Physical Controls on the Air-Sea Partitioning of CO_2

Ric Williams (Liverpool)

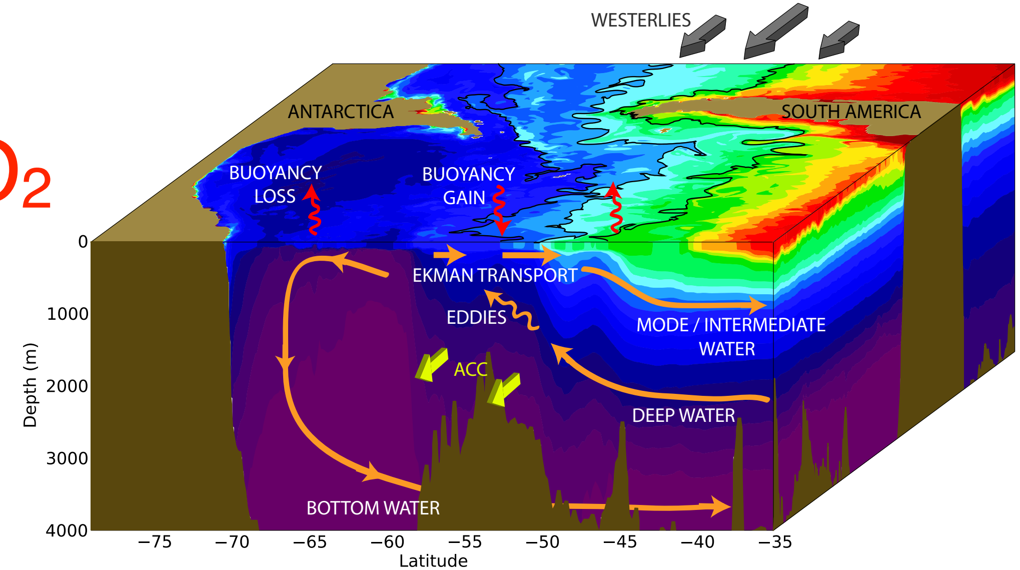
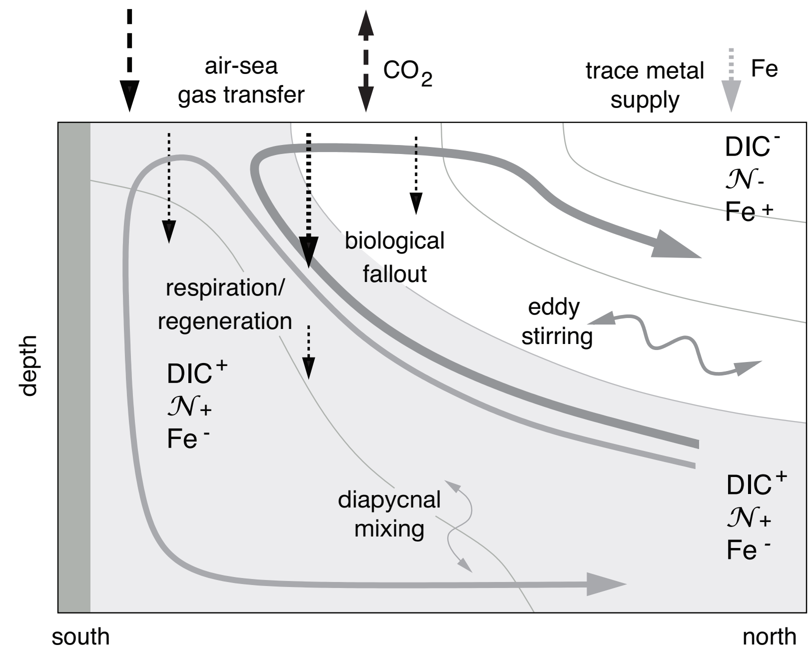


Image from Morrison et al., 2015: "Upwelling in the Southern Ocean." Phys. Today.

Challenges for the community

- how much heat & CO_2 is being sequestered?
- what are the controlling mechanisms?
- what are the wider climate implications?



Thanks to Mick Follows (MIT), Jon Lauderdale (MIT), Phil Goodwin (Southampton), Andy Ridgwell (Bristol), Alessandro Tagliabue (Liverpool), and other collaborators.

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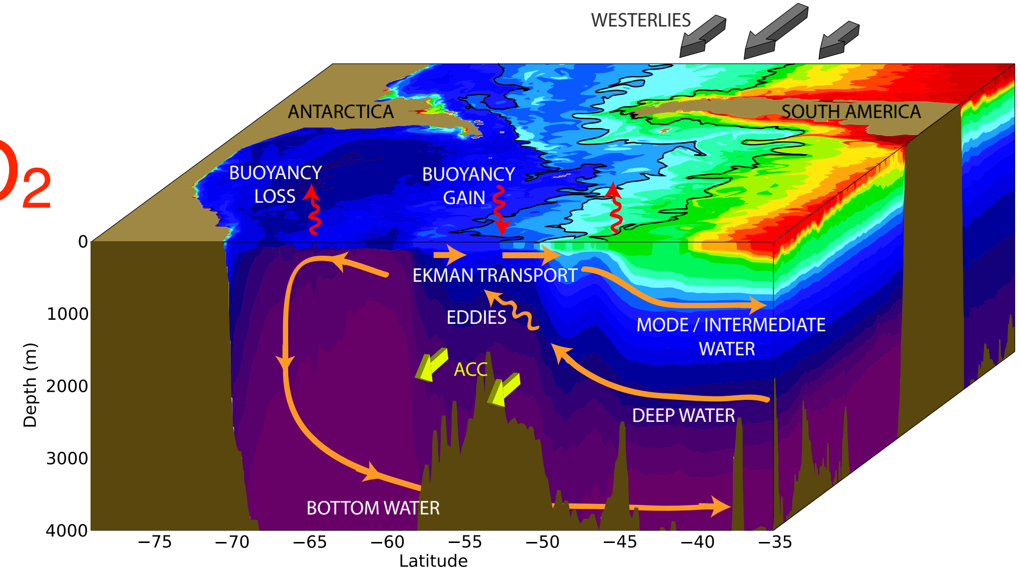

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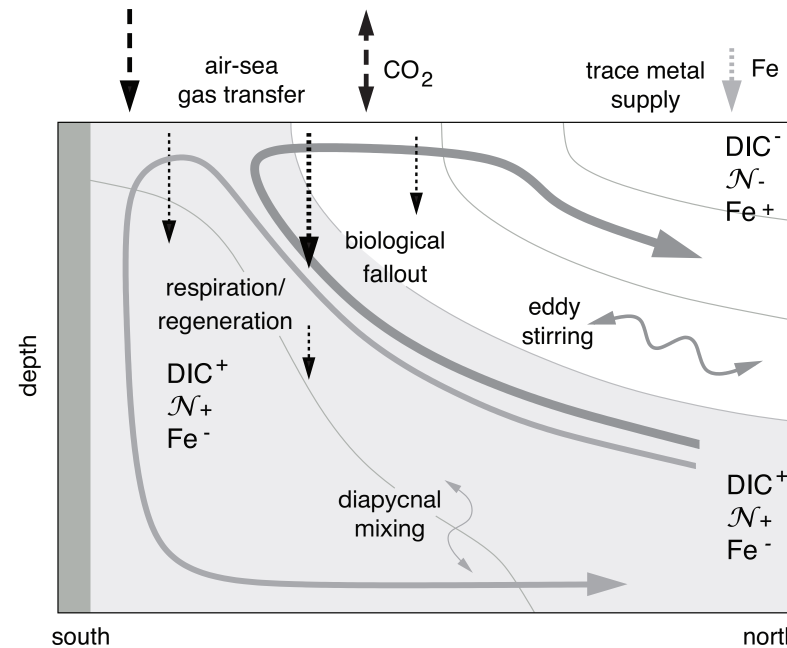
Lecture overview

1. Mechanisms

2. Frameworks

3. Effect of residual circulation

4. Global implications



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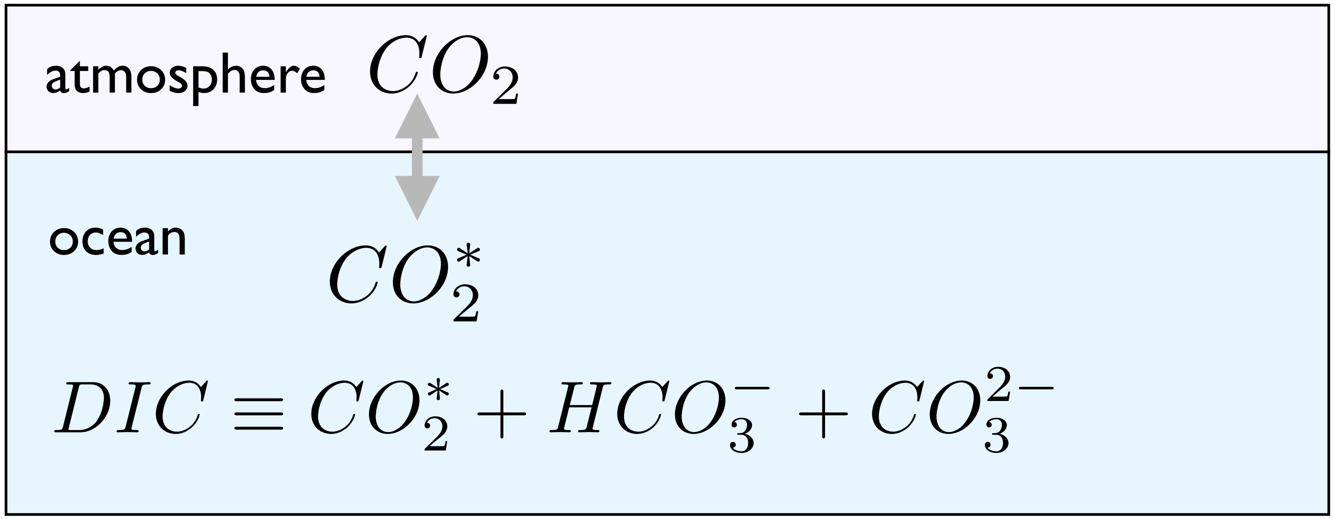
1. Mechanisms

carbonate chemistry



reactions in seawater

$$CO_2^* + H_2O = HCO_3^- + H^+$$

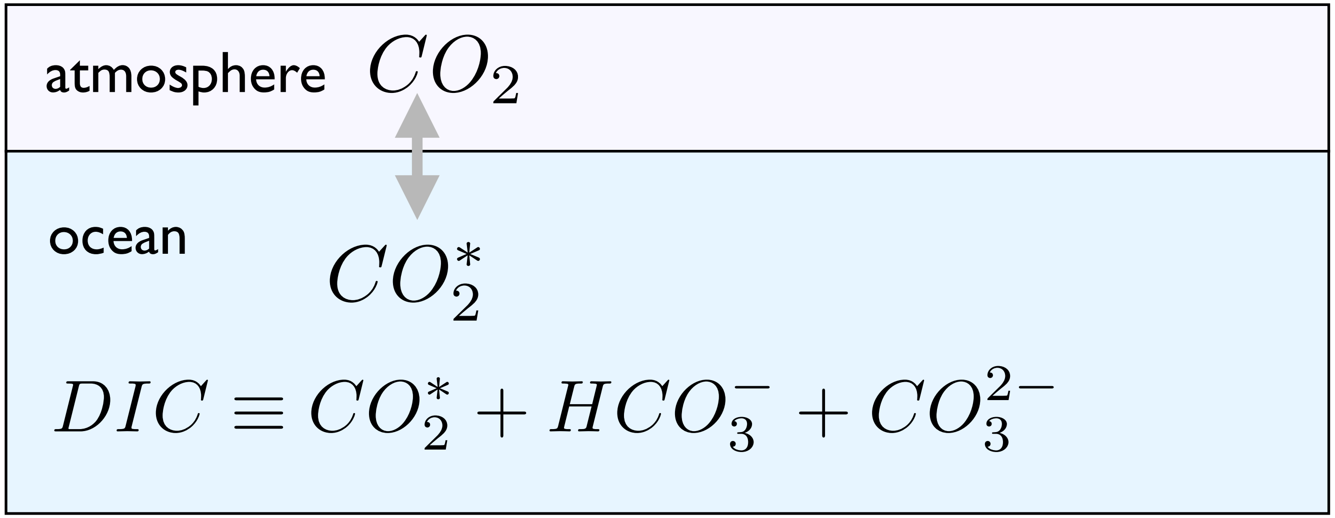
$$HCO_3^- = CO_3^{2-} + H^+$$

buffer factor

$$B = \frac{\Delta CO_2^*}{CO_2^*} \Bigg/ \frac{\Delta DIC}{DIC} \sim 10$$

1. Mechanisms

air-sea exchange



$$\frac{D}{Dt} DIC = -\frac{K_g}{h} \Delta CO_2^*$$

K_g air-sea transfer velocity
h mixed layer depth

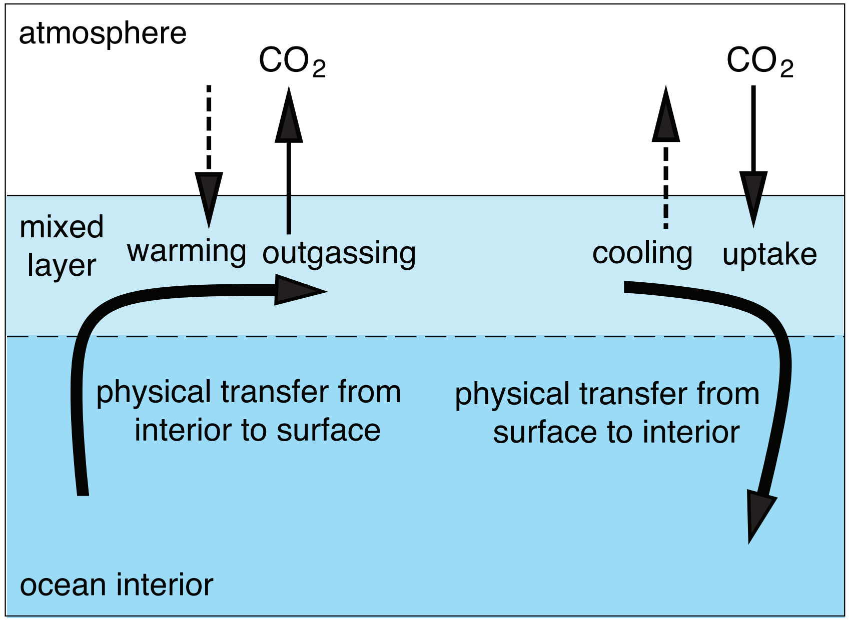
air-sea exchange timescale

$$\tau \sim \frac{h}{K_g} \frac{1}{B} \frac{DIC}{CO_2^*}$$

month 1/10 170

1. Mechanisms

physics



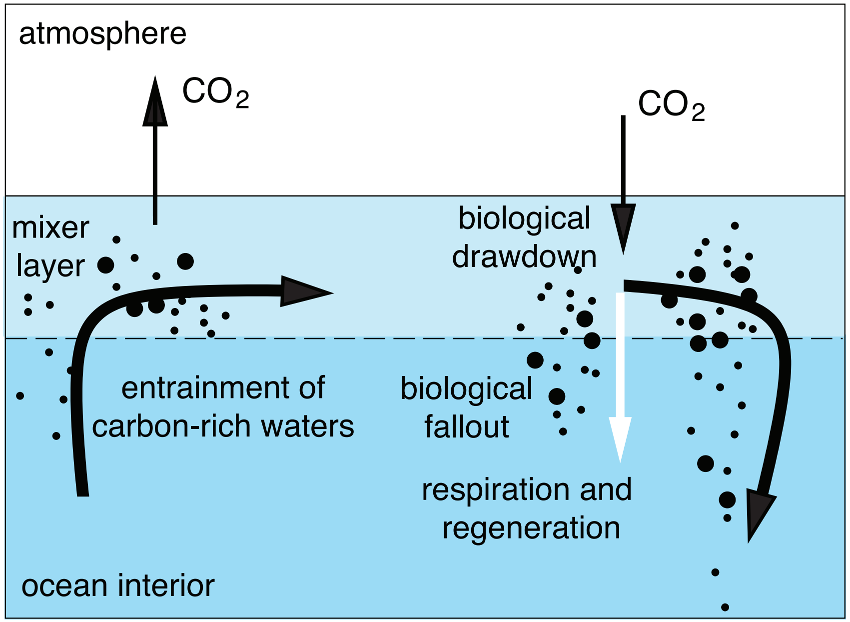
rate limiting processes on annual timescale:

subduction into main thermocline
entrainment into winter mixed layer
resulting annual air-sea uptake

fine-scale dynamical processes only important in modifying these processes

1. Mechanisms

biology

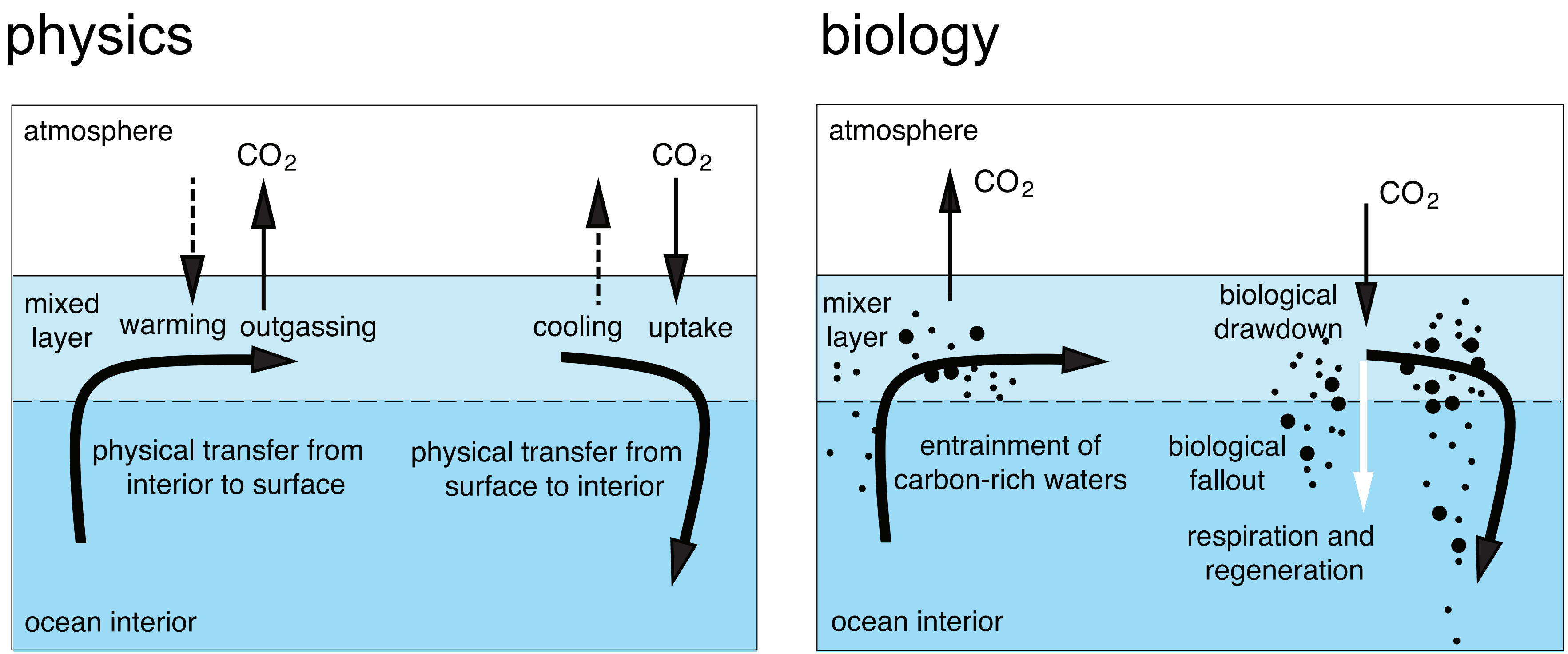


biological drawdown can respond to fine-scale delivery of nutrients & trace metals

affects DIC profile

Prevailing view:
biological response is *not directly* important for the anthropogenic response, but is crucial for glacial-interglacial cycles.

1. Mechanisms



see first order opposing signs in the physical & biological responses

2. Frameworks

preformed & regenerated

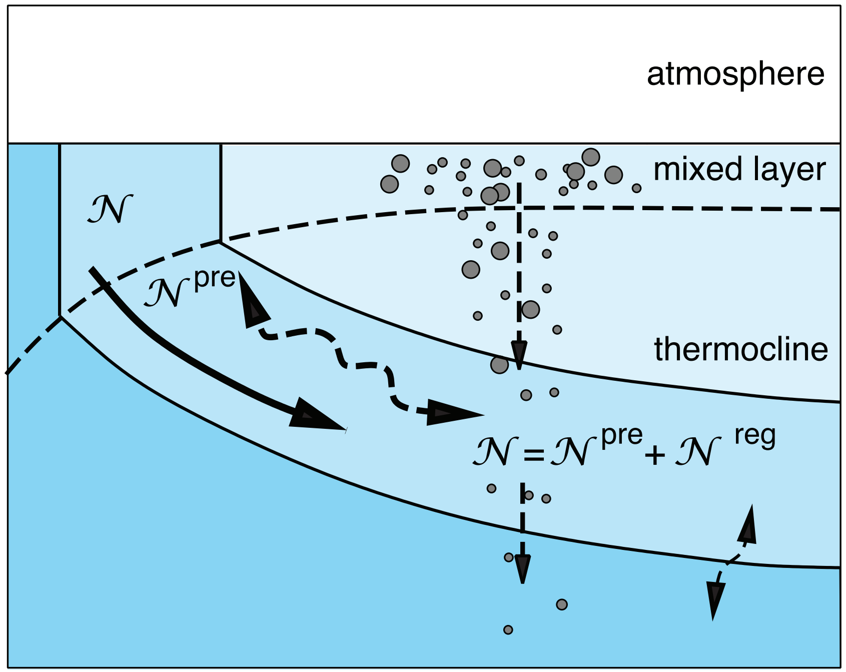
in mixed layer

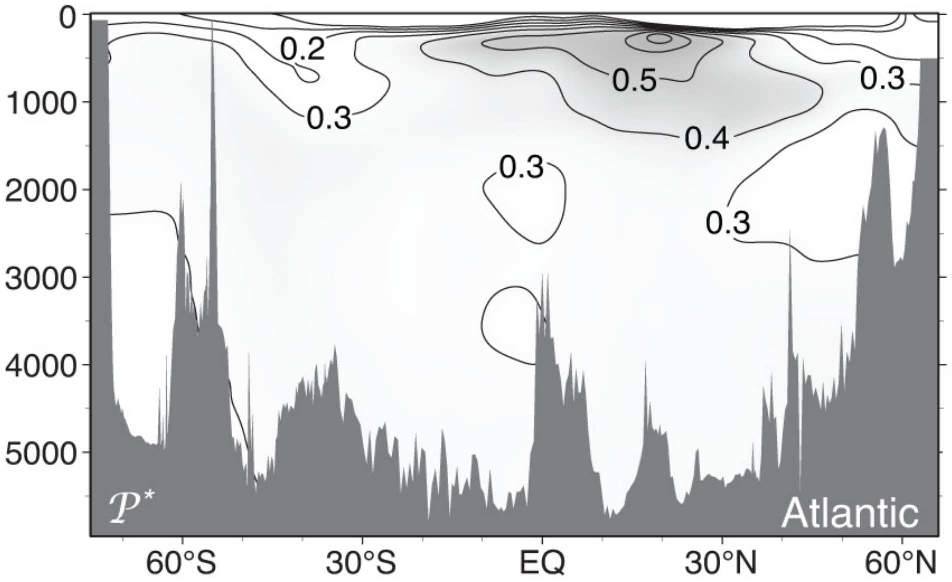
$$\mathcal{N} = \mathcal{N}^{pre}$$

in ocean interior

$$\mathcal{N} = \mathcal{N}^{pre} + \mathcal{N}^{reg}$$

efficiency of the biology $$\frac{\mathcal{N}^{reg}}{\mathcal{N}}$$



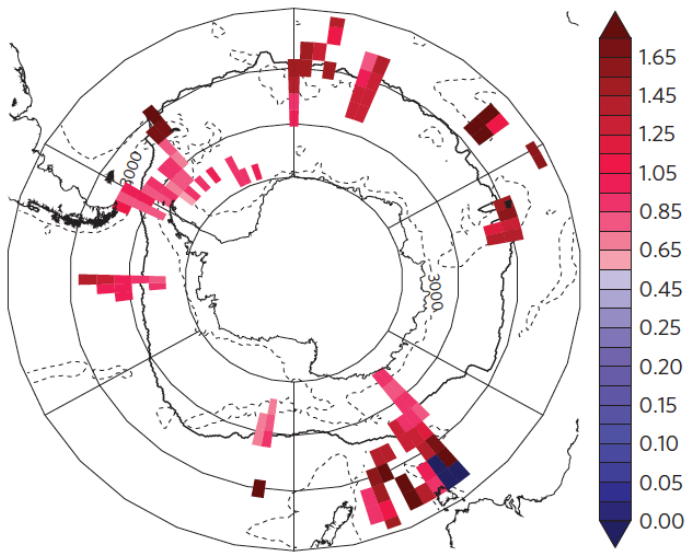


Ito & Follows (2005)

2. Frameworks

Dissolved free iron $$Fe' = Fe'^{pre} + Fe'^{reg} + Fe'^{benthic} - Fe'^{scav}$$

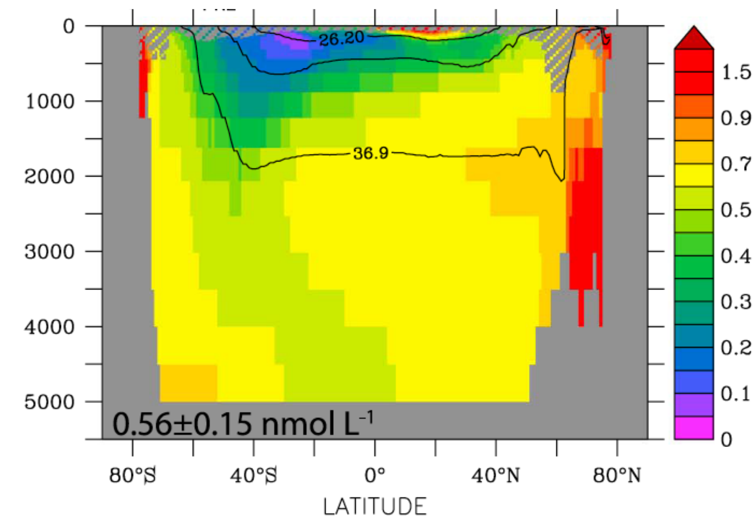
preformed +regenerated +benthic - scavenged



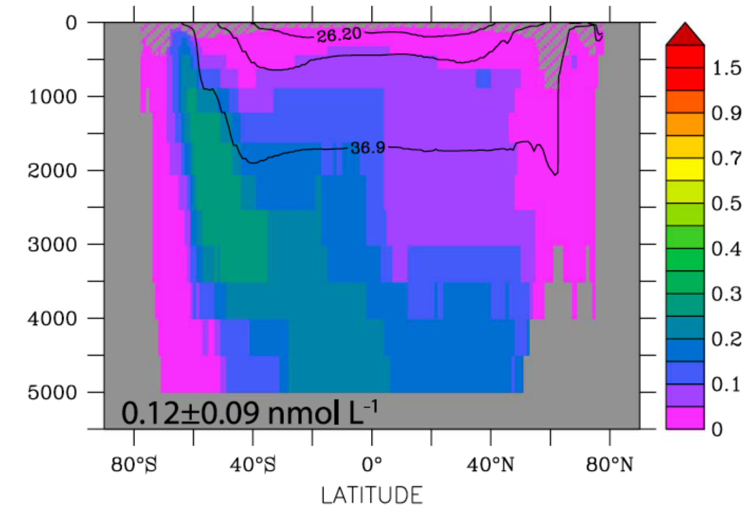
Dissolved free iron flux to surface dominated by winter entrainment

Tagliabue et al. (2014, Nature Geoscience)

preformed



benthic

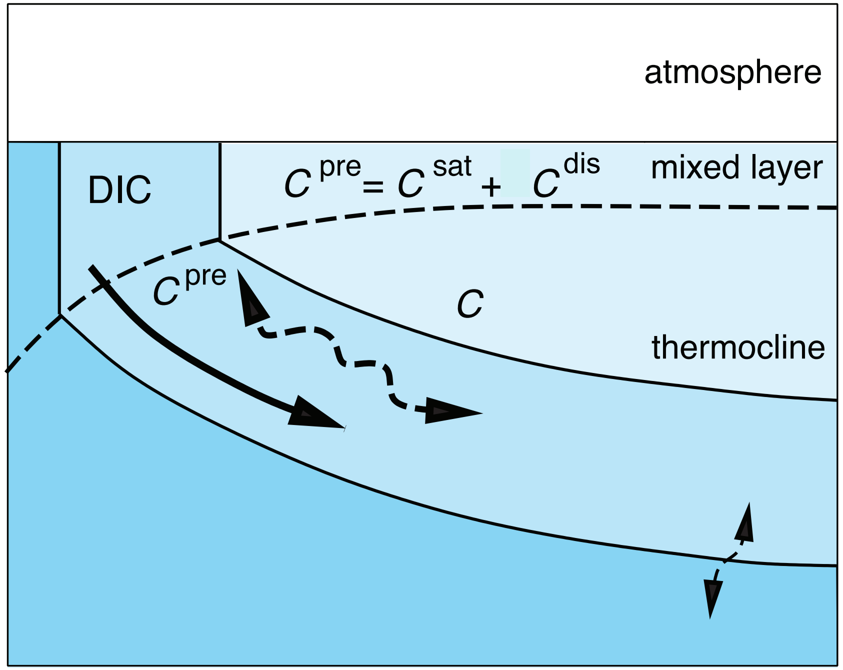


Supply of preformed & benthic Fe to the Southern Ocean

Tagliabue et al. (2014, GRL)

2. Frameworks

Dissolved inorganic carbon, DIC



in mixed layer

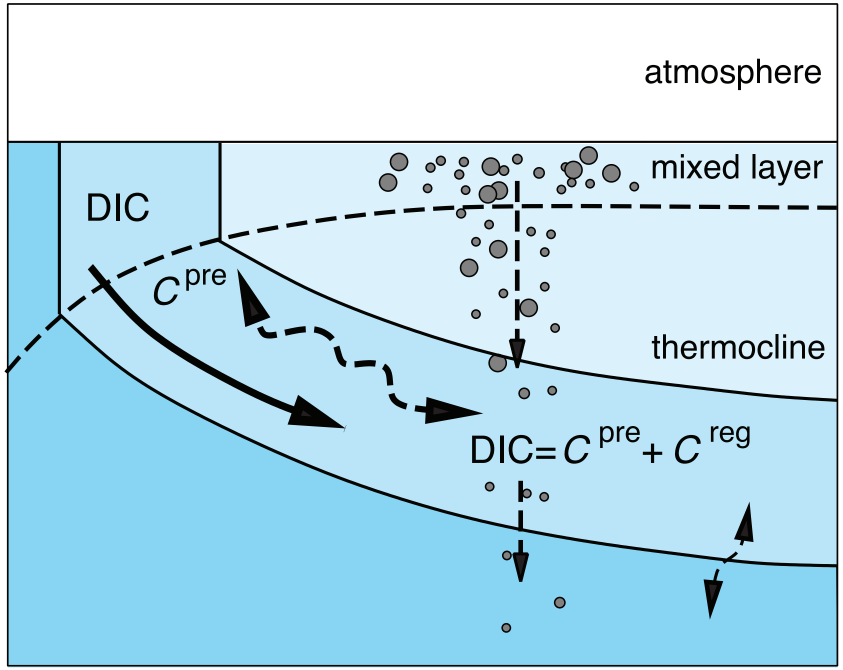
$$DIC = C^{pre}$$

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

saturated disequilibrium

2. Frameworks

Dissolved inorganic carbon, DIC



in ocean interior

$$DIC = C^{pre} + C^{reg}$$

$$C^{sat} + C^{dis} + C^{soft} + C^{carb}$$

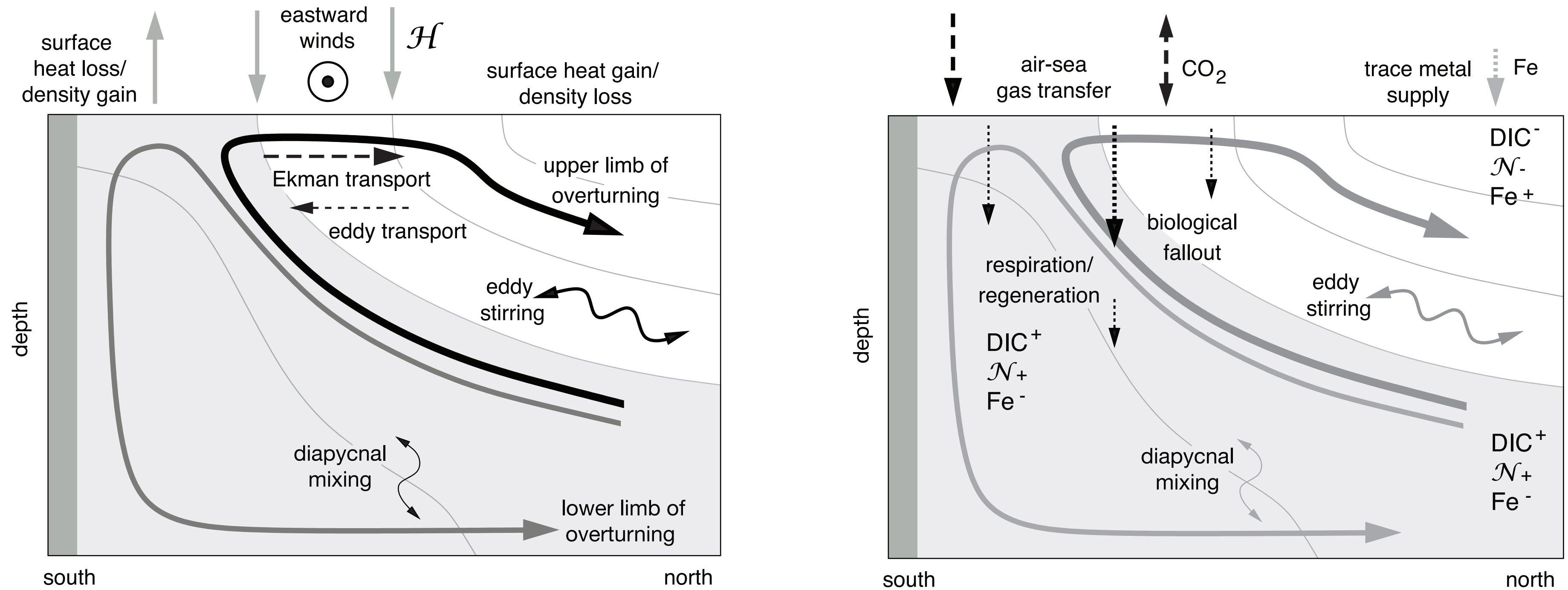
saturated

disequilibrium

soft tissue regenerated

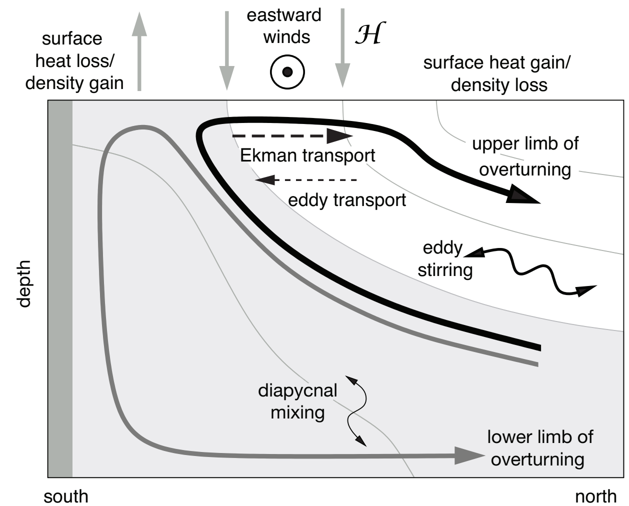
carbonate tissue regenerated

3. Residual circulation



- air-sea carbon uptake affected by how far surface waters are away from saturation
- air-sea carbon anomalies eroded on annual & longer timescales
- expect opposing preformed & regenerated nutrient responses

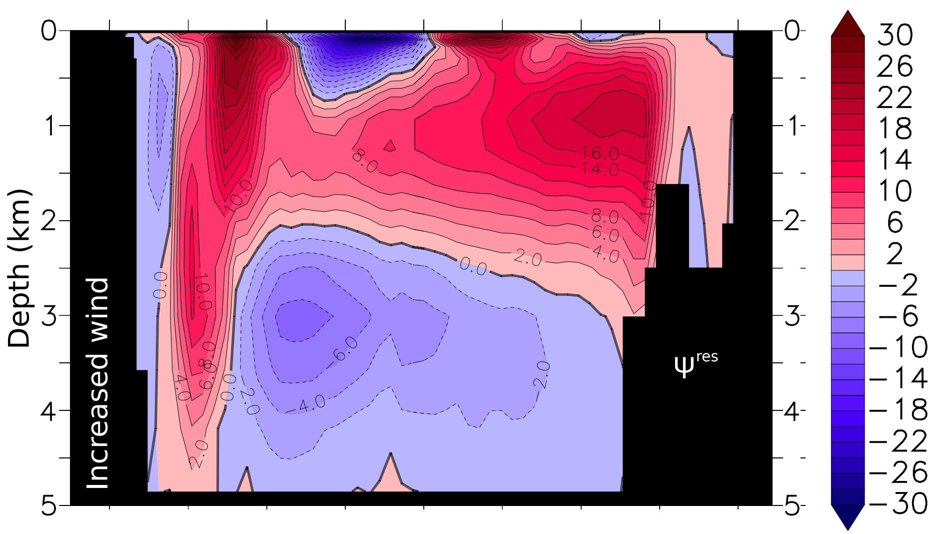
3. Residual circulation

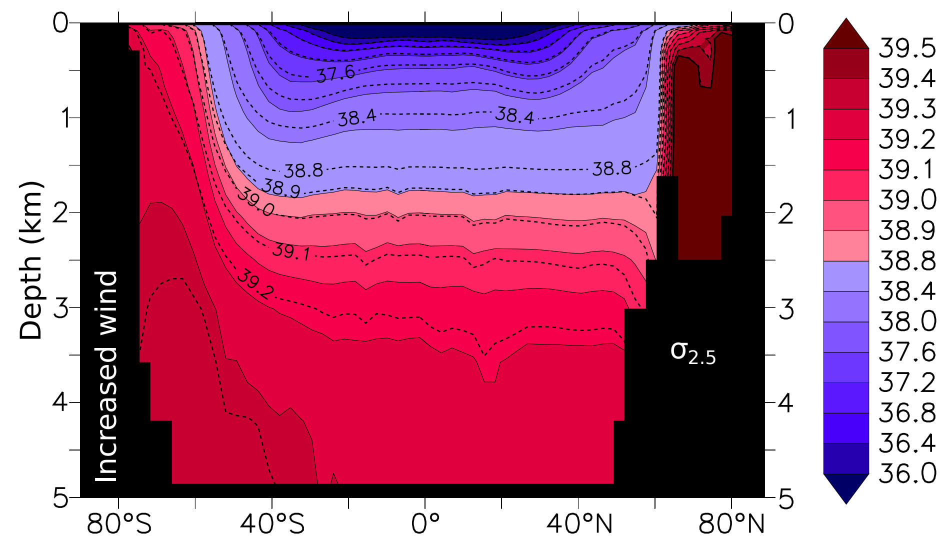


Consider effect of changes in residual circulation

$\psi_{res}=\psi_{Eul}+\psi_{eddy}$ $(\psi_{eddy}\approx K_{GM}S_i)$

example: stronger westerly wind stress





generally stronger ψ_{res}

generally thicker subtropical thermocline

MIT model 2.8°x2.8°, fixed K_{GM} in eddy closure, integrated 5000 years with online biogeochemistry

(Lauderdale et al., 2013, Climate Dynamics)

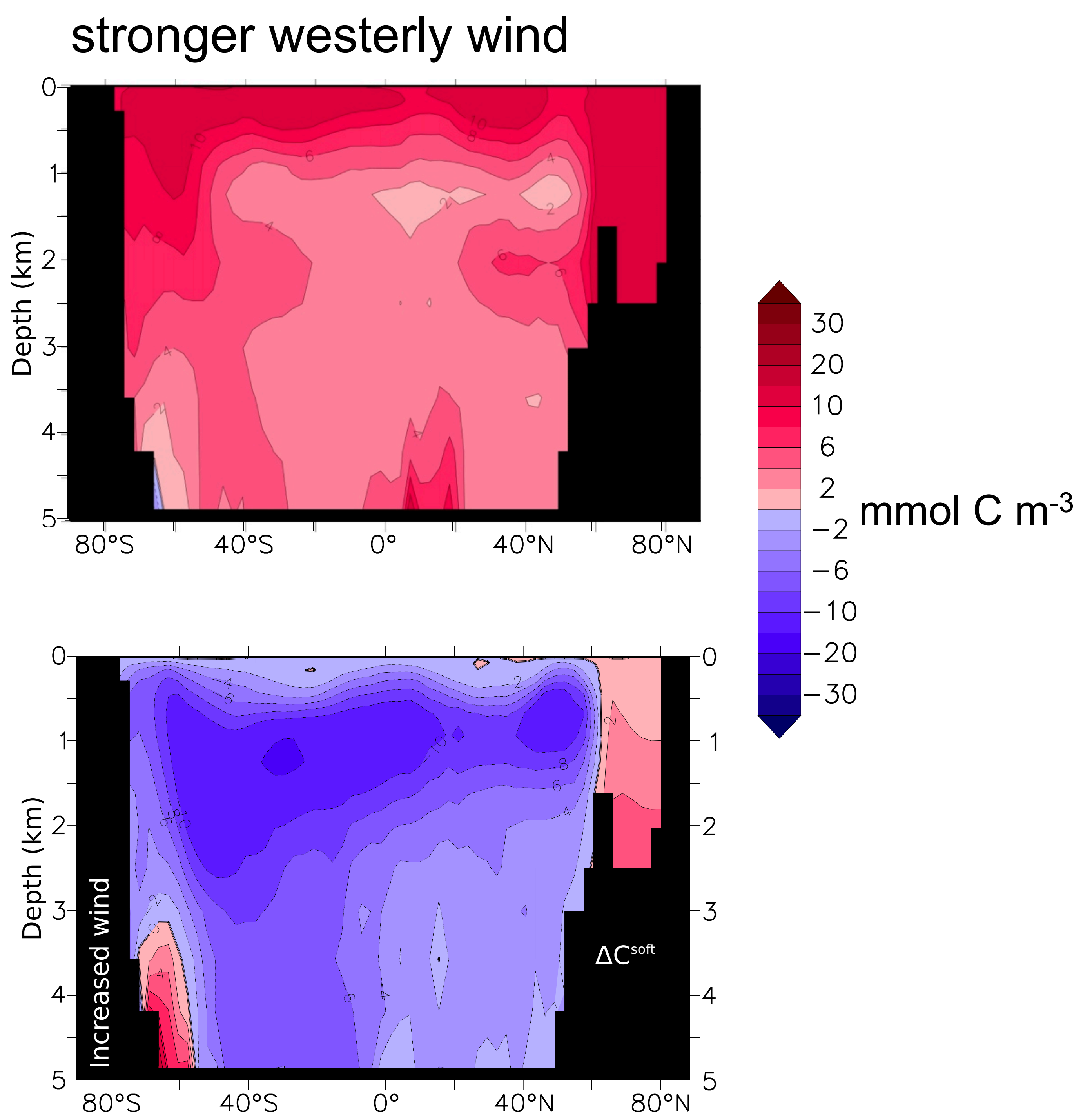
3. Residual circulation

ΔC^{pre}

preformed carbon anomaly *increases* via greater subduction

ΔC^{reg}

regenerated carbon anomaly *decreases*, as more nutrients are subducted

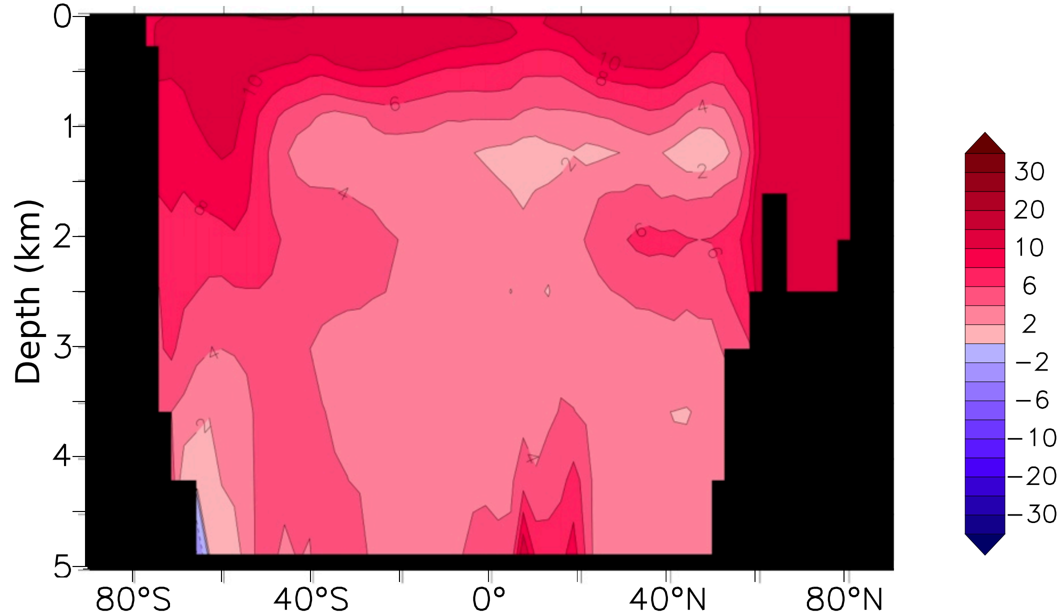


3. Residual circulation

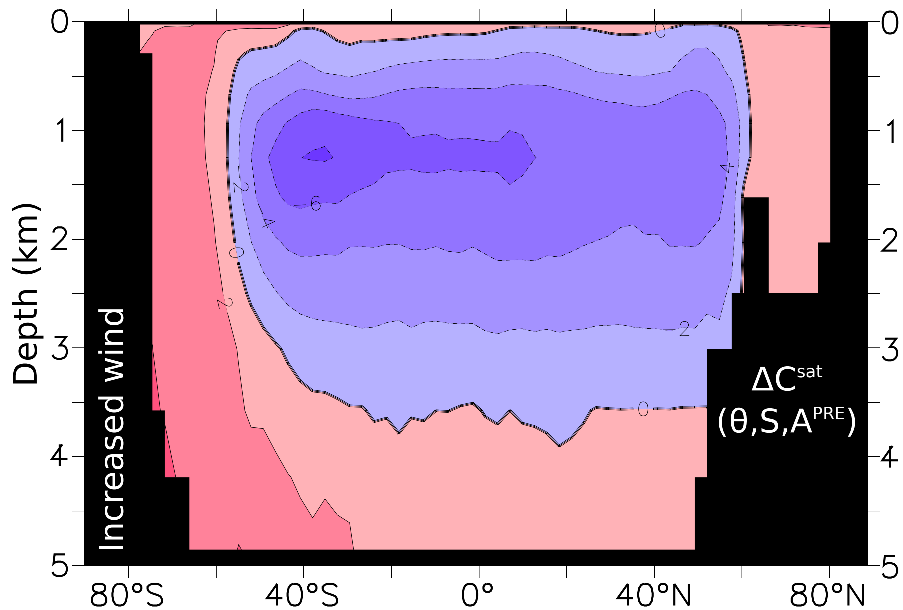
stronger westerly wind

ΔC^{pre}

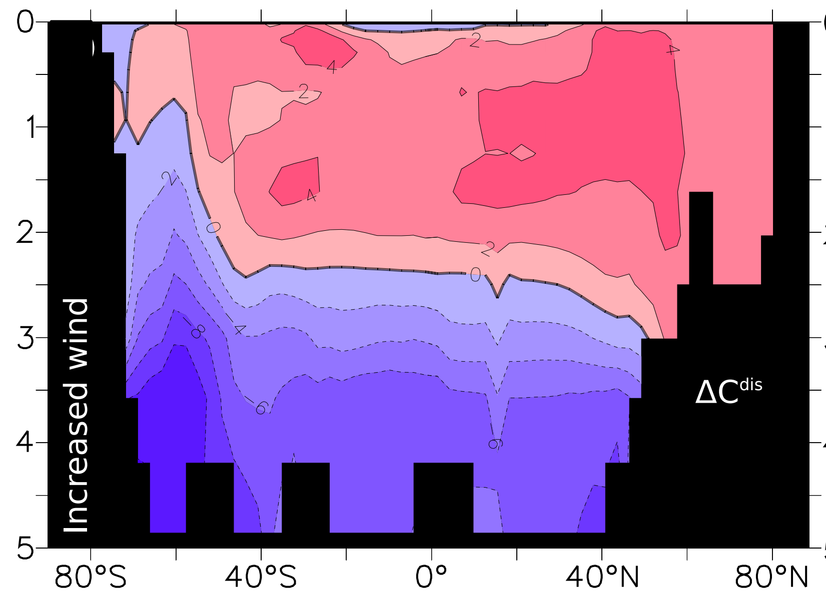
increases via greater subduction



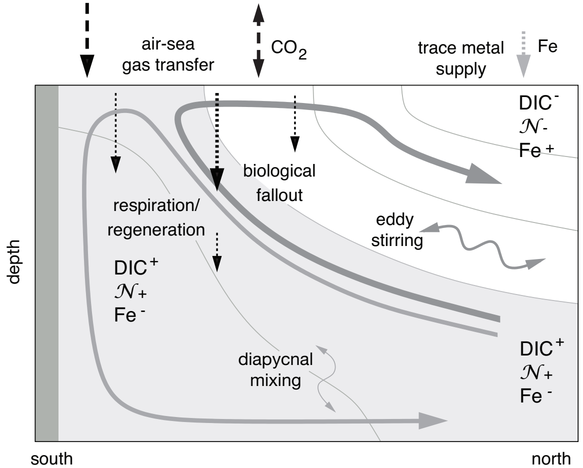
ΔC^{sat} from *T, S & Alk* decreases from warmer thermocline



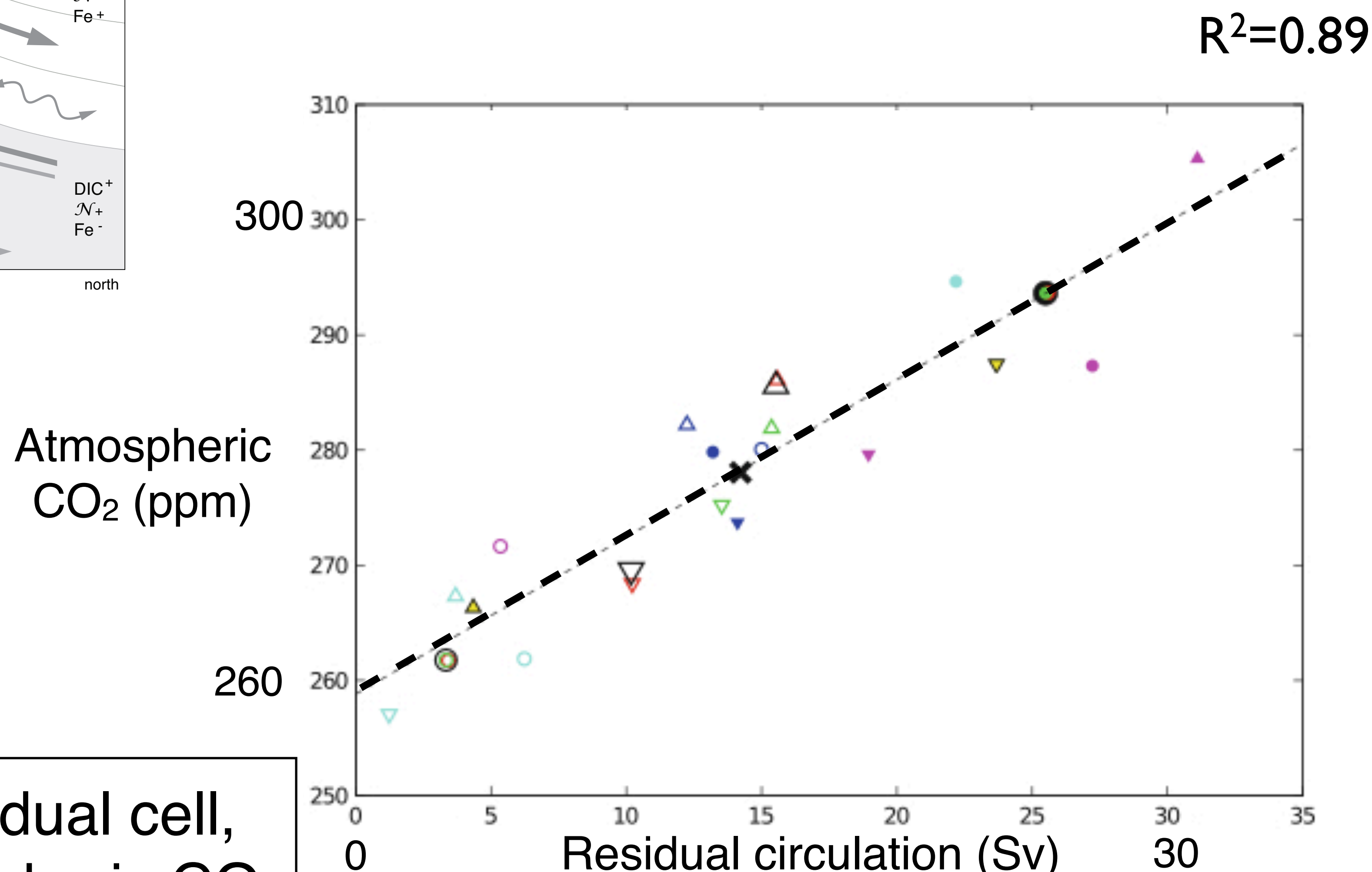
ΔC^{dis} *increases* due to shorter residence time



3. Residual circulation



27 experiments: variety of winds, GM values, limited buoyancy forcing changes

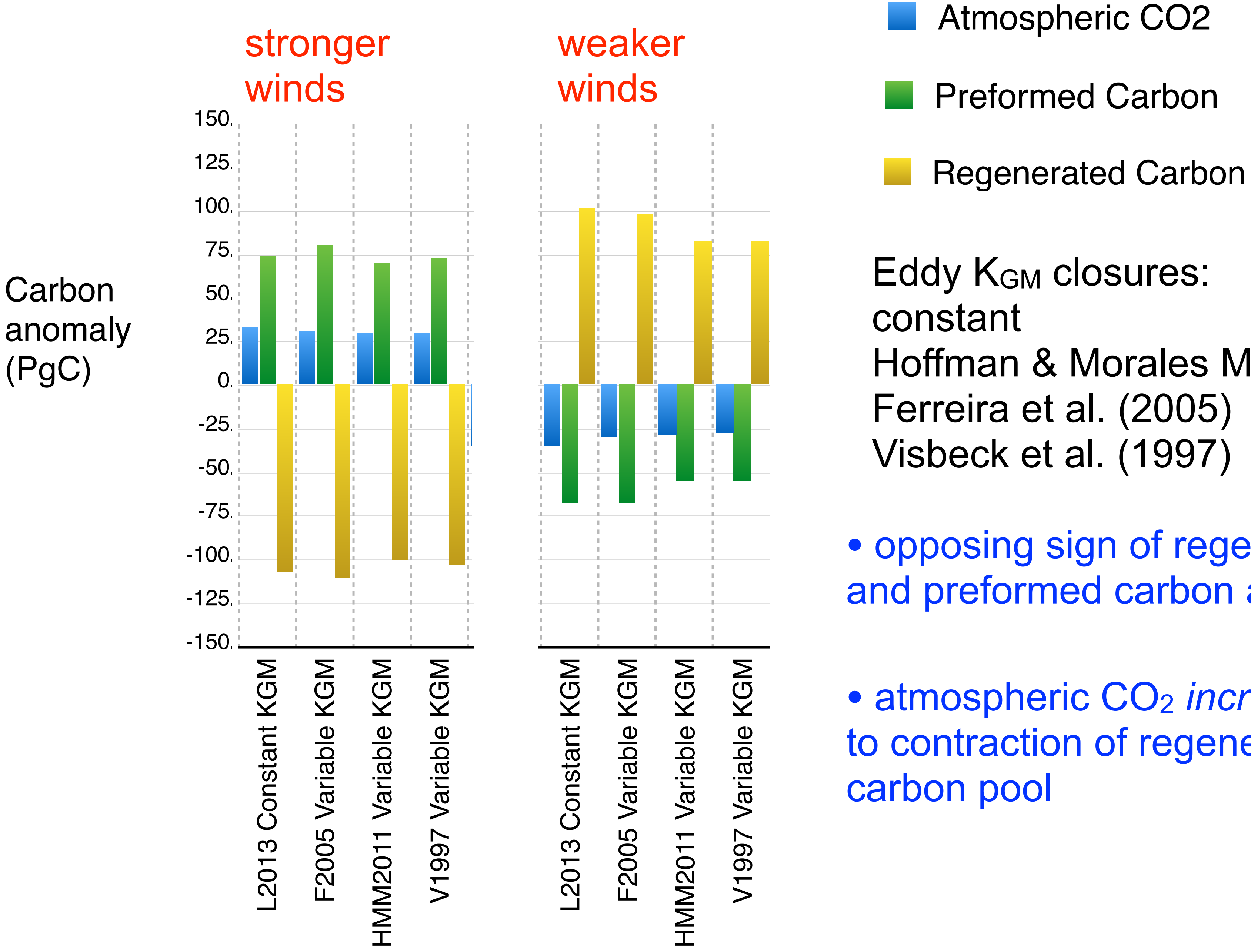


stronger residual cell, greater atmospheric CO_2

(Lauderdale et al., 2013, Climate Dynamics)

Consistent with paleo argument: enhanced upwelling driving last deglacial (Anderson et al., 2009)

3. Residual circulation wind changes & different eddy closures



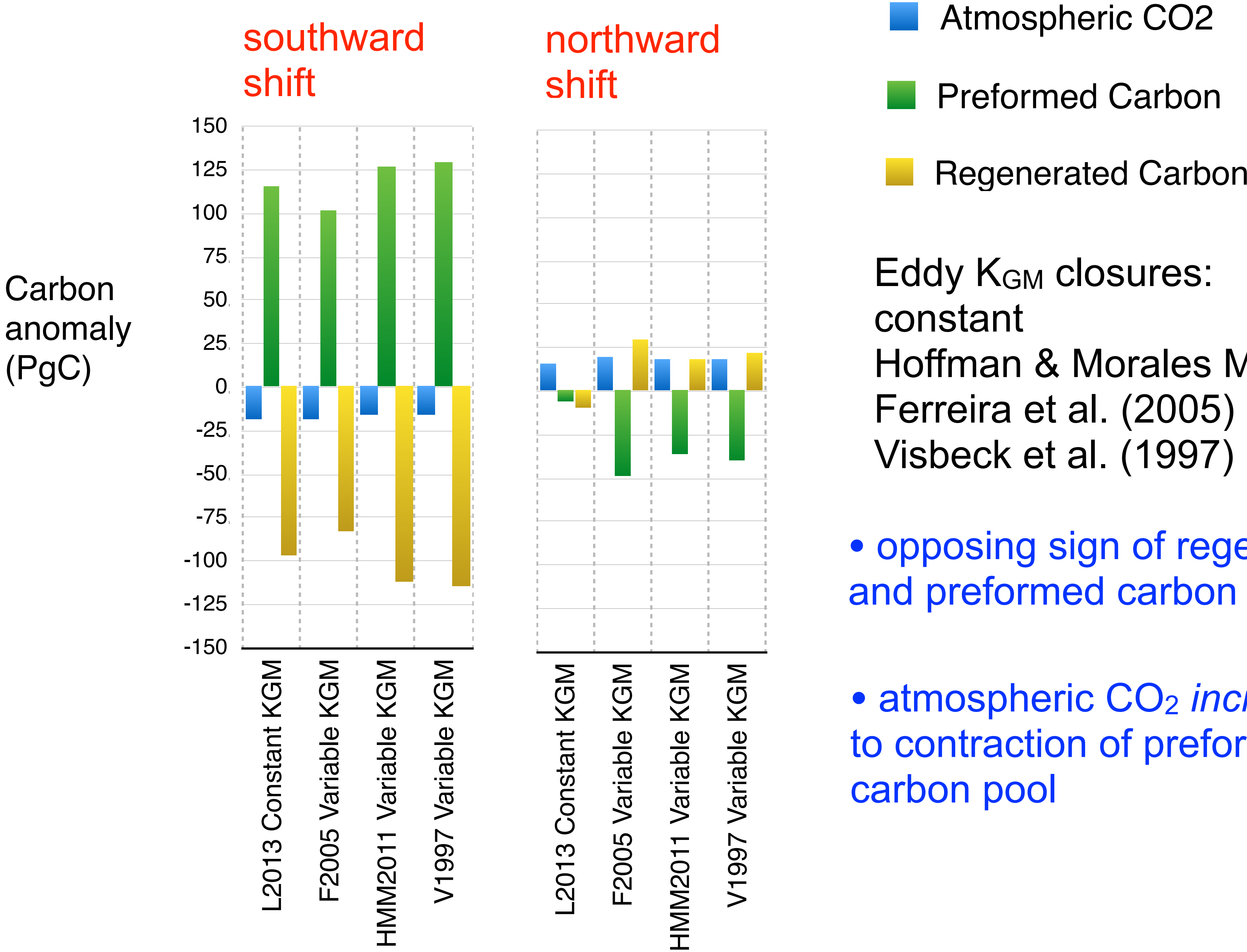
Eddy K_{GM} closures:
constant
Hoffman & Morales Maqueda (2011)
Ferreira et al. (2005)
Visbeck et al. (1997)

- opposing sign of regenerated and preformed carbon anomalies

- atmospheric CO_2 *increase* due to contraction of regenerated carbon pool

see Jon Lauderdale poster

3. Residual circulation wind changes & different eddy closures



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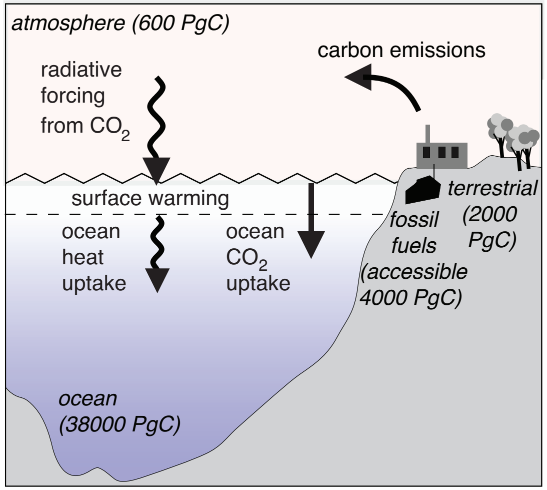
4. Global implications

Southern Ocean probably playing a crucial role:

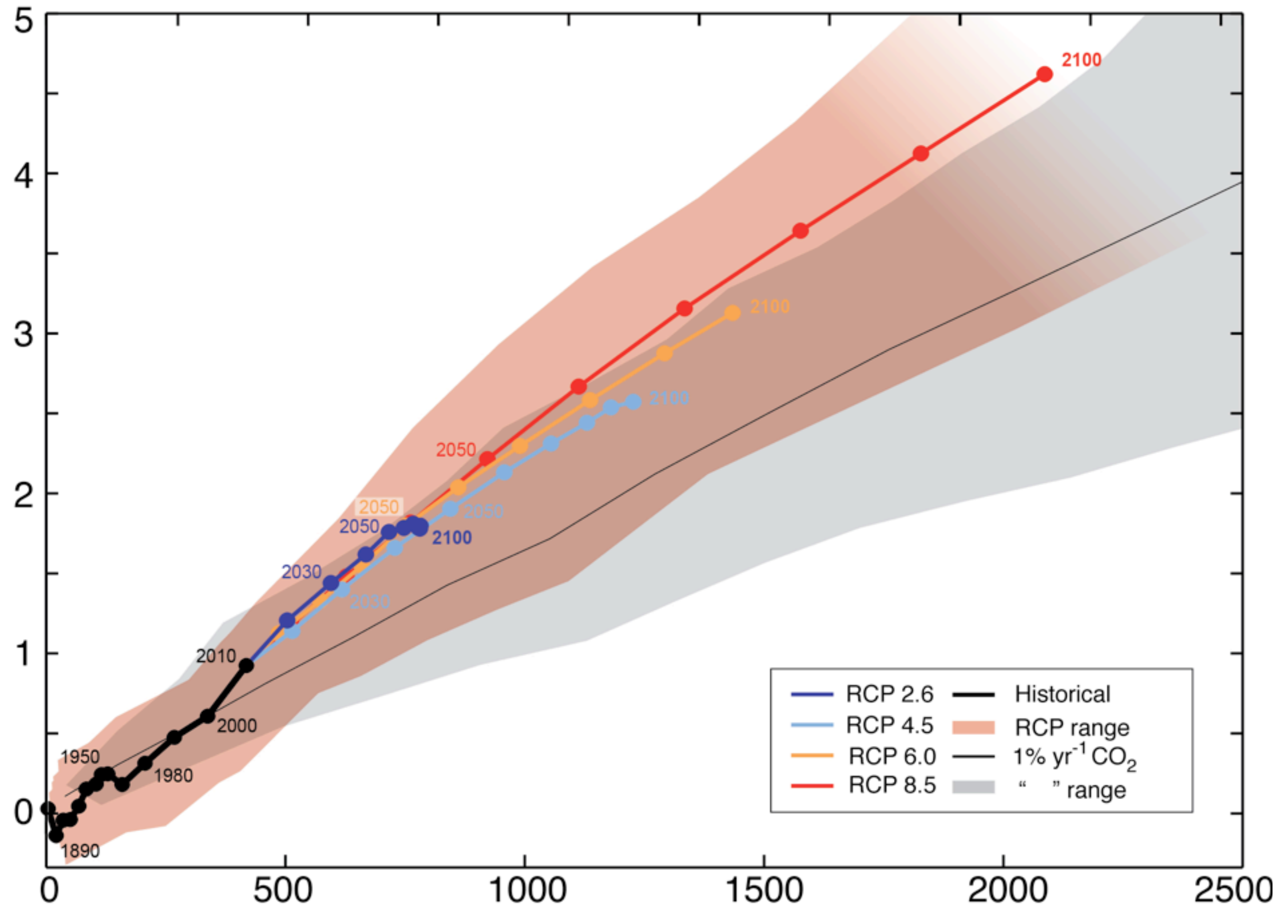
- sequestering heat
- sequestering anthropogenic CO_2

Ultimately important for global climate change



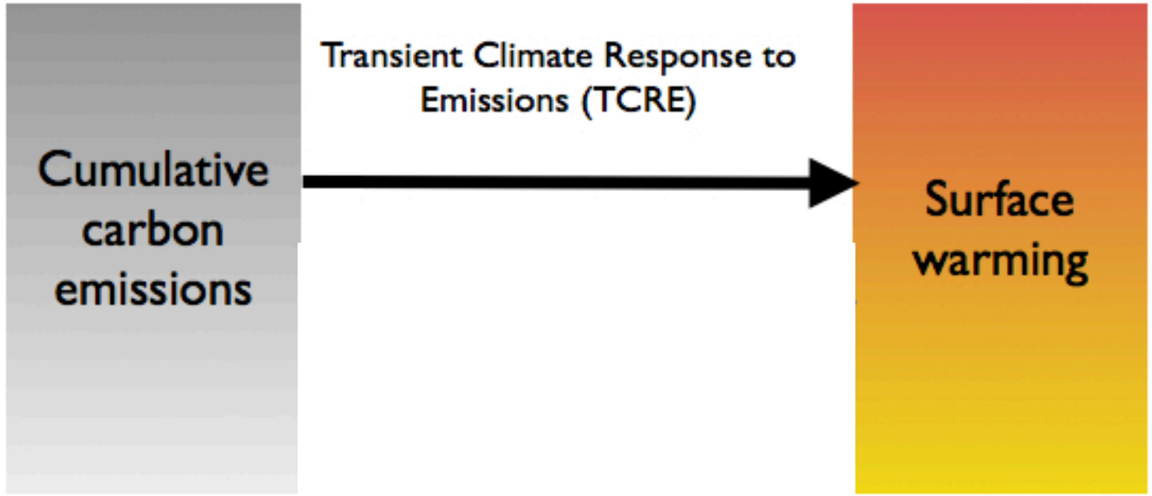
ΔT

surface temperature anomaly, (^{o}C) since 1870



cumulative carbon emission, I_{em} (PgC) since 1870

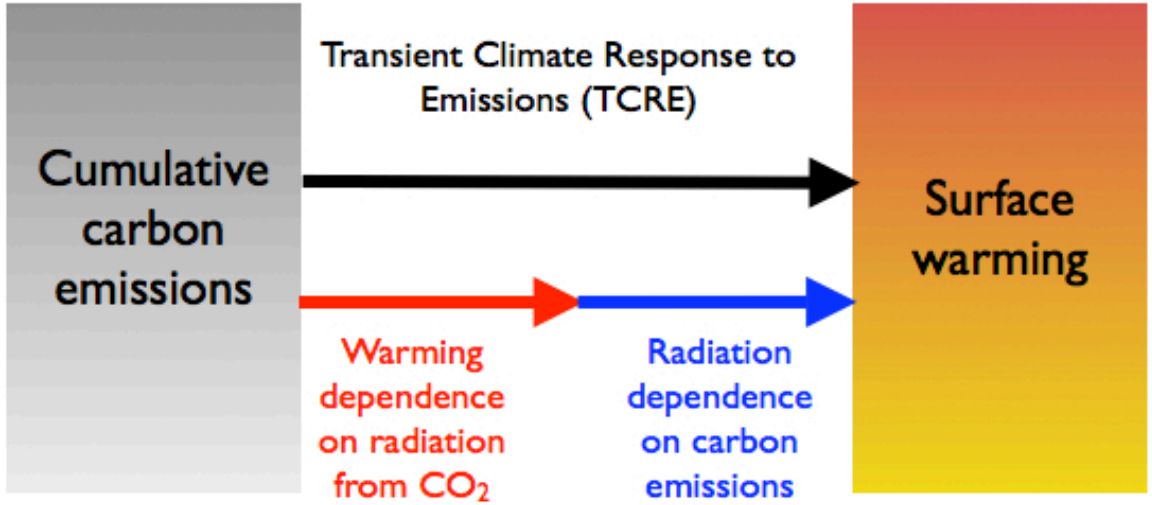
IPCC (2013)



$$\Delta T = \left(\frac{\partial T}{\partial I_{em}}\right) \Delta I_{em}$$

global surface temperature change

change in cumulative carbon emissions



$$\Delta T = \left(\frac{\partial T}{\partial R}\right)\left(\frac{\partial R}{\partial I_{em}}\right)\Delta I_{em}$$

global surface temperature change

change in cumulative carbon emissions

warming dependence on radiative forcing, *R* from CO_2

radiative forcing *R* dependence on carbon emissions, I_{em}

$$\Delta T = \left(\frac{\partial T}{\partial R}\right)\left(\frac{\partial R}{\partial I_{em}}\right)\Delta I_{em}$$

global surface temperature change

warming dependence on forcing, *R* from CO_2

forcing *R* dependence on carbon emissions

change in cumulative carbon emissions

$$\frac{1}{\lambda}(1 - N^*(t))$$

$$\frac{a}{I_B}(1 + I^*_{Usat}(t))$$

time-varying variables:

N^* normalised ocean heat uptake (relative to *R*)

I^*_{Usat} normalised ocean carbon undersaturation (relative to I_{em})

constants:

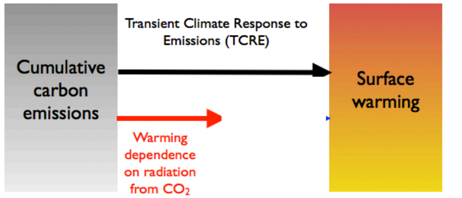
λ^{-1} =0.5 to 1.2 K(W m^{-2})$^{-1}$ climate parameter

a =5.35 Wm^{-2} radiative forcing from CO_2

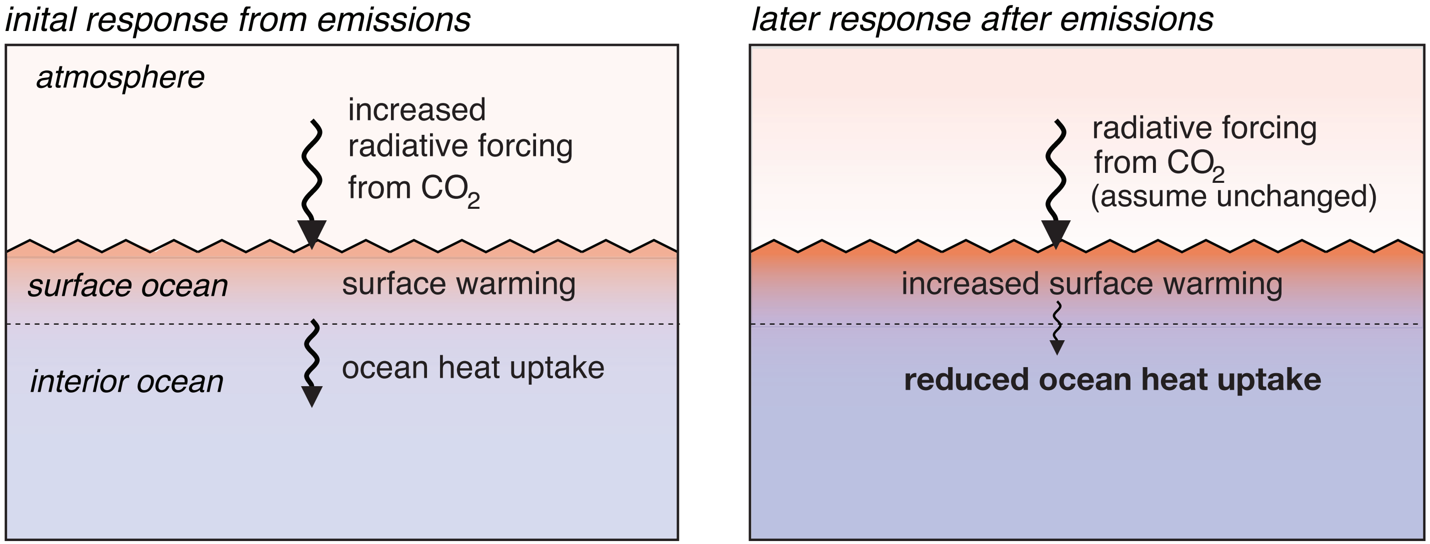
I_B = 3500PgC buffered ocean+atmos C inventory

Goodwin et al. (2015) *Nature Geoscience*

$$\Delta T(t) = \frac{1}{\lambda}(1 - N^*(t))\,\frac{a}{I_B}(1 + I^*_{Usat}(t))\;\Delta I_{em}(t)$$

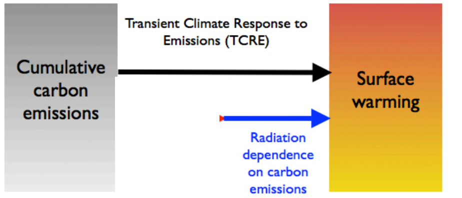


how does surface warming vary in time?



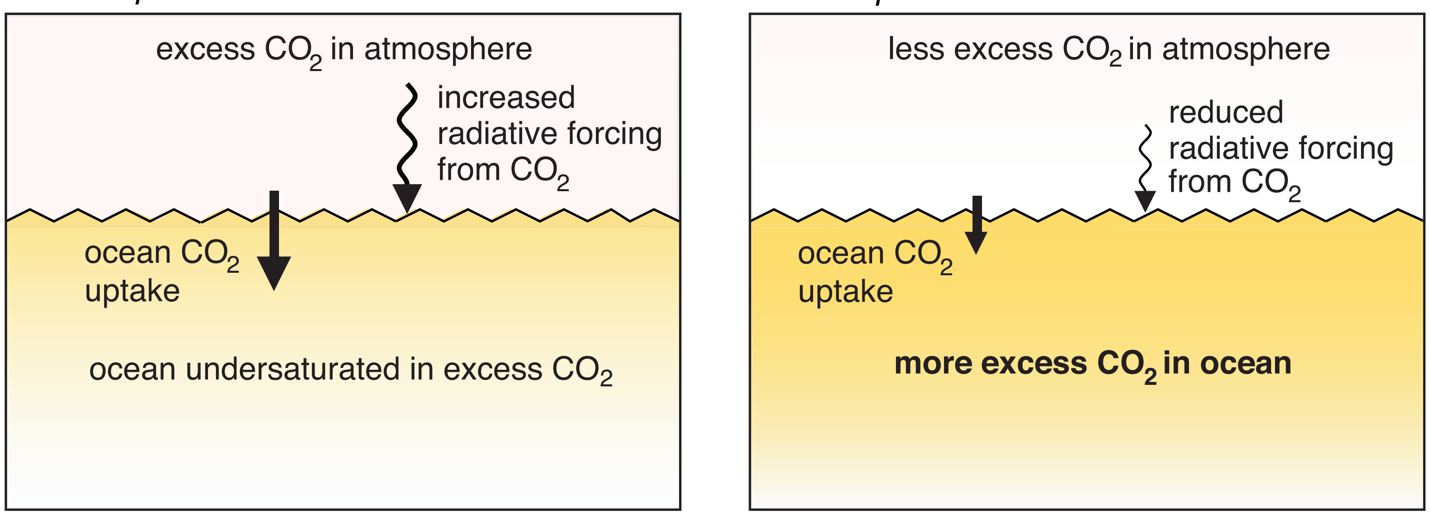
surface warming *increases* in time
due to weakening ocean heat uptake

$$\Delta T(t) = \frac{1}{\lambda}\left(1 - N^*(t)\right)\frac{a}{I_B}\left(1 + I^*_{Usat}(t)\right)\Delta I_{em}(t)$$



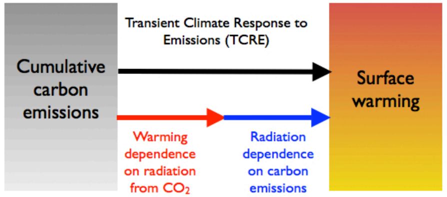
how does radiative forcing from CO_2 vary in time?

inital response from emissions — *later response after emissions*

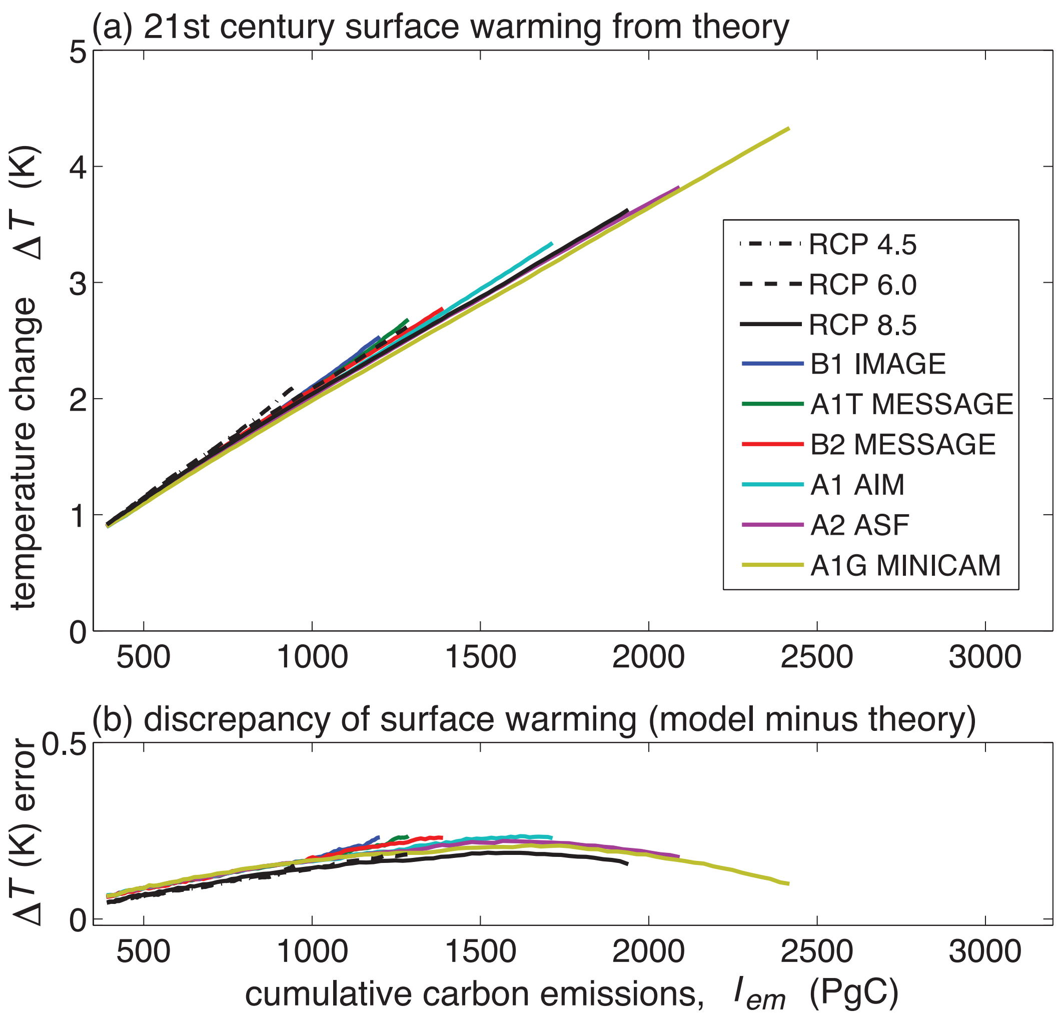


radiative forcing *decreases* in time
due to ocean carbon uptake

$$\Delta T(t) = \frac{1}{\lambda}\left(1 - N^*(t)\right)\frac{a}{I_B}\left(1 + I^*_{Usat}(t)\right)\Delta I_{em}(t)$$



test in a coarse-resolution atmosphere-ocean model (GENIE) with coupled circulation & biogeochemistry

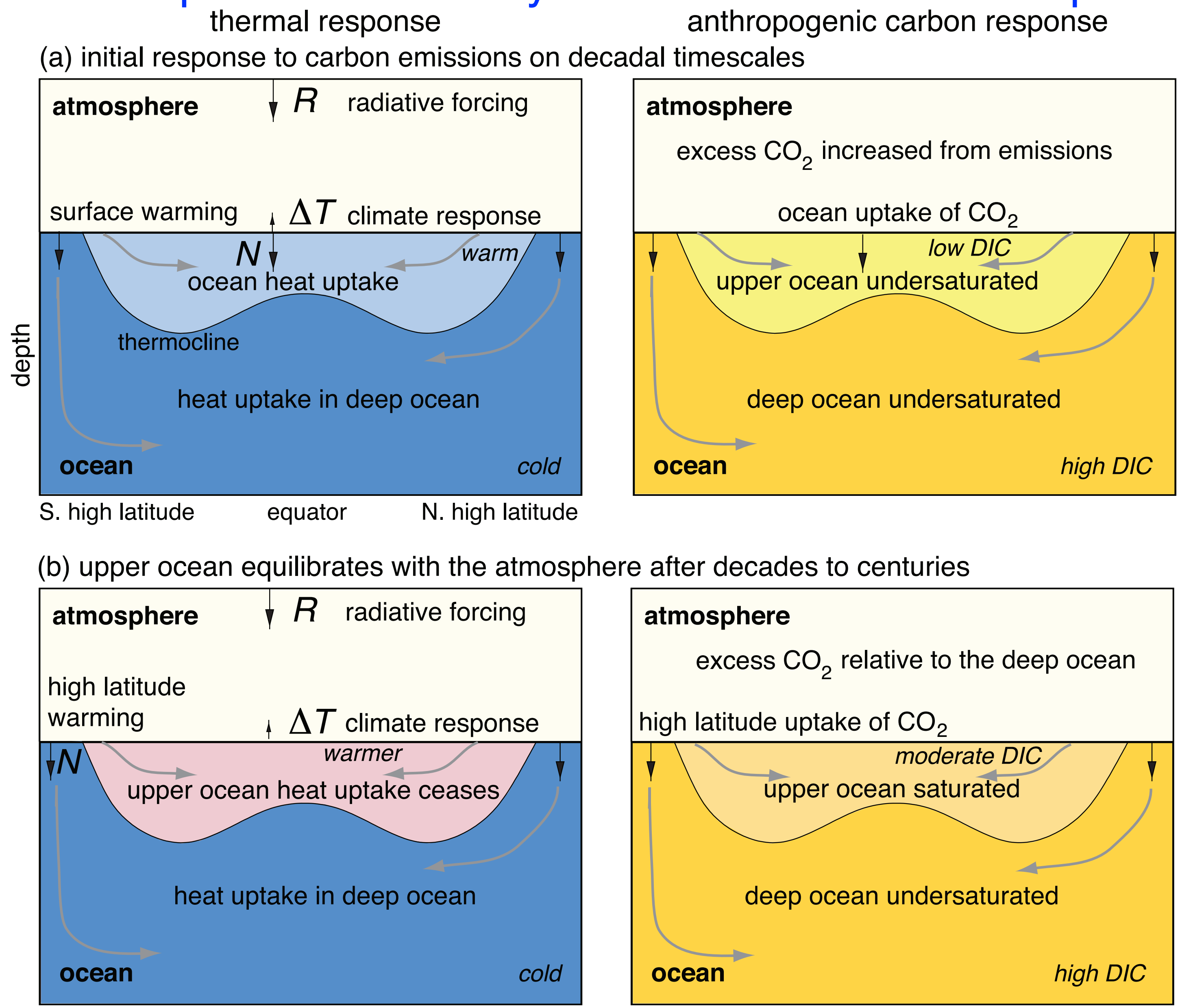


response from year 2000 to 2100 driven by IPCC scenarios

(Goodwin et al., 2015, *Nature Geoscience*)

why the similar transient response?

heat & carbon sequestration mainly achieved via ventilation process



heat & carbon sequestration can though differ via air-sea timescales & biology ....

6. Challenges

1. Southern Ocean likely to be crucial in sequestering heat & carbon

rate limiting processes unclear, probably:

- subduction into main thermocline
- entrainment into winter mixed layer
- mismatch drives annual air-sea transfer

2. Residual circulation crucial for communication with the rest of ocean:

- stronger residual circulation *increases* atmospheric CO_2.

link to carbon transport is unclear

also role of deep cell is unclear

3. Global climate implications from ocean heat & carbon drawdown

- Partly compensating due to ventilation
- Mismatch in heat & carbon uptake likely to be important