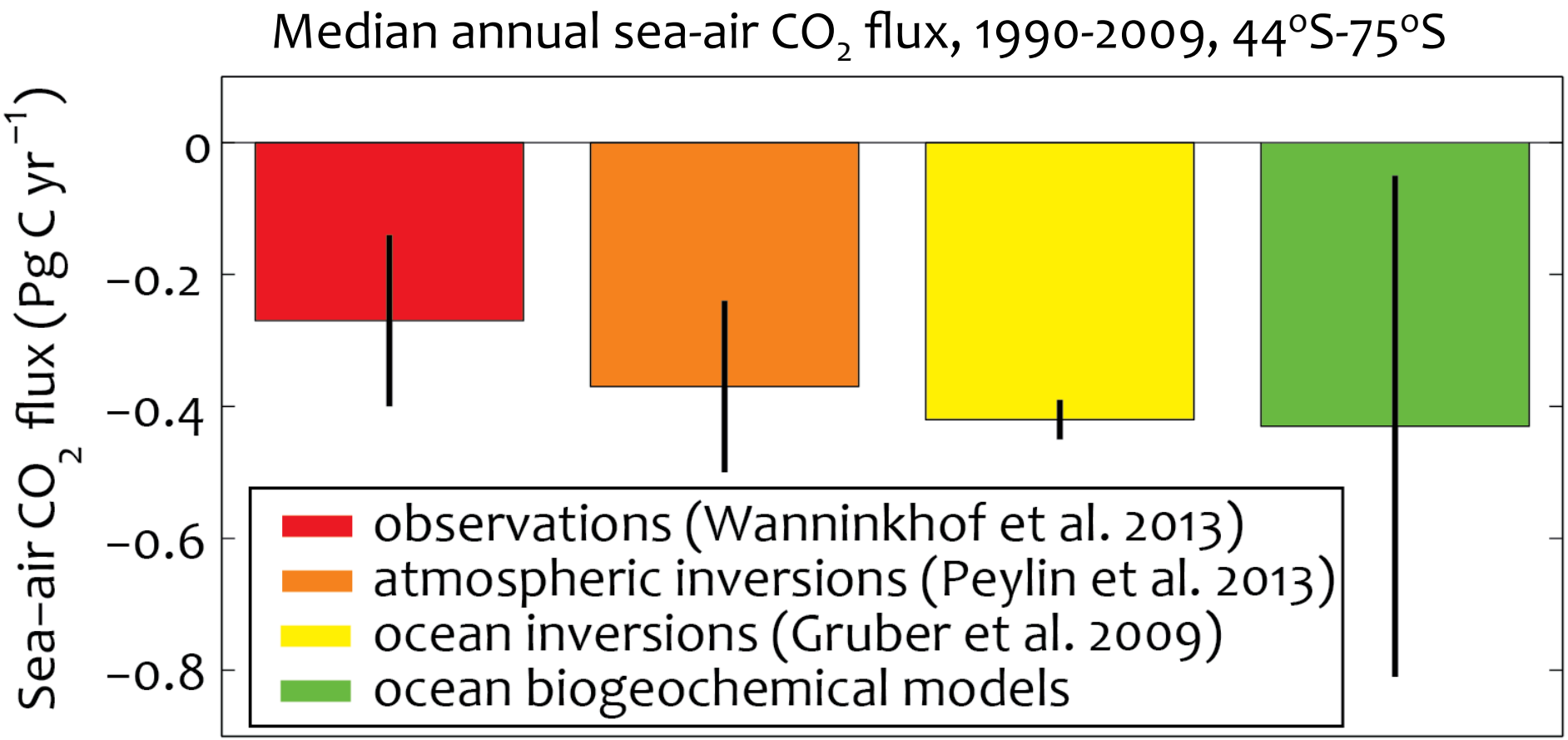
Part I:
Known knowns

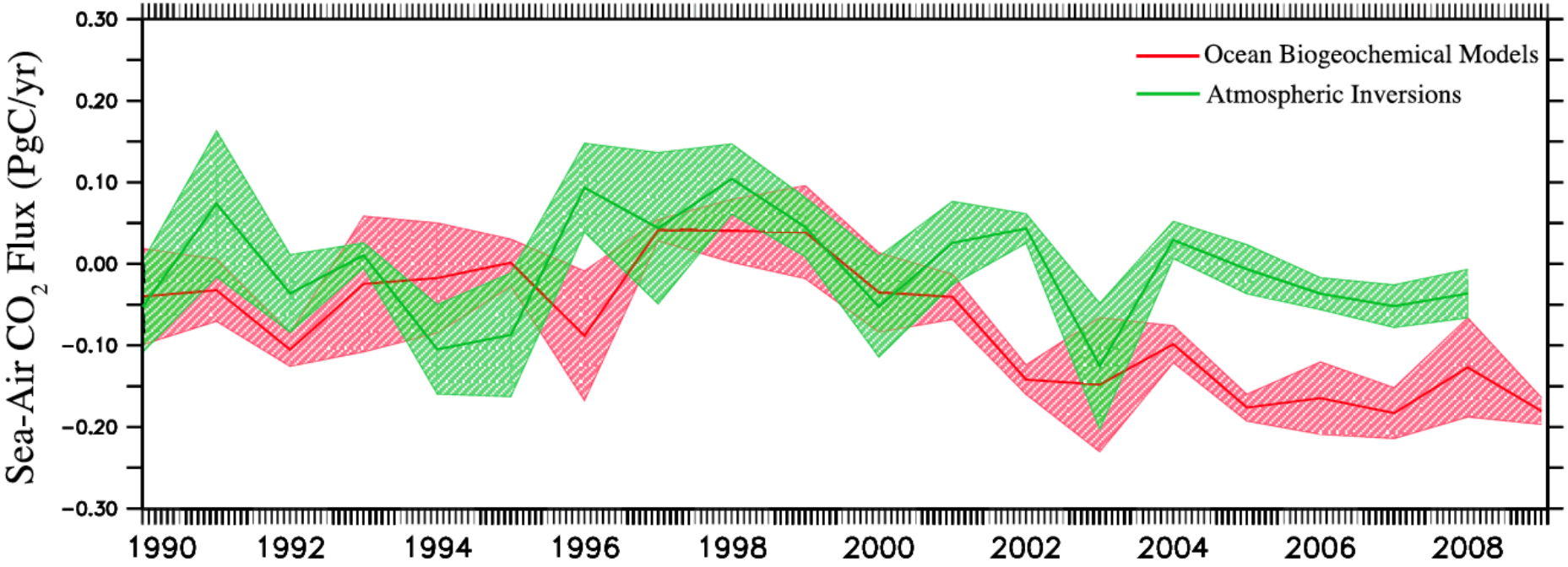
Southern Ocean is a sink for atmospheric CO_2



data from Lenton et al. (2013)

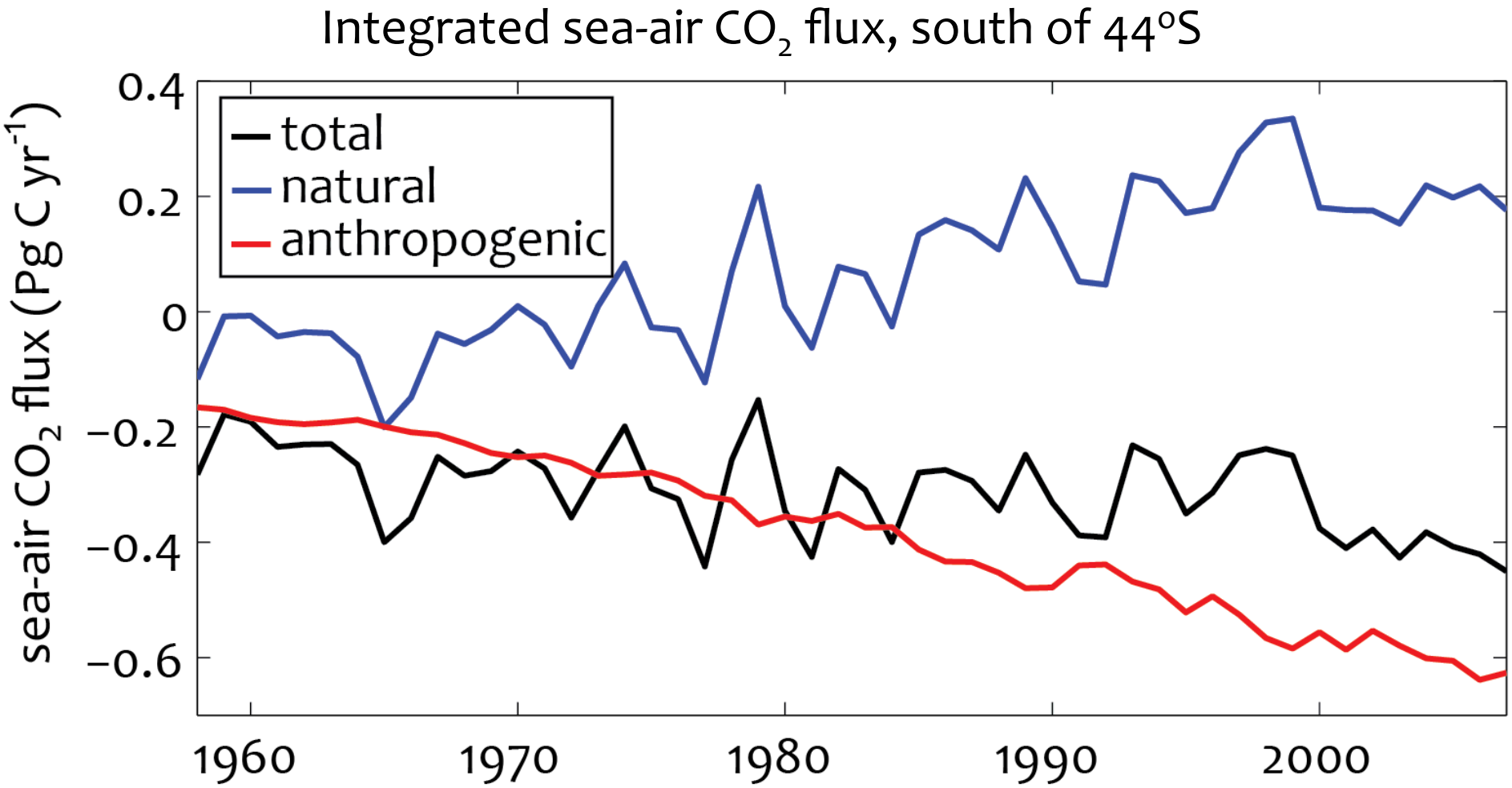
Southern Ocean has large CO_2 flux variability

Integrated sea-air CO_2 flux, 44°S-75°S



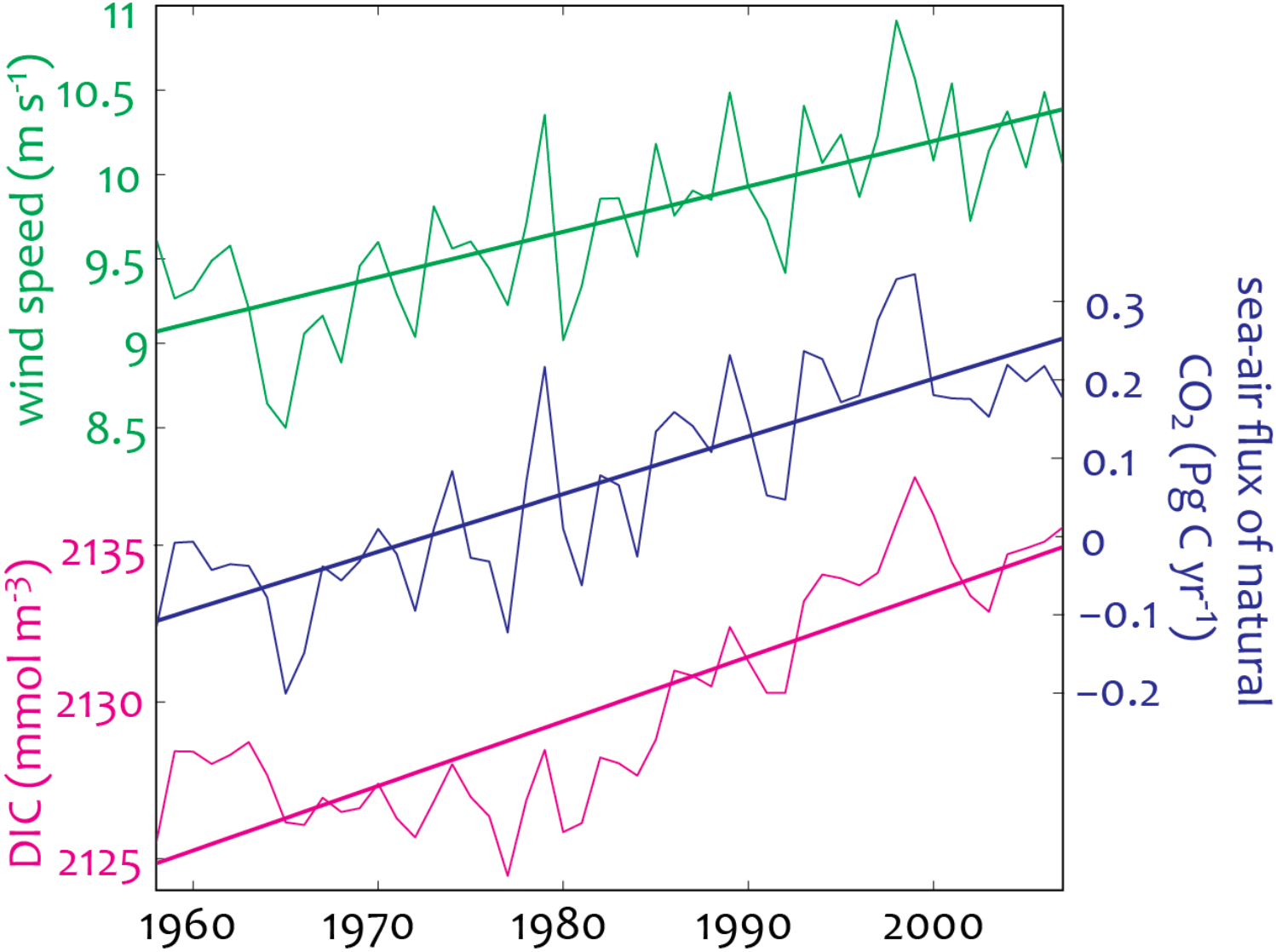
Lenton et al. (2013)

Total CO_2 flux variance ≈ Natural CO_2 flux variance



Lovenduski et al. (2013)

Wind drives natural CO_2 flux variability

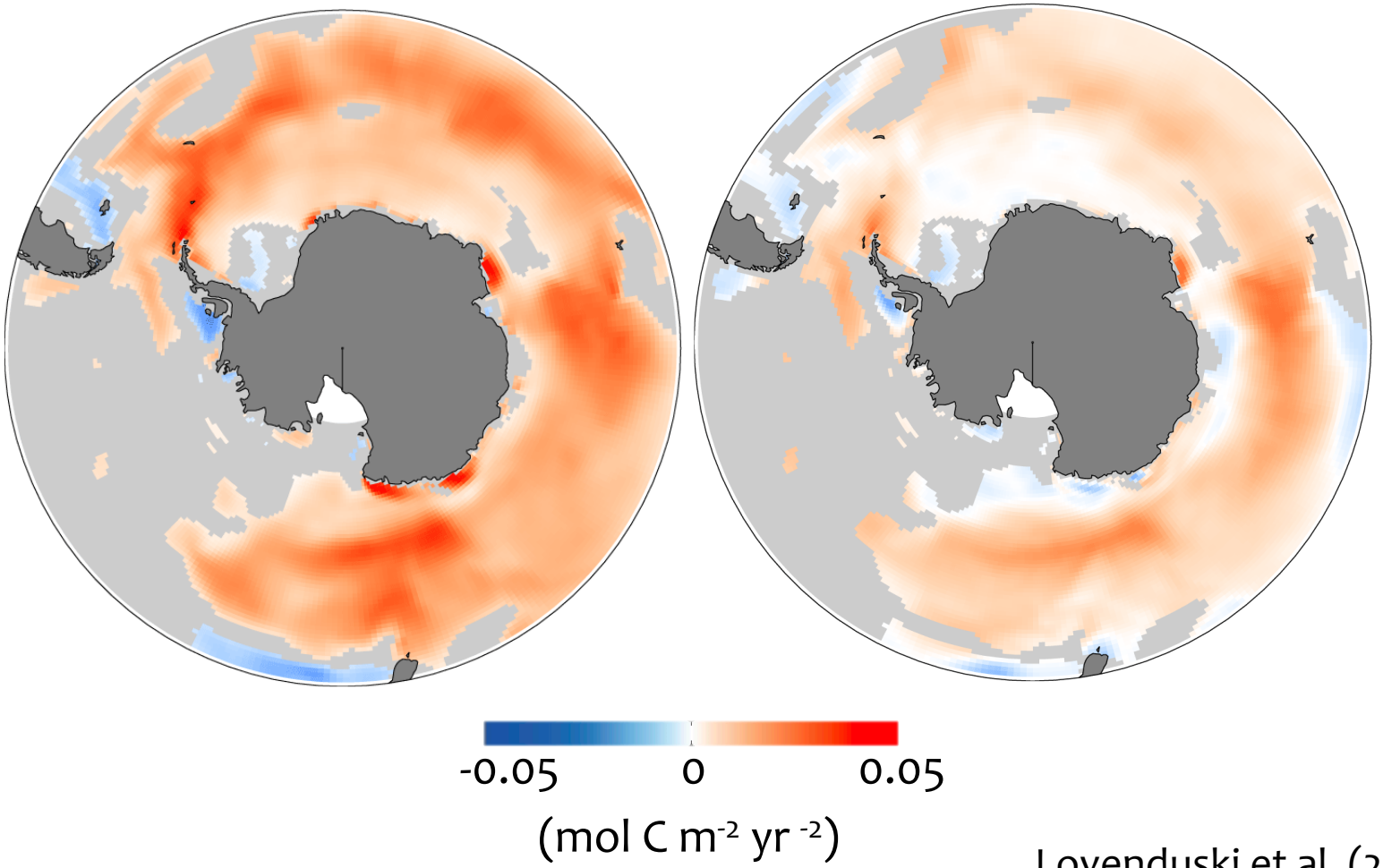


Lovenduski et al. (2013)

Wind drives natural CO_2 flux trend

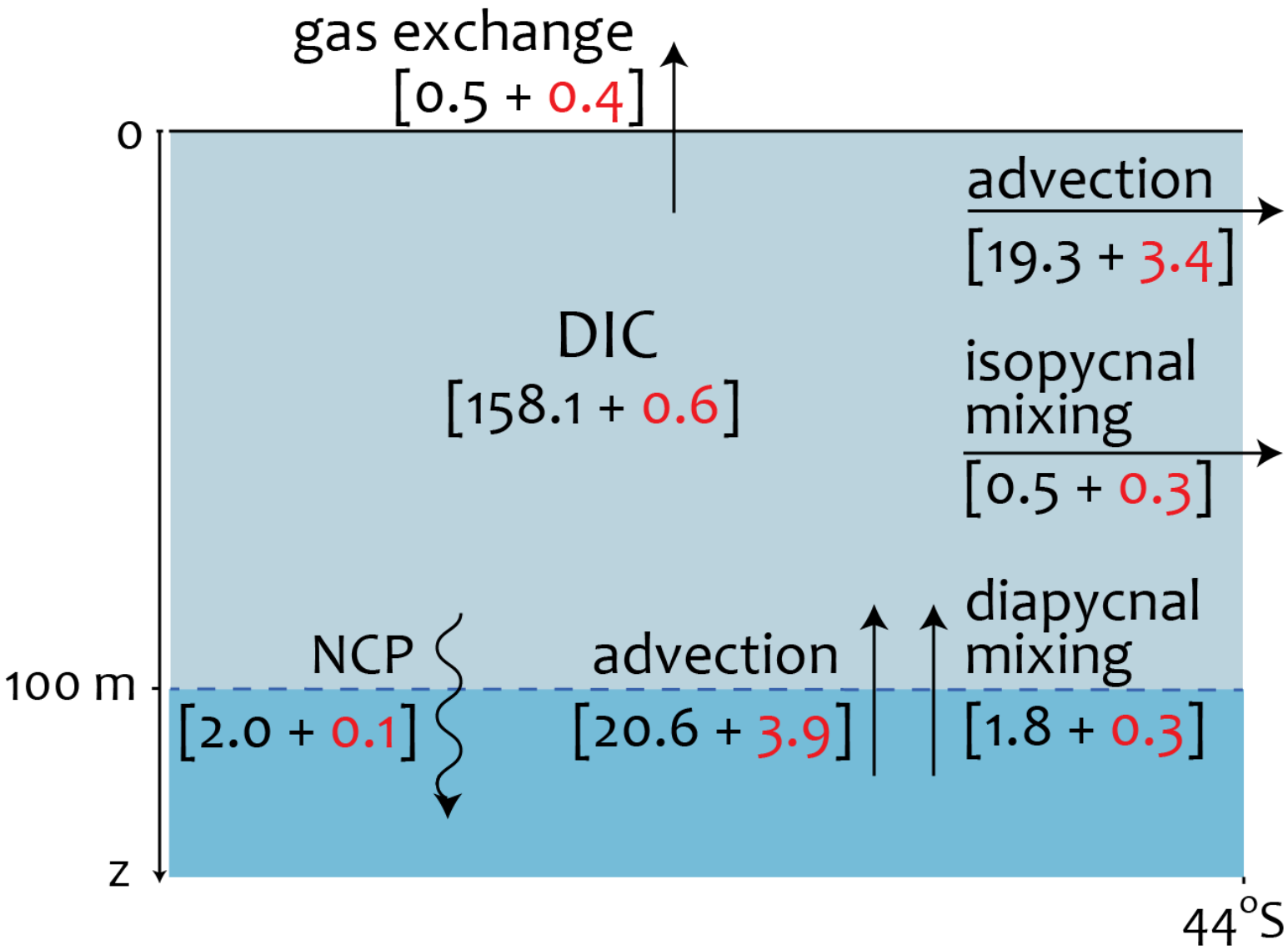
Linear trend
1958-2007

Trend congruent
with wind



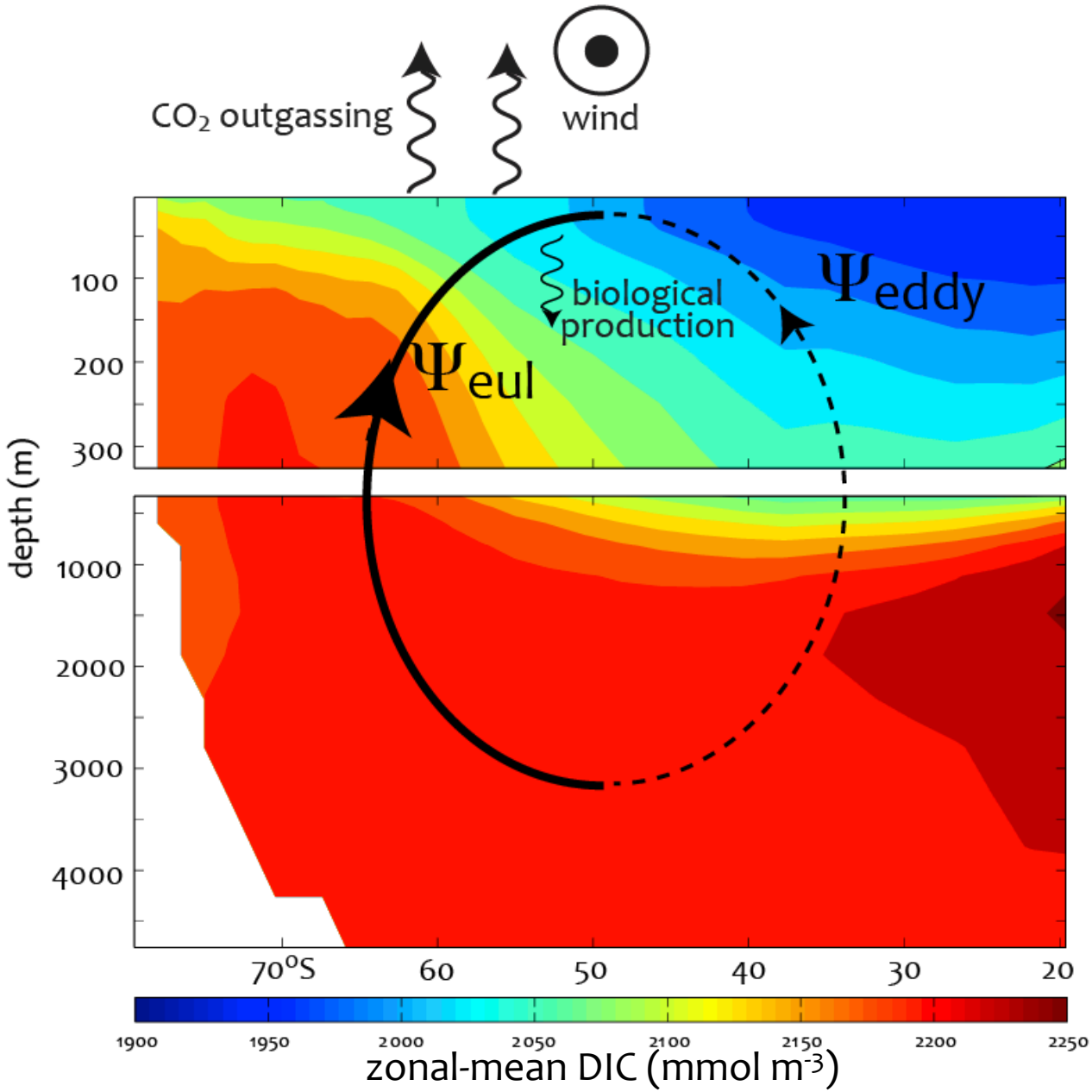
Lovenduski et al. (2013)

Stronger wind = higher surface DIC

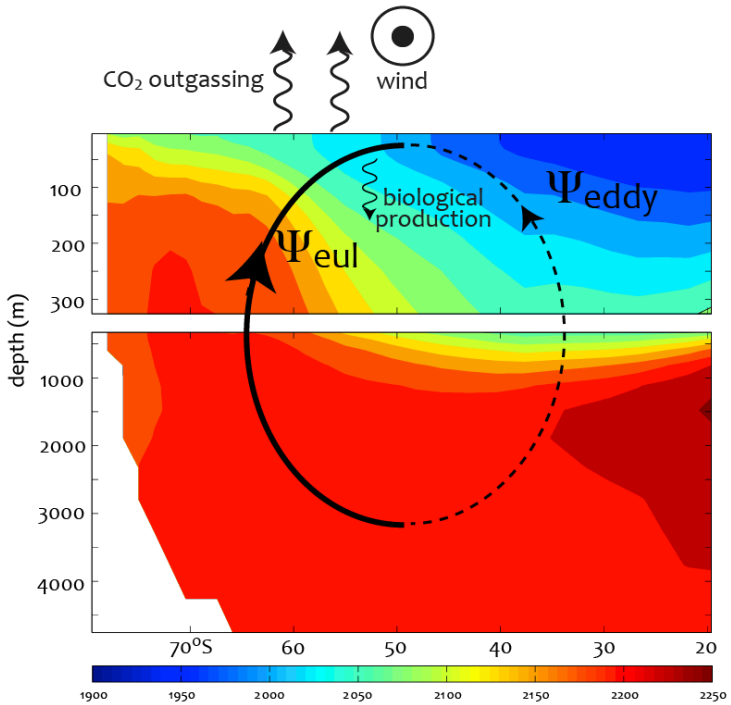


Lovenduski et al. (2013)

Mechanism


CO2 outgassing
wind
biological production
Ψeddy
Ψeul
depth (m)
100
200
300
1000
2000
3000
4000
70°S
60
50
40
30
20
1900
1950
2000
2050
2100
2150
2200
2250
zonal-mean DIC (mmol m-3)

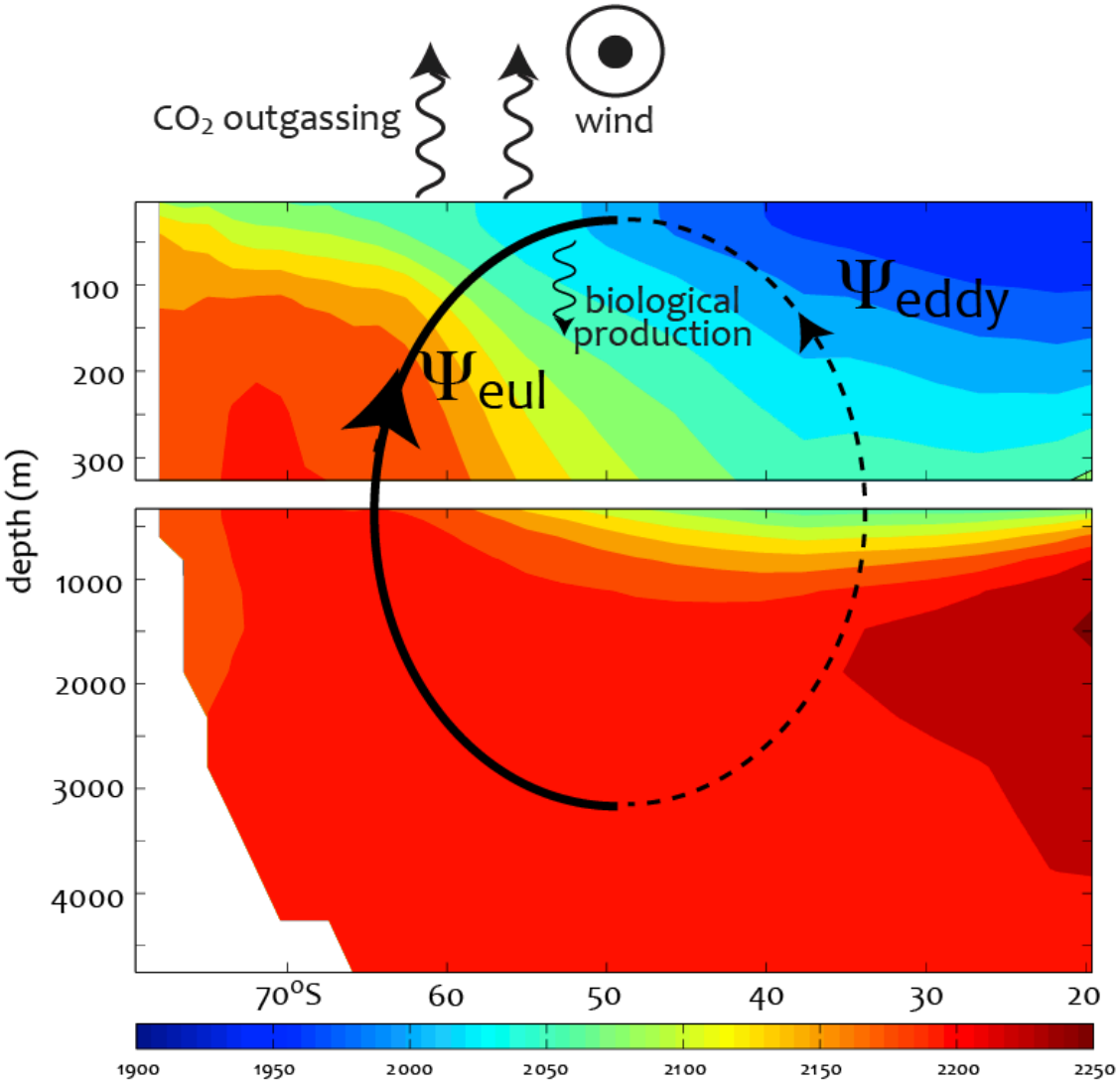
Corroborating model results



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	Menviel et al. 2008
MITgcm	Lovenduski and Ito 2009
NASA GISS	Romanou et al. 2013
UVic	Zickfeld et al. 2007

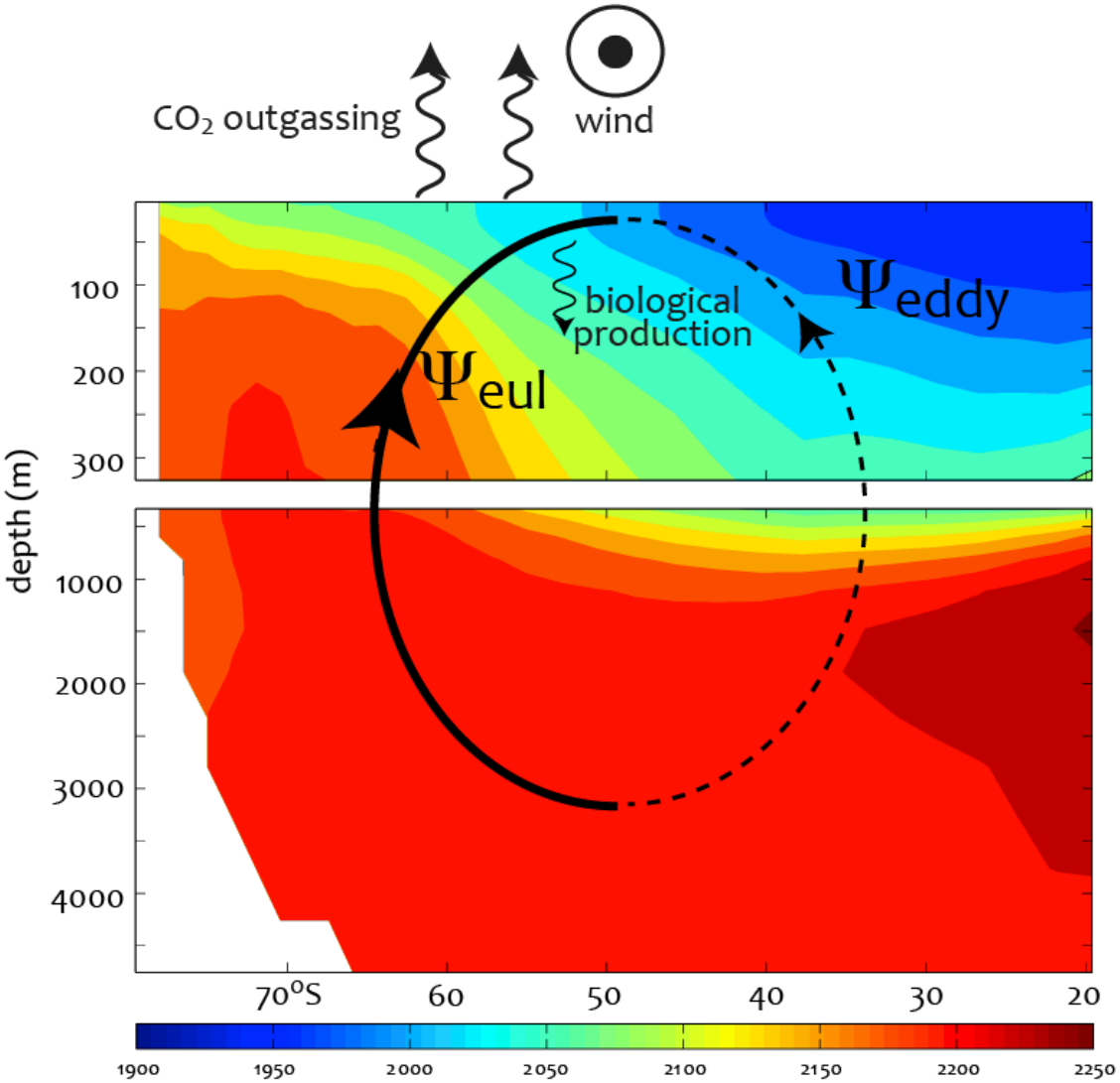
Part II:
Known unknowns

Observing the mechanism



1. Is the model-predicted CO_2 flux trend real?
2. Has meridional overturning increased?
3. Has biological production changed?

Observing the mechanism



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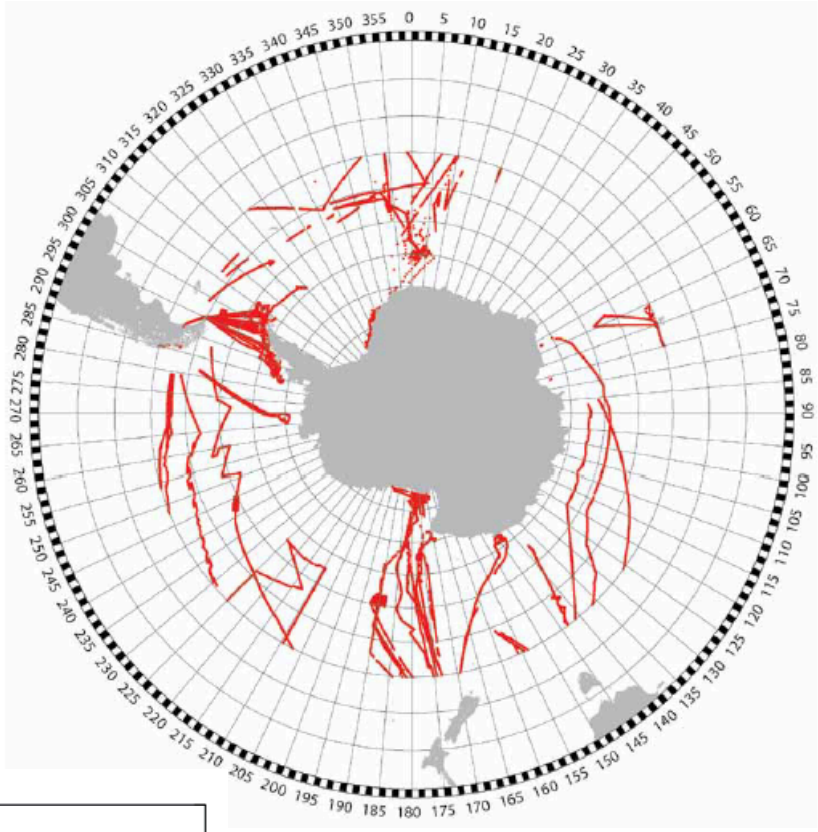
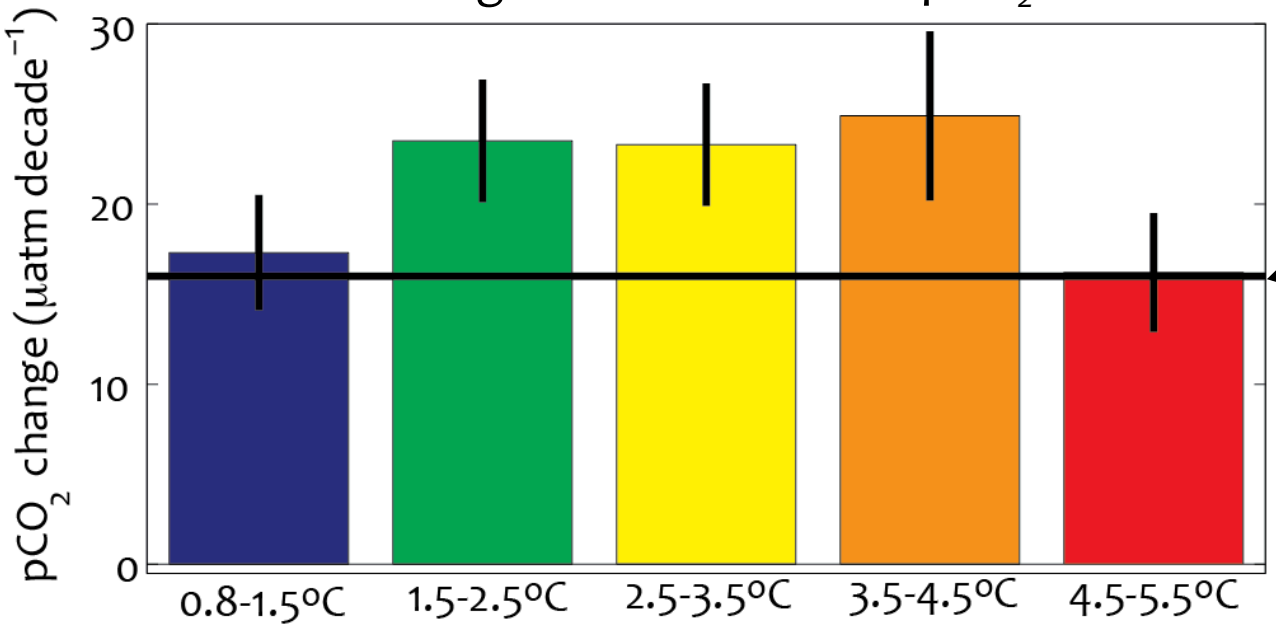
Observed wintertime pCO_2 changes 1986-2010

Wintertime data locations →



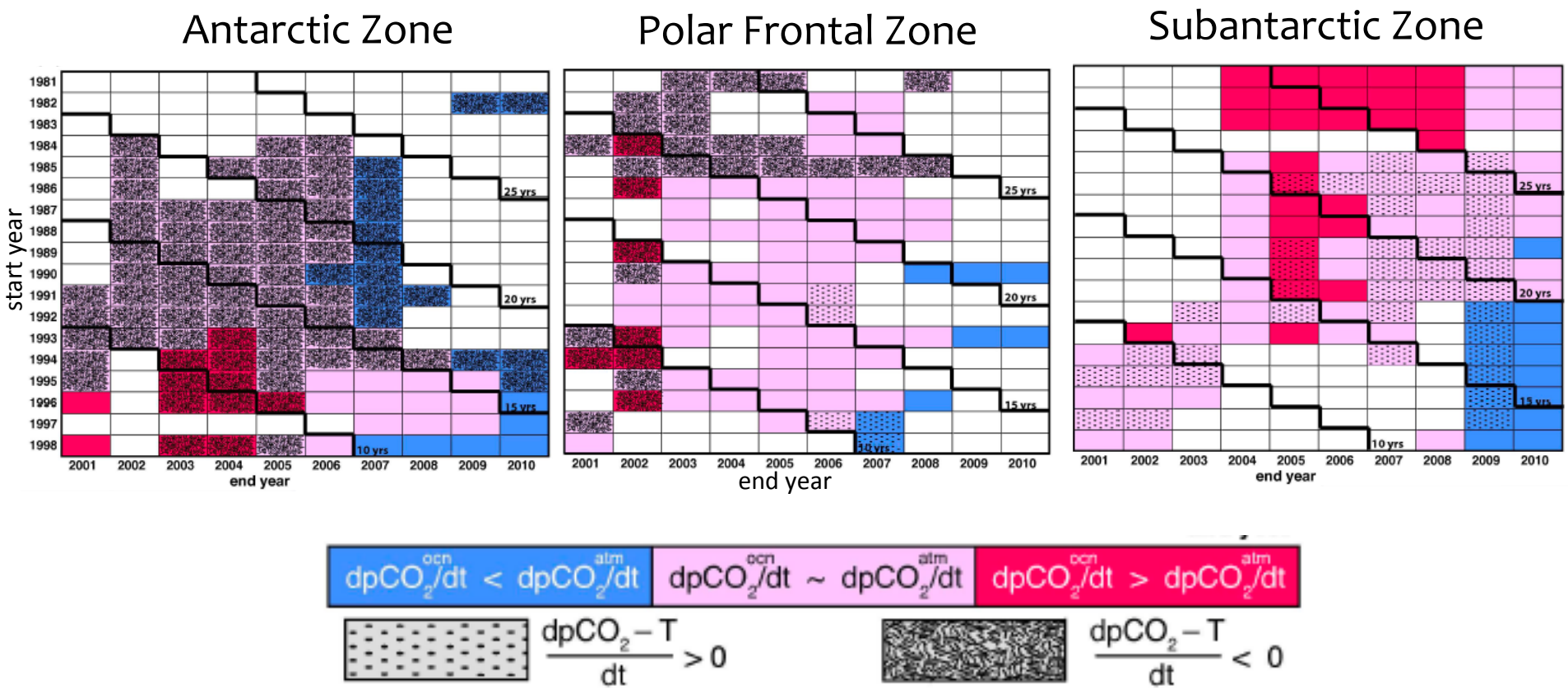
Change in surface ocean pCO_2



Change in atmospheric pCO_2

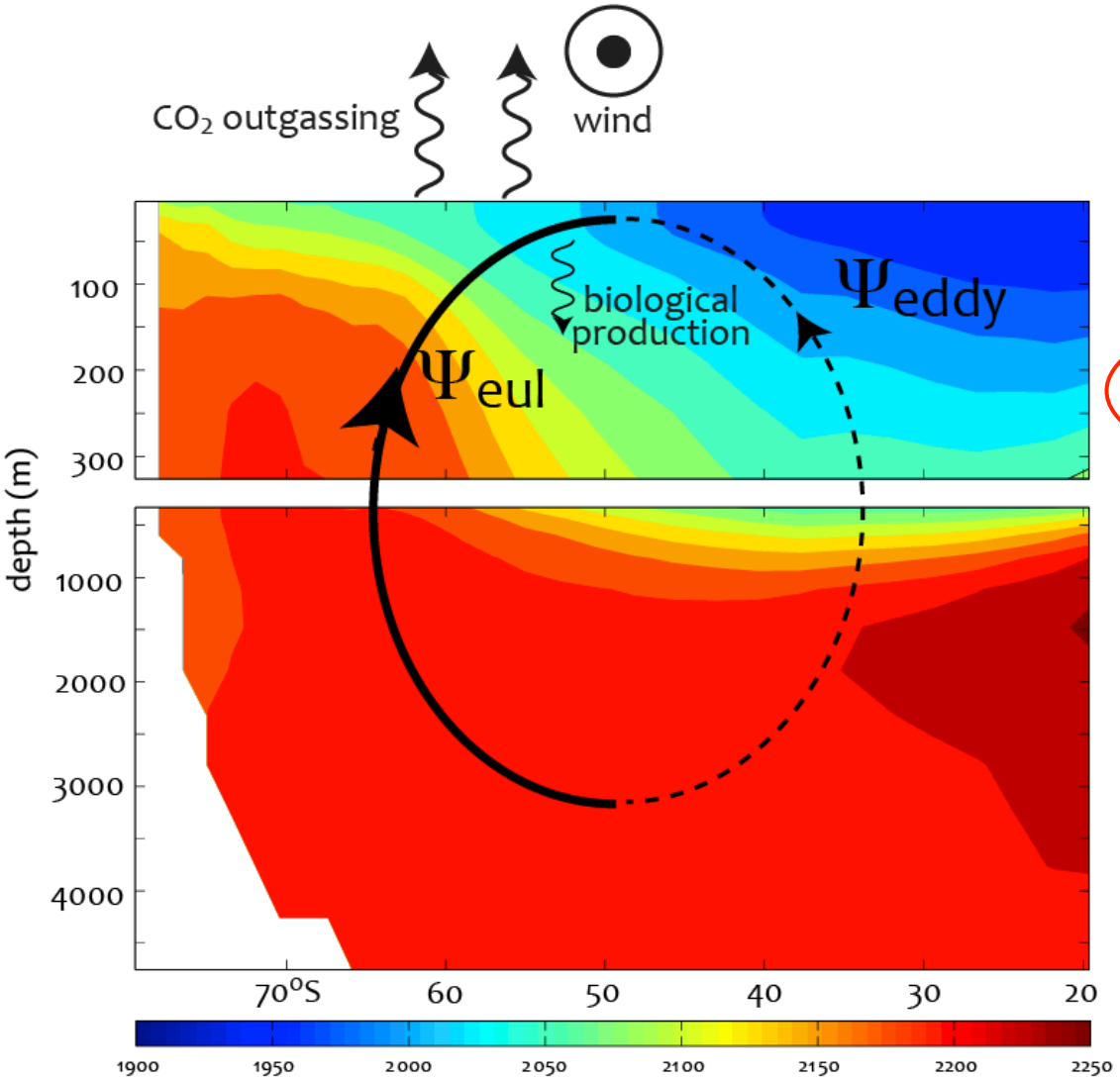
data from Takahashi et al. (2012)

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



Fay and McKinley (2013)

Observing the mechanism



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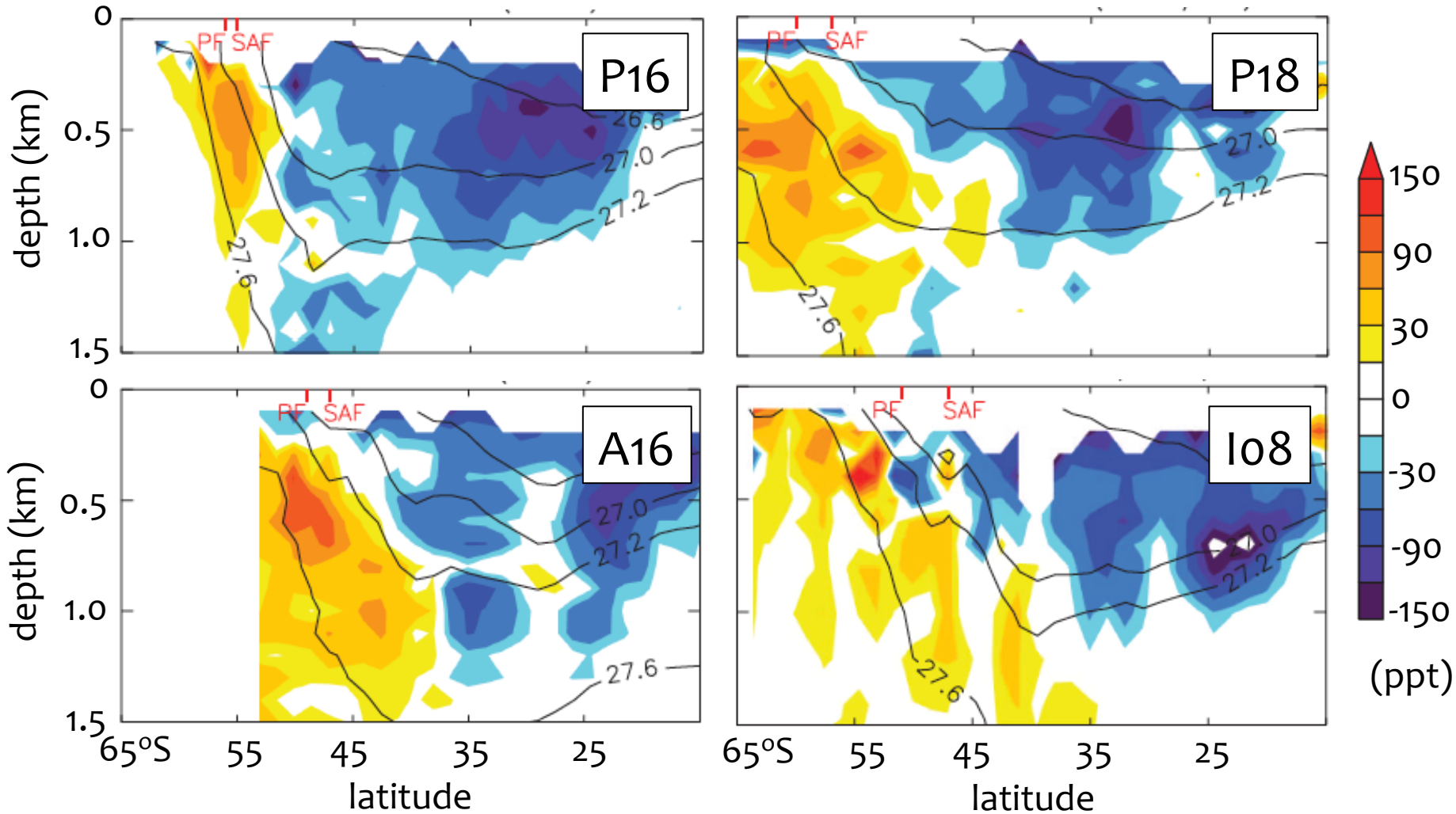
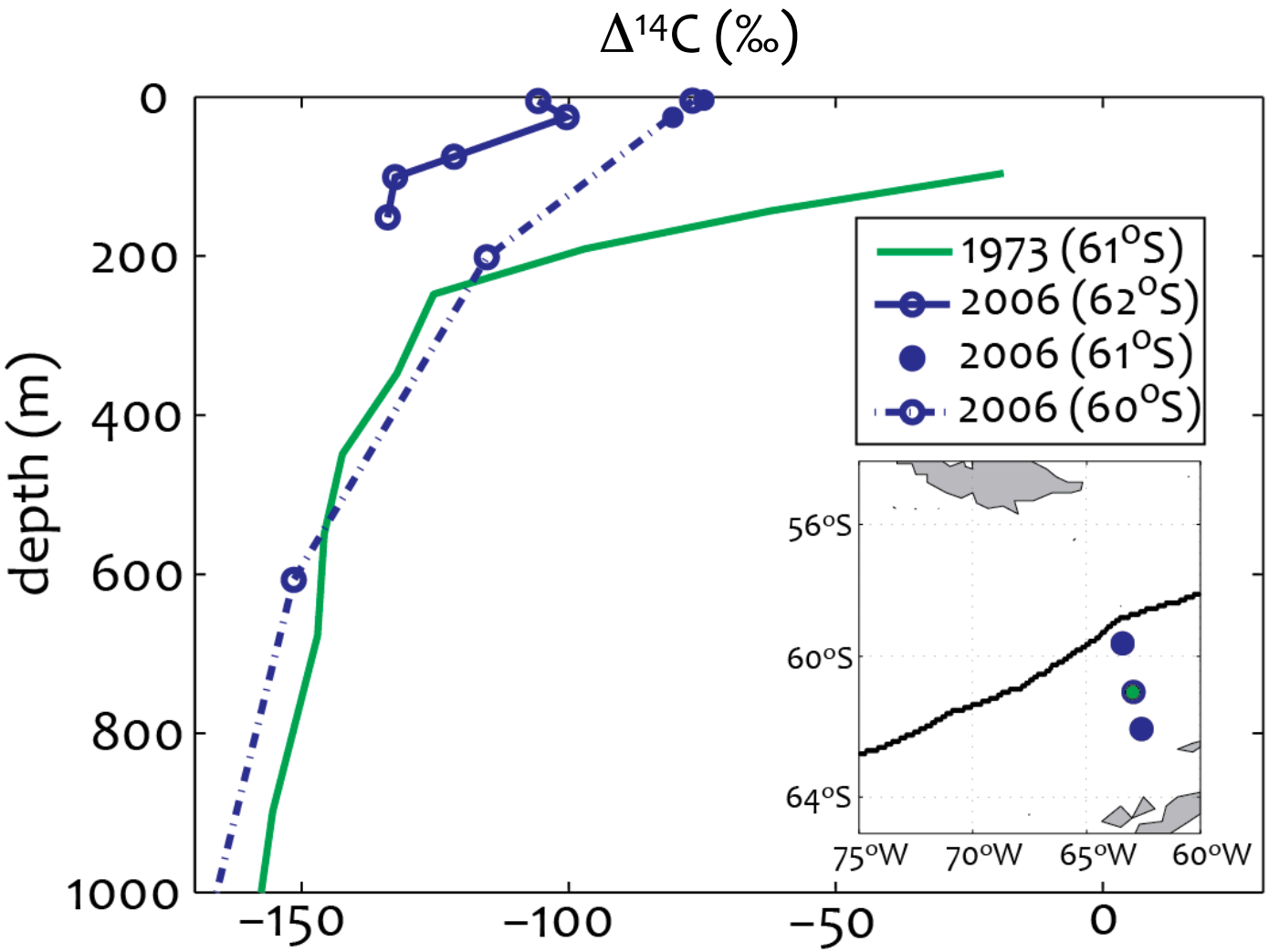
CFC-12 changes

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



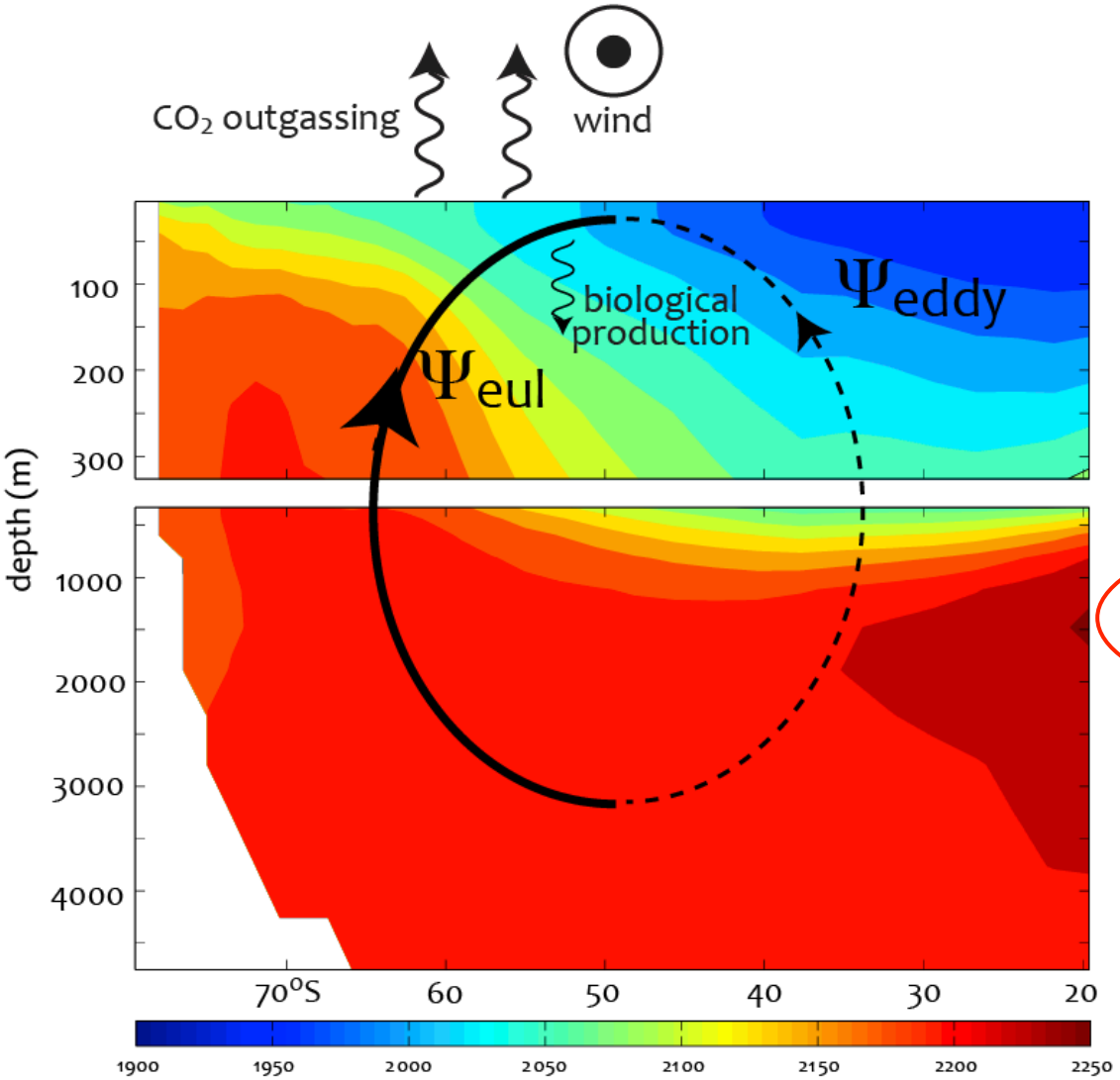
Waugh et al. (2013)

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



Munro et al. (in prep.)

Observing the mechanism



1. Is the model-predicted CO_2 flux trend real?
2. Has meridional overturning increased?
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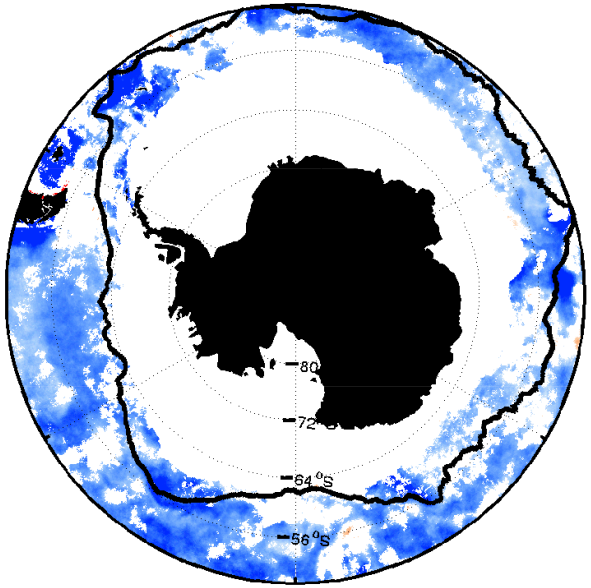
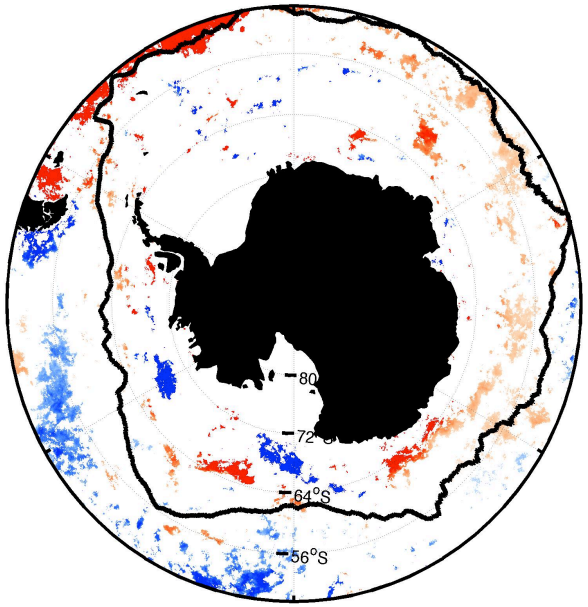
Net community production trends

satellite data, 2003 - 2011

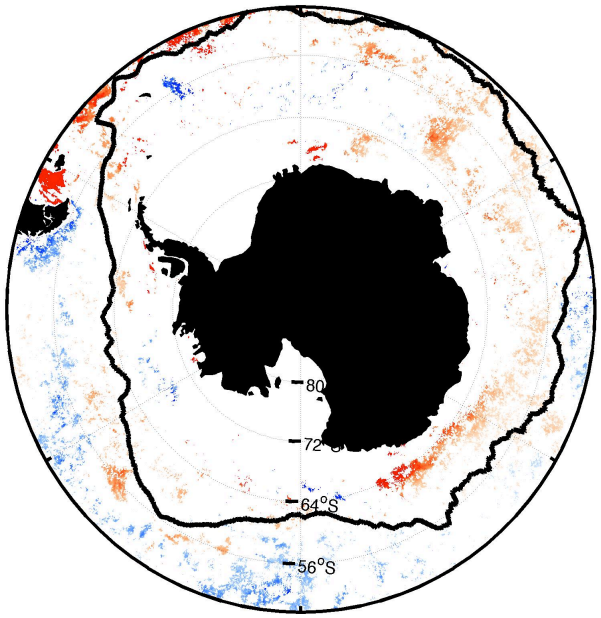
CbPM algorithm



VGPM algorithm



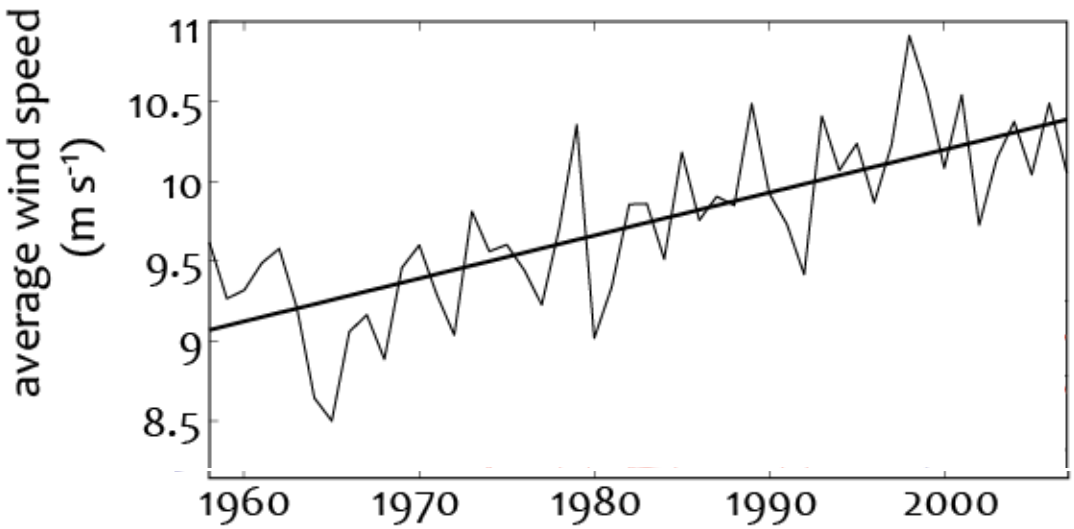
Arrigo algorithm



(mol C m^{-2} yr^{-2})

Munro et al. (in prep.)

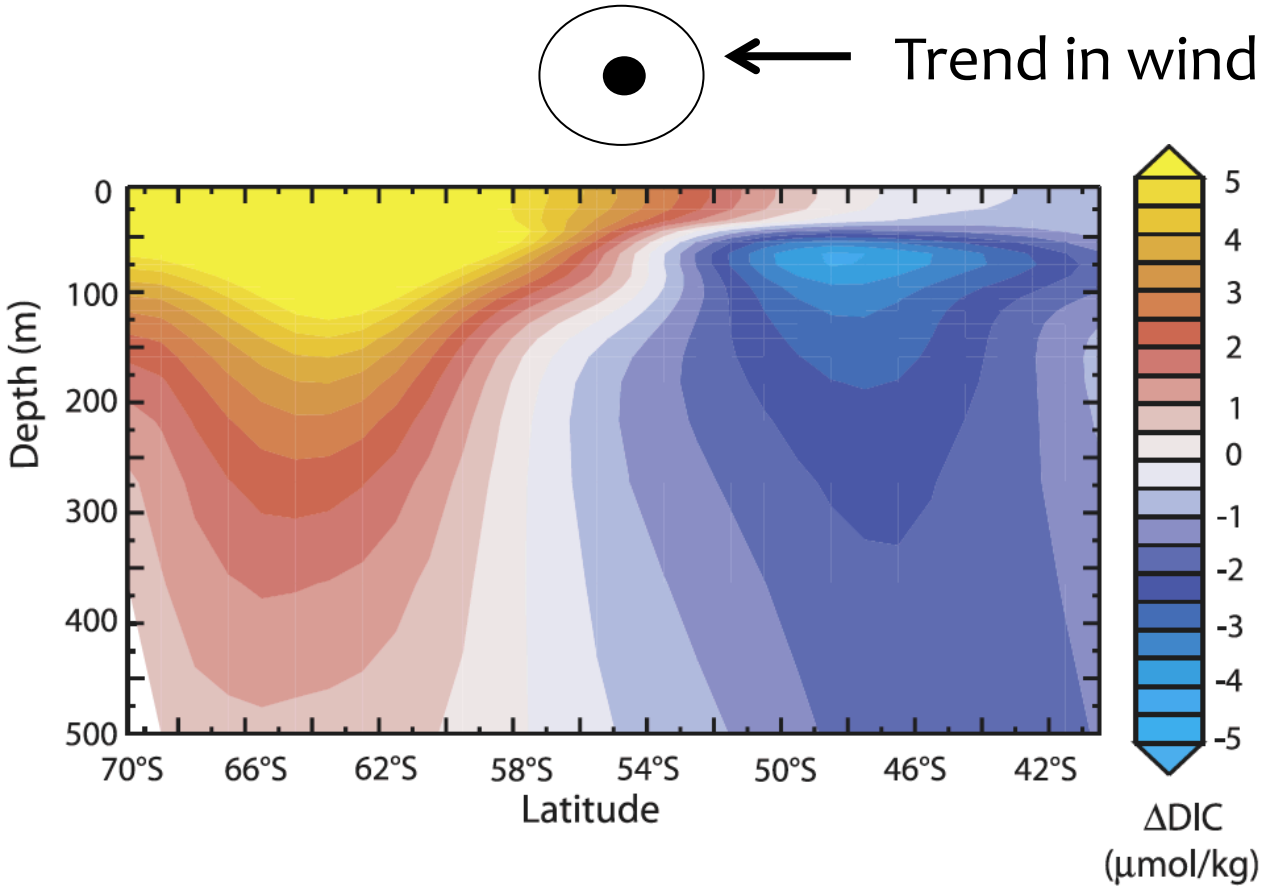
If the wind is increasing….



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



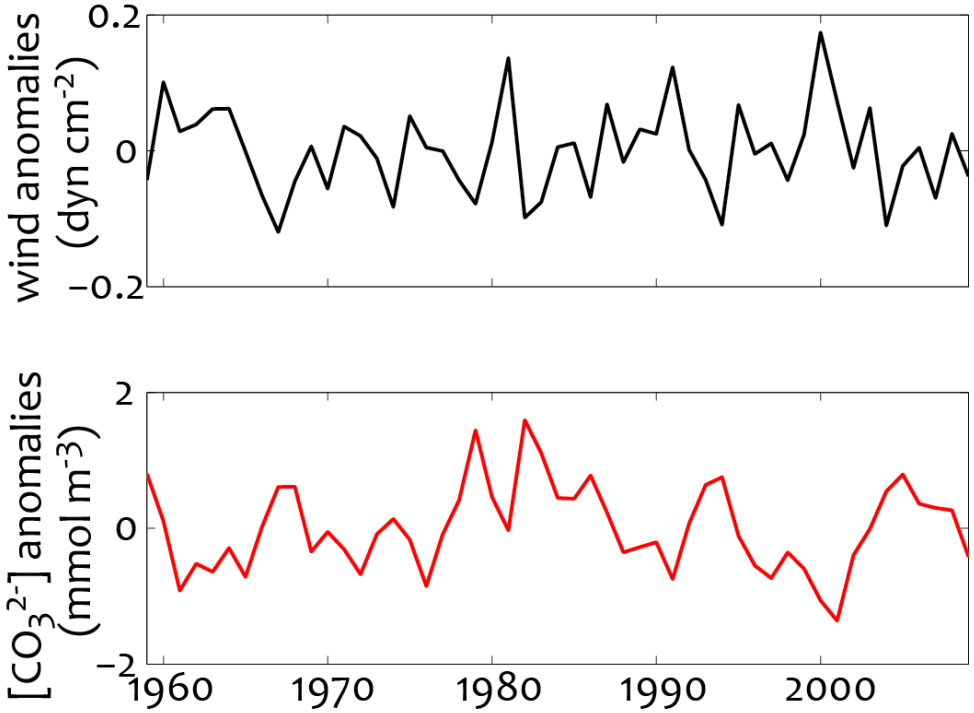
$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$$

$$[CO_3^{2-}] \approx Alk - DIC$$

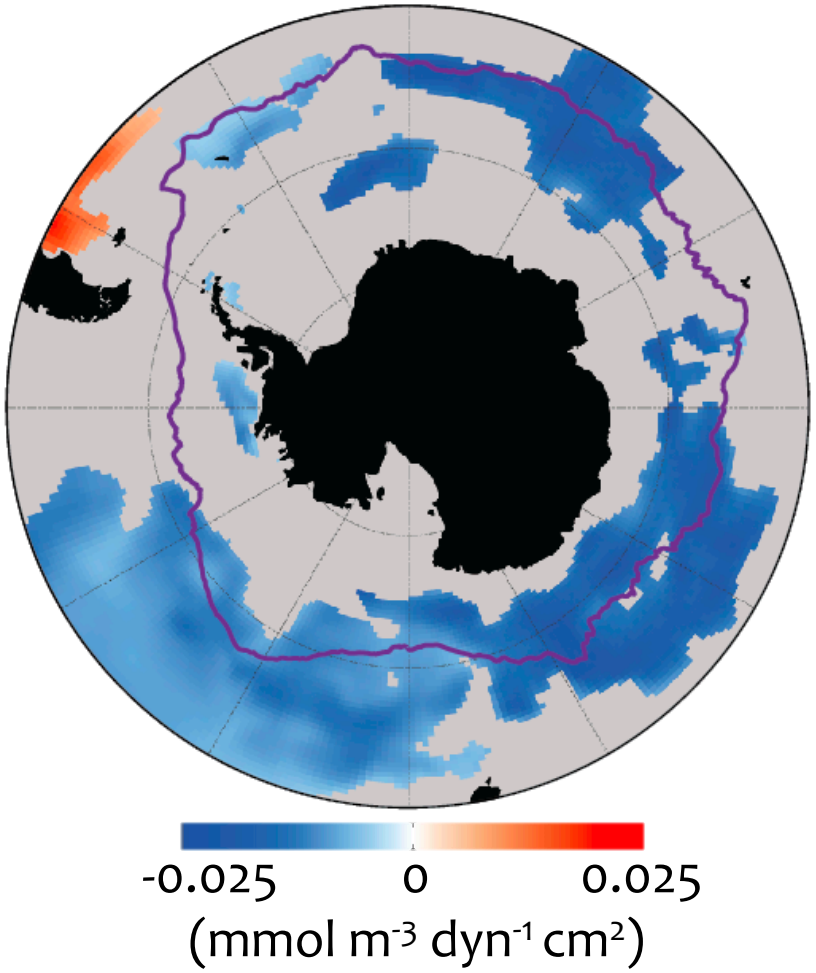
Lenton et al. (2009)

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

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



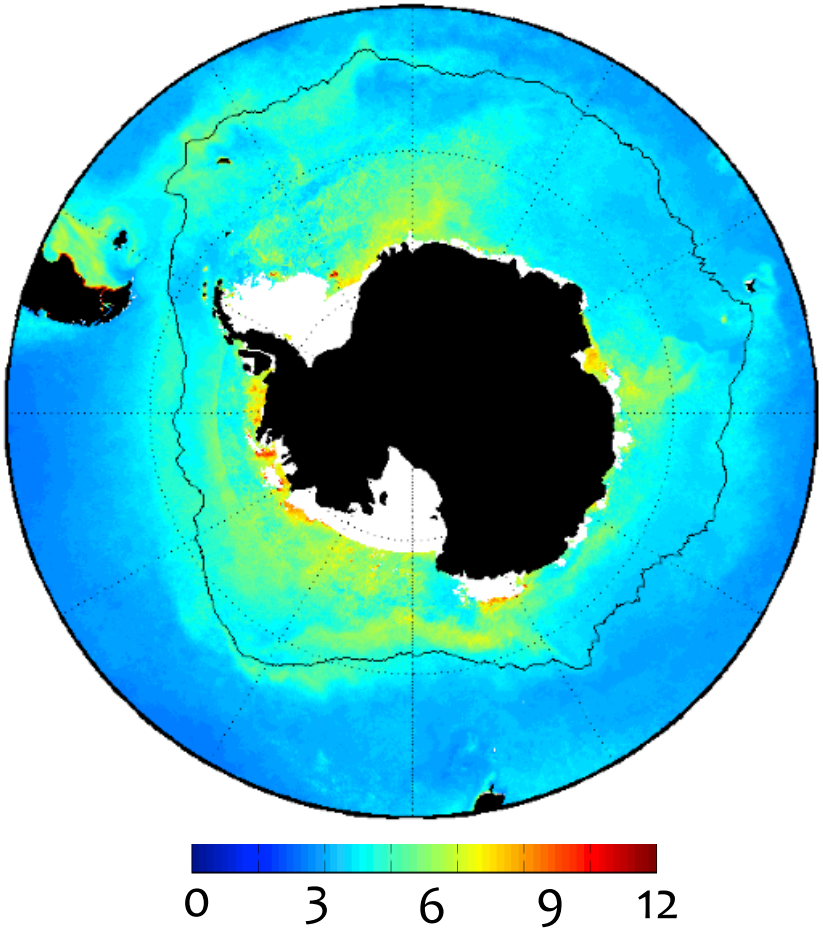
Wind – [CO_3^{2-}] regression



Conrad et al. (in prep.)

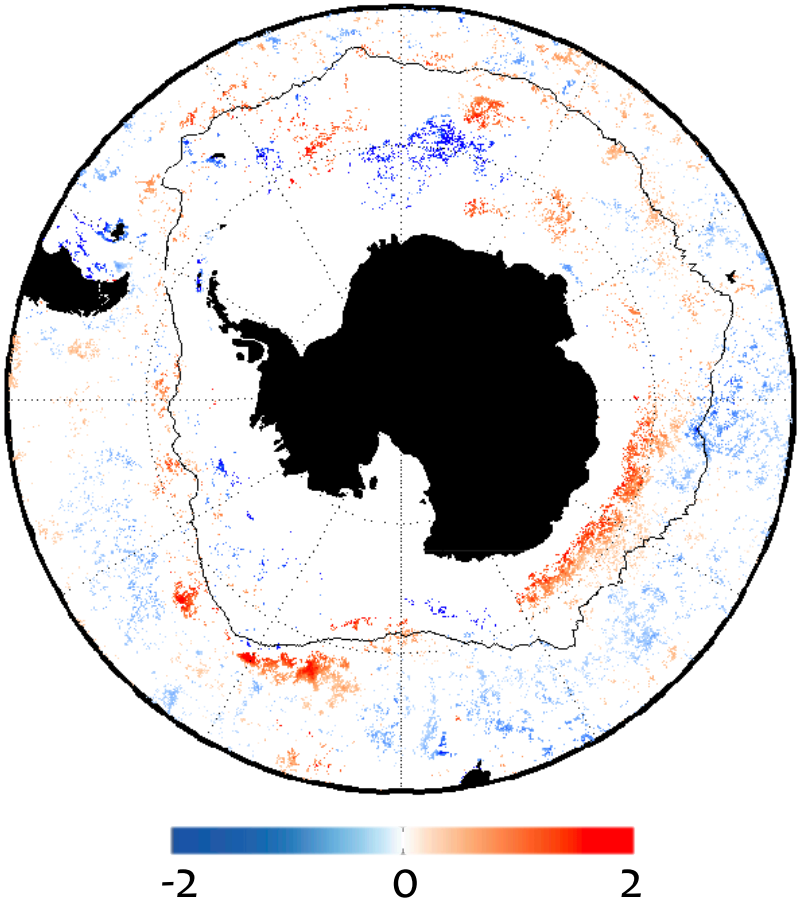
Calcification rate, 2003-2013

Summertime mean



(mg PIC m^{-3} d^{-1})

Summertime trend



(mg PIC m^{-3} d^{-1} $decade^{-1}$)

Freeman and Lovenduski (in prep.)

Conclusions

Known knowns:

- Southern Ocean is a sink for atmospheric CO_2
- Models indicate high variability and significant trends in sea-air CO_2 flux from the Southern Ocean
- Models indicate that wind drives variability and trends in CO_2 flux, via changes in circulation and surface DIC

Known unknowns:

- Is the model-predicted CO_2 flux trend real?
  → It depends who you ask!
- Has meridional overturning increased?
  → Probably
- Has biological production changed?
  → Still unclear

The End!