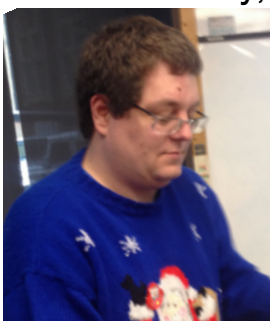
Impact of winds, diapycnal mixing and eddies on the ACC and atmospheric pCO_2

David Munday, Lesley Allison, Helen Johnson, David Marshall



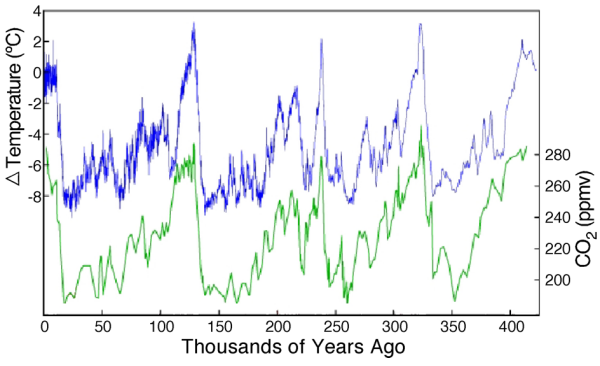

British Antarctic Survey
Met Office
UNIVERSITY OF OXFORD

Structure:

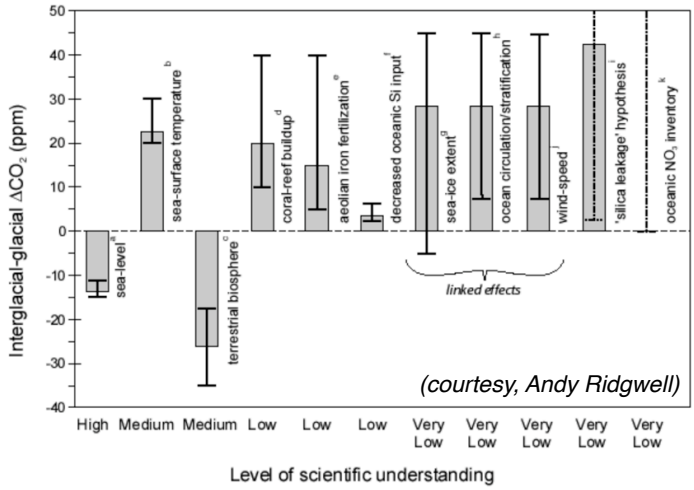
1. Background and motivation
2. Comments on forcing and adjustment of the ACC
3. Eddy-resolving box model of the ACC and carbon cycle

NERC SCIENCE OF THE ENVIRONMENT

1. Background and motivation



(after Petit, 1999)

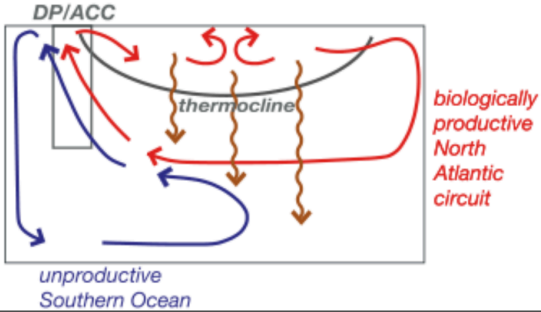


(courtesy, Andy Ridgwell)

e.g., Toggweiler et al. (2006):

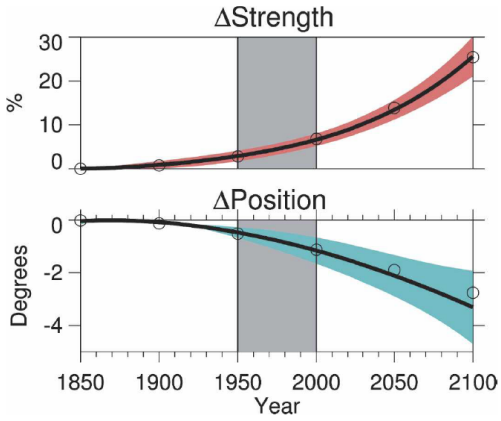
Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages

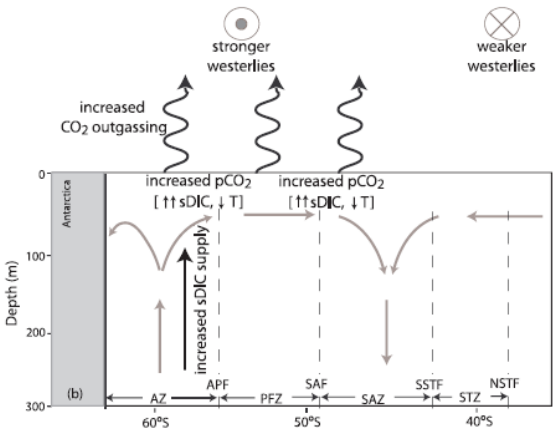
J. R. Toggweiler,[1] Joellen L. Russell,[2,3] and S. R. Carson[1,4]



Fyfe at al. (2007):

IPCC AR4 multi-model ensemble maximum southern hemisphere wind stress





(Lovenduski et al., 2008)

Le Quéré et al.. (2007):

Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change

Corinne Le Quéré,[1,2,3]* Christian Rödenbeck,[1] Erik T. Buitenhuis,[1,2] Thomas J. Conway,[4] Ray Langenfelds,[5] Antony Gomez,[6] Casper Labuschagne,[7] Michel Ramonet,[8] Takakiyo Nakazawa,[9] Nicolas Metzl,[10] Nathan Gillett,[11] Martin Heimann[1]

Böning et al. (2008):

The response of the Antarctic Circumpolar Current to recent climate change

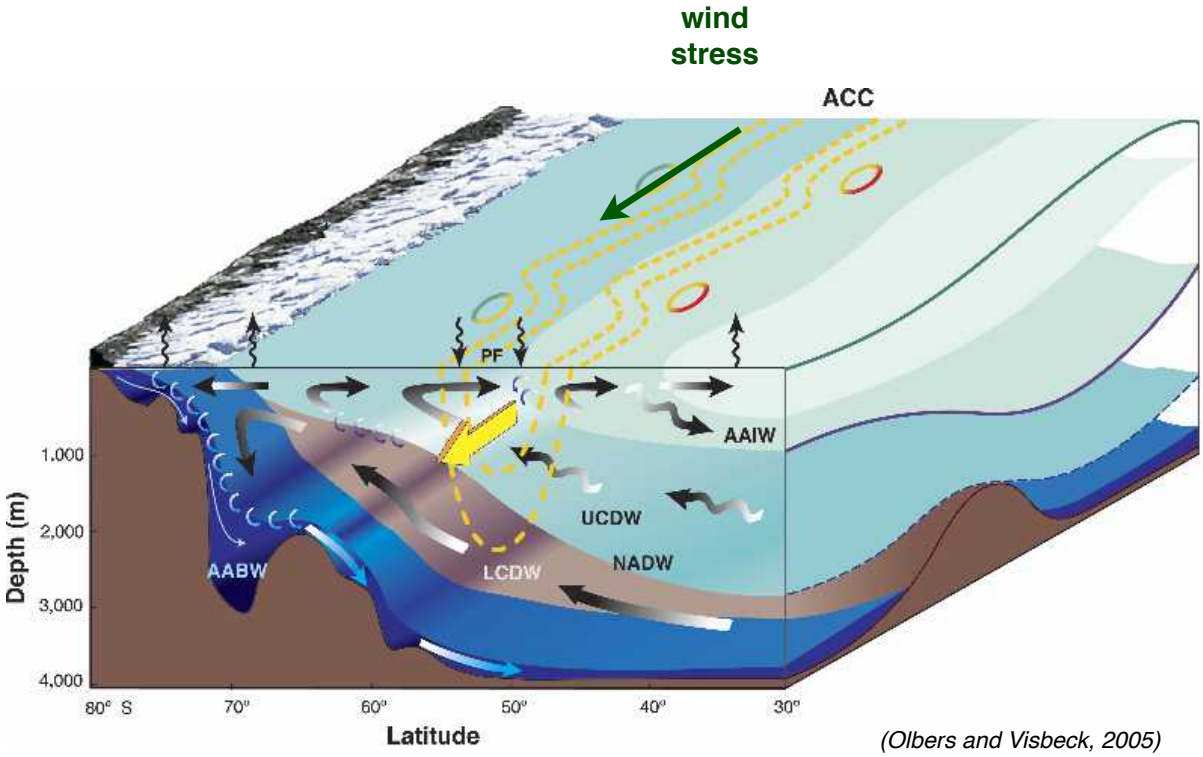
C. W. BÖNING[1]*, A. DISPERT[1], M. VISBECK[1], S. R. RINTOUL[2] AND F. U. SCHWARZKOPF[1]

Impact of eddies?

2. Comments on forcing of the ACC and its adjustment

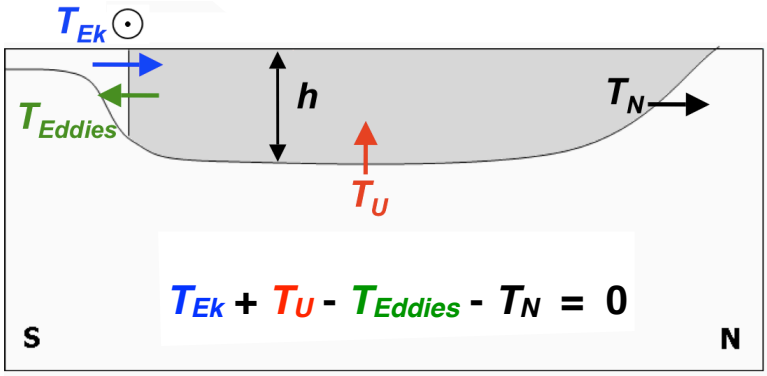
Classical paradigm:

Antarctic Circumpolar Current is driven by **Southern Ocean** *wind* and *buoyancy forcing*

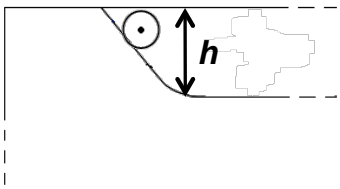


(Olbers and Visbeck, 2005)

Gnanadesikan (1999):



Implications for ACC transport?



$$T_{ACC} \approx -\frac{g'h^2}{2f}$$

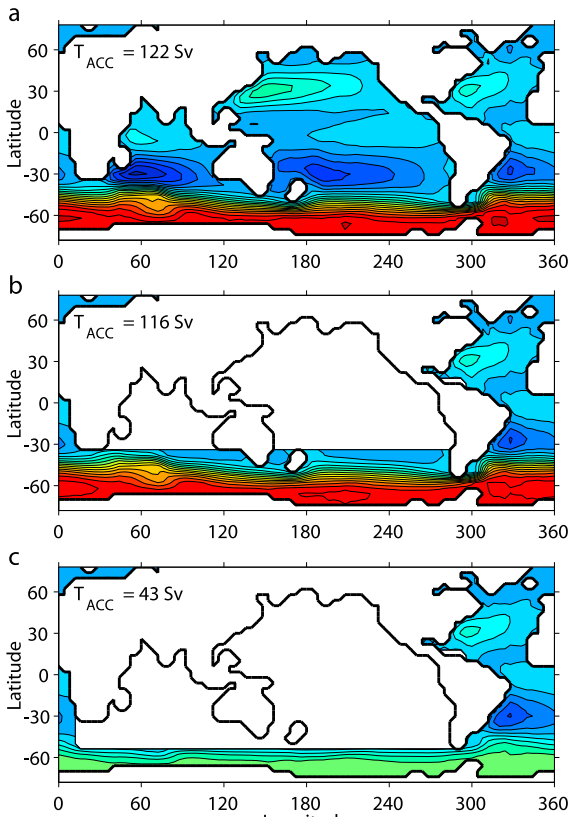
(cf. Gnanadesikan and Hallberg, 2000)

Suggests ACC transport determined by processes that maintain the global pycnocline/MOC:

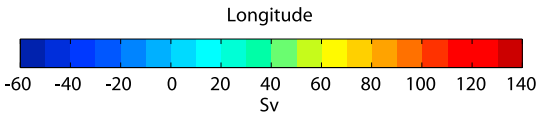
- Southern Ocean wind forcing;
- diapycnal mixing;
- NADW formation *(e.g., Fučkar and Vallis, 2007)*;
- Southern Ocean eddies.

(a) Which Southern Ocean wind forcing?

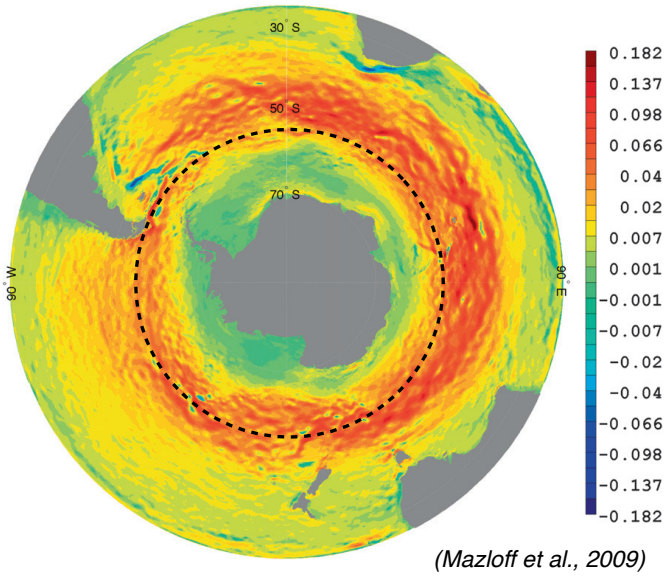
(Allison et al., 2010)



MITgcm

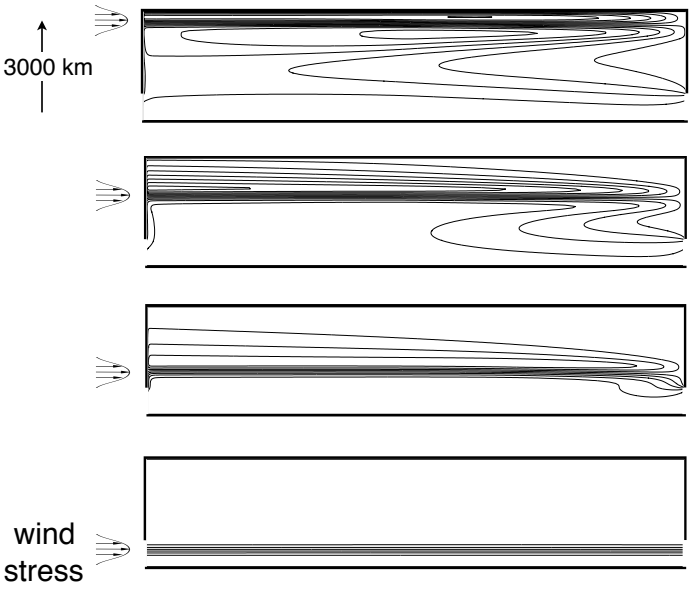


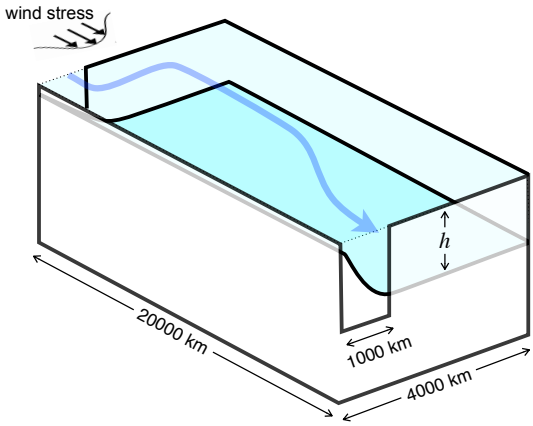
Wind work on the ACC (from SOSE, W m^{-2}):



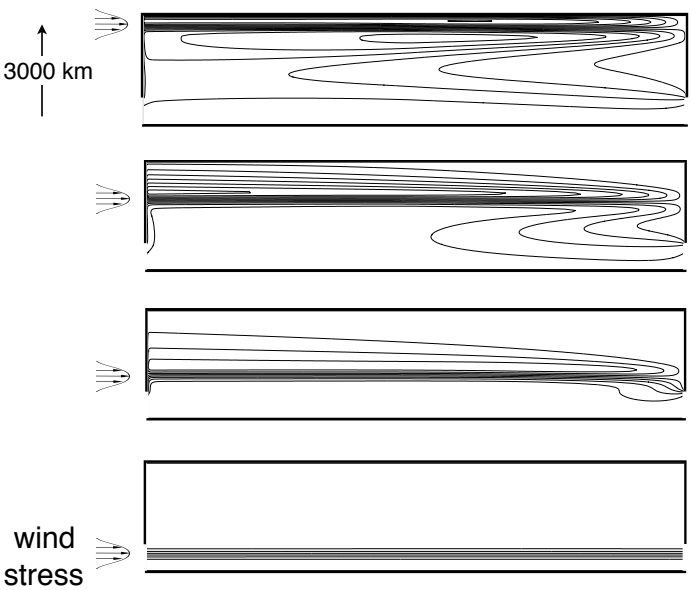
(Mazloff et al., 2009)

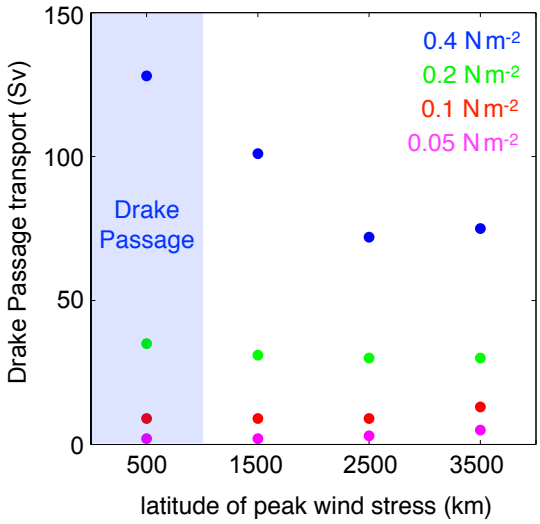
Reduced-gravity model: *(Marshall et al., 2015)*



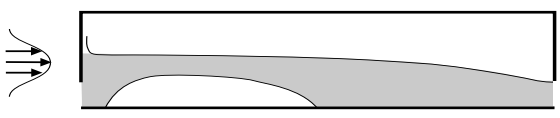


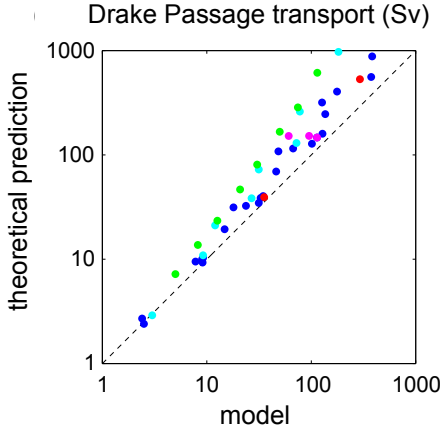
Reduced-gravity model: *(Marshall et al., 2015)*



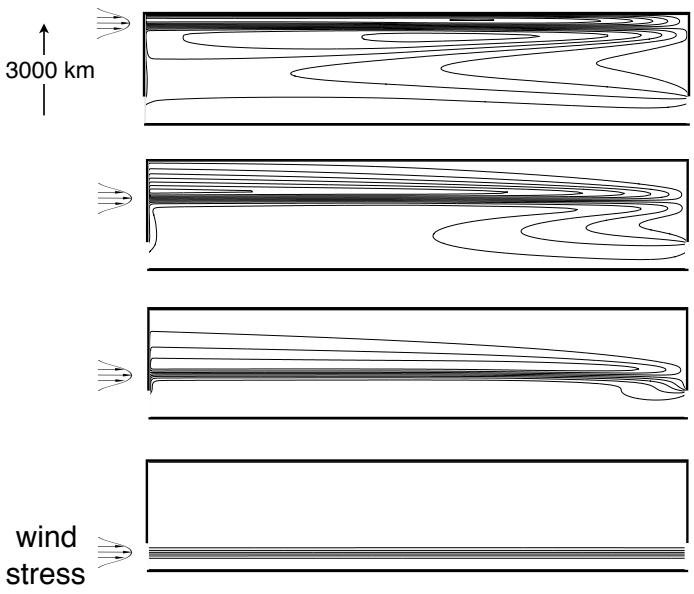


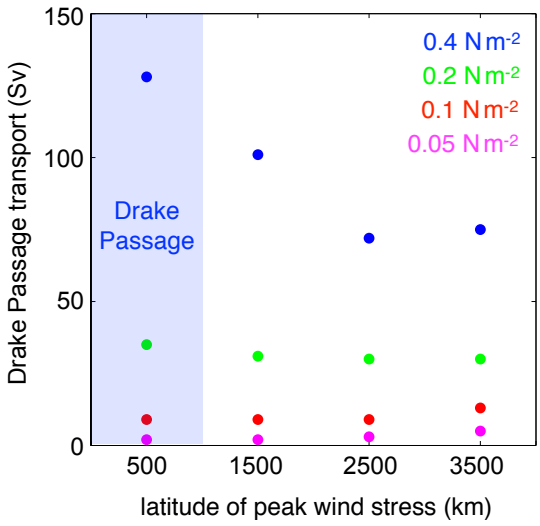
Solution: integrate wind stress over circumpolar contours *(Allison et al., 2010):*





Reduced-gravity model: *(Marshall et al., 2015)*





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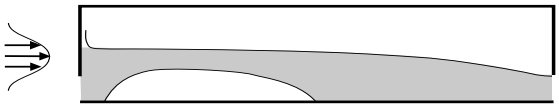
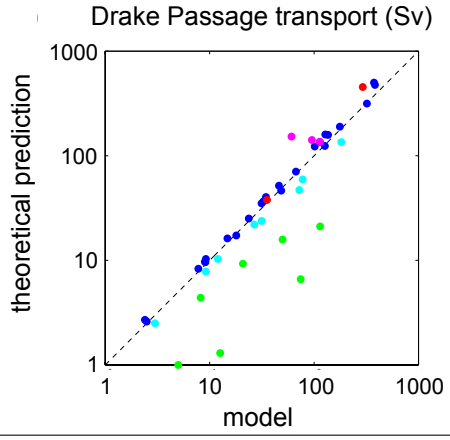
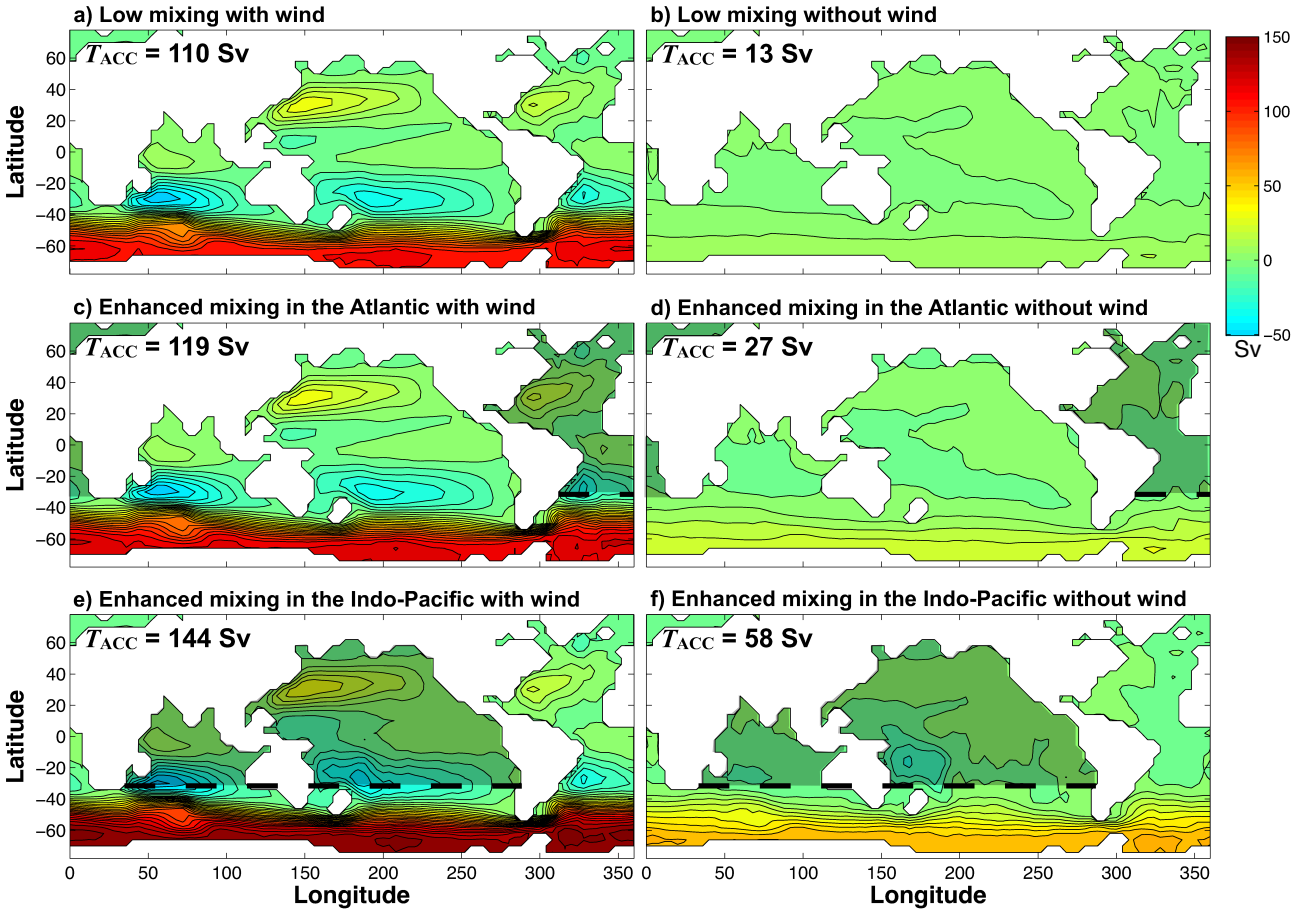
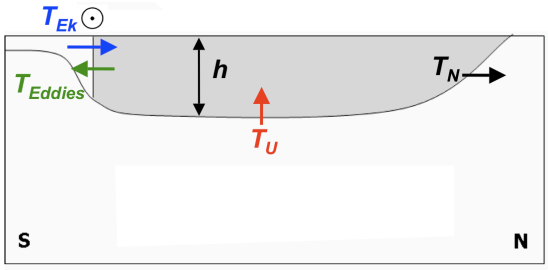




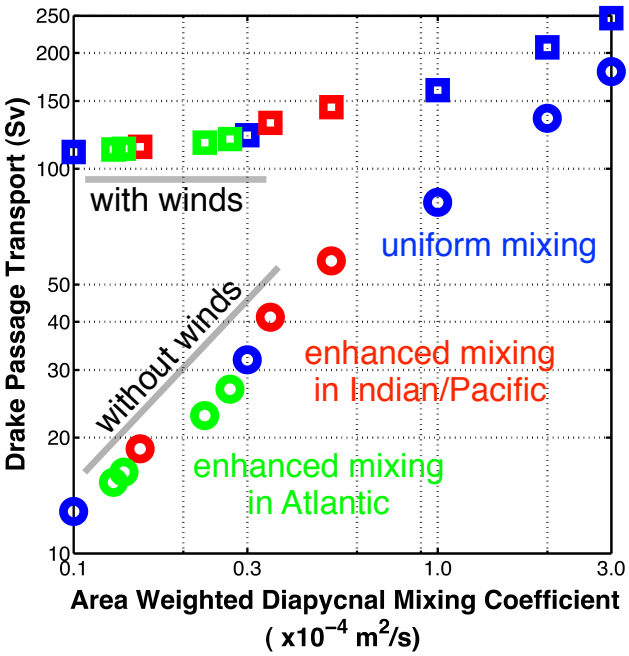
(b) Global Diapycnal mixing? *(Munday et al., 2011)*





neglect T_N :

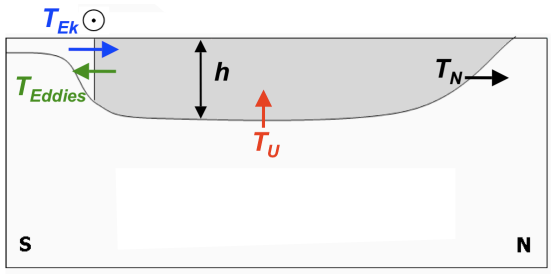
$$\frac{d(\ln T_{\mathrm{ACC}})}{d(\ln \int_A \kappa_{\mathrm{v}} dA)} = \frac{2T_{\mathrm{U}}}{2T_{\mathrm{U}} + T_{\mathrm{Ek}}}$$

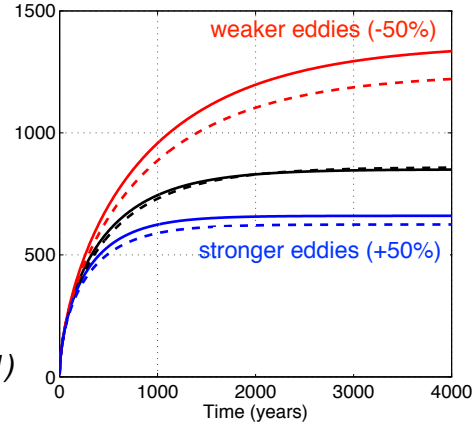


(c) Adjustment time scale?

- dominated by Southern Ocean eddies and NADW formation

(Allison et al., 2011; Jones et al., 2011; Samelson, 2011)





(Allison et al., 2011)

e.g., in response to a 10% wind stress anomaly:

$$\frac{\partial h}{\partial t} \approx \frac{\Delta T_{\mathrm{Ek}}}{A} \sim \frac{3 \times 10^6\,\mathrm{m^3\,s^{-1}}}{2 \times 10^{14}\,\mathrm{m^2}} = 1.5 \times 10^{-8}\,\mathrm{m\,s^{-1}} \approx 0.5\,\mathrm{m\,yr^{-1}}$$

Böning et al. (2008):

The response of the Antarctic Circumpolar Current to recent climate change

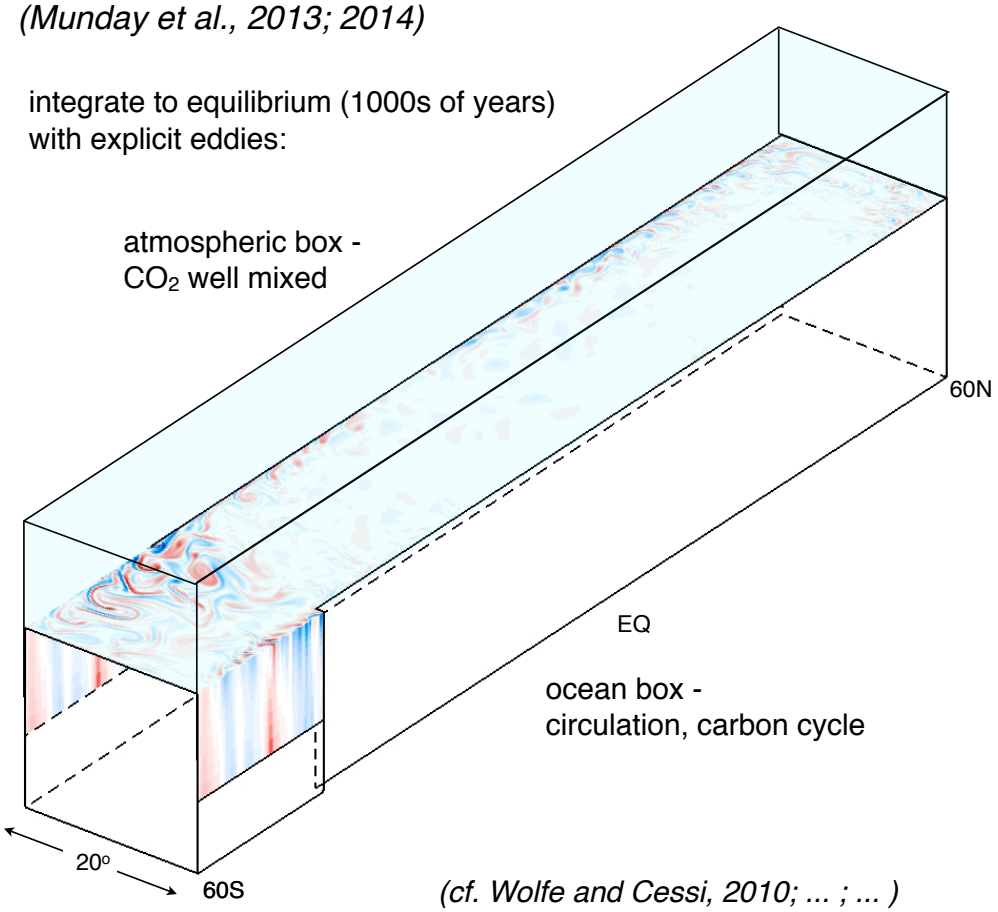
C. W. BÖNING[1]*, A. DISPERT[1], M. VISBECK[1], S. R. RINTOUL[2] AND F. U. SCHWARZKOPF[1]

3. Eddy-resolving box model of the ACC and carbon cycle

(Munday et al., 2013; 2014)

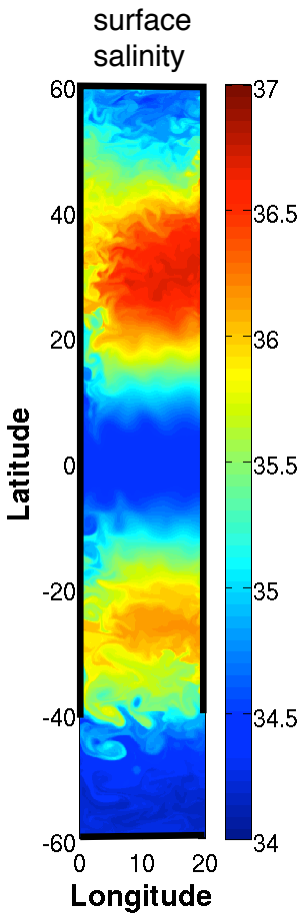
integrate to equilibrium (1000s of years)
with explicit eddies:

atmospheric box -
CO_2 well mixed



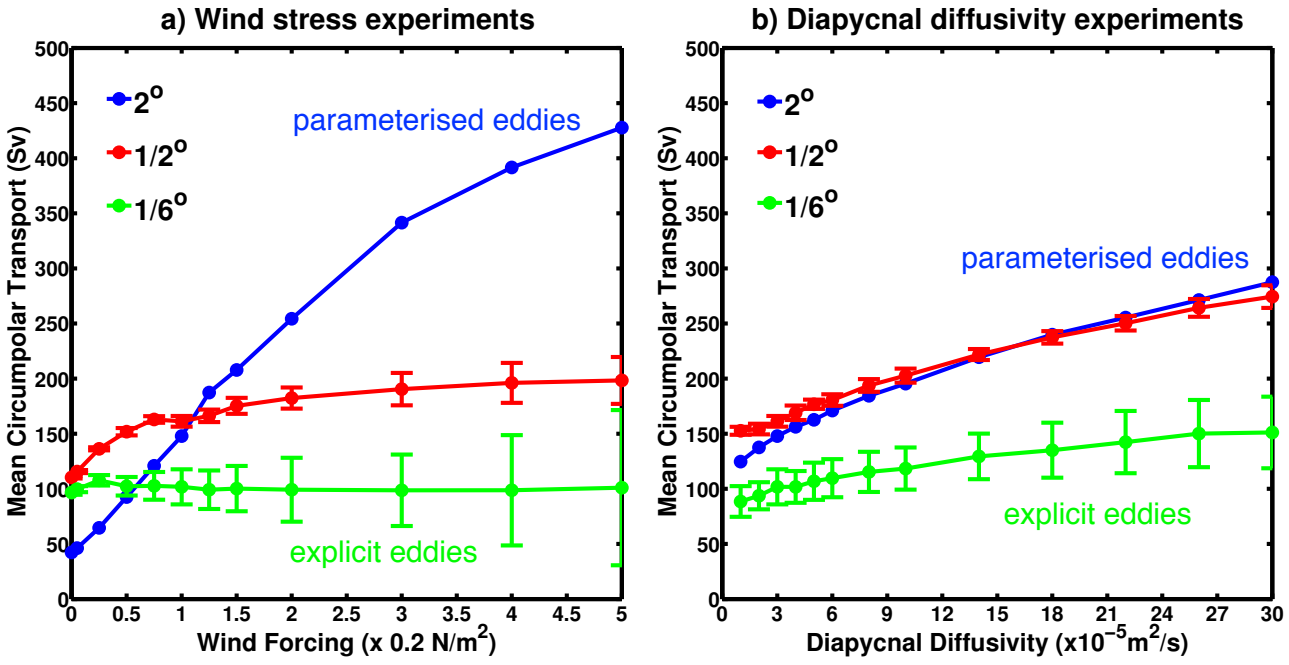
ocean box -
circulation, carbon cycle

(cf. Wolfe and Cessi, 2010; ... ; ...)



Circumpolar transport - eddy saturation

(Munday et al., 2013)

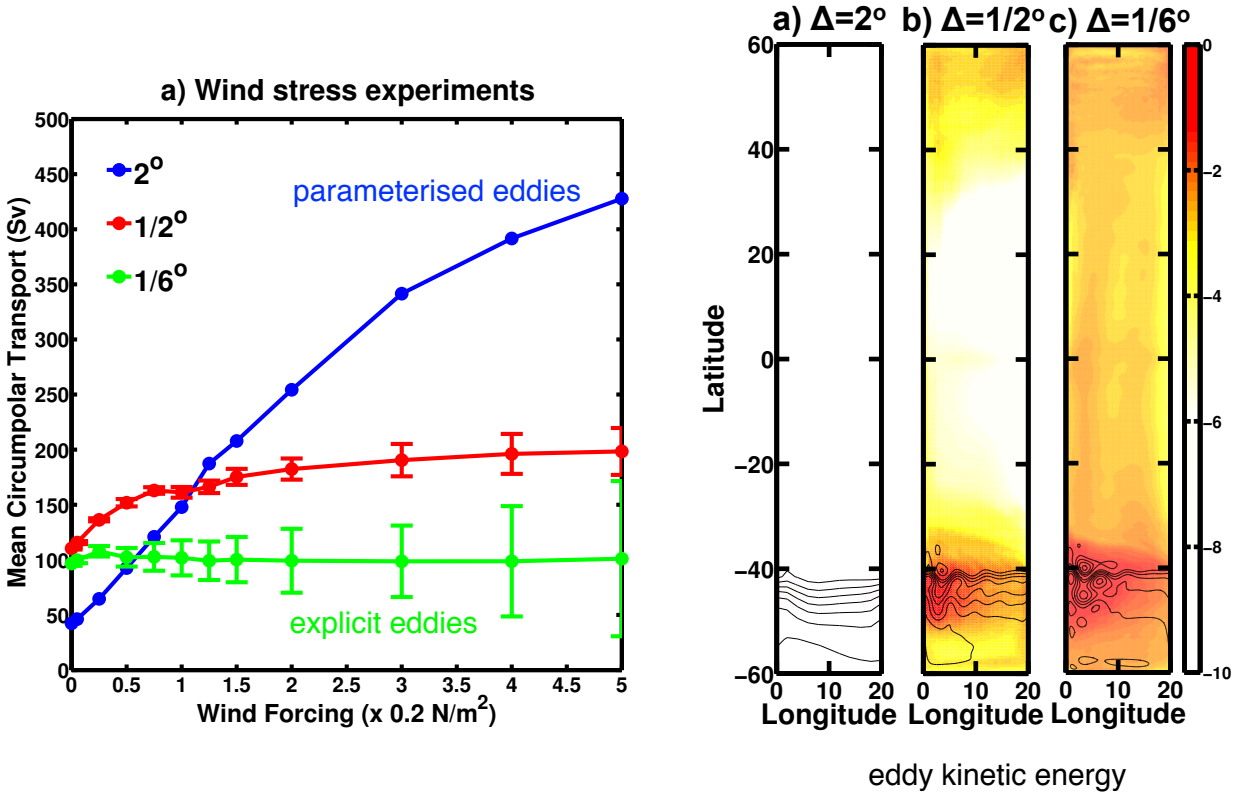


cf. Straub (1993), Hallberg and Gnanadesikan (2001), Tansley and Marshall (2001), Hallberg and Gnanadesikan (2006), Meredith and Hogg (2006), Hogg and Blundell (2010), Farneti et al. (2010), Farneti and Delworth (2010), ...

NB: Hogg and Munday (2014)

Circumpolar transport - eddy saturation

(Munday et al., 2013)

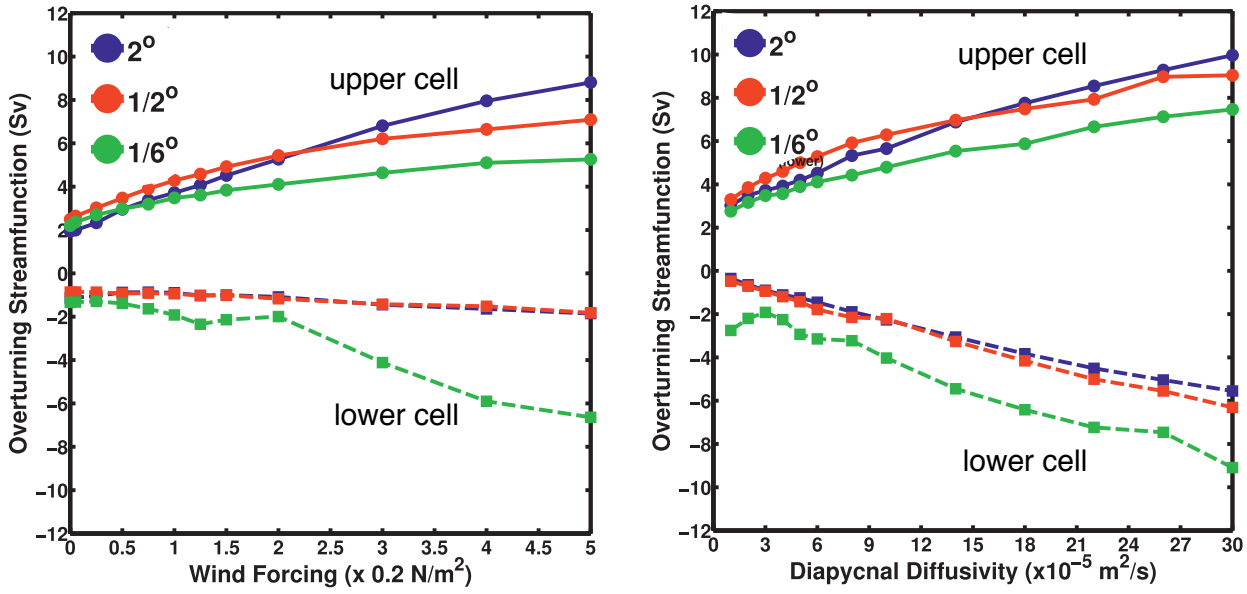


cf. Straub (1993), Hallberg and Gnanadesikan (2001), Tansley and Marshall (2001), Hallberg and Gnanadesikan (2006), Meredith and Hogg (2006), Hogg and Blundell (2010), Farneti et al. (2010), Farneti and Delworth (2010), ...

NB: Hogg and Munday (2014)

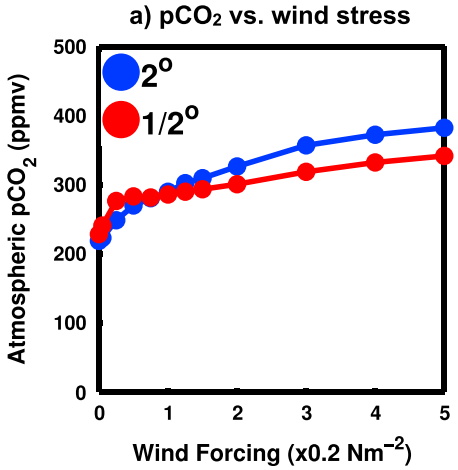
Residual overturning - eddy compensation?

(Munday et al., 2013)



Atmospheric CO_2

(Munday et al., 2014)



Decomposition:

(following Goodwin et al., 2008)

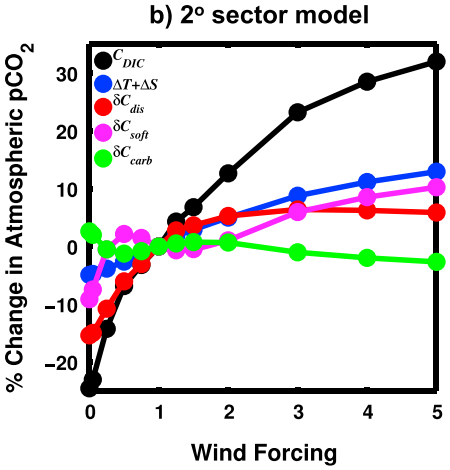
C_{DIC}

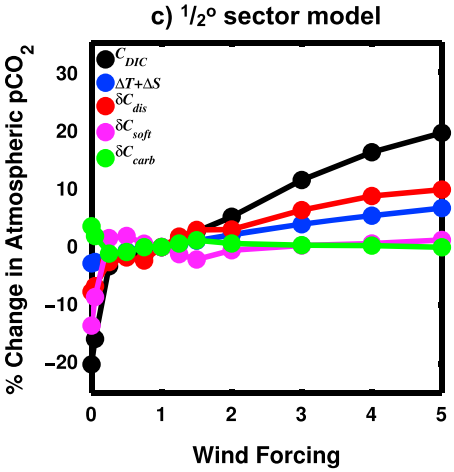
$\Delta T+\Delta S$

δC_{dis}

δC_{soft}

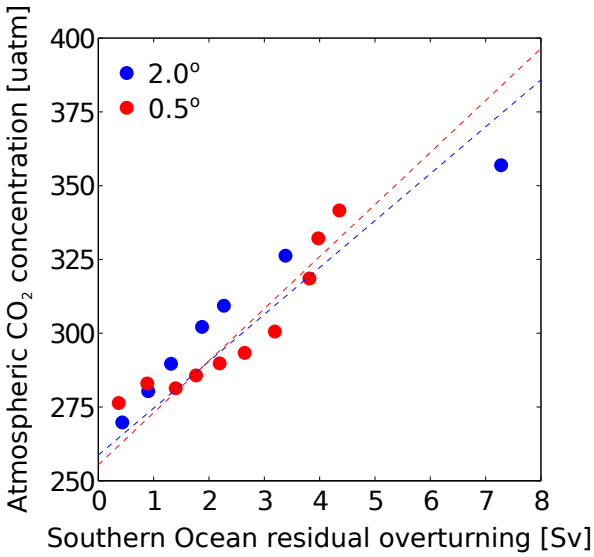
δC_{carb}

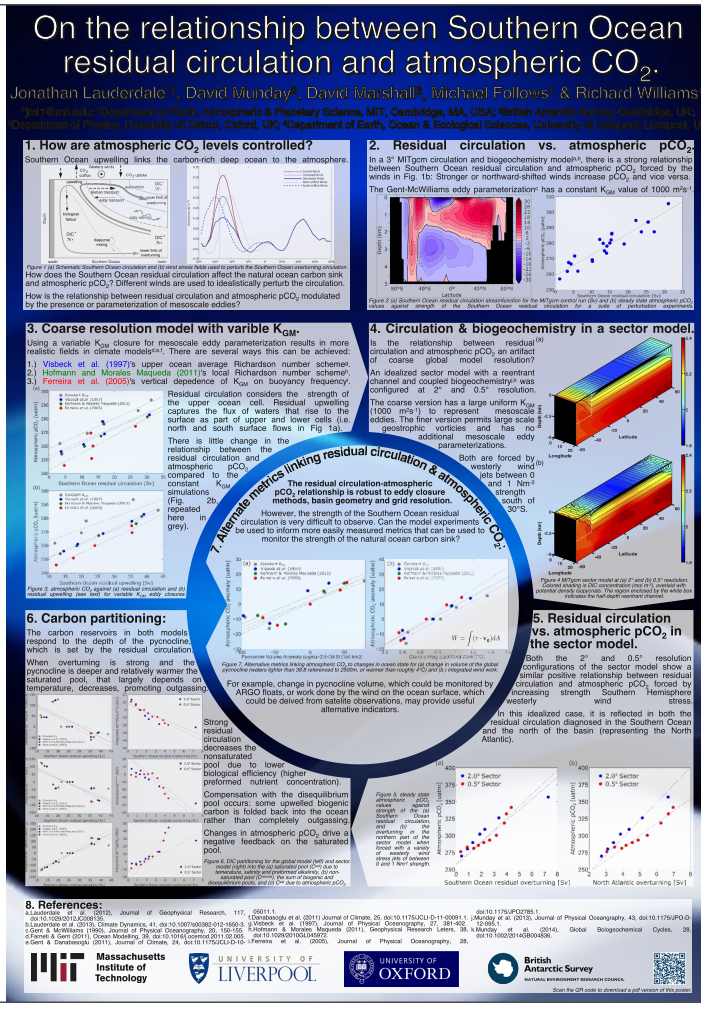




Relation between atmospheric CO_2 and residual overturning?

(c.f. Lauderdale et al., 2013)

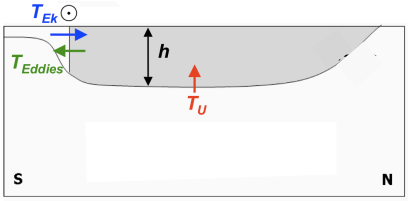


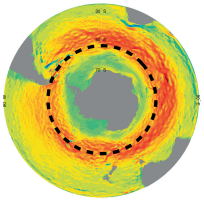


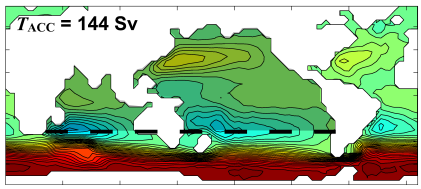
Summary of key points

In our models:

- ACC driven by winds along circumpolar streamlines and global diapycnal mixing.



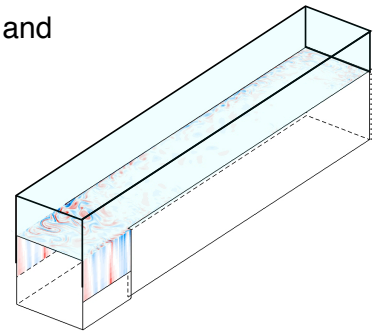




- Both the equilibrium ACC and its adjustment are extremely sensitive to the representation of eddies - implications for climate models!

- Eddy-permitting box model:

  - ACC is remarkably insensitive* to Southern Ocean winds and somewhat sensitive to diapycnal mixing;
  - reduced sensitivity of residual overturning to Southern Ocean winds;
  - reduced sensitivity of atmospheric CO_2 to Southern Ocean winds;
  - strong relation between atmospheric CO_2 and residual overturning - *see Jon Lauderdale's poster.*



- Role of buoyancy forcing? *(e.g., Hogg, 2010)*

marshall@atm.ox.ac.uk