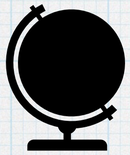
해양물리의 관점에서 보는 탄소~~순~~환 교환

연세대학교 대기과학과
Air-Sea Modeling Lab 송하준

해양물리의 관점에서 보는 탄소~~순~~환 교환

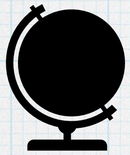
연세대학교 대기과학과
Air-Sea Modeling Lab 송하준

In this talk . . .



Global carbon budget

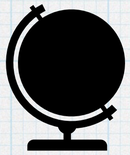
In this talk . . .



Global carbon budget

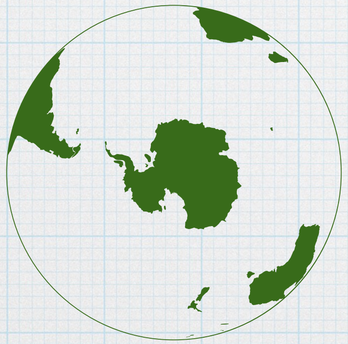
- Natural and anthropogenic carbon in the ocean (large scale)

In this talk . . .



Global carbon budget

- Natural and anthropogenic carbon in the ocean (large scale)

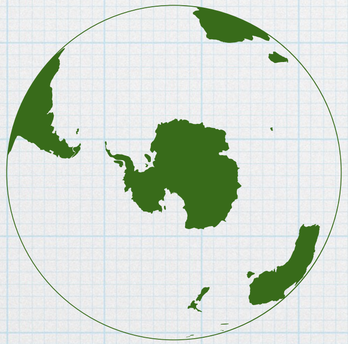


- CO_2 flux and the Southern Ocean
- CO_2 flux in the mesoscale
- Decadal Variability in the CO_2 flux

In this talk . . .

Global carbon budget

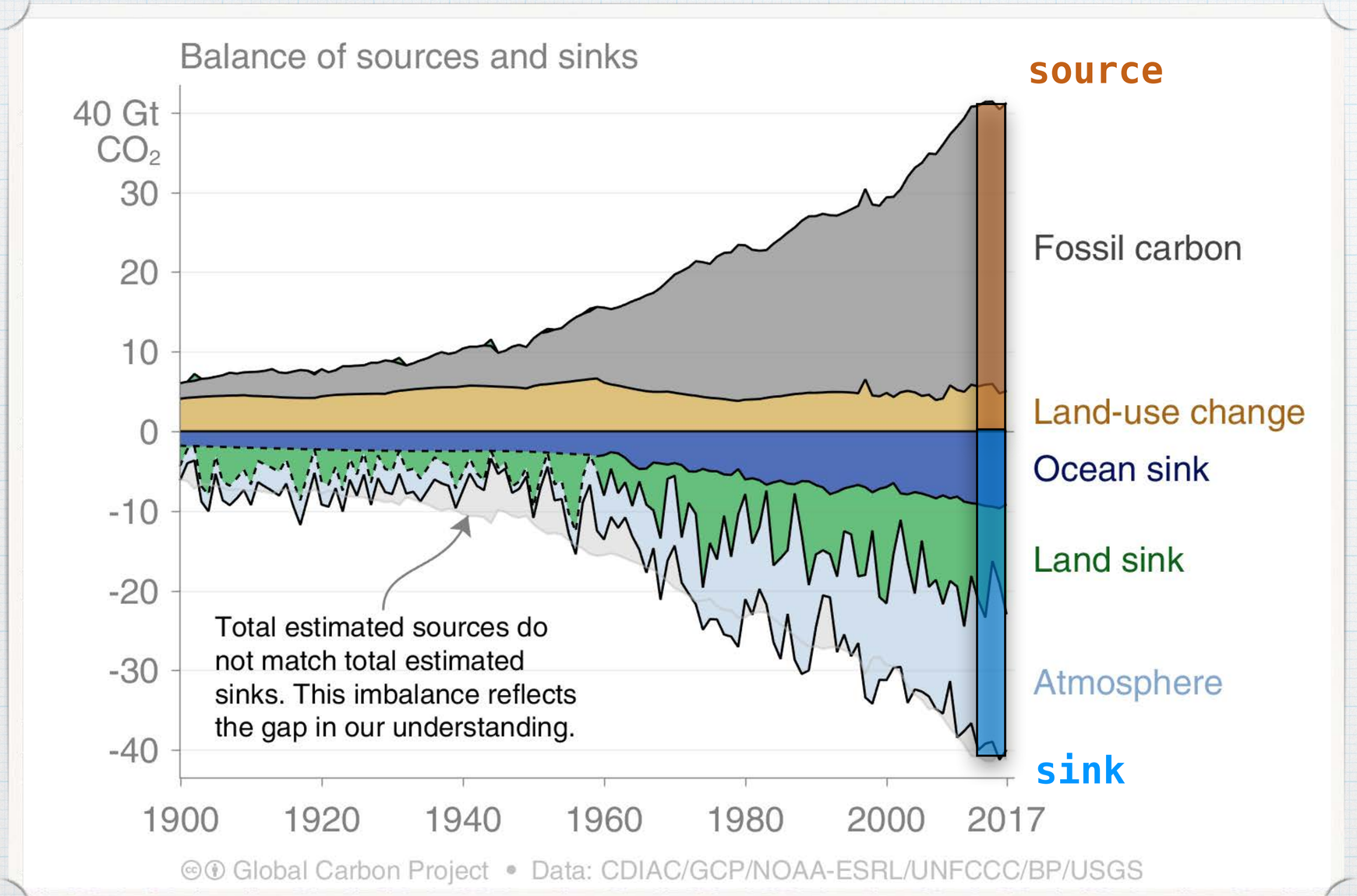
- Natural and anthropogenic carbon in the ocean (large scale)



- CO_2 flux and the Southern Ocean
- CO_2 flux in the mesoscale
- Decadal Variability in the CO_2 flux

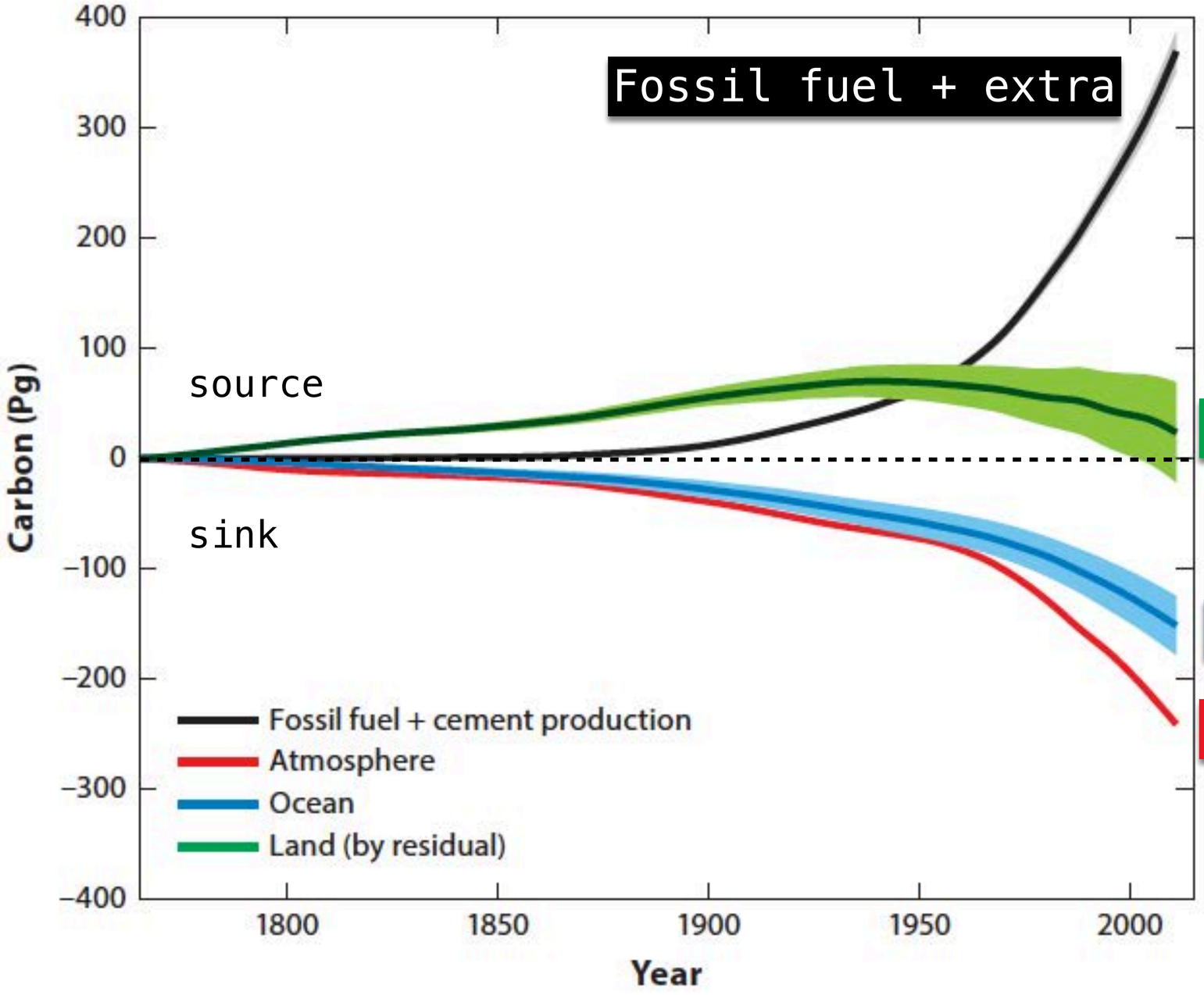
New findings in the CO_2 flux and challenges

Anthropogenic carbon global budget



Global Carbon Project

Cumulative sources and sinks of anthropogenic carbon since 1765



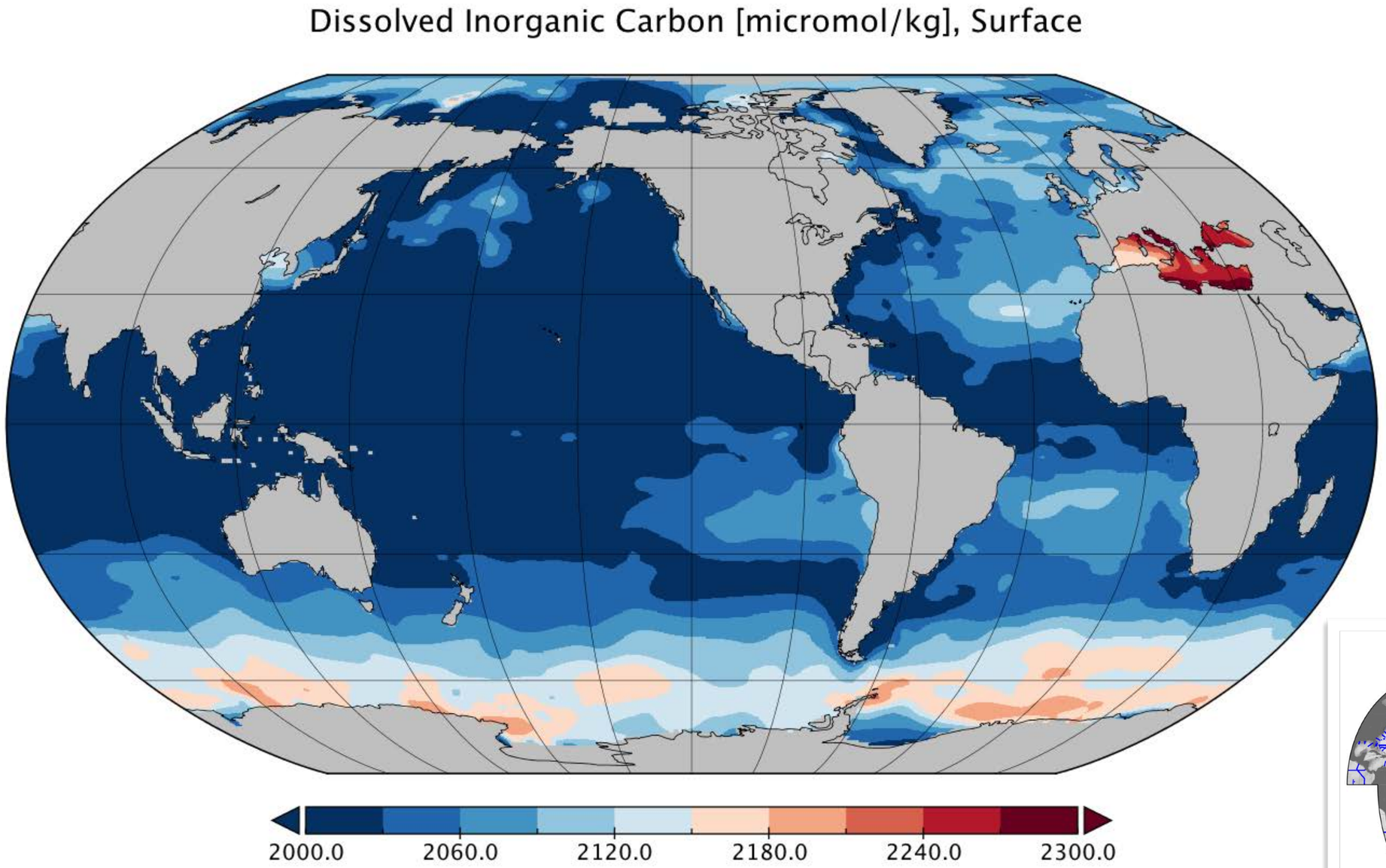
Land

Ocean

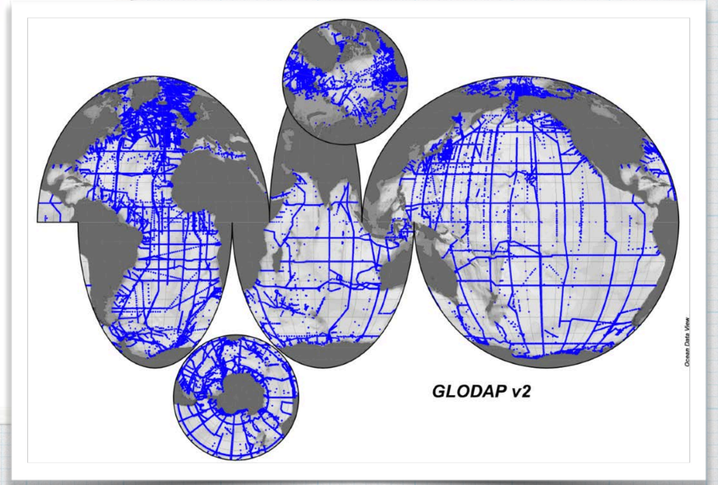
Atmosphere

McKinley et al., 2017

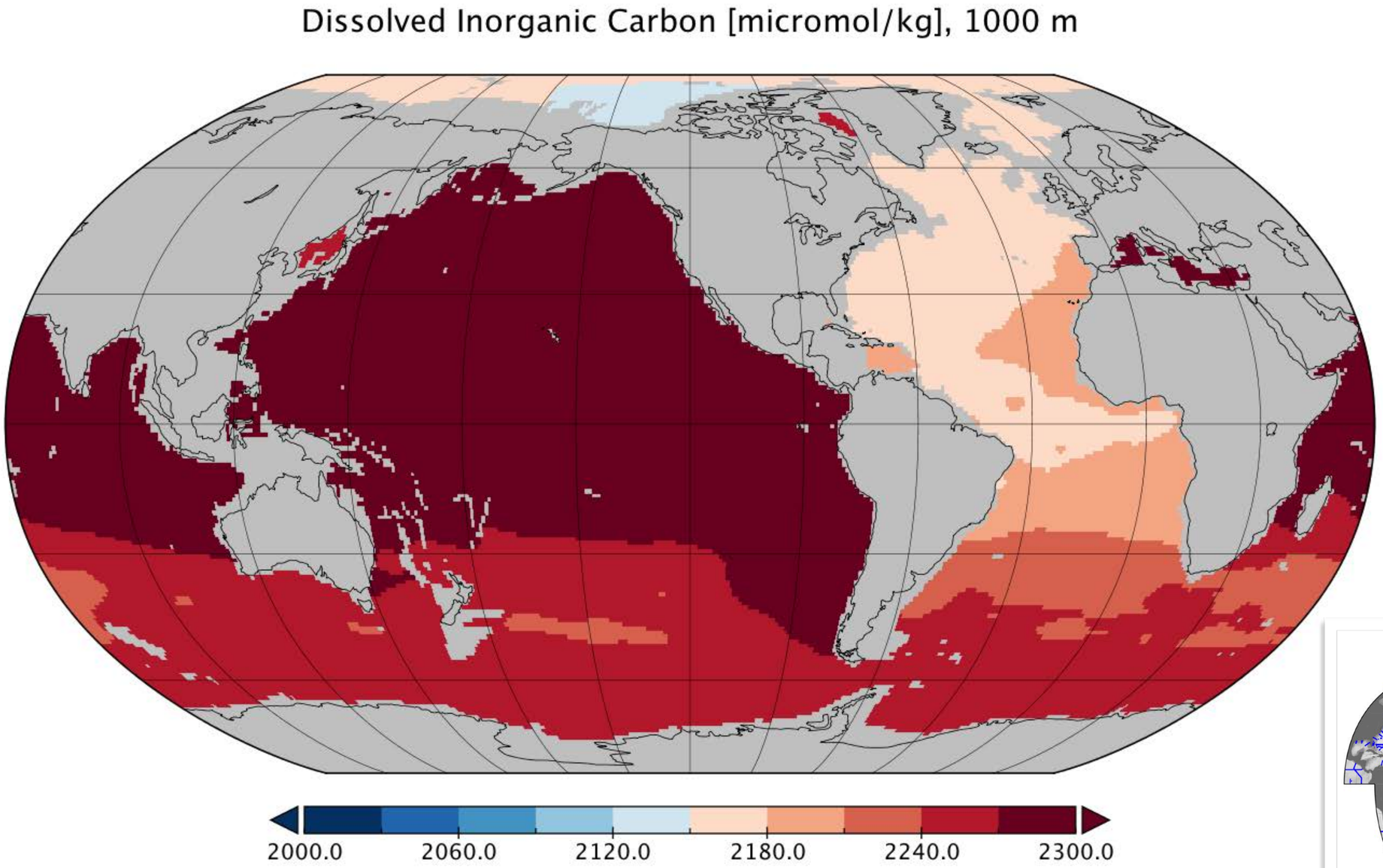
Dissolved Inorganic Carbon, surface



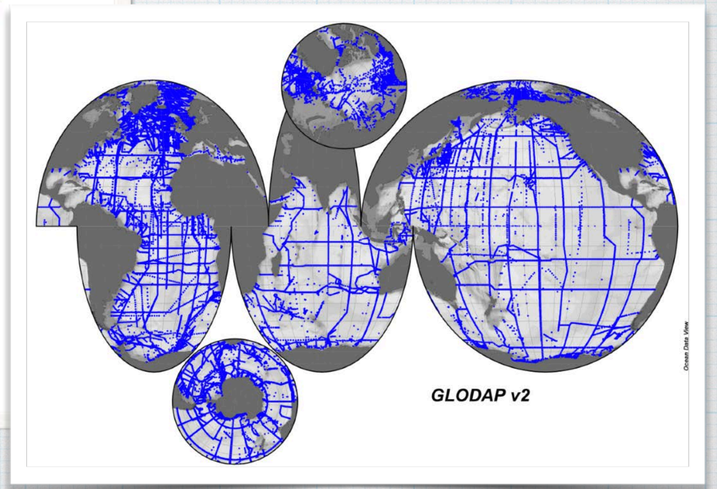
GLODAP v2



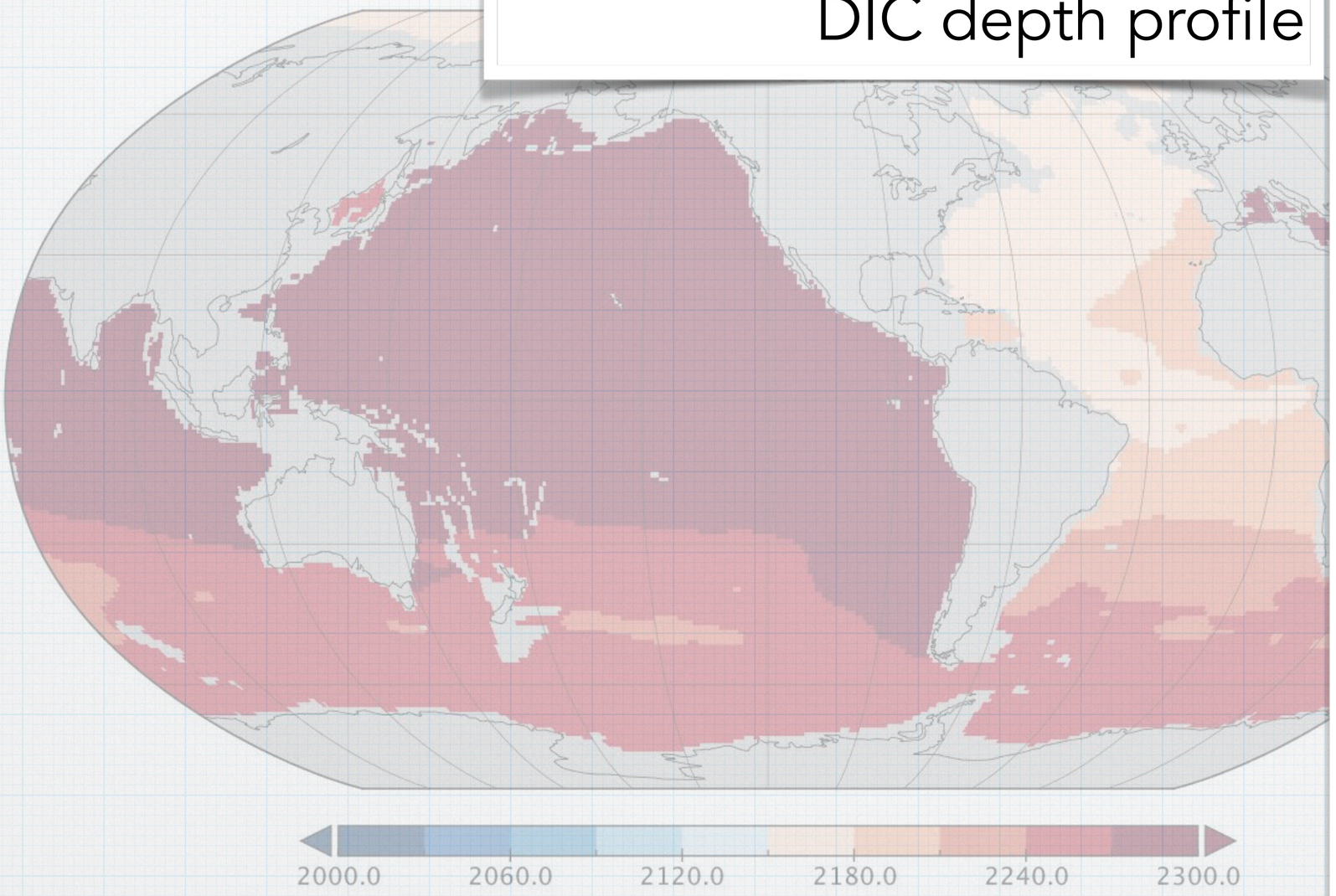
Dissolved Inorganic Carbon, 1000 m



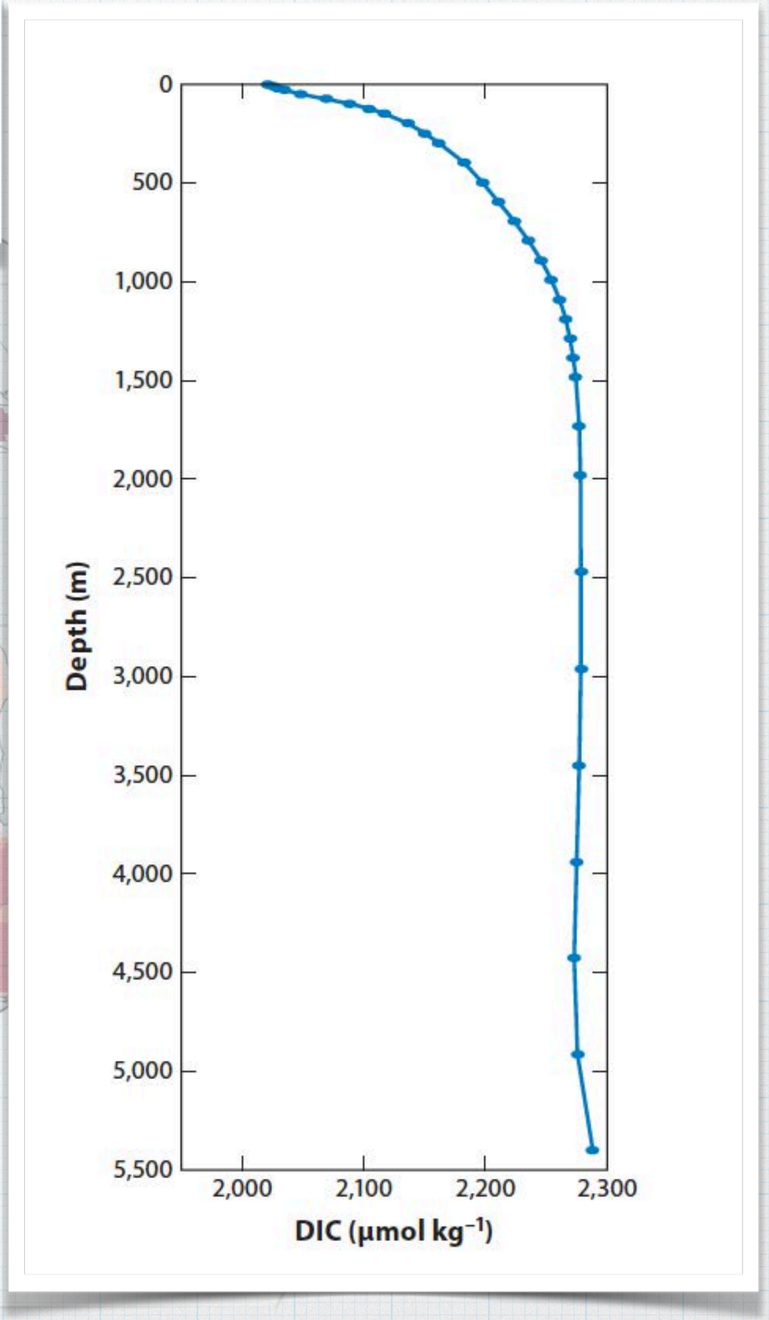
GLODAP v2



Global area-weighted mean DIC depth profile

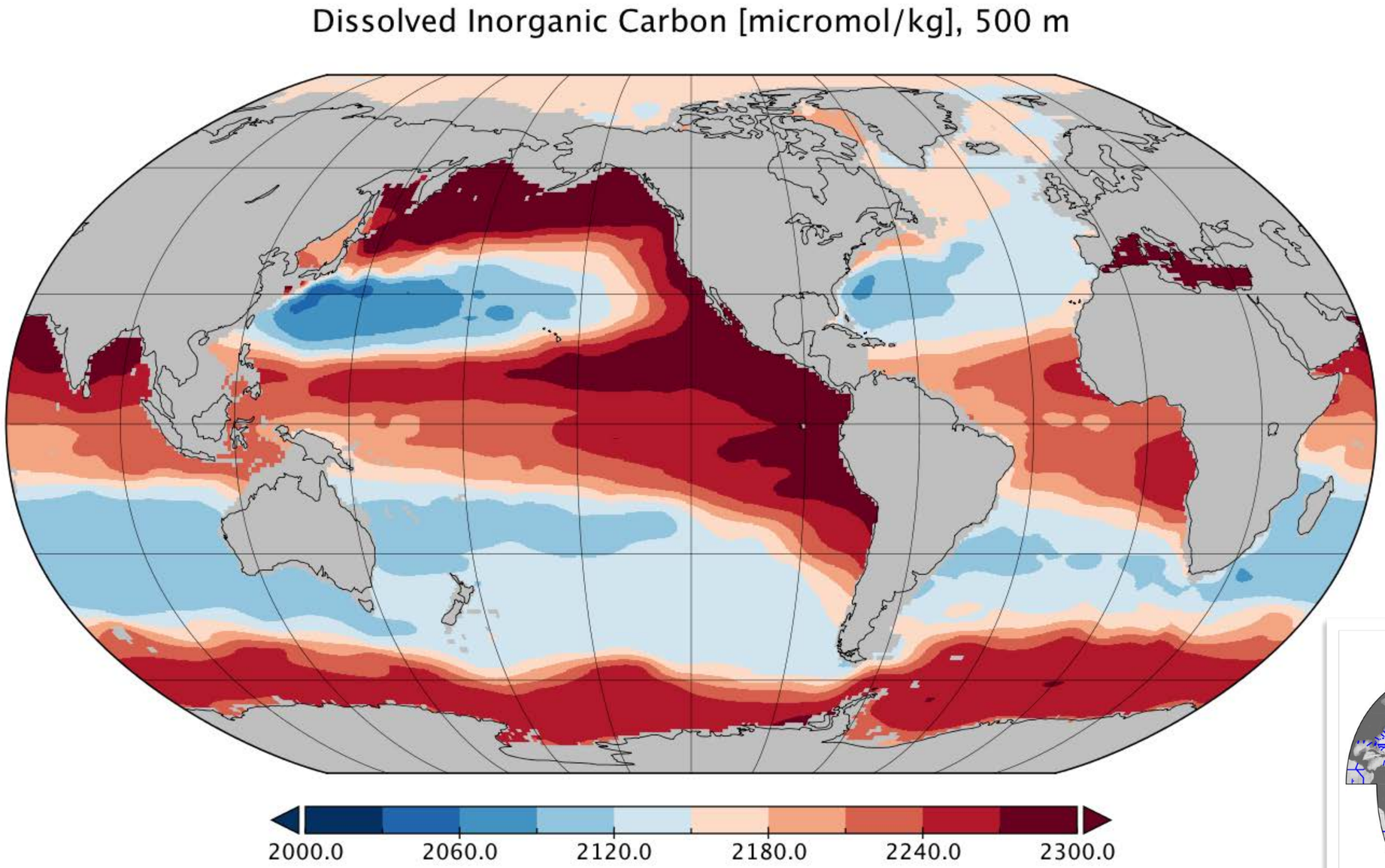


GLODAP v2

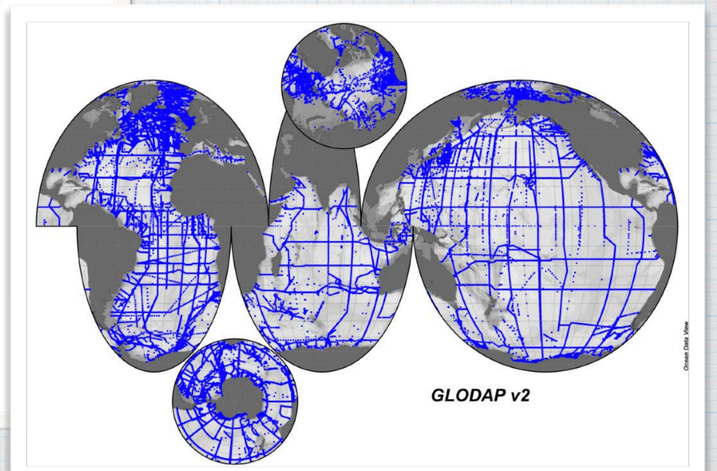


McKinley et al., 2017

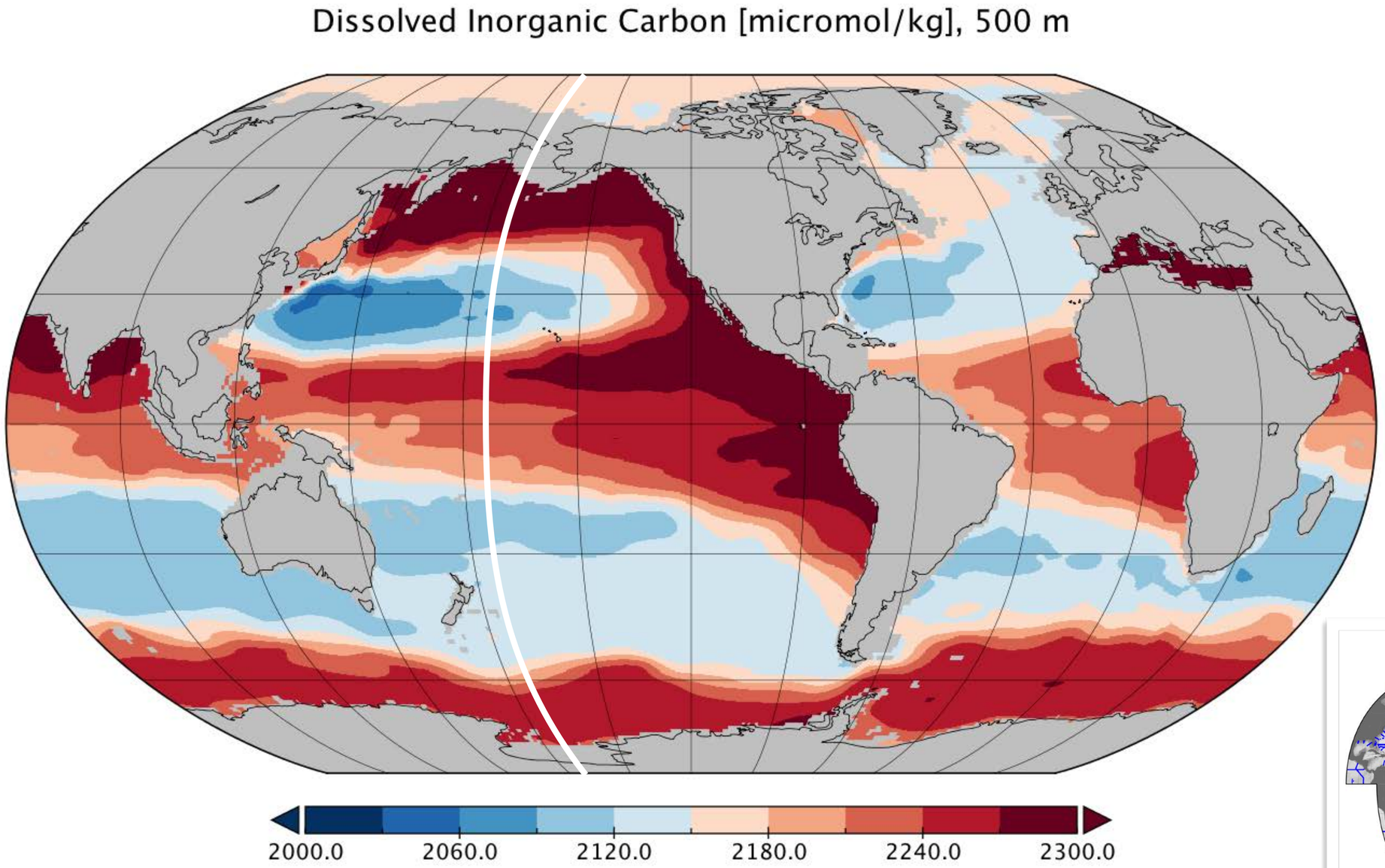
Dissolved Inorganic Carbon, 500 m



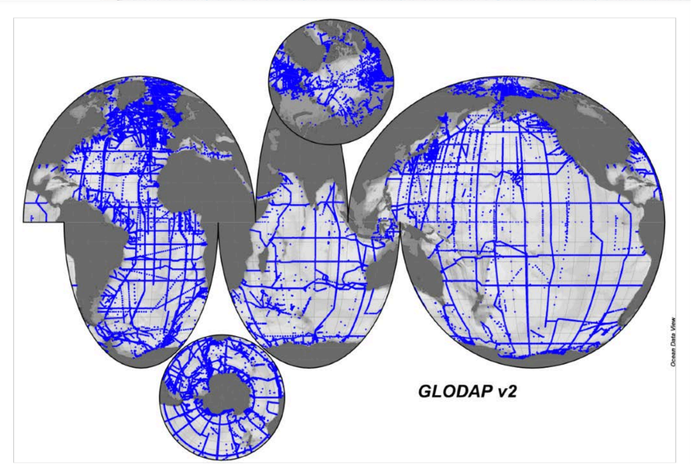
GLODAP v2



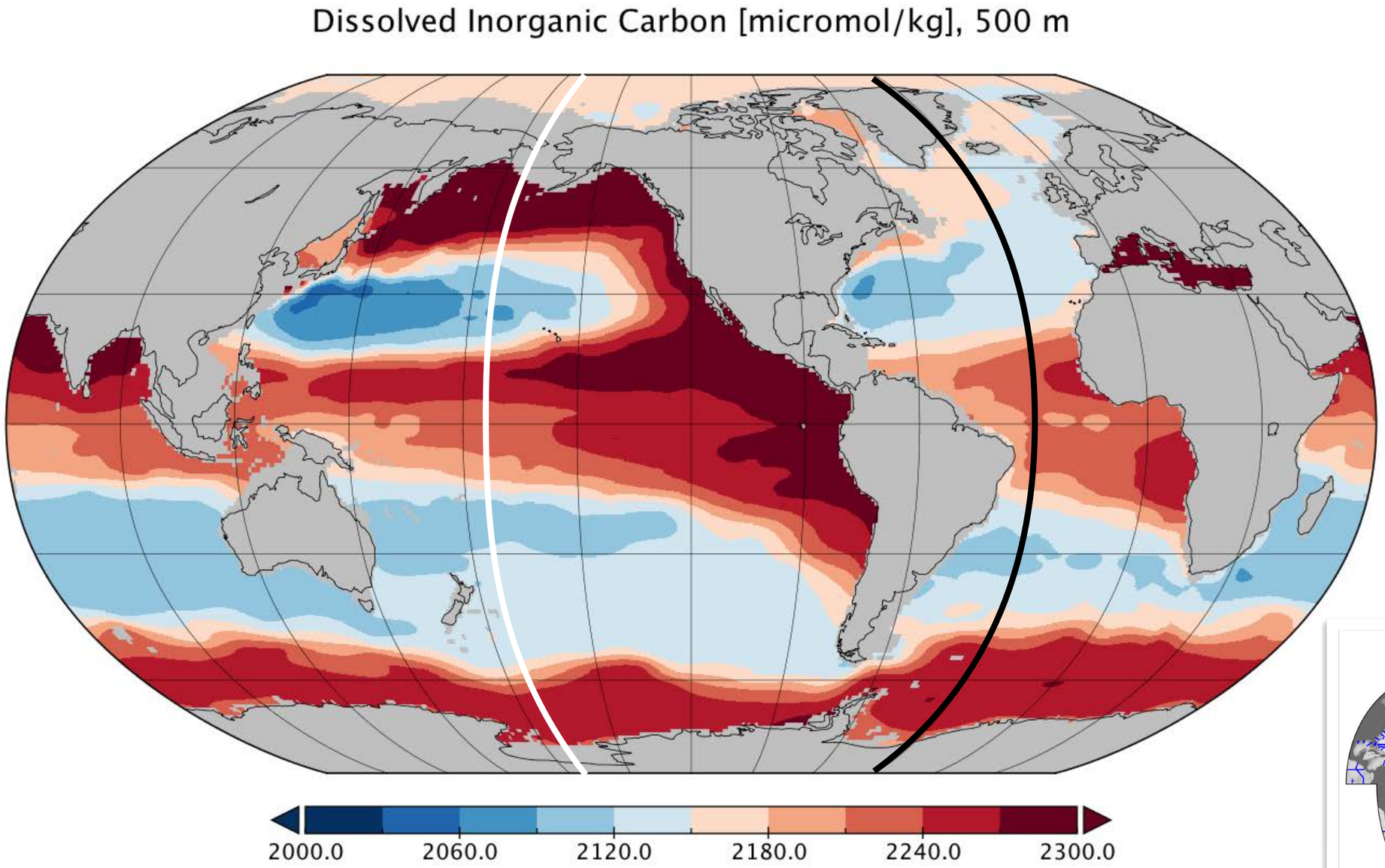
Dissolved Inorganic Carbon, 500 m



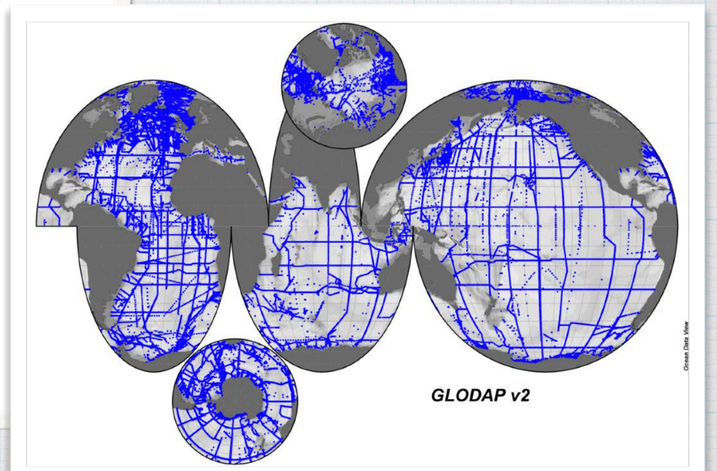
GLODAP v2



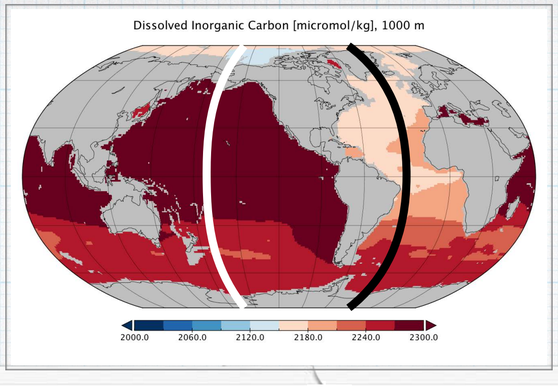
Dissolved Inorganic Carbon, 500 m



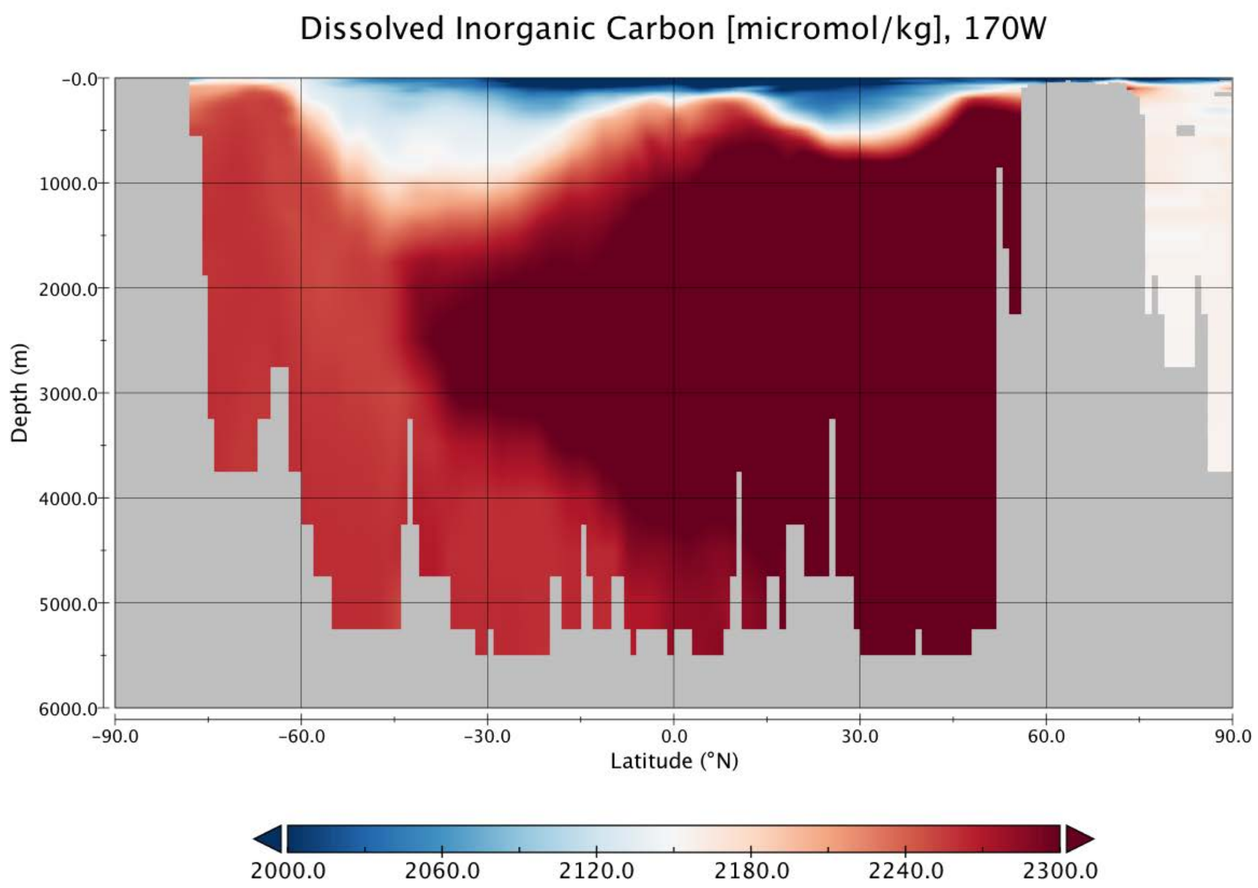
GLODAP v2

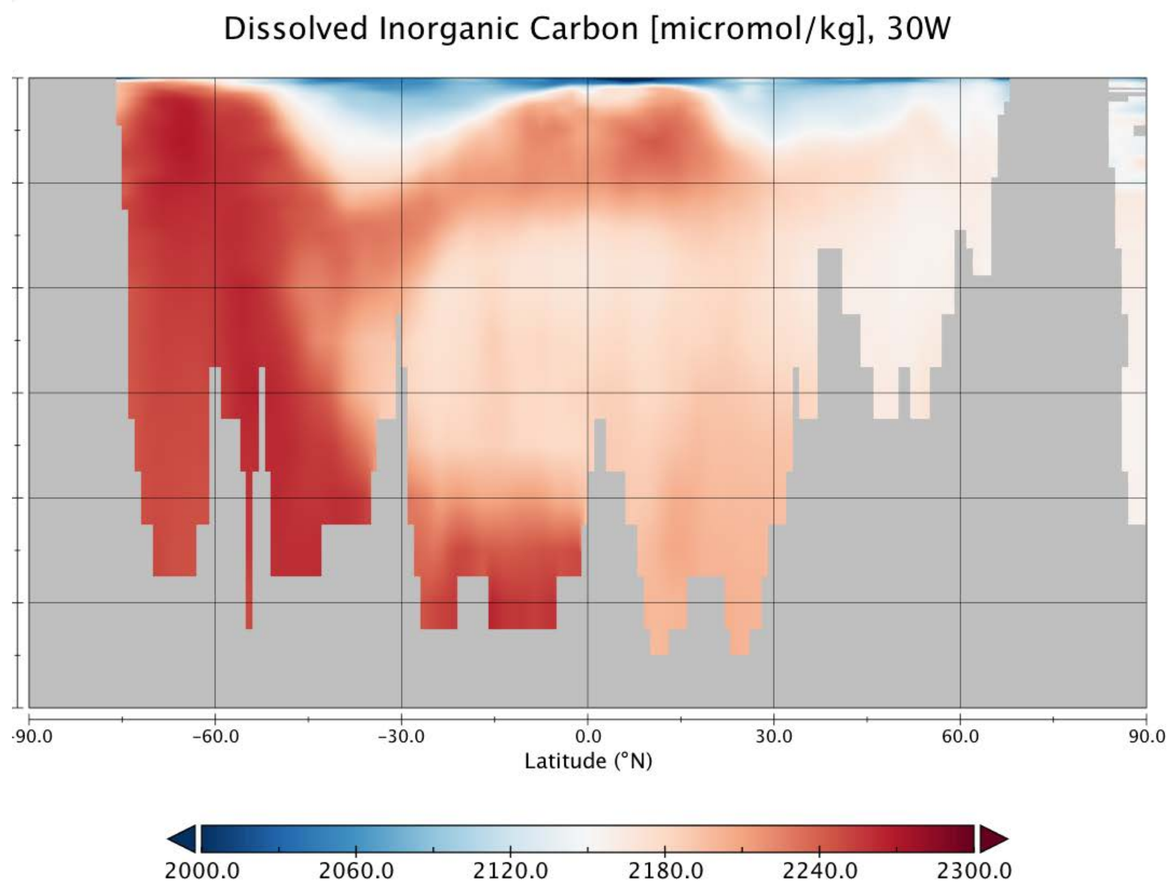


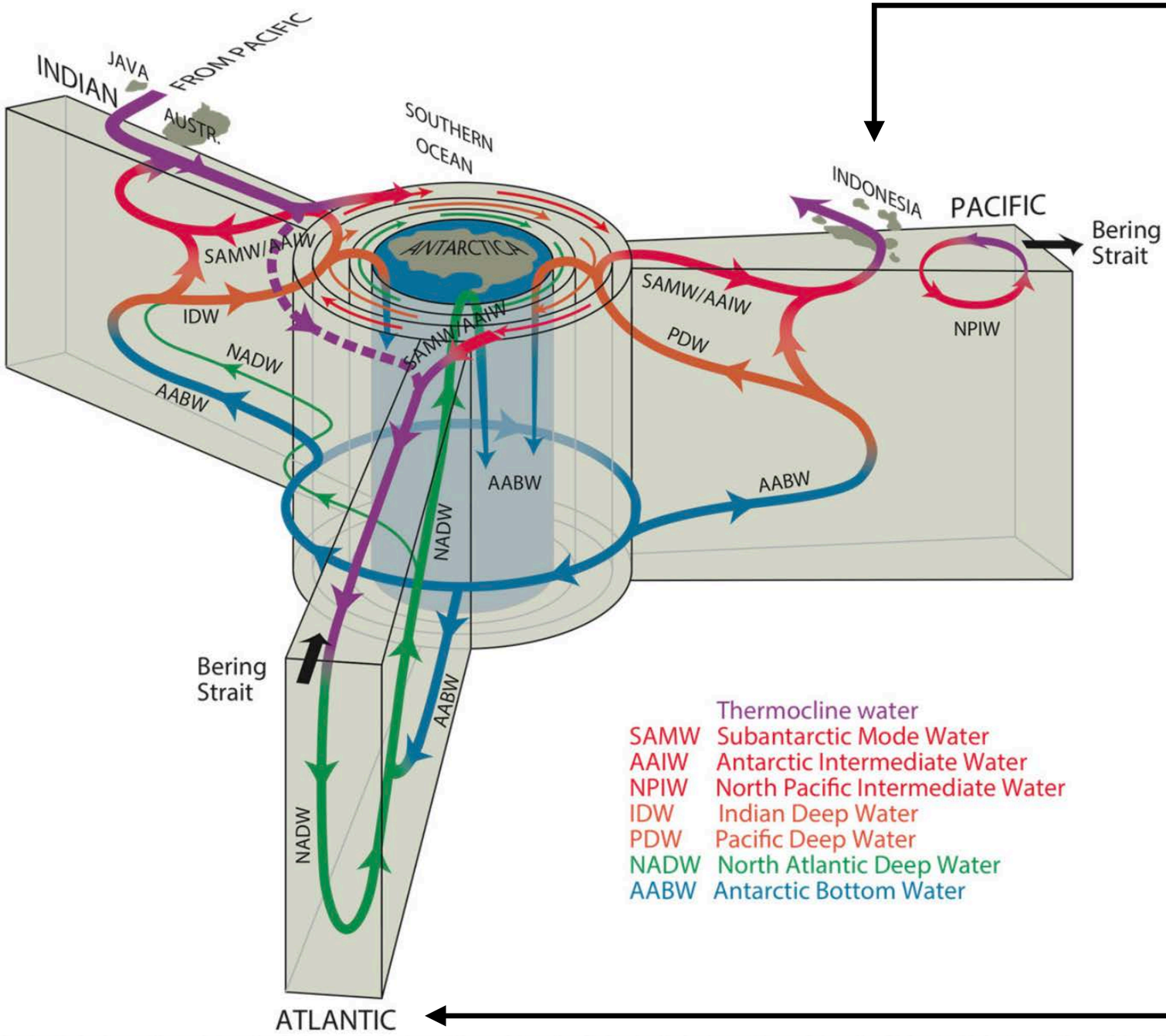
Vertical section, Pacific

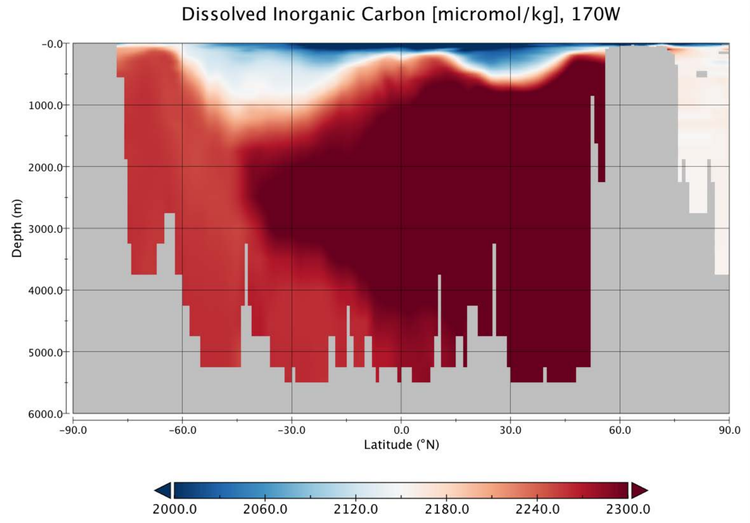


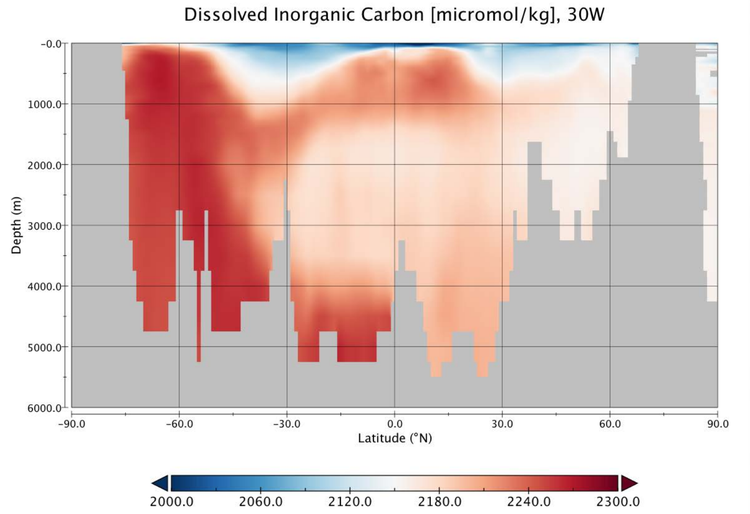
Vertical section, Atlantic



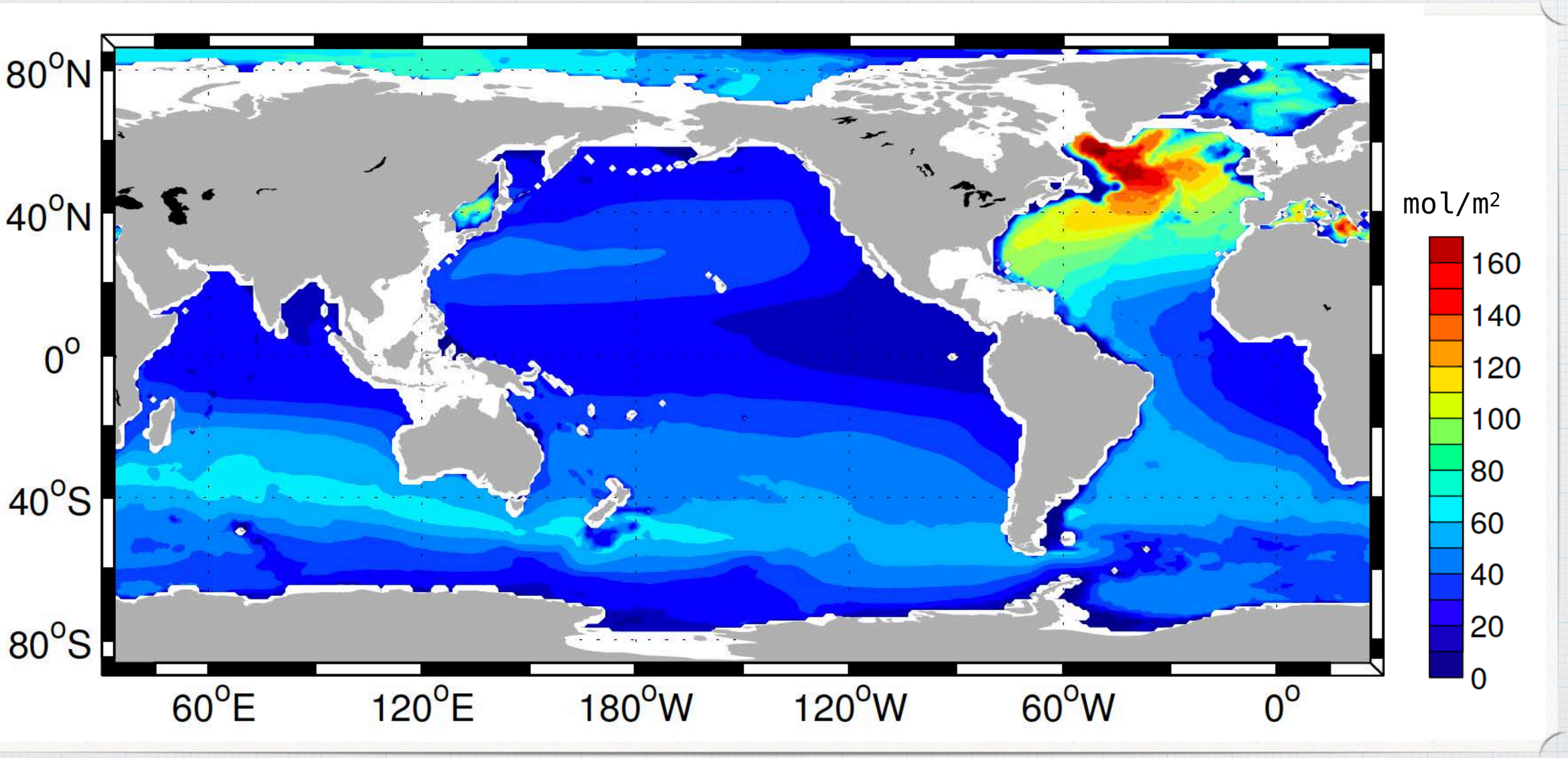



INDIAN
JAVA
FROM PACIFIC
AUSTR.
SOUTHERN OCEAN
INDONESIA
PACIFIC
Bering Strait
ANTARCTICA
SAMW/AAIW
IDW
NADW
AABW
PDW
NPIW
Bering Strait
ATLANTIC
Thermocline water
SAMW Subantarctic Mode Water
AAIW Antarctic Intermediate Water
NPIW North Pacific Intermediate Water
IDW Indian Deep Water
PDW Pacific Deep Water
NADW North Atlantic Deep Water
AABW Antarctic Bottom Water


Dissolved Inorganic Carbon [micromol/kg], 170W
Depth (m)
Latitude (°N)
2000.0 2060.0 2120.0 2180.0 2240.0 2300.0

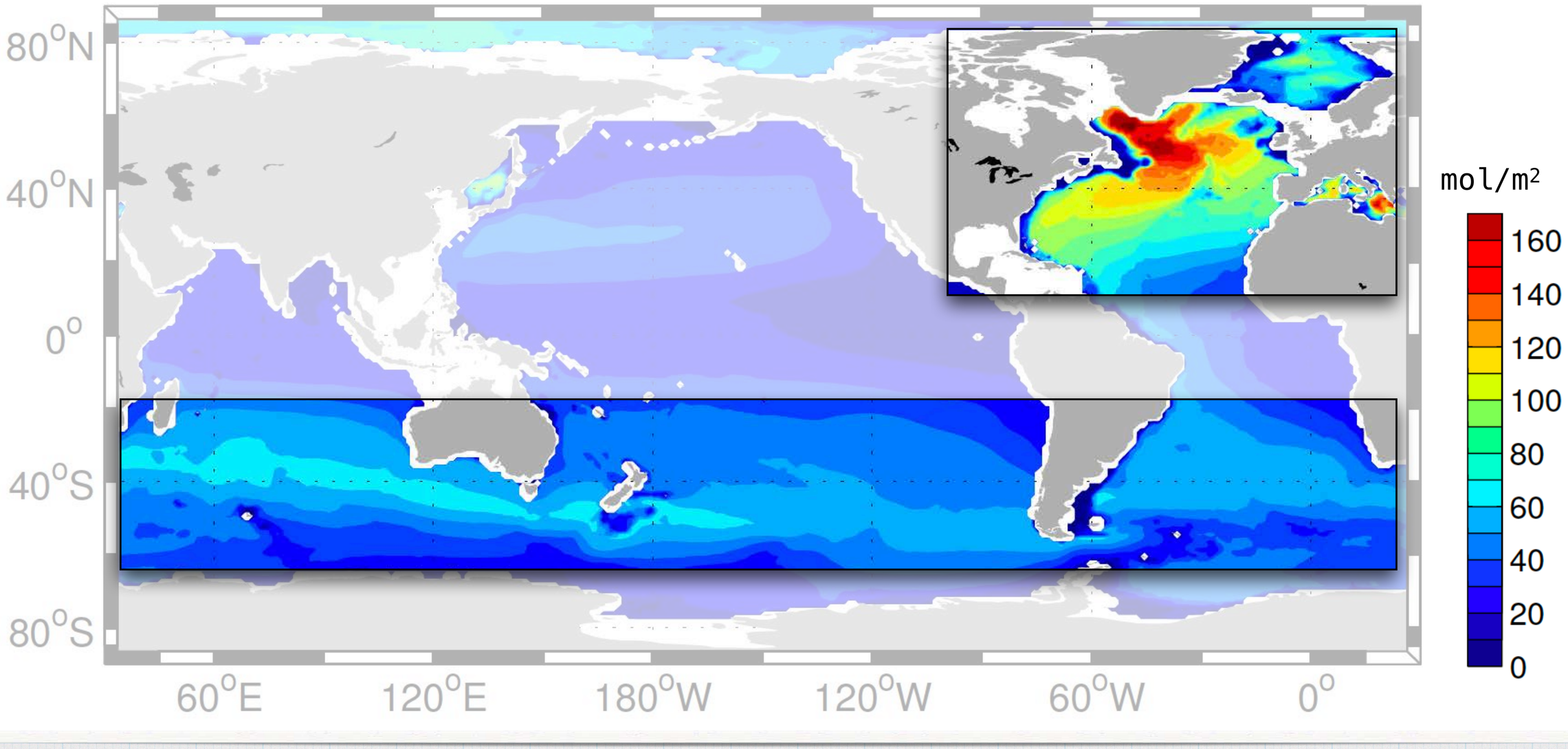

Dissolved Inorganic Carbon [micromol/kg], 30W
Depth (m)
Latitude (°N)
2000.0 2060.0 2120.0 2180.0 2240.0 2300.0

Column inventory of anthropogenic carbon



Khatiwala et al., 2013

Column inventory of anthropogenic carbon



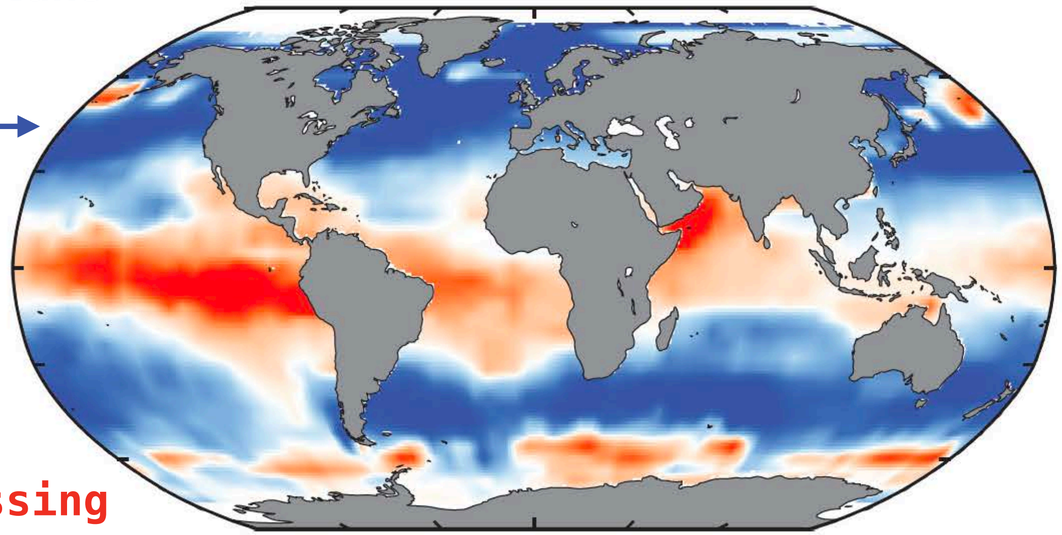
Khatiwala et al., 2013

Global CO_2 flux

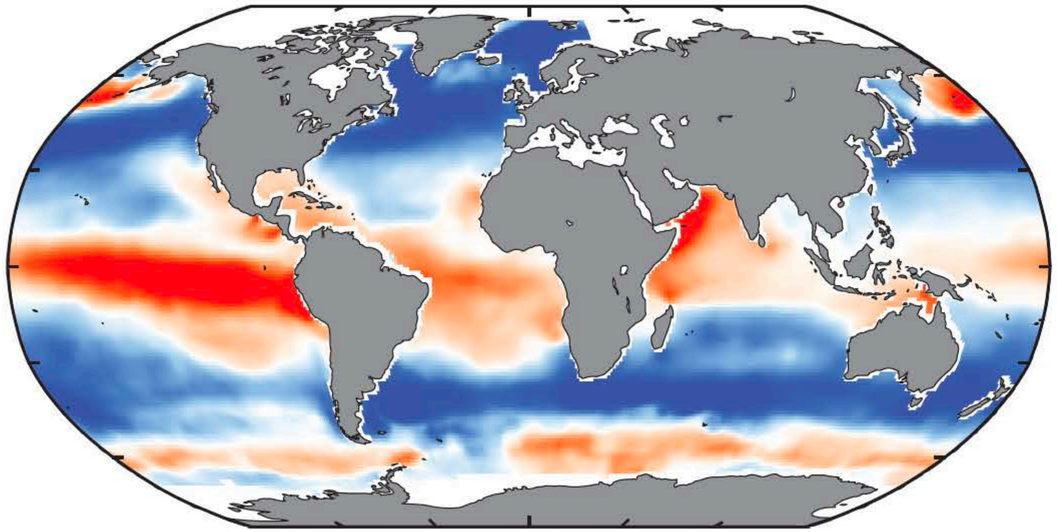
Takahashi et al. (2009) climatology

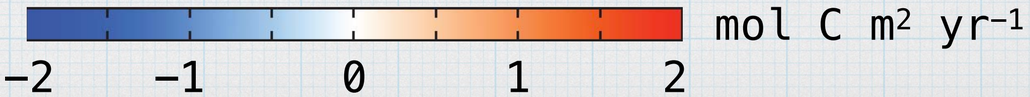
Uptake

Outgassing

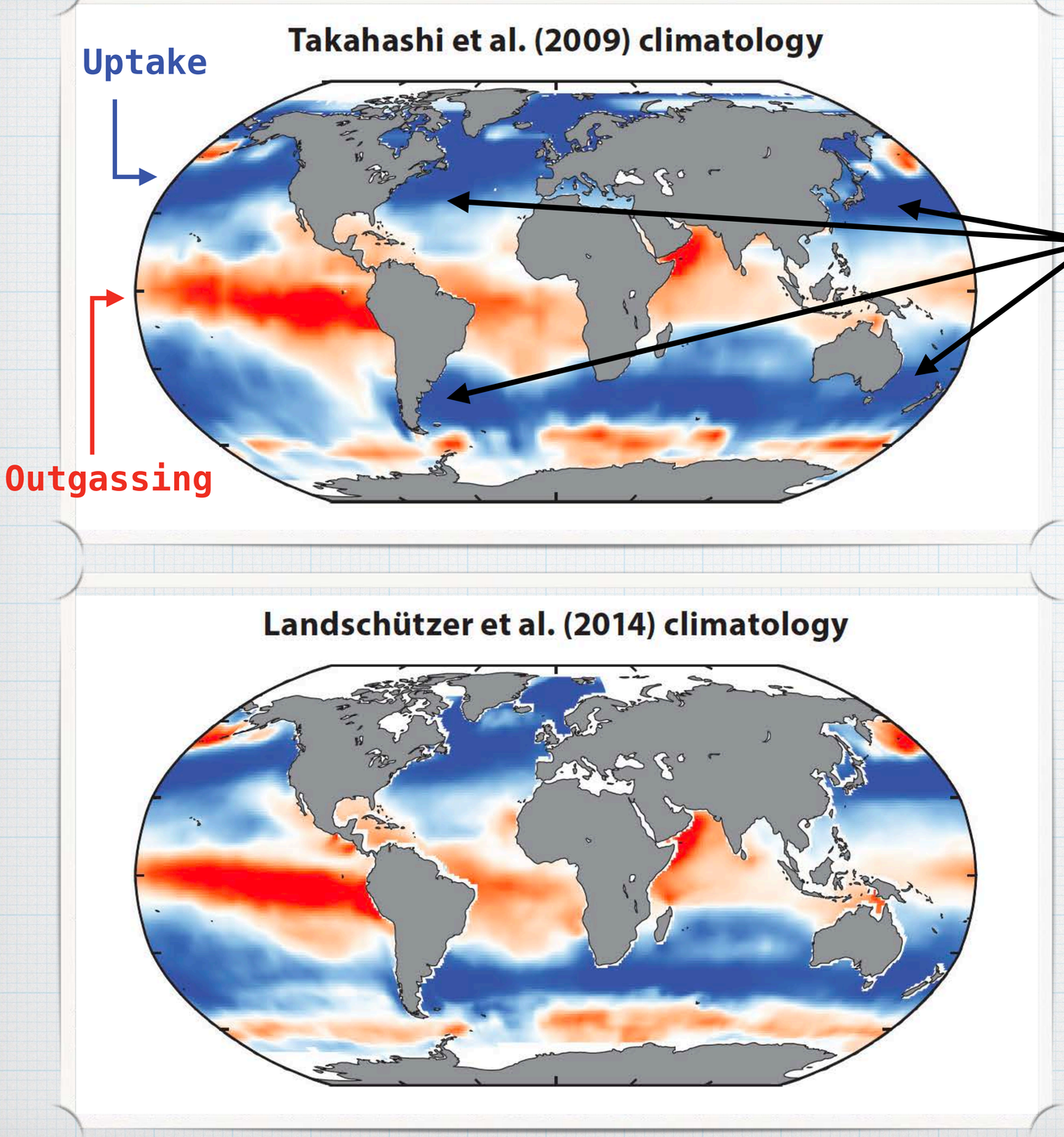


Landschützer et al. (2014) climatology

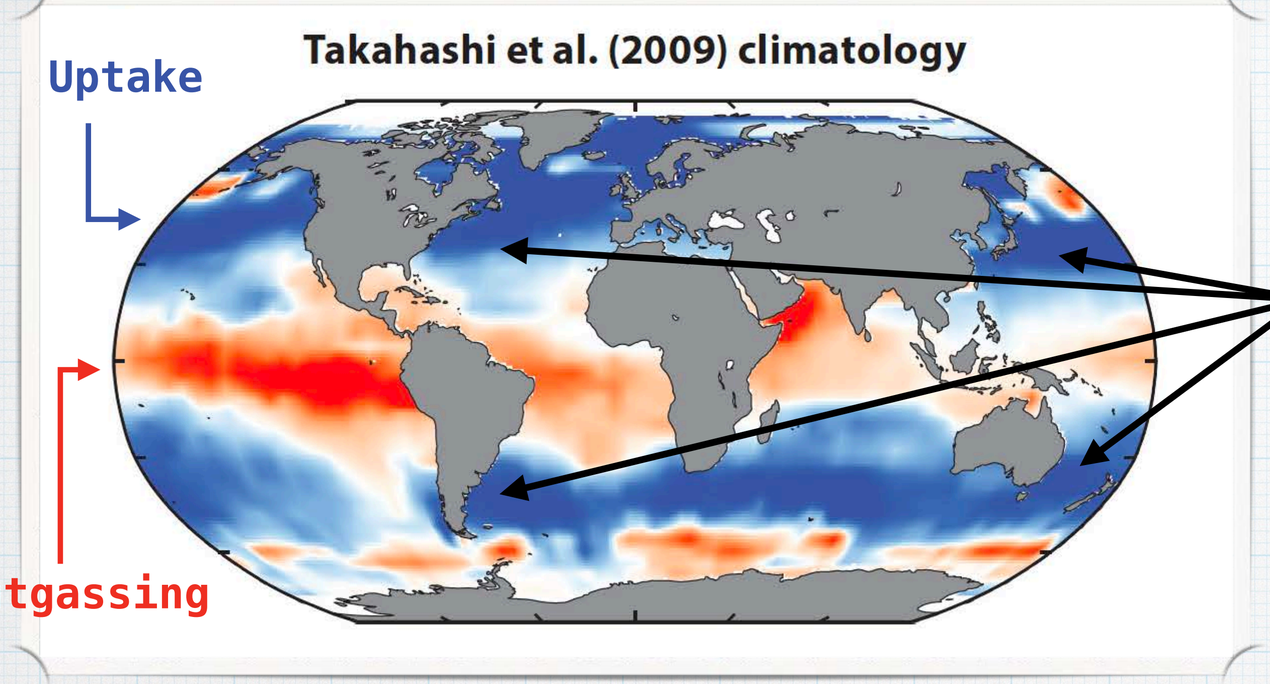




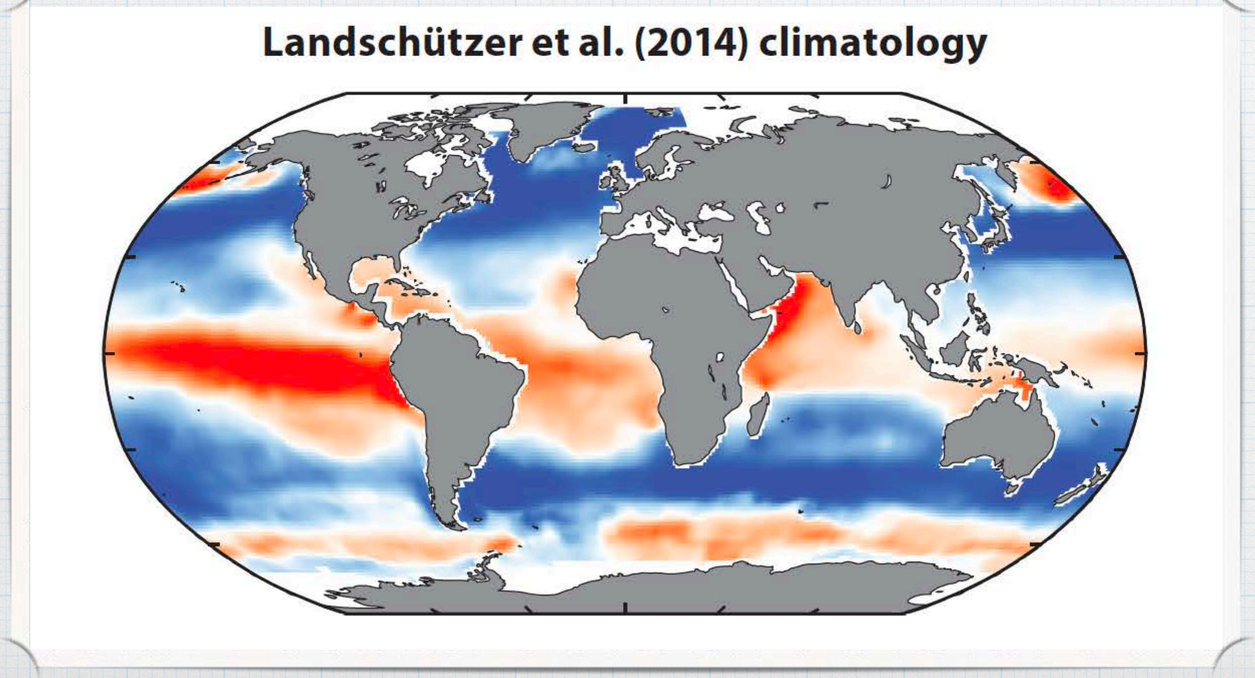
Global CO_2 flux



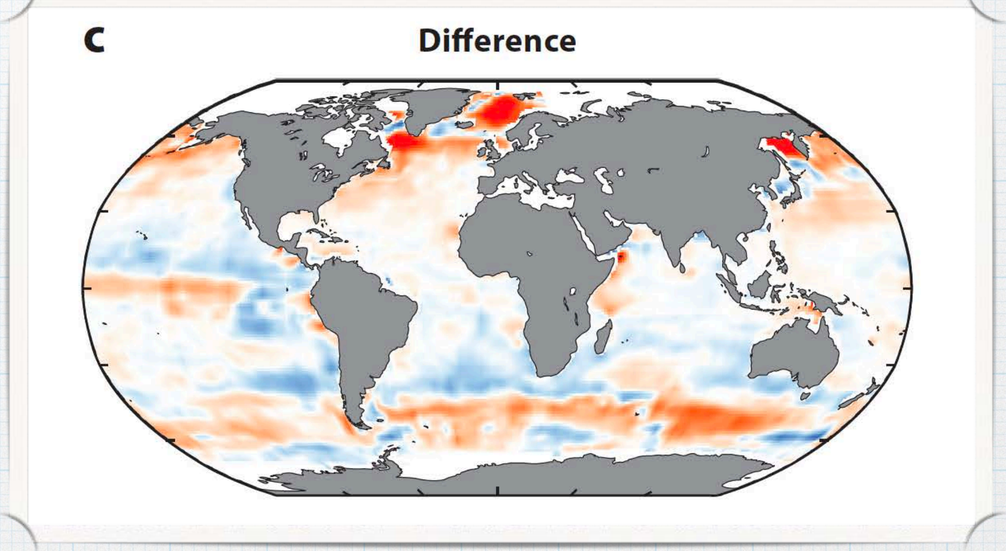
Global CO_2 flux



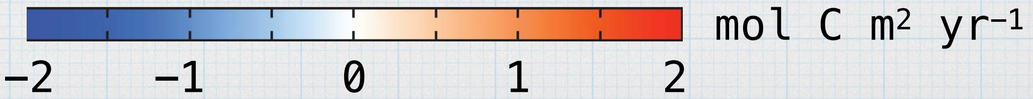
Western boundary currents



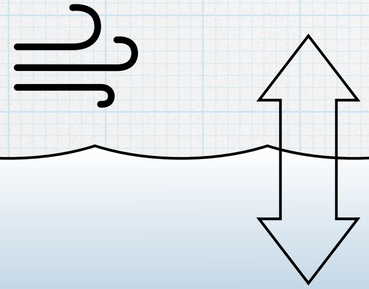
Landschützer – Takahashi



McKinley et al., 2017

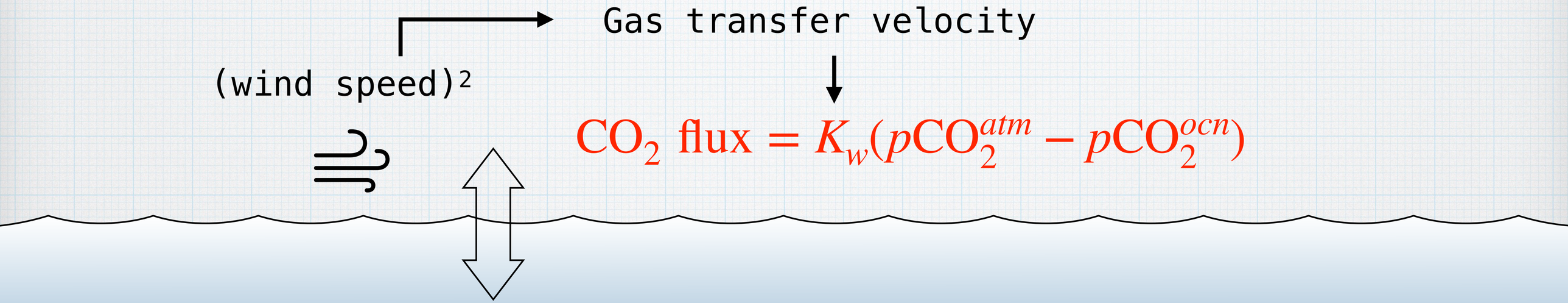


CO_2 flux

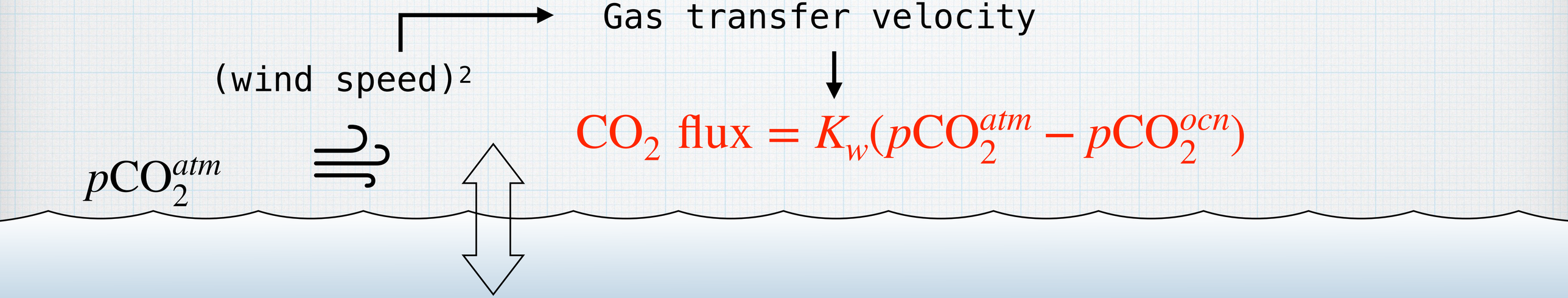


$$\mathrm{CO_2\ flux} = K_w(p\mathrm{CO}_2^{atm} - p\mathrm{CO}_2^{ocn})$$

CO_2 flux

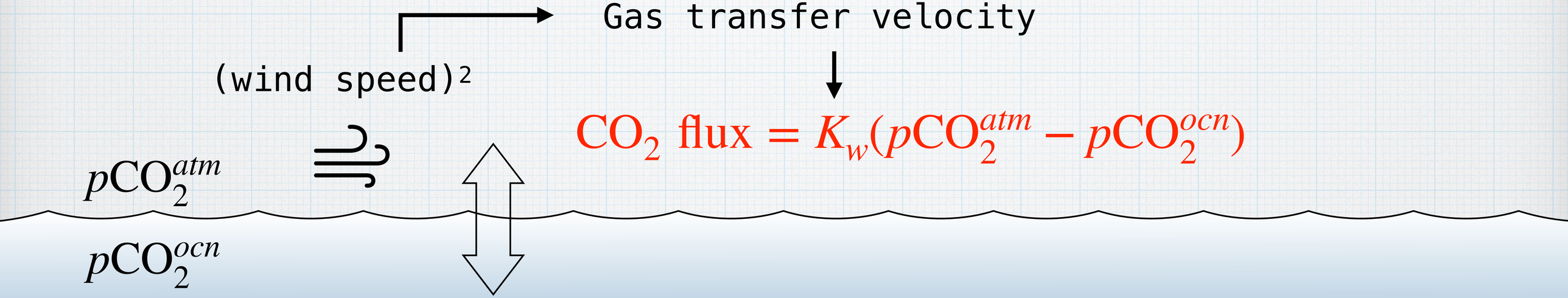

Gas transfer velocity
(wind speed)²
$CO_2 \text{ flux} = K_w(pCO_2^{atm} - pCO_2^{ocn})$

CO_2 flux

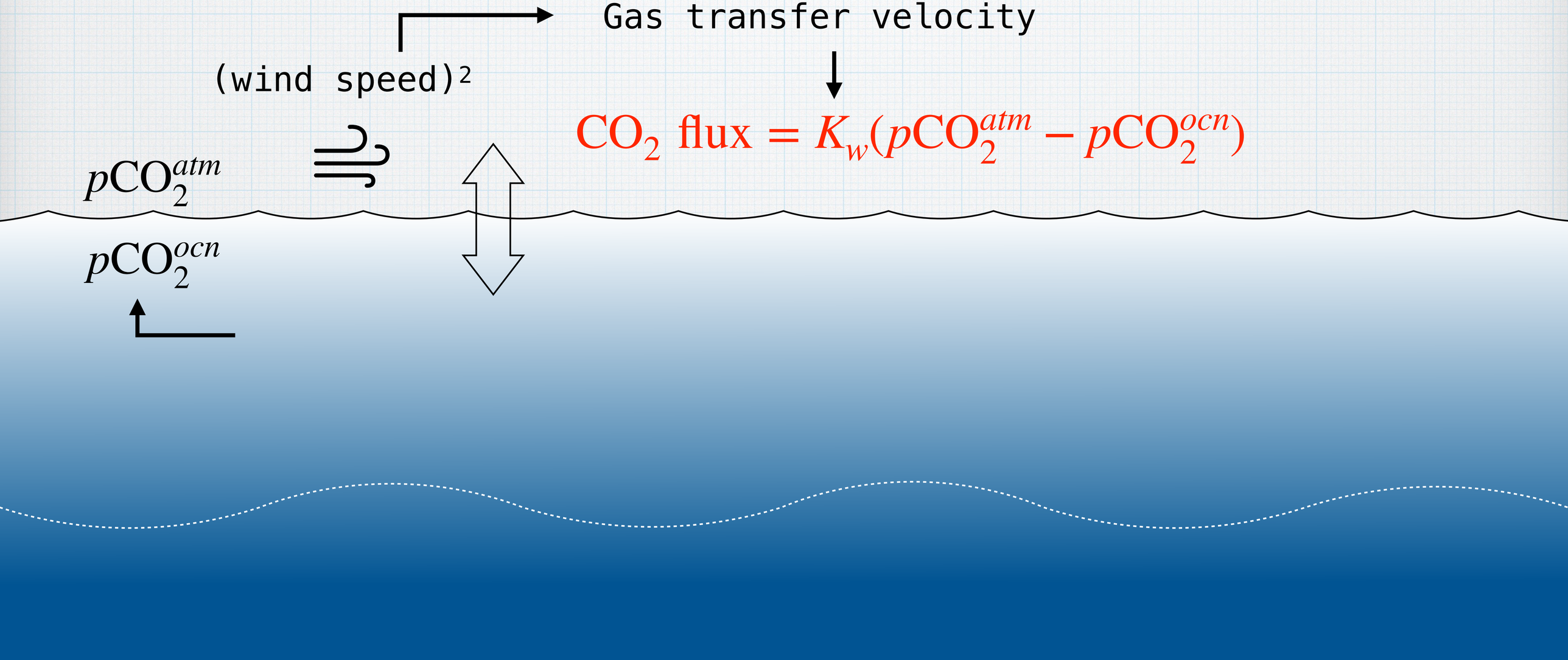


$$CO_2 \text{ flux} = K_w(pCO_2^{atm} - pCO_2^{ocn})$$

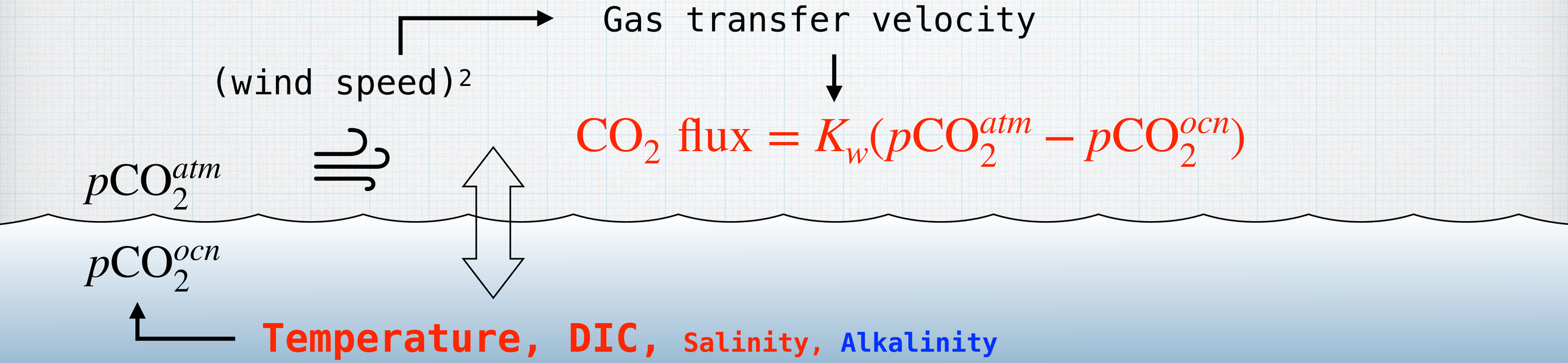
CO_2 flux


Gas transfer velocity
(wind speed)²
$\mathrm{CO_2\ flux} = K_w(p\mathrm{CO_2^{atm}} - p\mathrm{CO_2^{ocn}})$
$p\mathrm{CO_2^{atm}}$
$p\mathrm{CO_2^{ocn}}$

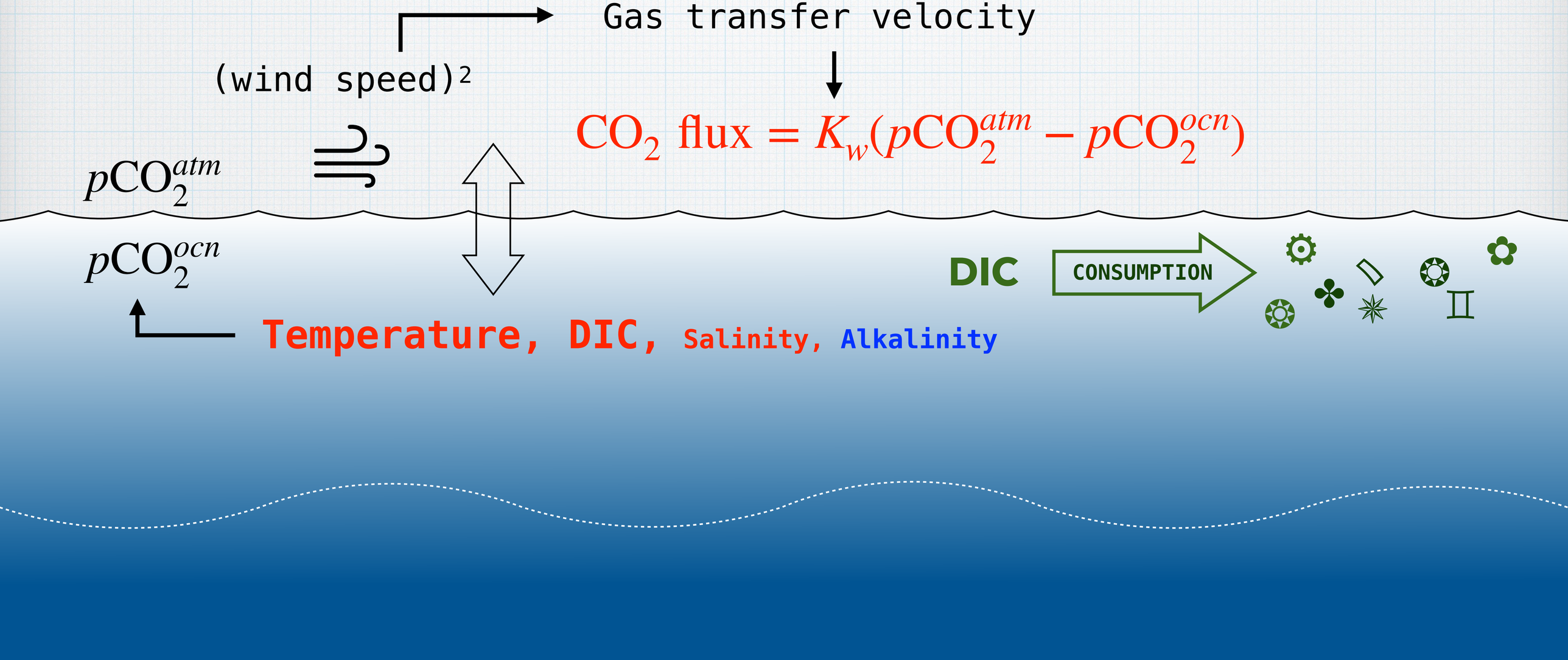
CO_2 flux


Gas transfer velocity
(wind speed)²
$\mathrm{CO_2\ flux} = K_w(p\mathrm{CO_2^{atm}} - p\mathrm{CO_2^{ocn}})$
$p\mathrm{CO_2^{atm}}$
$p\mathrm{CO_2^{ocn}}$

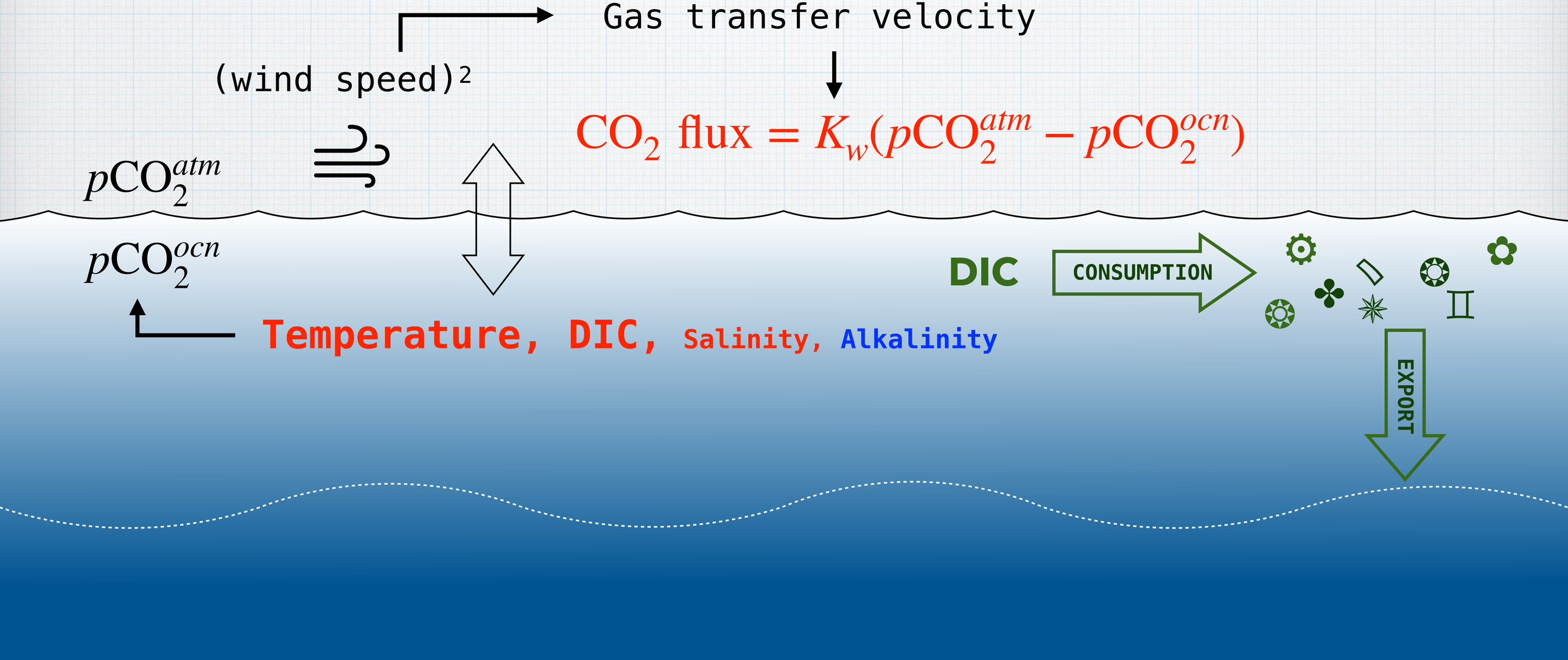
CO_2 flux


Gas transfer velocity
(wind speed)²
CO_2 flux = $K_w(pCO_2^{atm} - pCO_2^{ocn})$
pCO_2^{atm}
pCO_2^{ocn}
Temperature, DIC, Salinity, Alkalinity

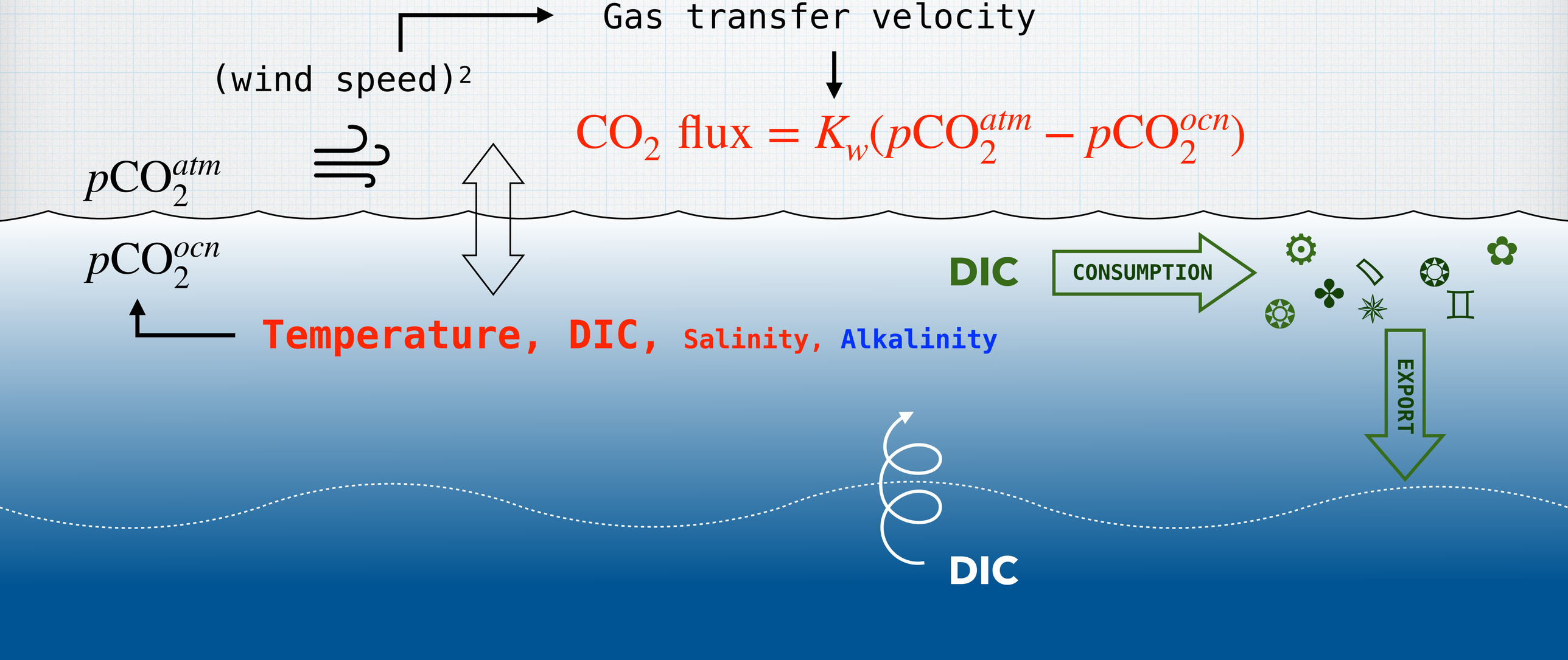
CO_2 flux


Gas transfer velocity
(wind speed)²
$CO_2\ \text{flux} = K_w(pCO_2^{atm} - pCO_2^{ocn})$
pCO_2^{atm}
pCO_2^{ocn}
DIC
CONSUMPTION
Temperature, DIC, Salinity, Alkalinity

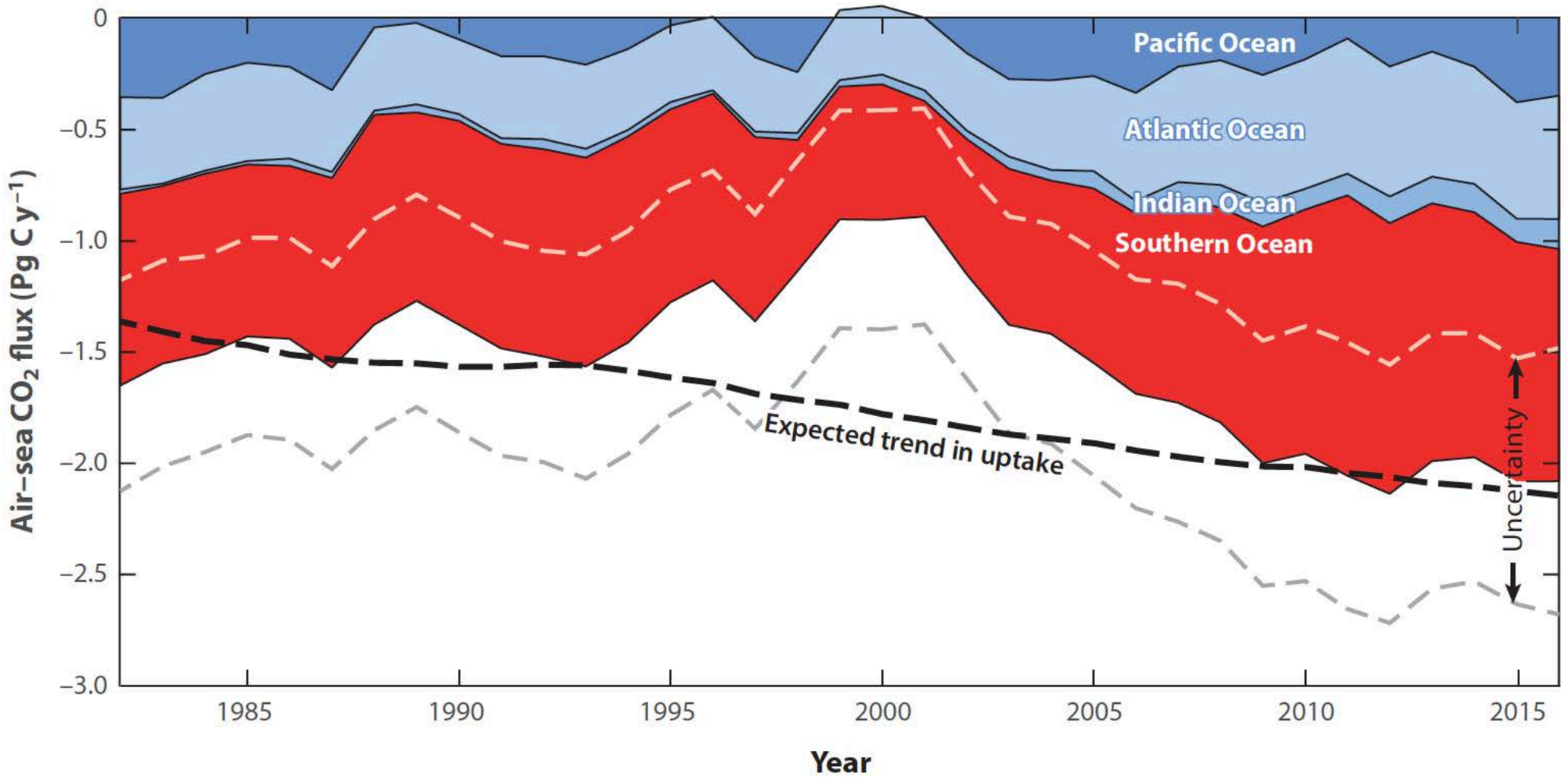
CO_2 flux


Gas transfer velocity
(wind speed)²
$CO_2\ \text{flux} = K_w(pCO_2^{atm} - pCO_2^{ocn})$
pCO_2^{atm}
pCO_2^{ocn}
DIC
CONSUMPTION
EXPORT
Temperature, DIC, Salinity, Alkalinity

CO_2 flux


Gas transfer velocity
(wind speed)²
$CO_2\ \text{flux} = K_w(pCO_2^{atm} - pCO_2^{ocn})$
pCO_2^{atm}
pCO_2^{ocn}
DIC
CONSUMPTION
EXPORT
Temperature, DIC, Salinity, Alkalinity
DIC

Ocean's CO_2 uptake



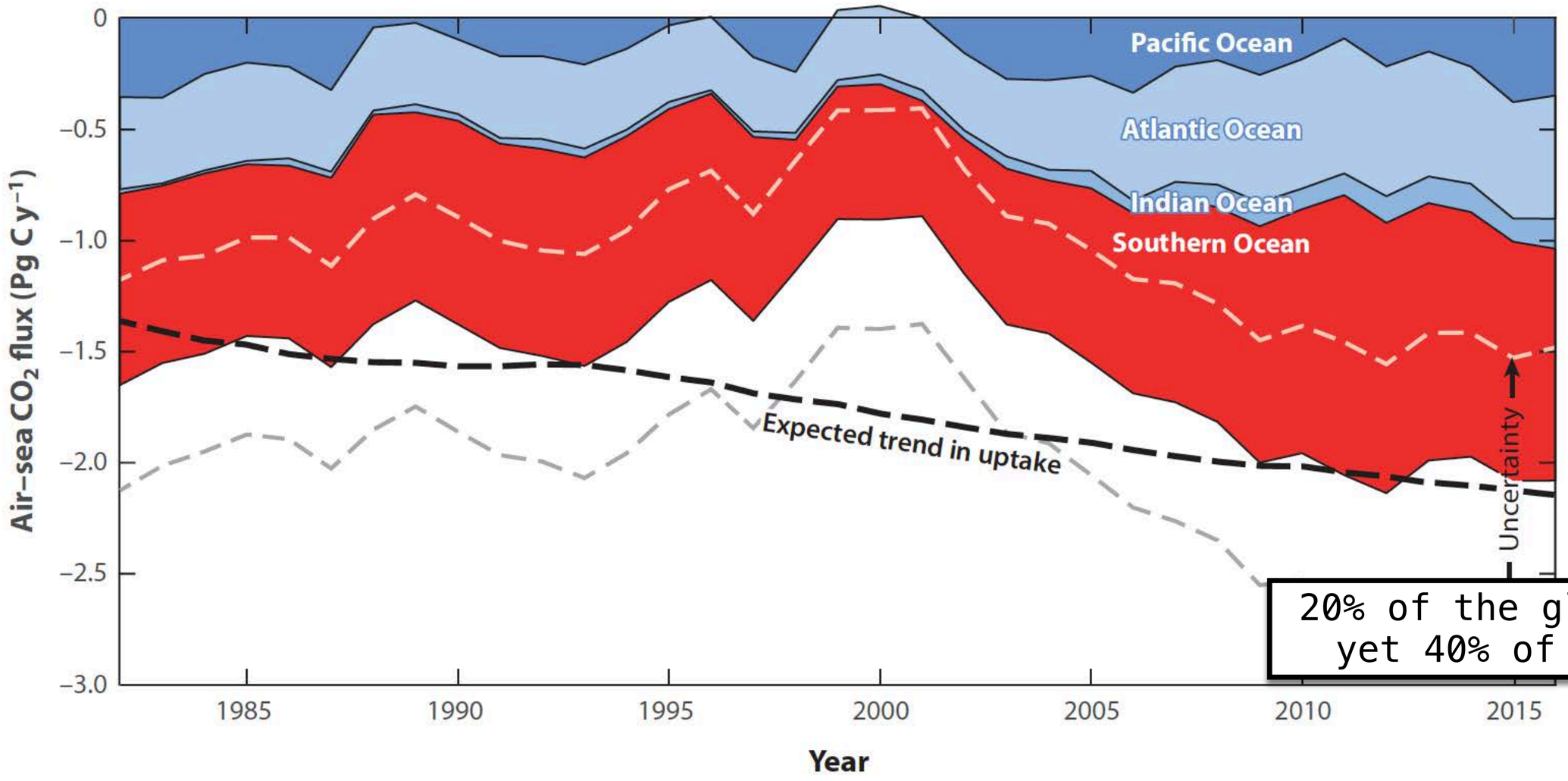
Pacific Ocean

Atlantic Ocean

Southern Ocean

Gruber et al., 2019

Ocean's CO_2 uptake



Pacific Ocean

Atlantic Ocean

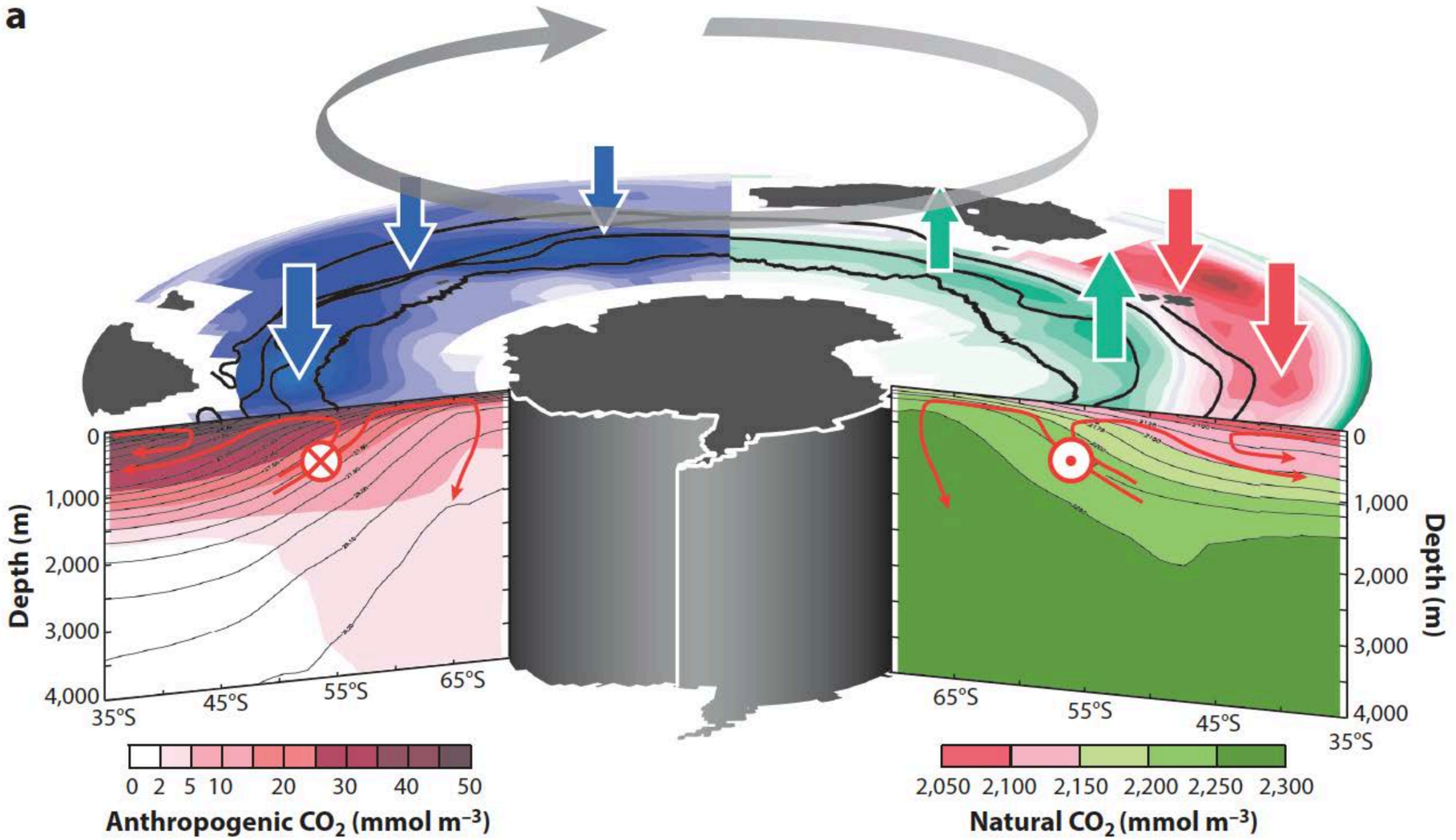
Southern Ocean

20% of the global ocean, yet 40% of CO_2 uptake

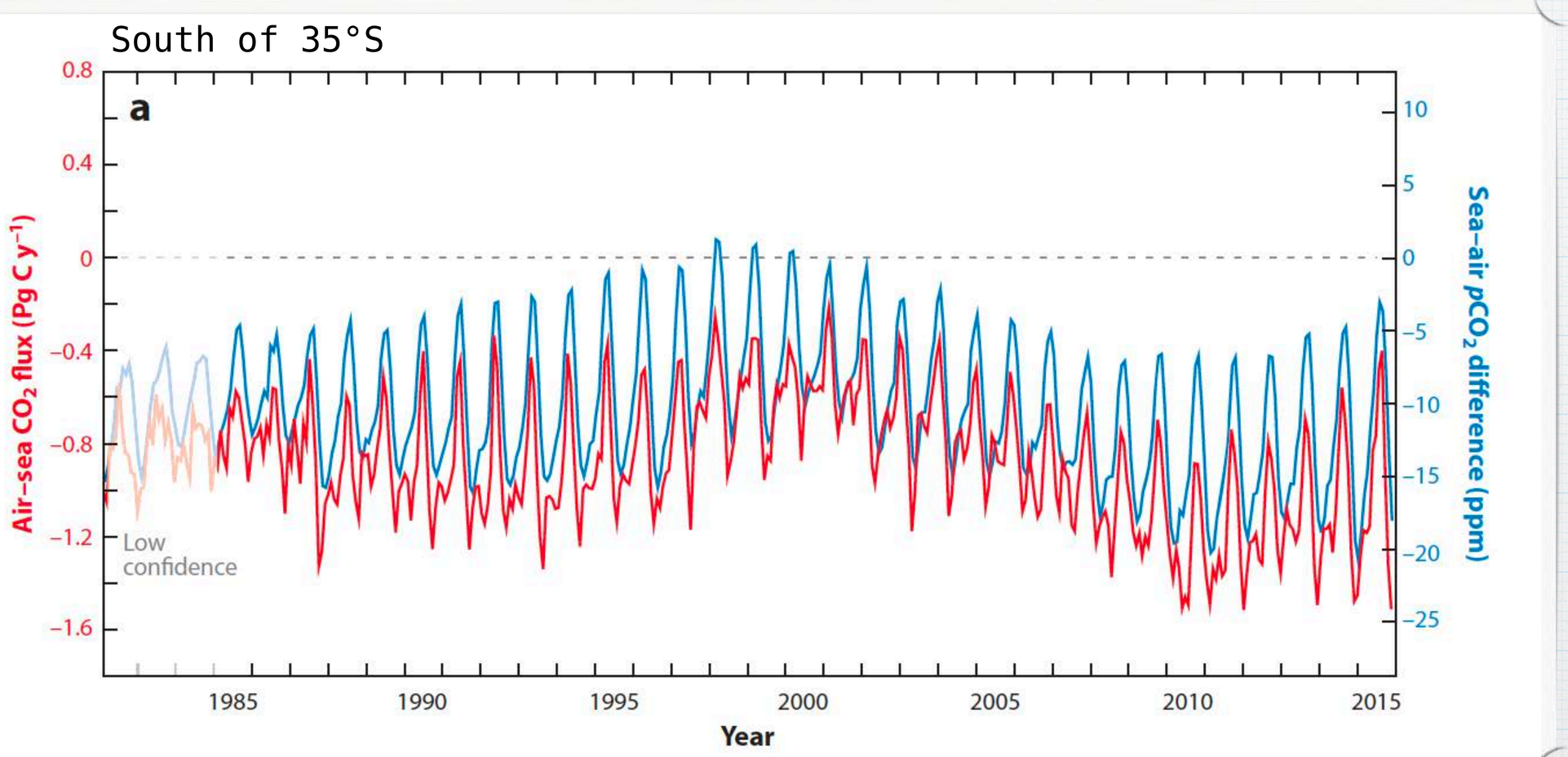
Gruber et al., 2019

Southern Ocean's CO_2 uptake

Gruber et al., 2019

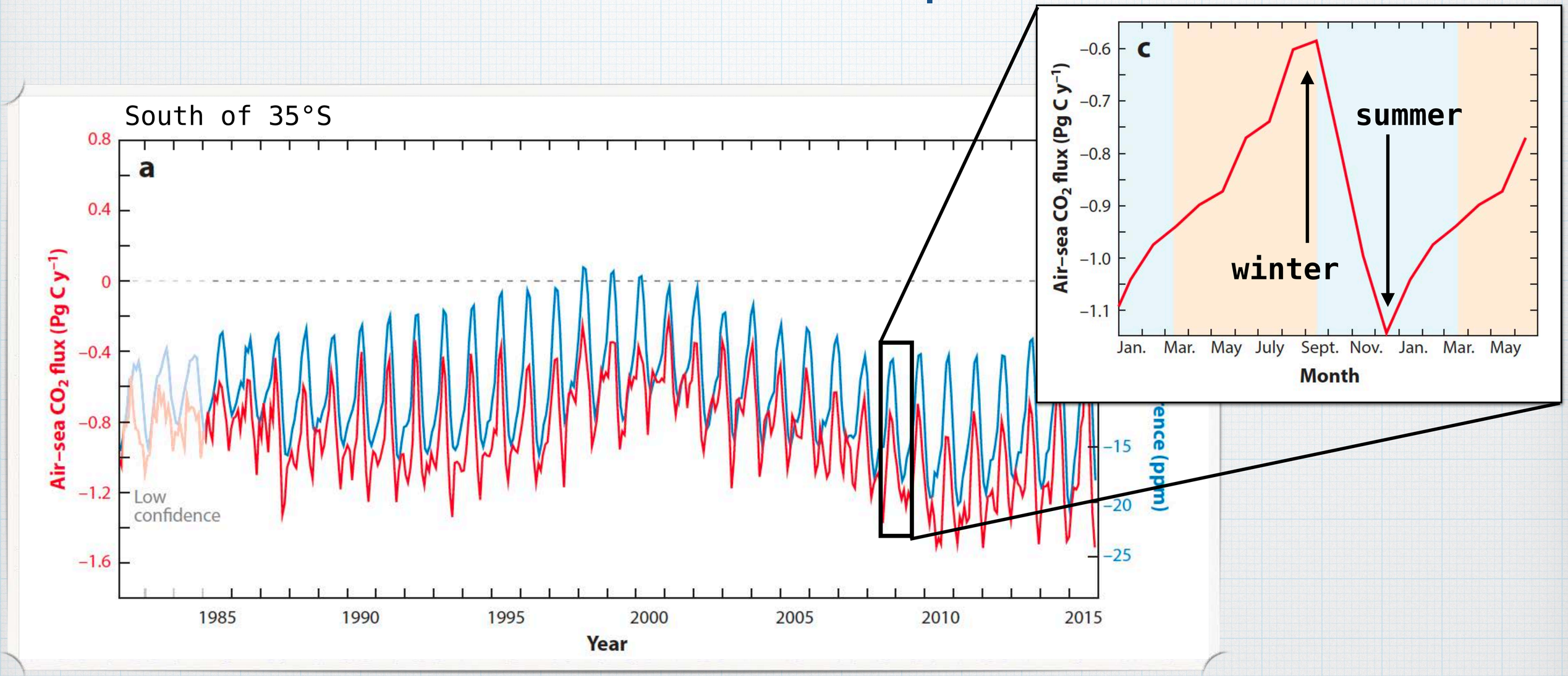


Southern Ocean's CO_2 uptake



Gruber et al., 2019

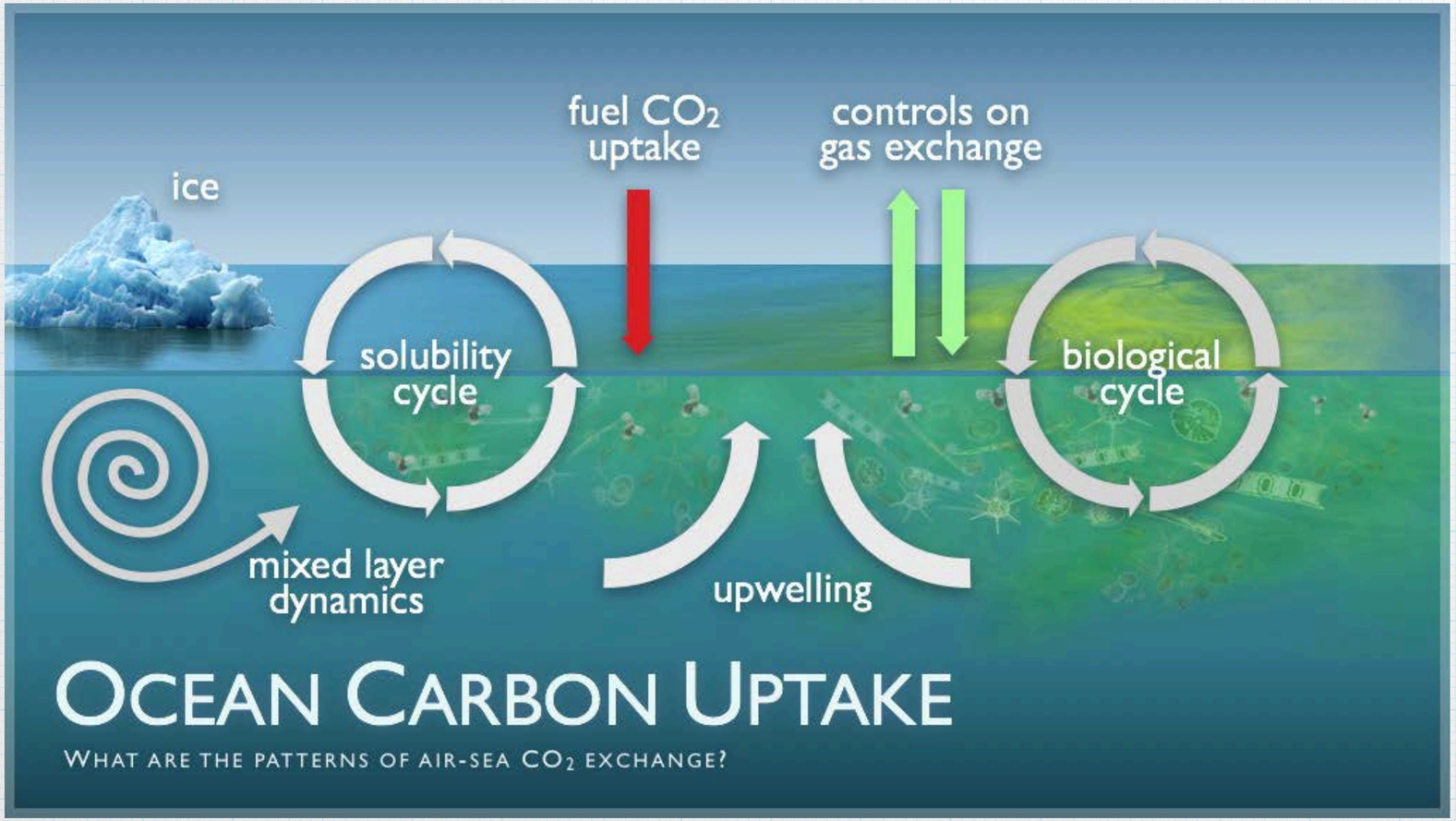
Southern Ocean's CO_2 uptake

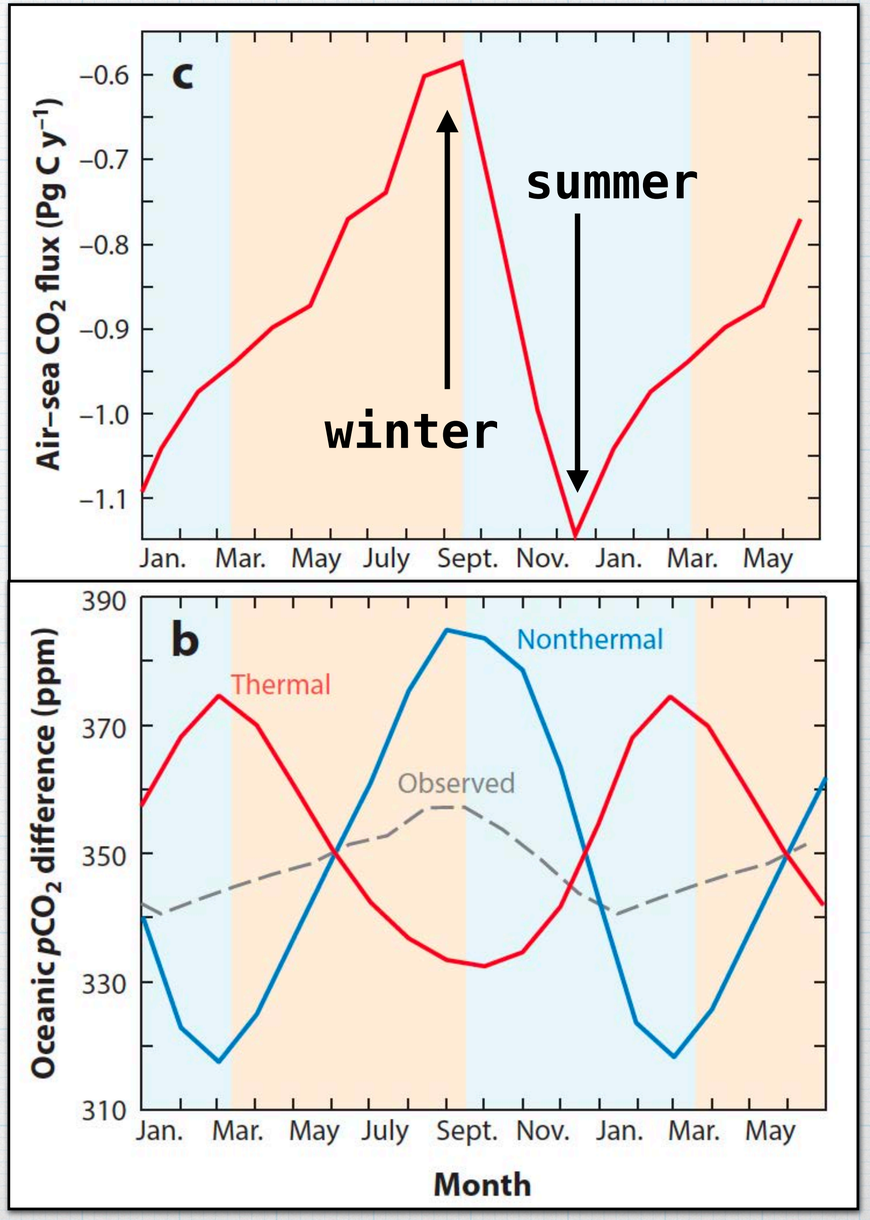


Gruber et al., 2019

Southern Ocean's CO_2 uptake

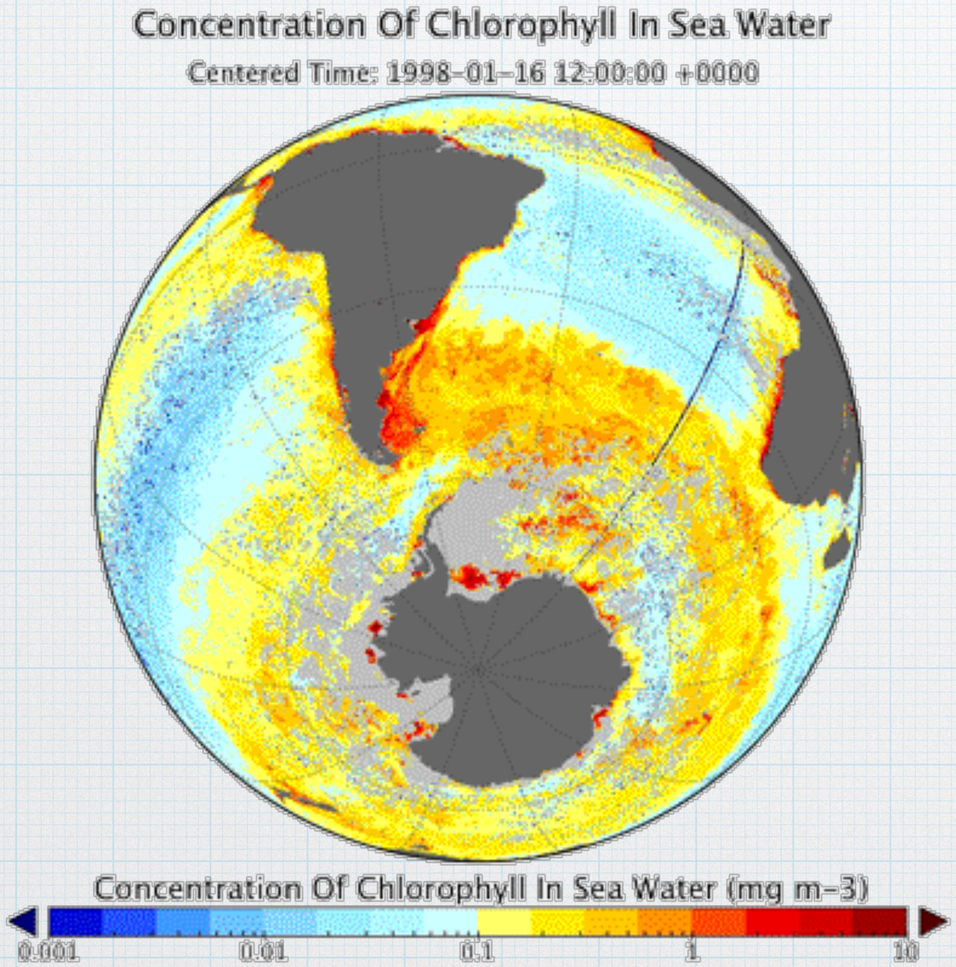
South of 35°S

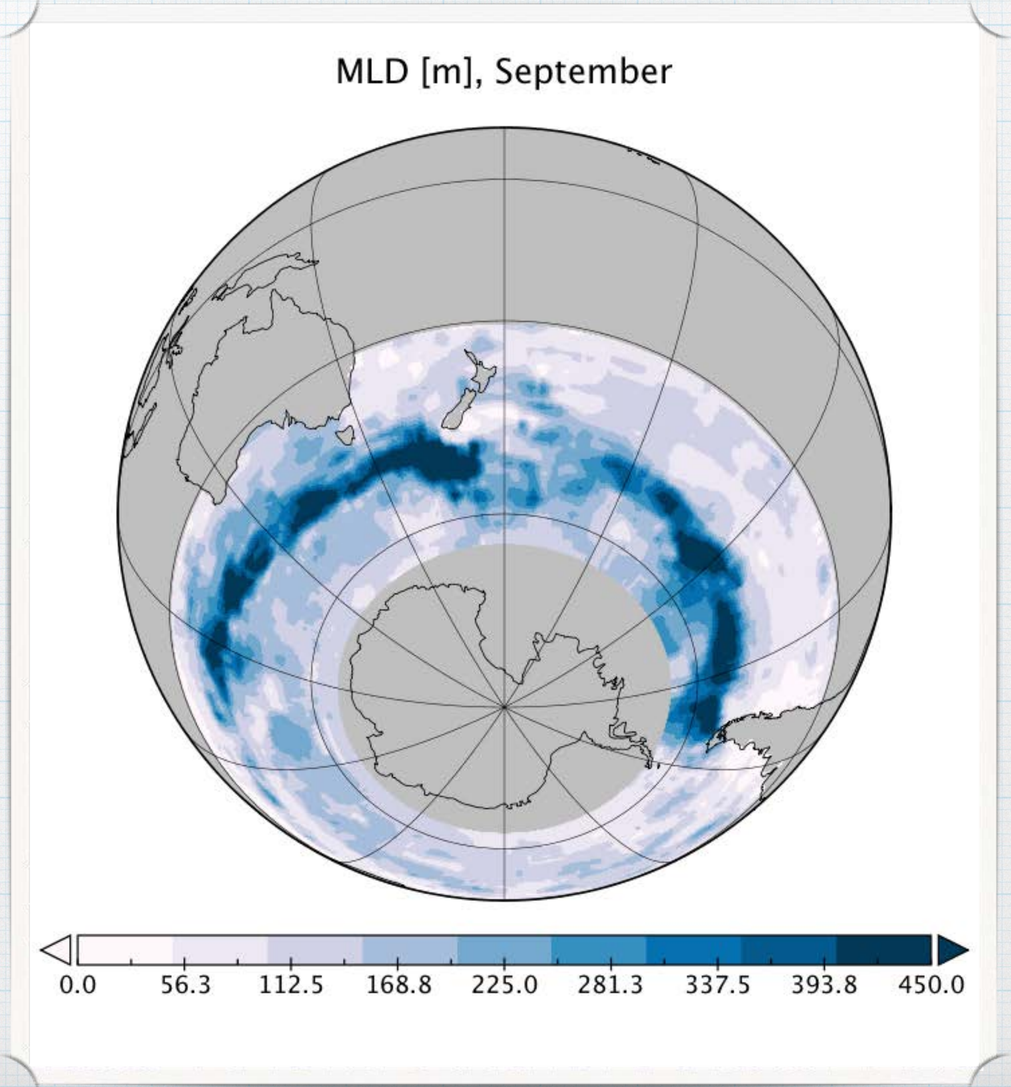




Driver for the seasonality in CO_2 flux

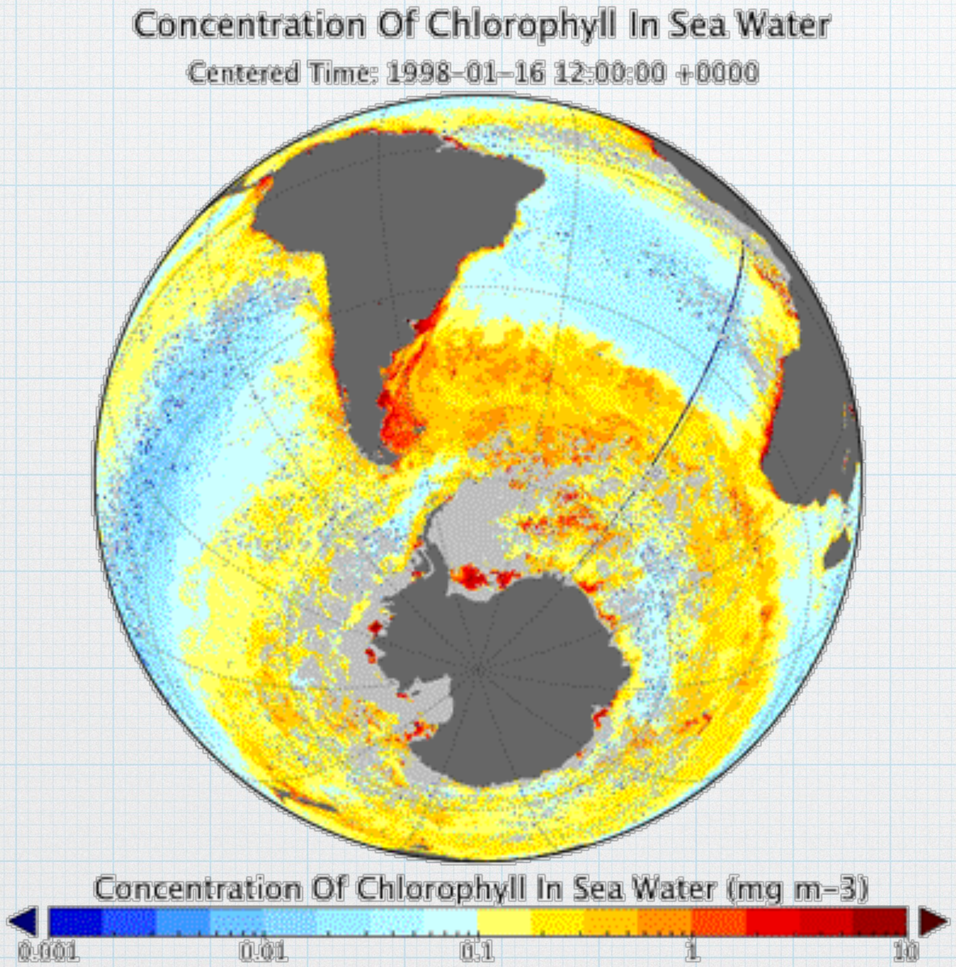
Dong et al., 2006

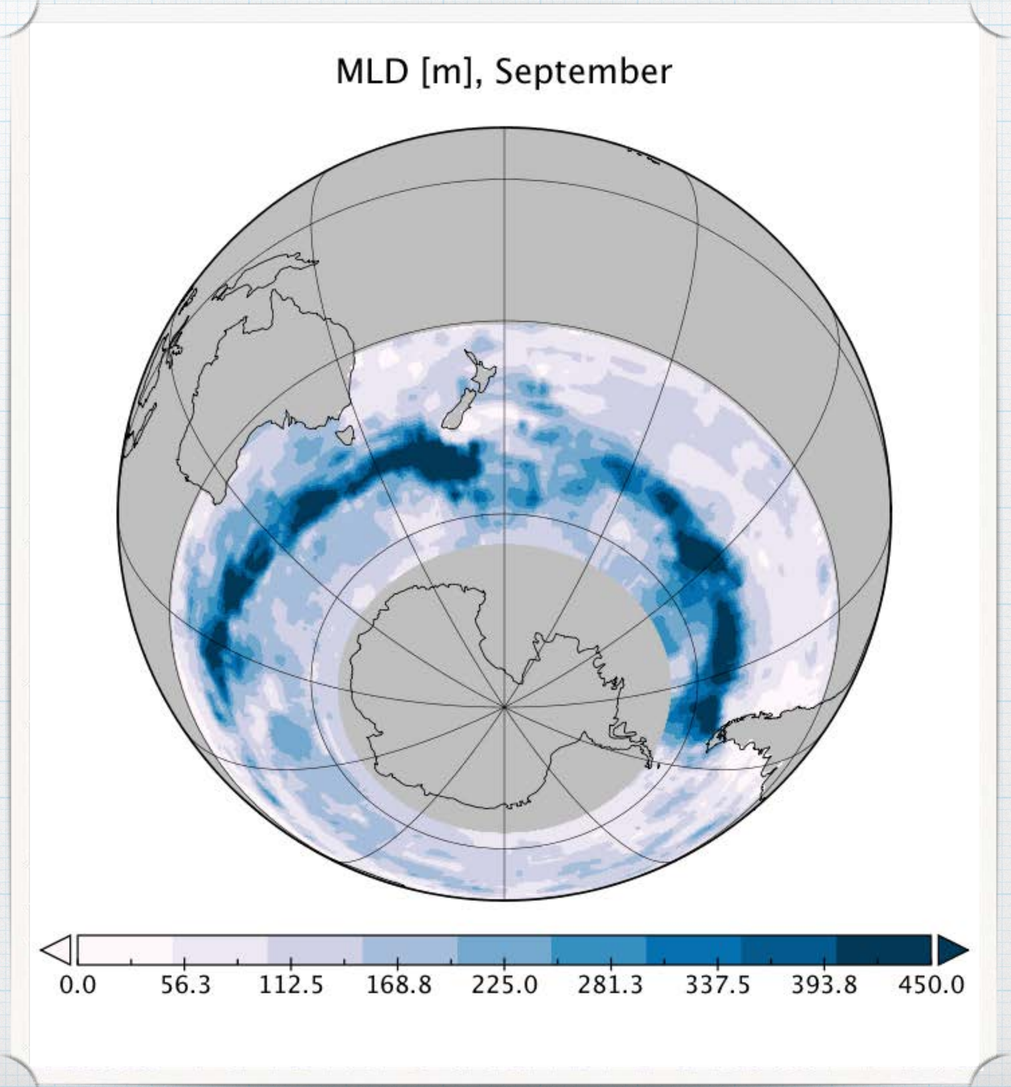


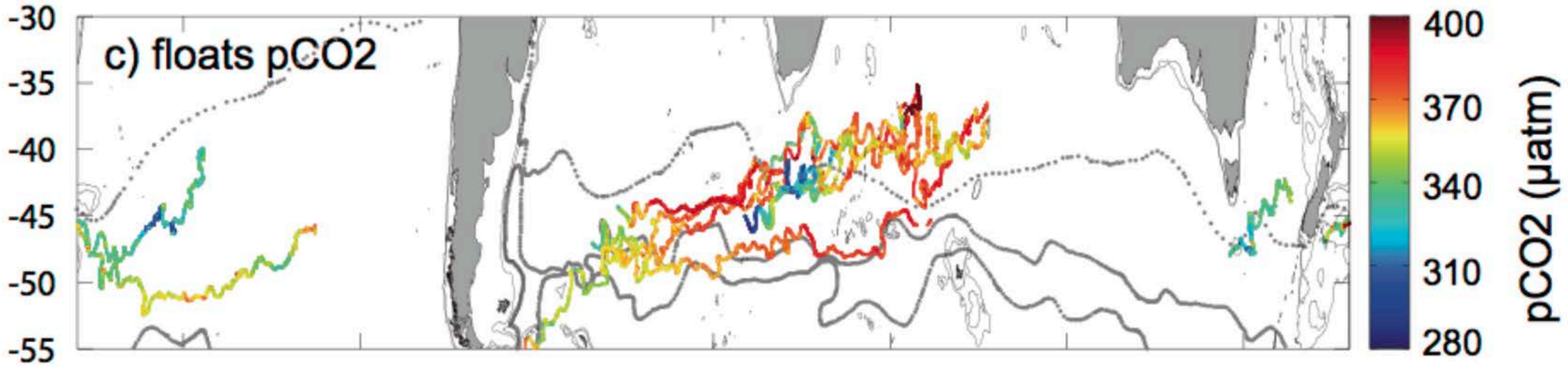


Driver for the seasonality in CO_2 flux

Dong et al., 2006



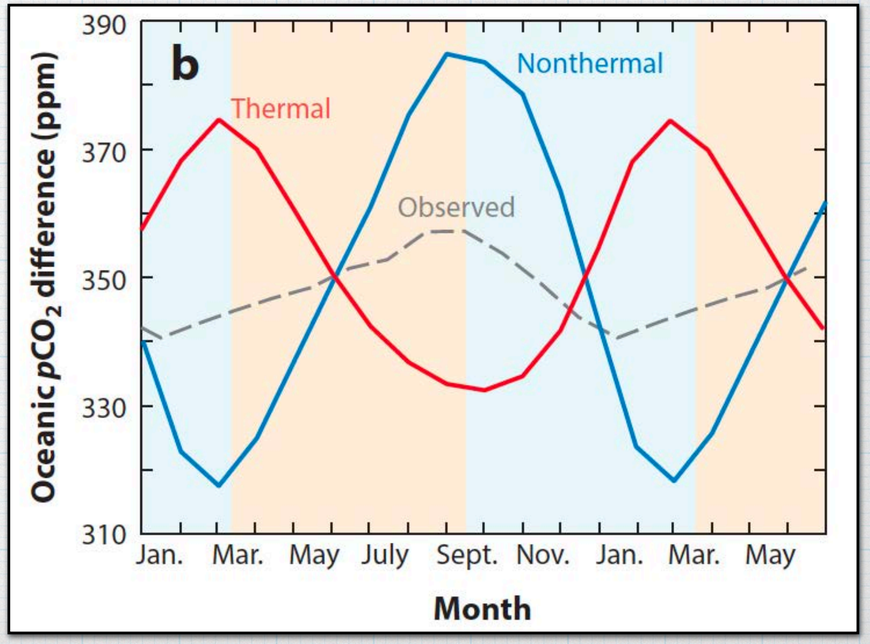




Resplandy et al., 2014

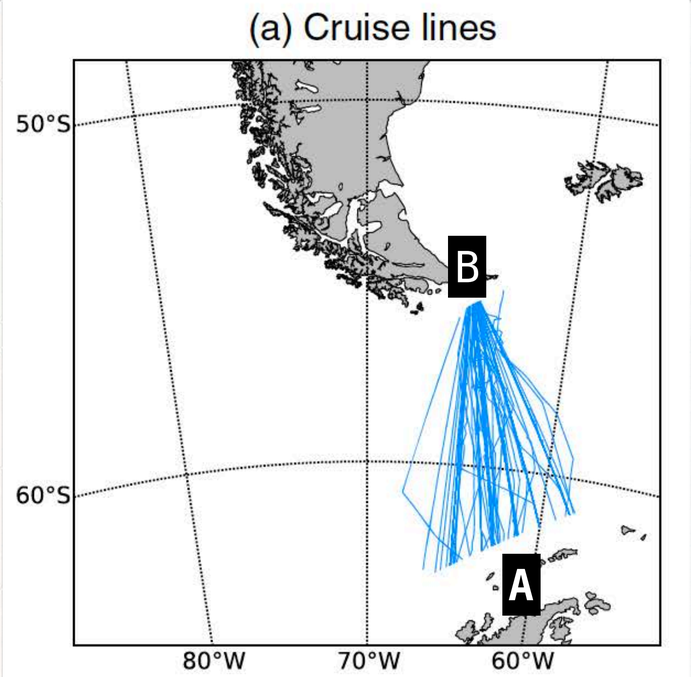
Mesoscale pCO_2

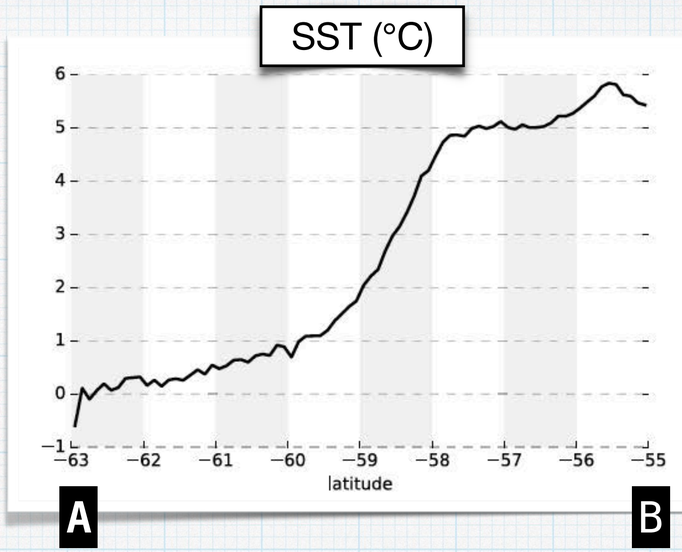
"On spatial scales of 100 km, we find gradients ranging from 5 to 50 µatm for pCO2 … with highest values in energetic and frontal regions."

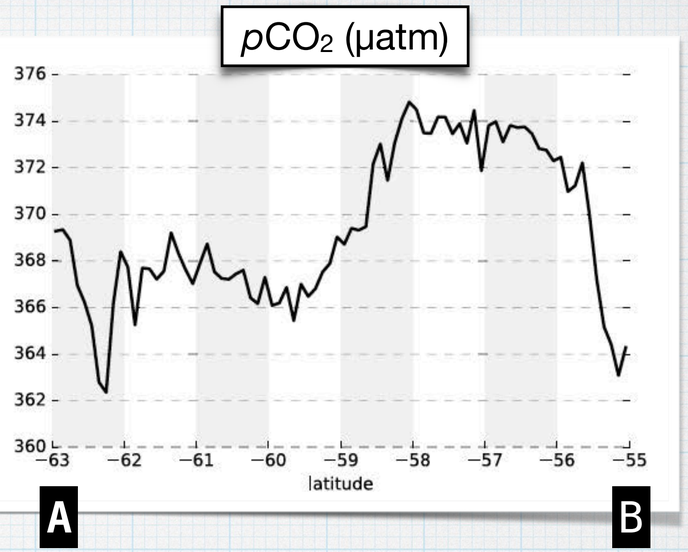


Mesoscale pCO_2

Antarctic Research Supply Vessel, *Laurence M. Gould*, 2002–2015



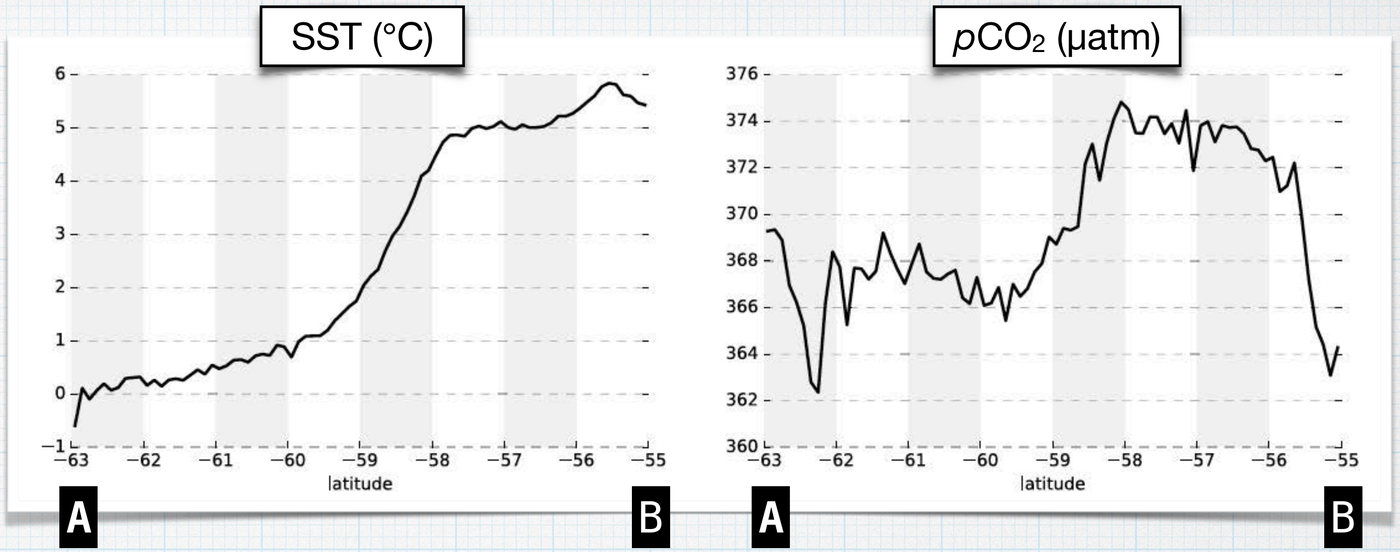


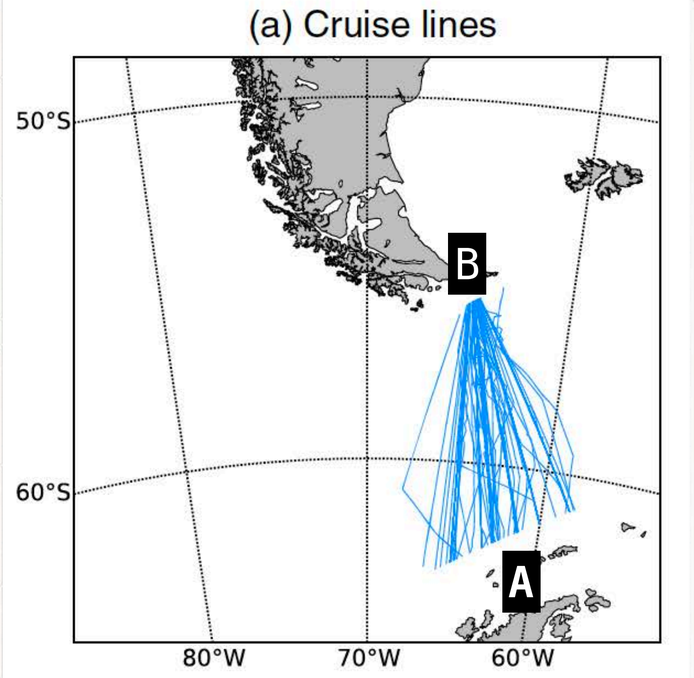


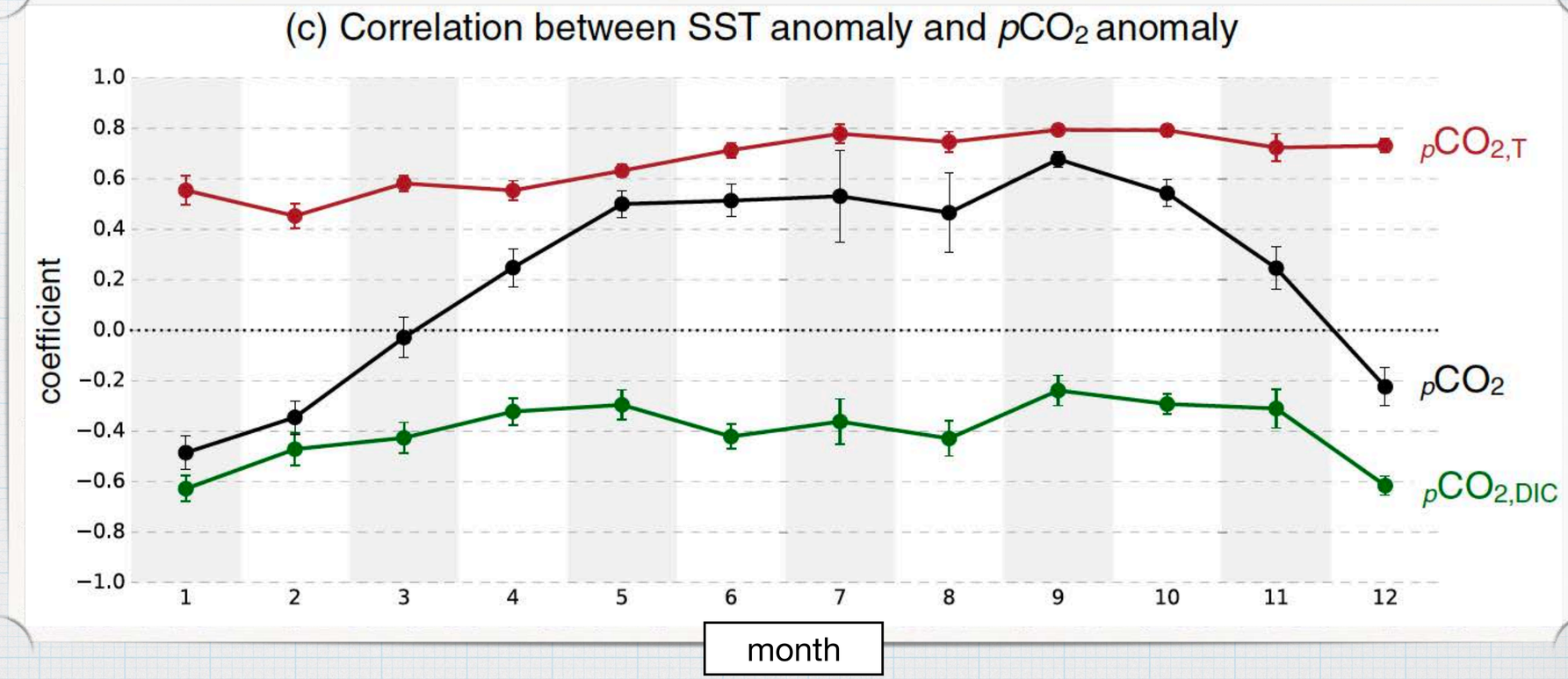
Song et al., 2016

Mesoscale pCO_2

Antarctic Research Supply Vessel, *Laurence M. Gould*, 2002–2015

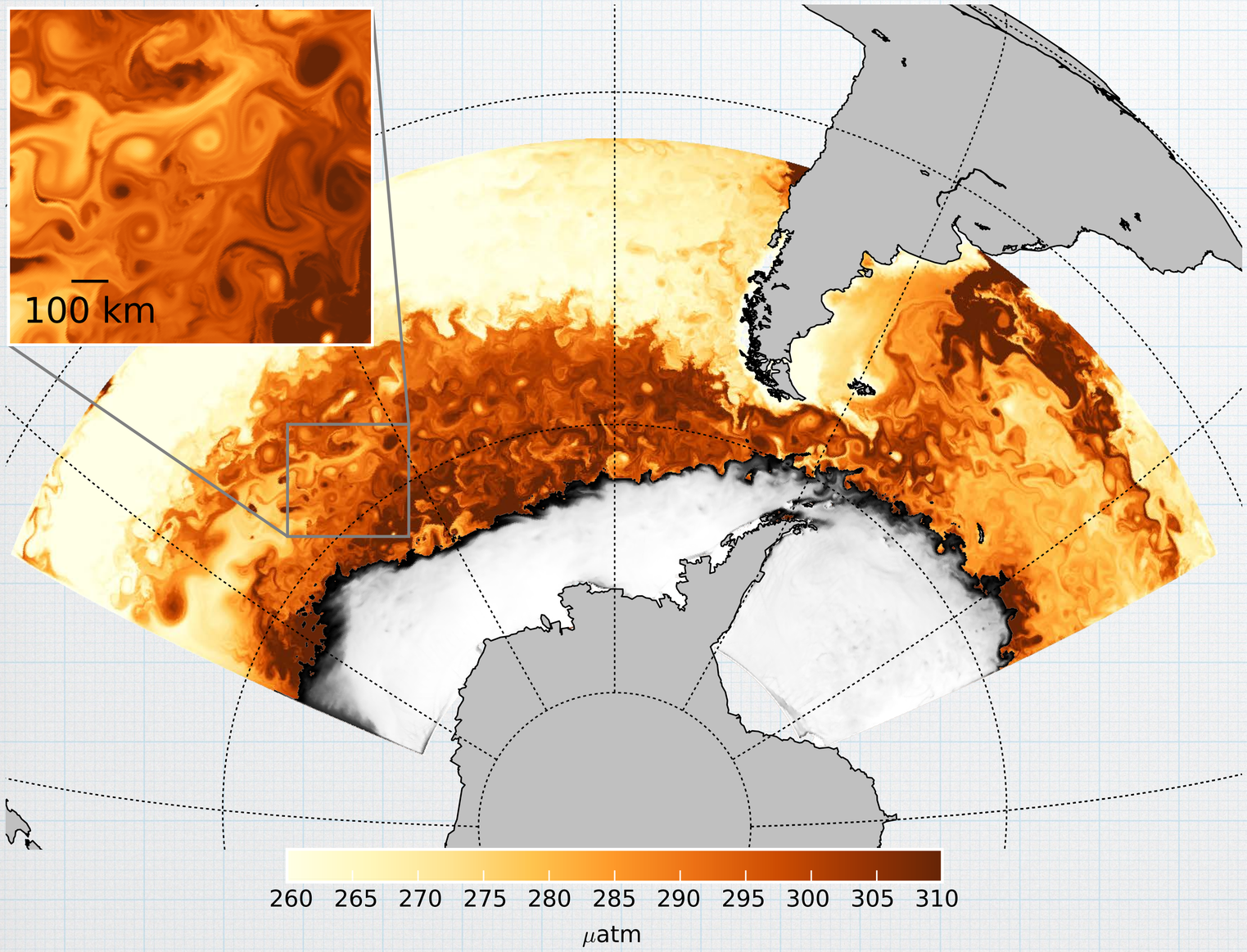






Song et al., 2016

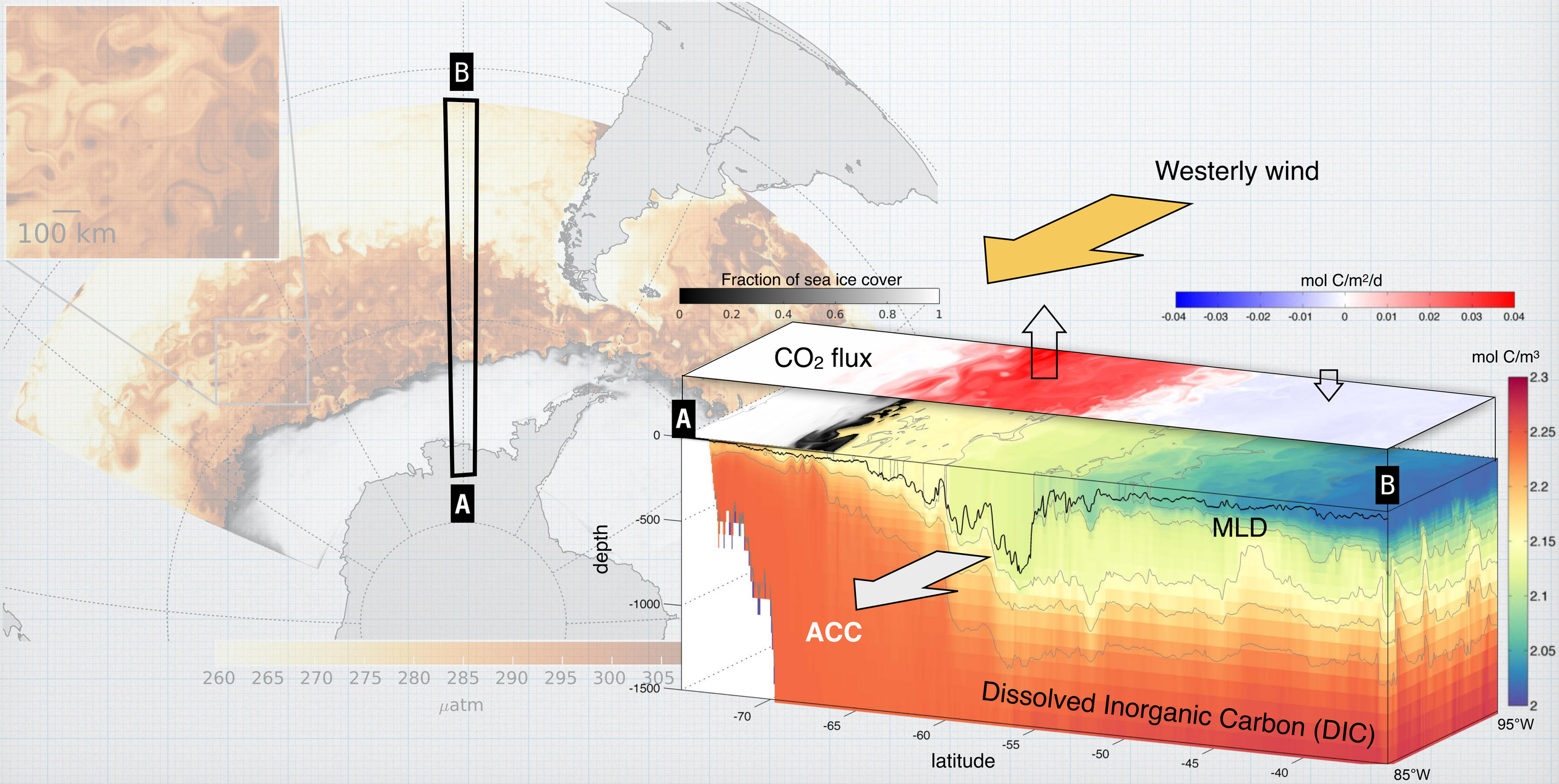
MITgcm 1/20° model



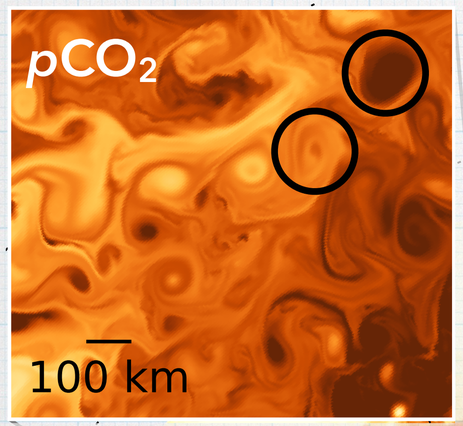
pCO_2, September

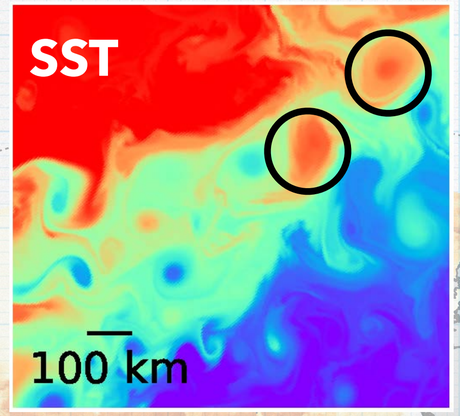
Song et al., 2016

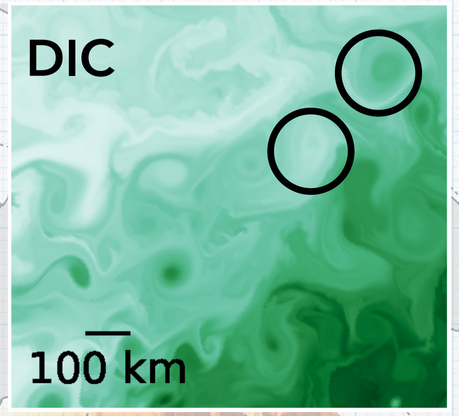
MITgcm 1/20° model



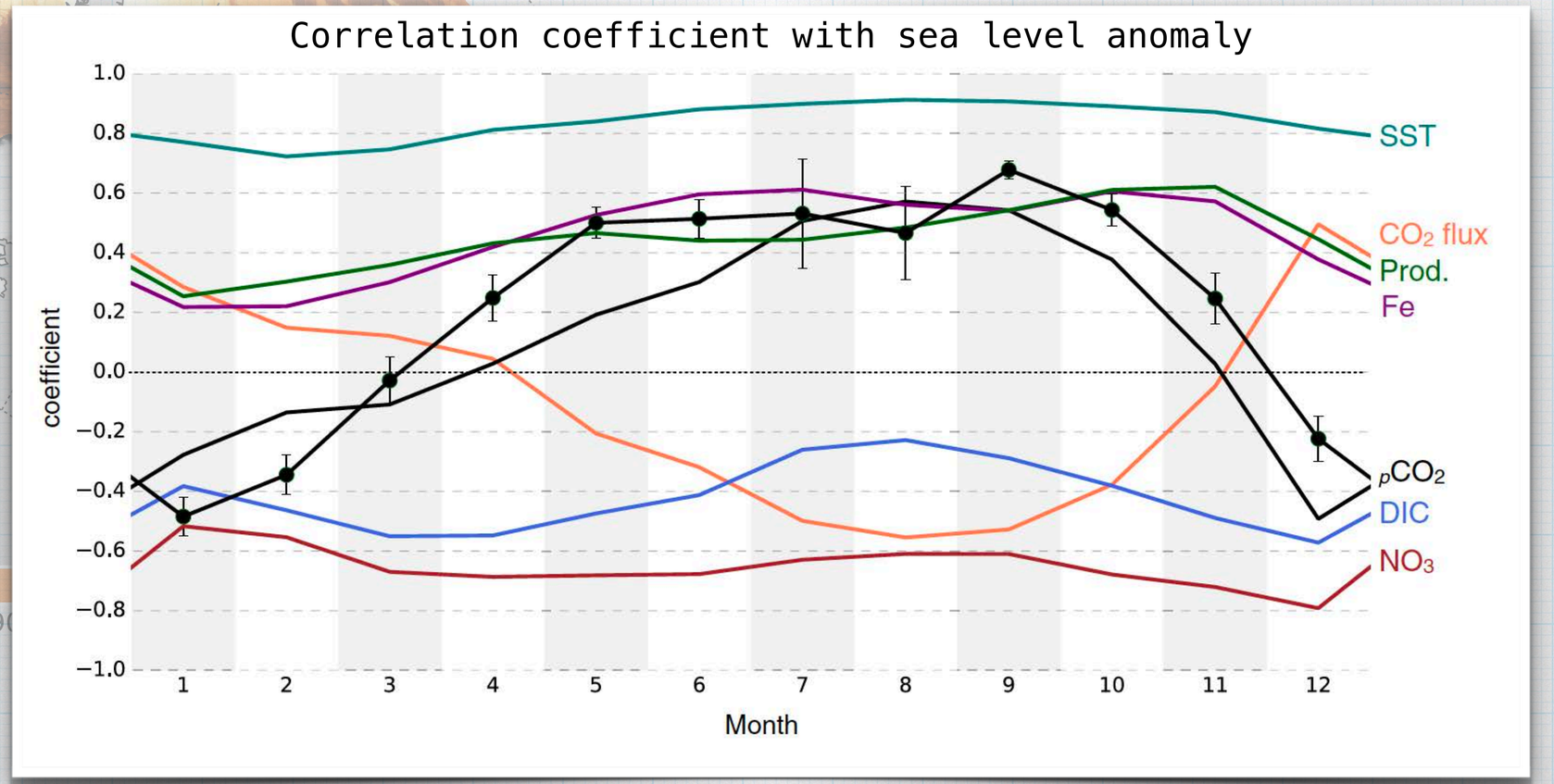
MITgcm 1/20° model

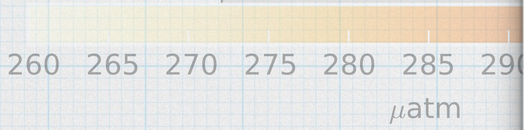


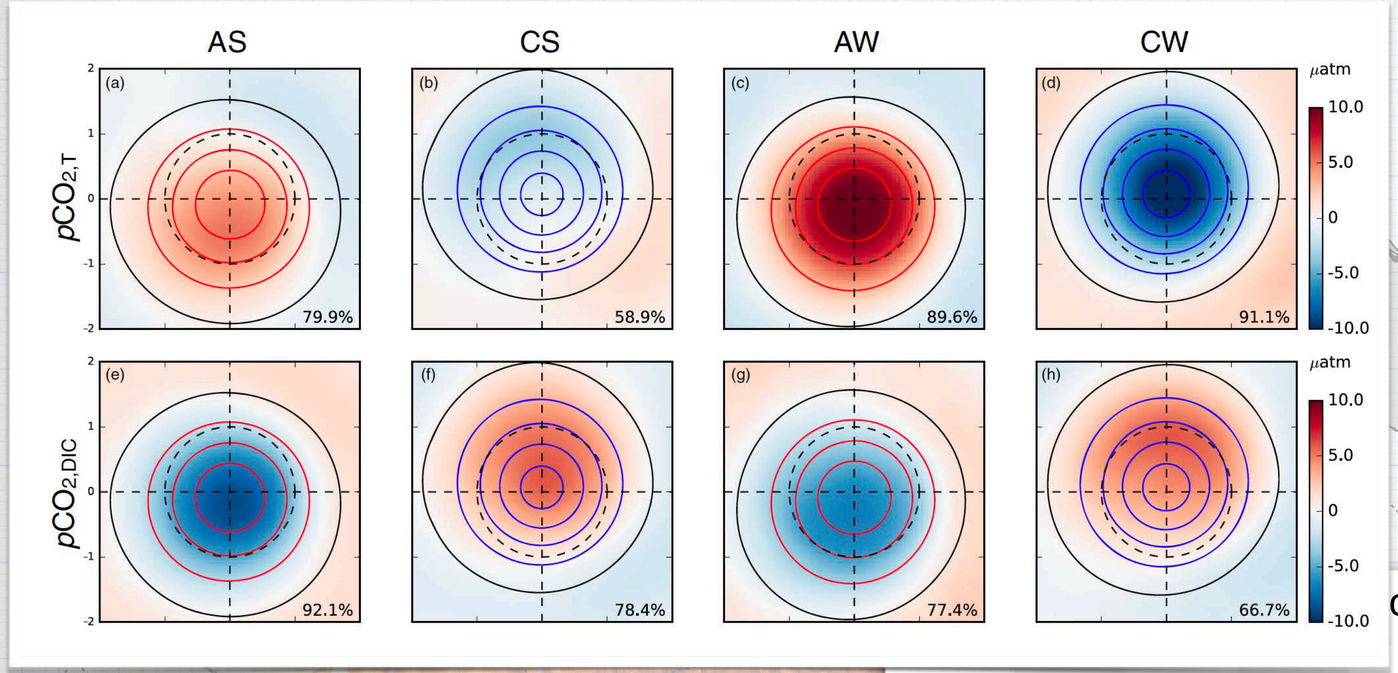




Song et al., 2016

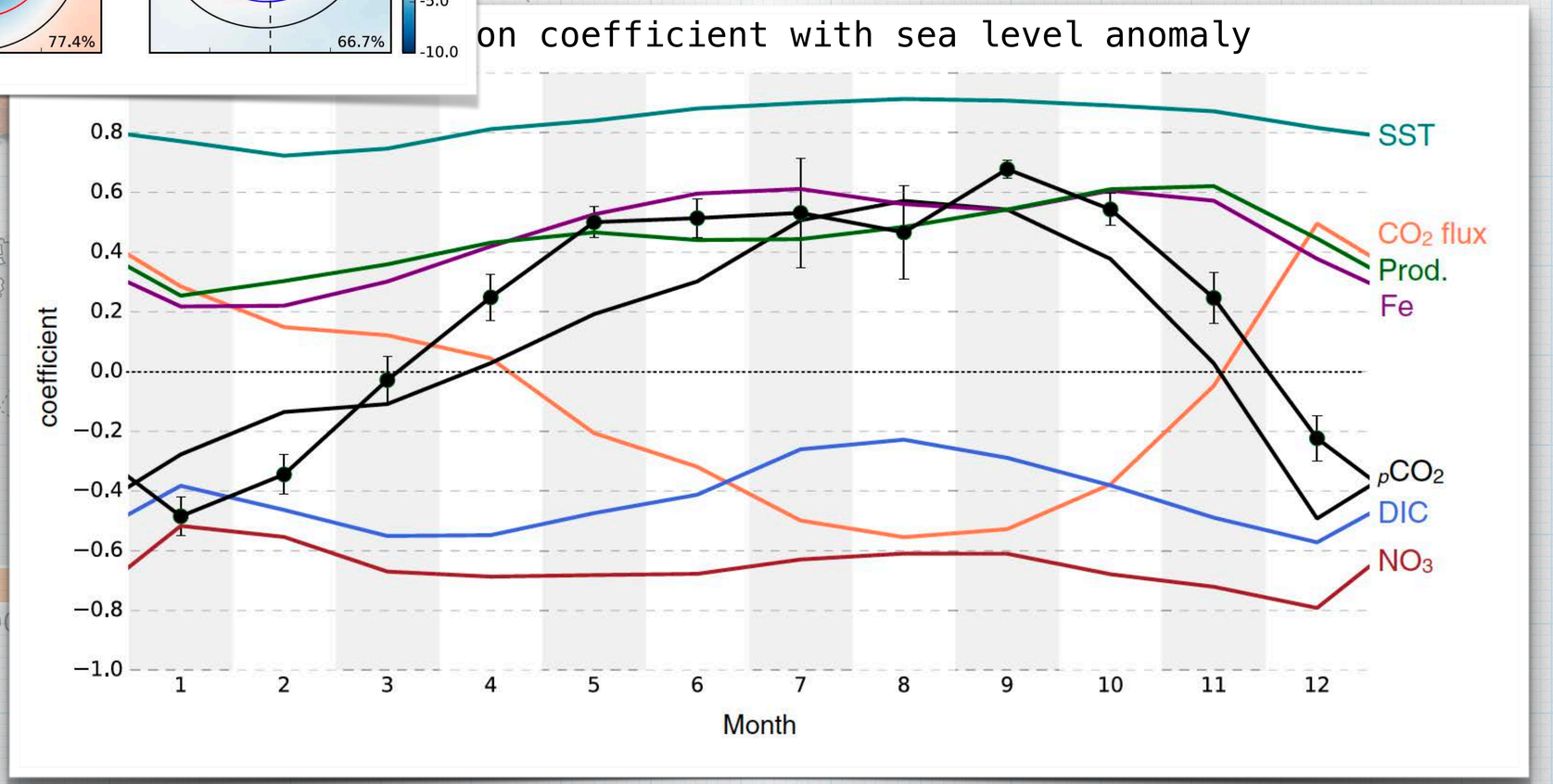






Song et al., 2016

on coefficient with sea level anomaly



$$\frac{\Delta pCO_2}{pCO_2} \approx \beta \Delta T + \gamma \frac{\Delta DIC}{DIC}$$

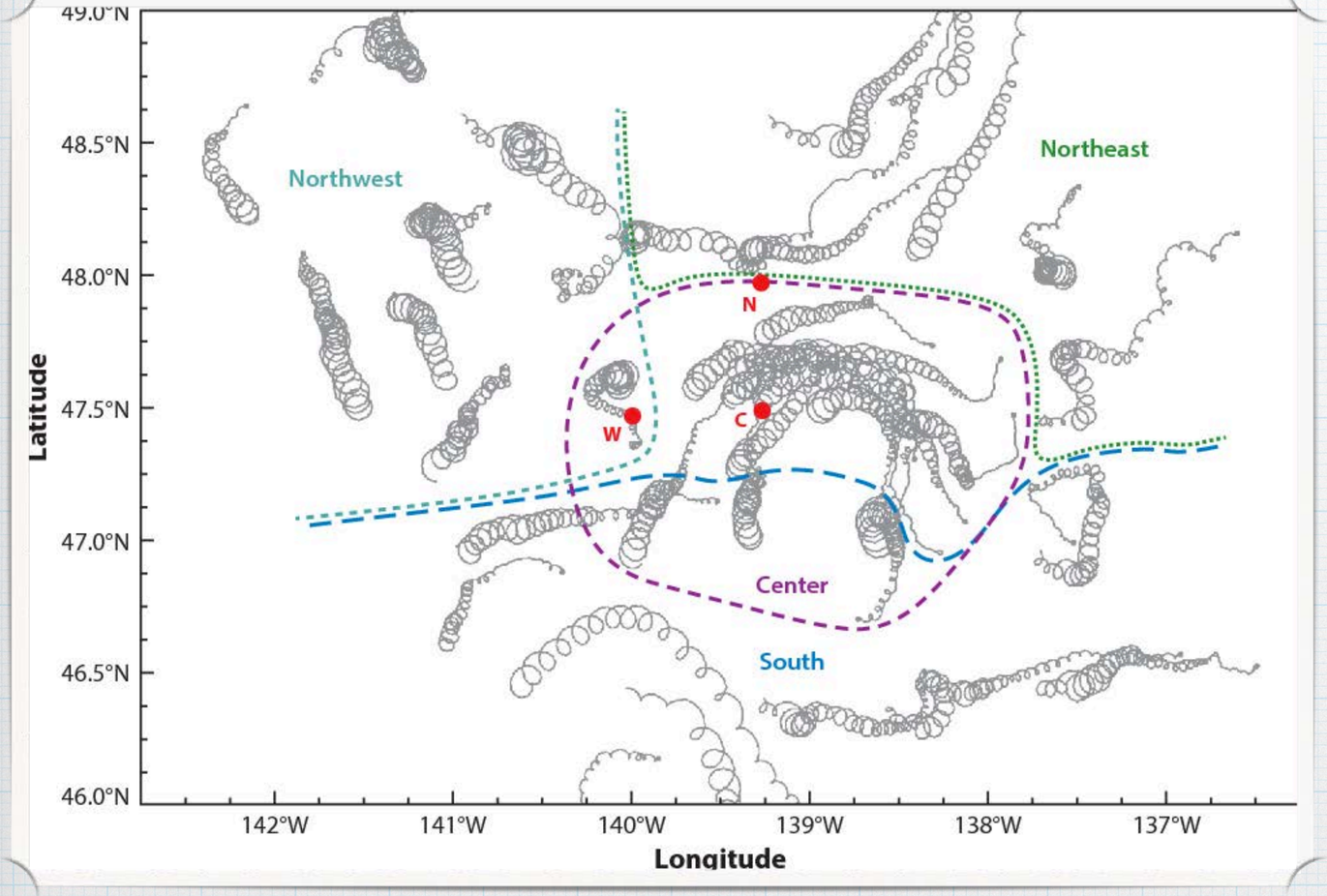
260 265 270 275 280 285 290 μatm

0.0423 °C^{-1} ~ 10

Takahashi et al., 1993

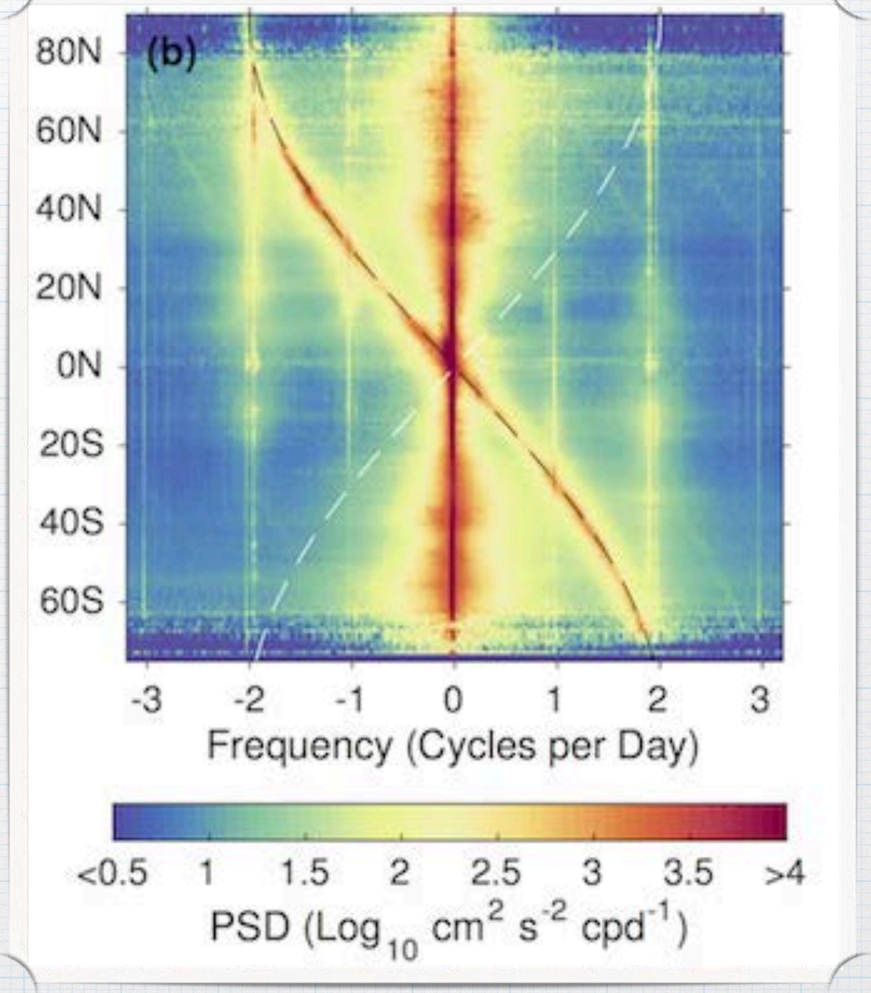
Near inertial waves

Drifter tracks in the Ocean Storms Experiment



Alford et al., 2016

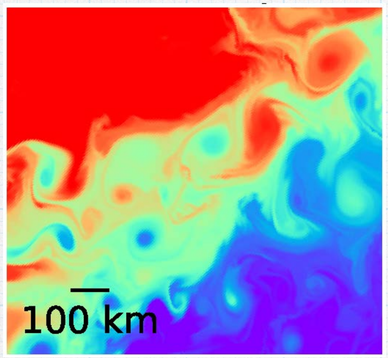
Rotary velocity power spectra

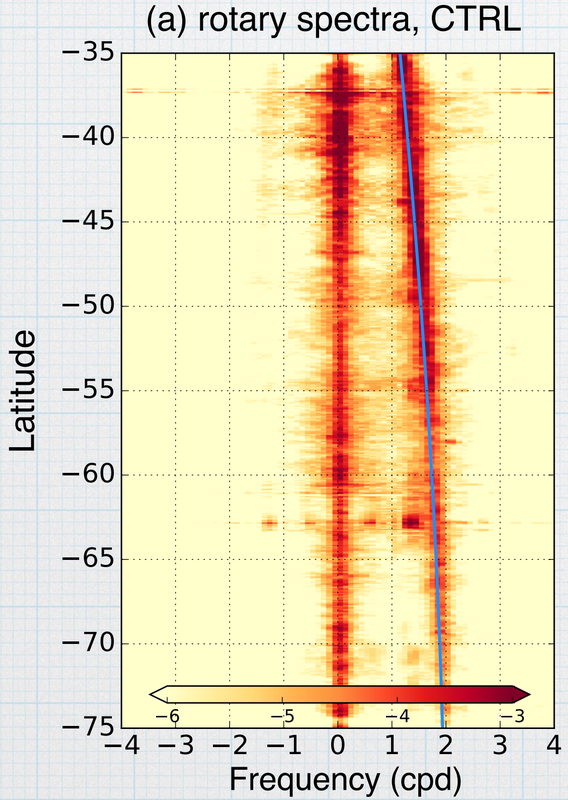


Elipot et al., 2016

Near inertial waves

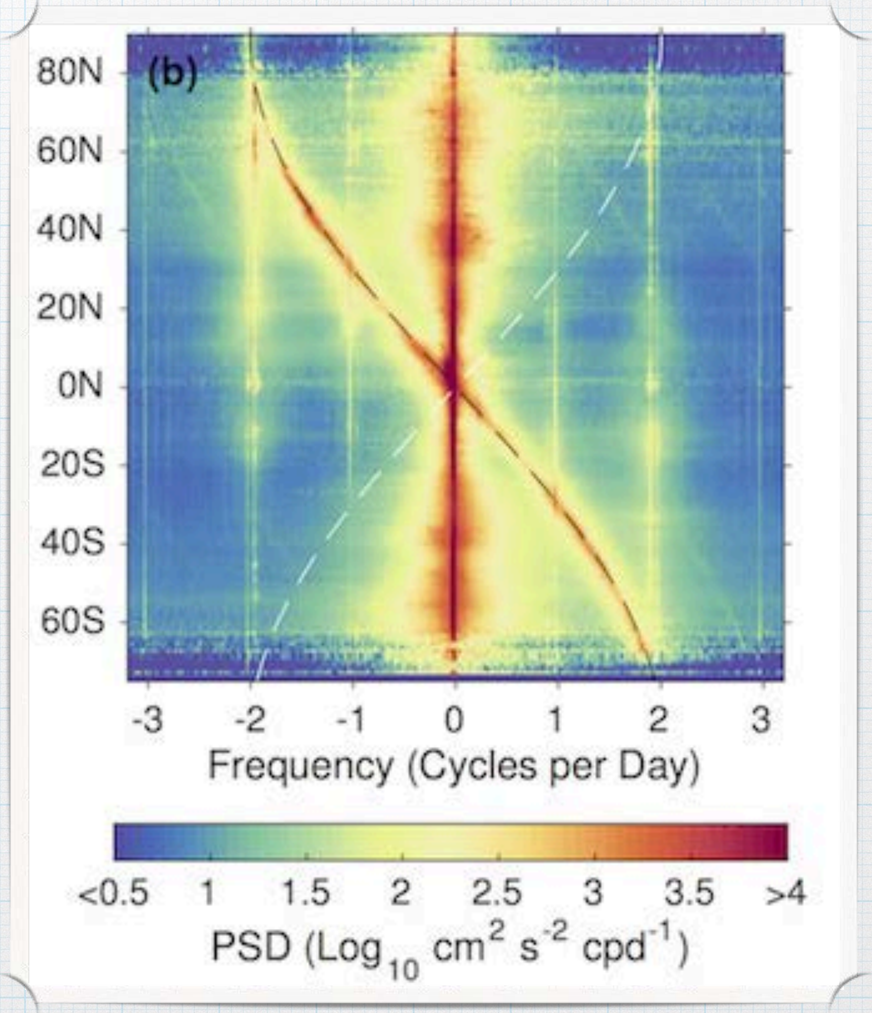
1/20° Eddy-resolving MITgcm





Song et al., in revision

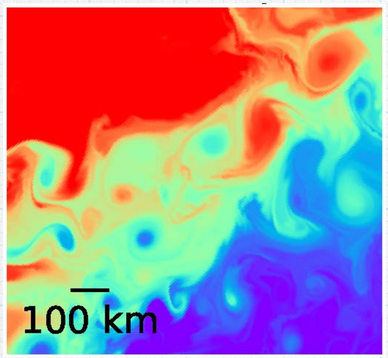
Rotary velocity power spectra



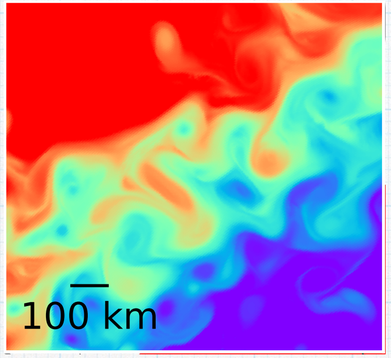
Elipot et al., 2016

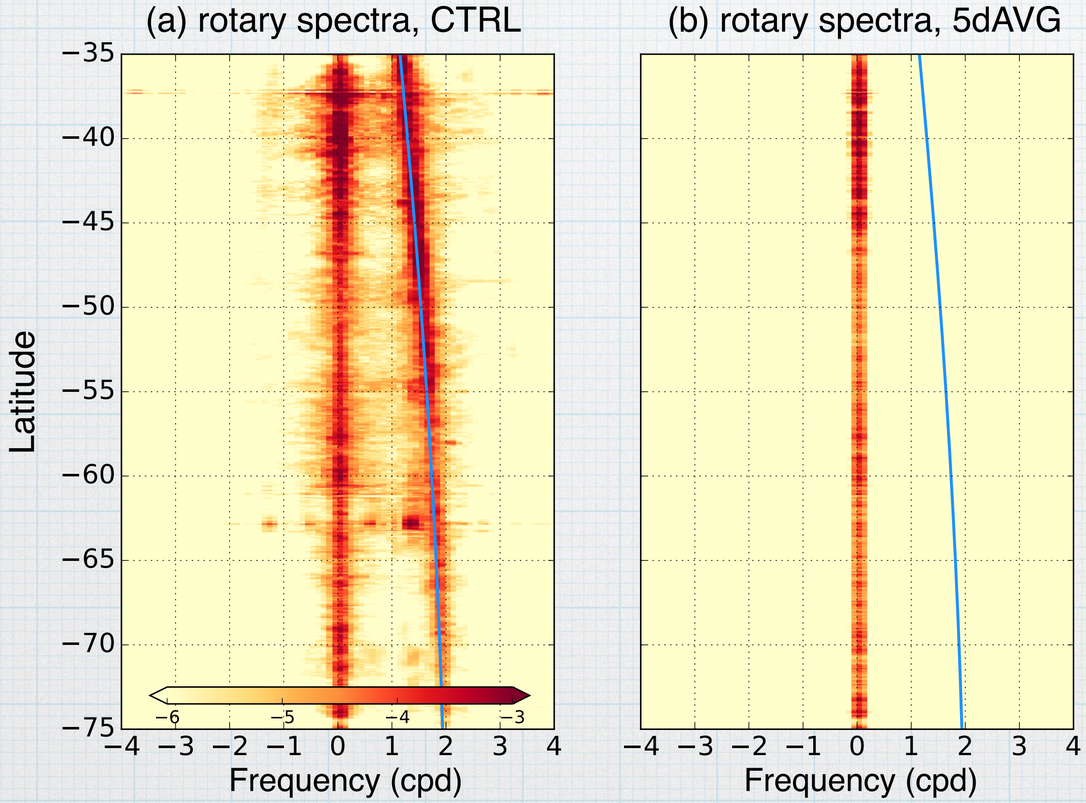
Near inertial waves

1/20° Eddy-resolving MITgcm



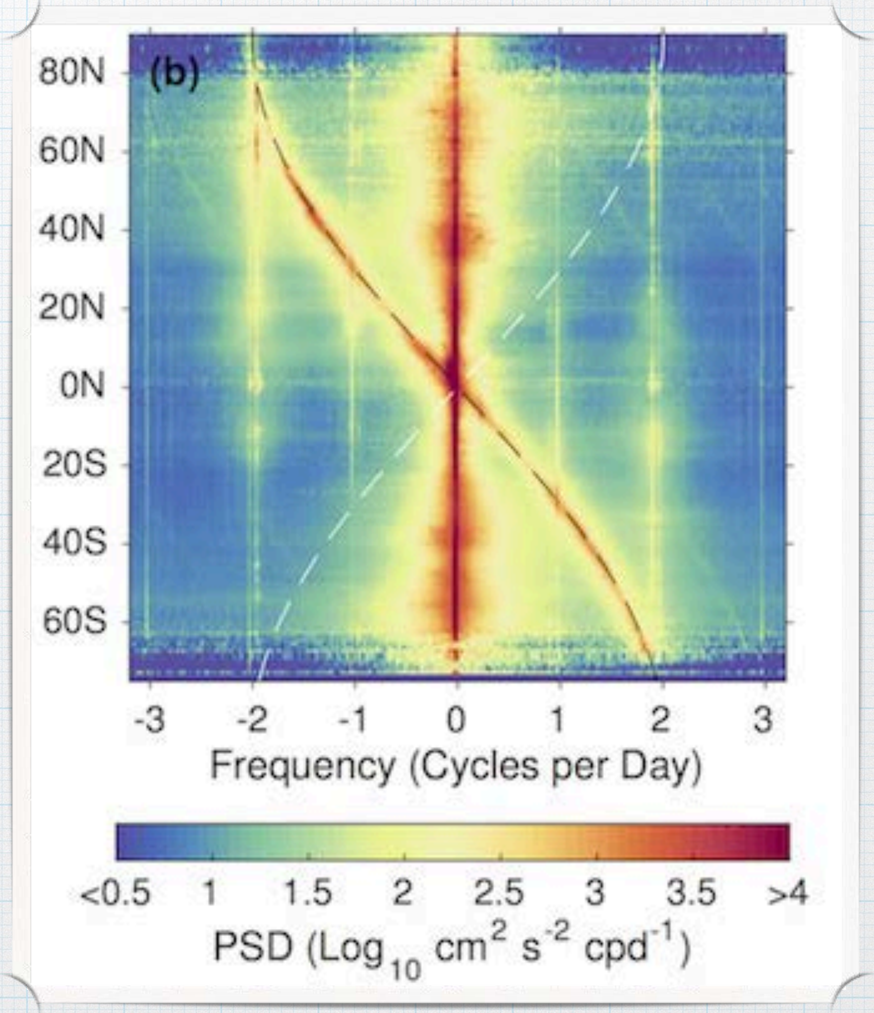
Offline simulation using $\langle T \rangle_{5d}$, $\langle S \rangle_{5d}$, $\langle u \rangle_{5d}$, $\langle v \rangle_{5d}$





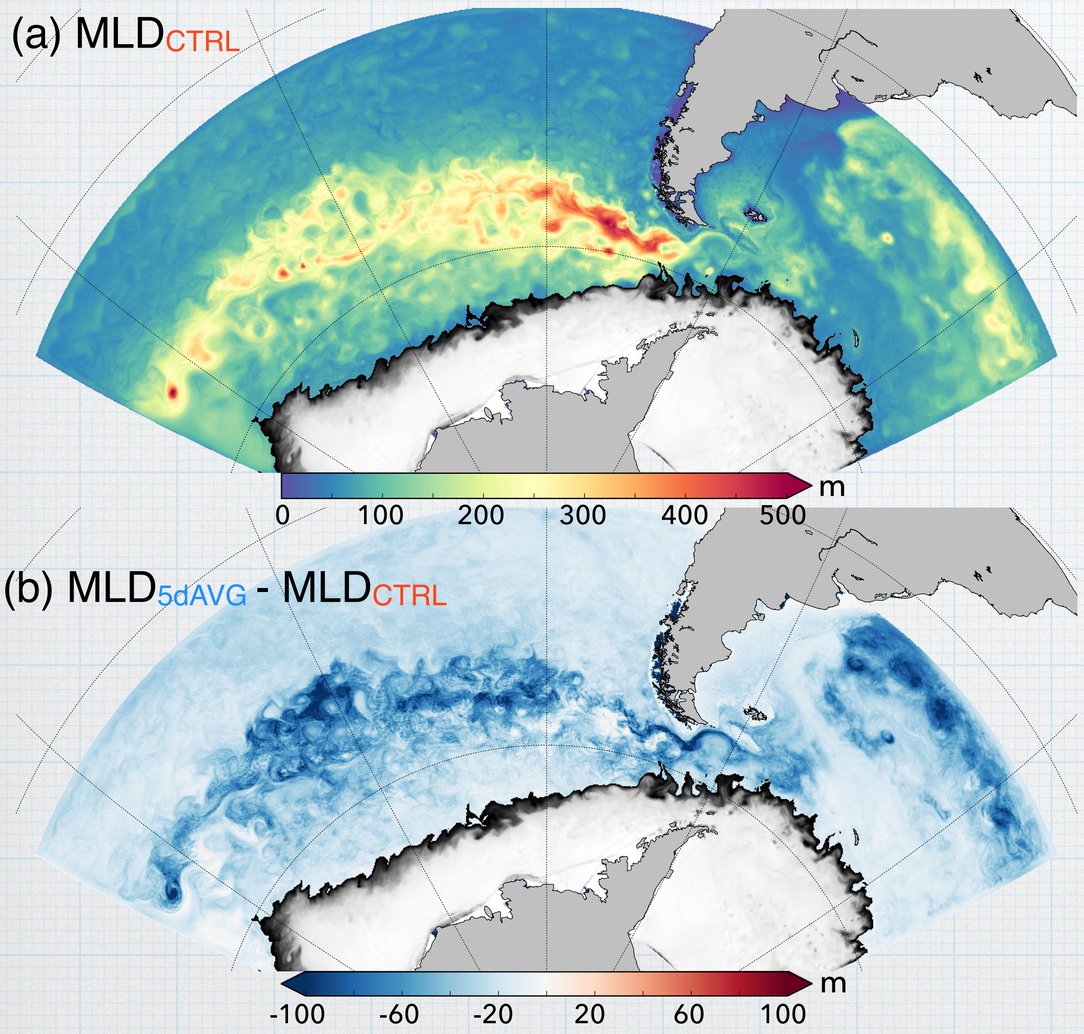
Song et al., in revision

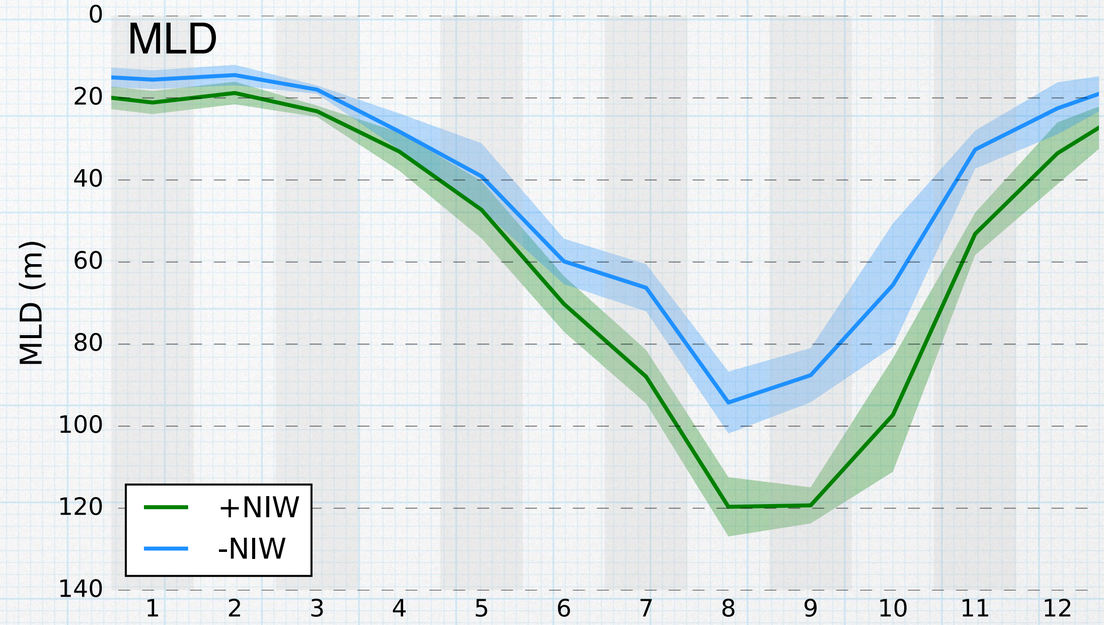
Rotary velocity power spectra

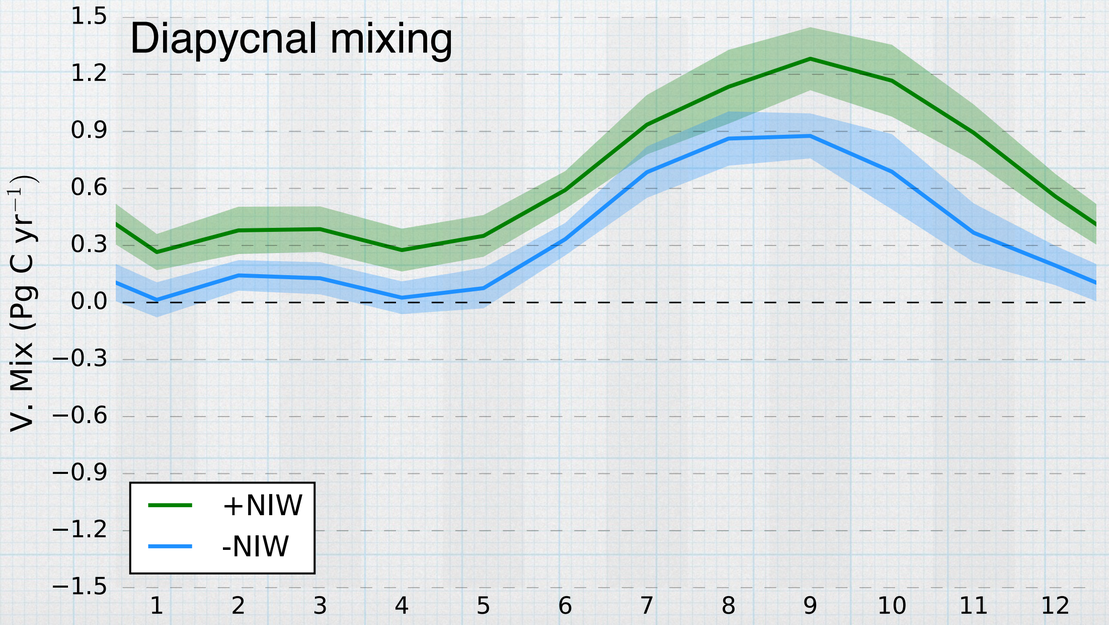


Elipot et al., 2016

Near inertial waves

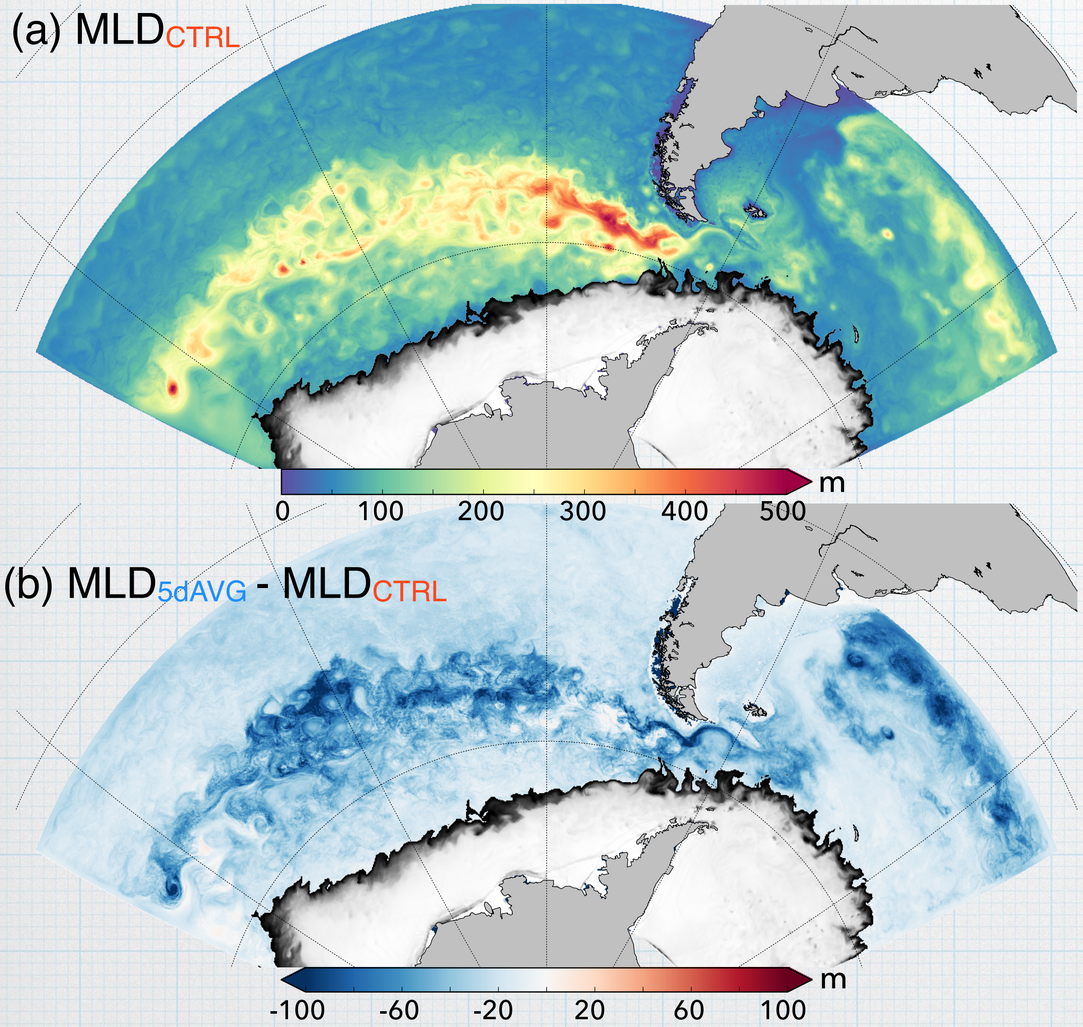


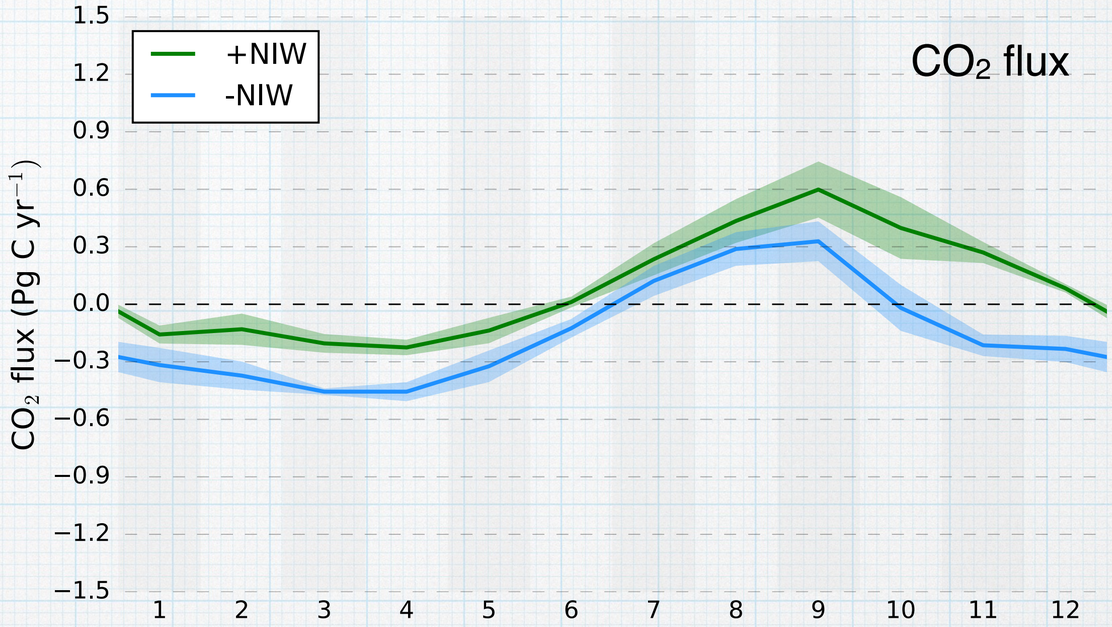


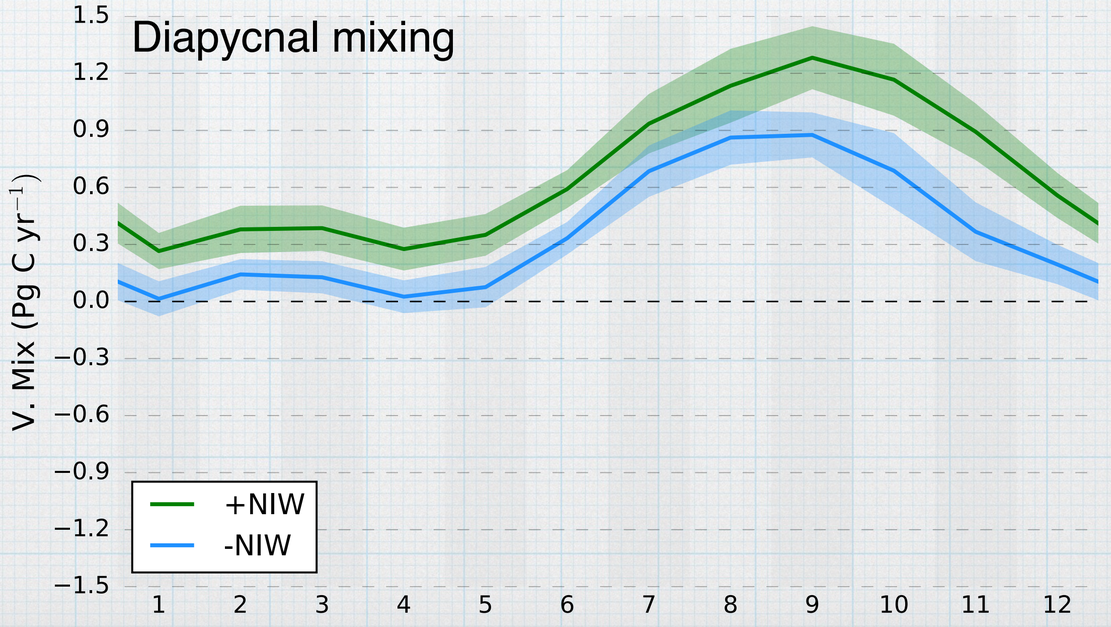


Song et al., in revision

Near inertial waves





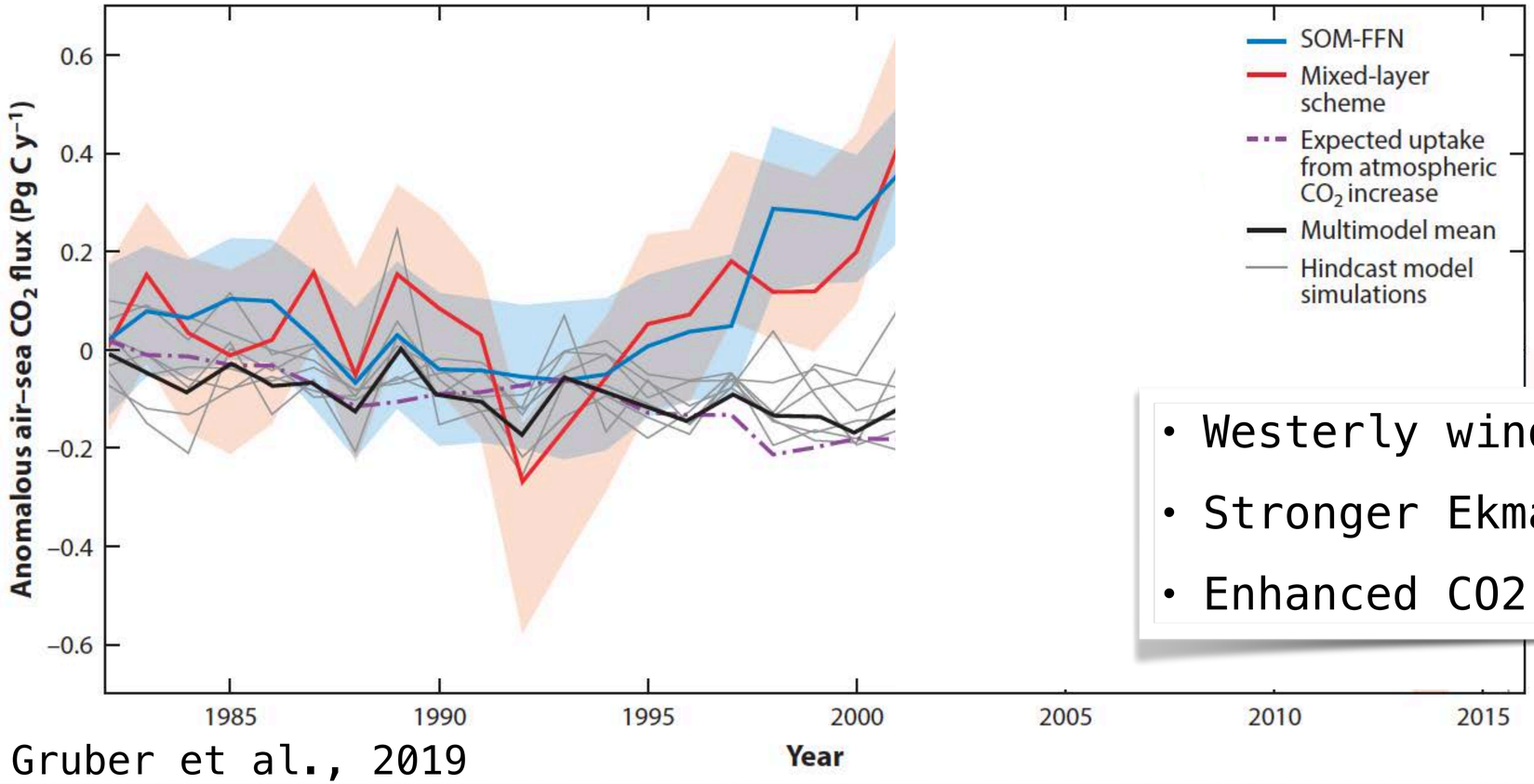


Song et al., in revision

CO2 flux SO, decadal variability

"the Southern Ocean sink of CO2 has weakened between 1981 and 2004"

Le Quéré et al., 2007



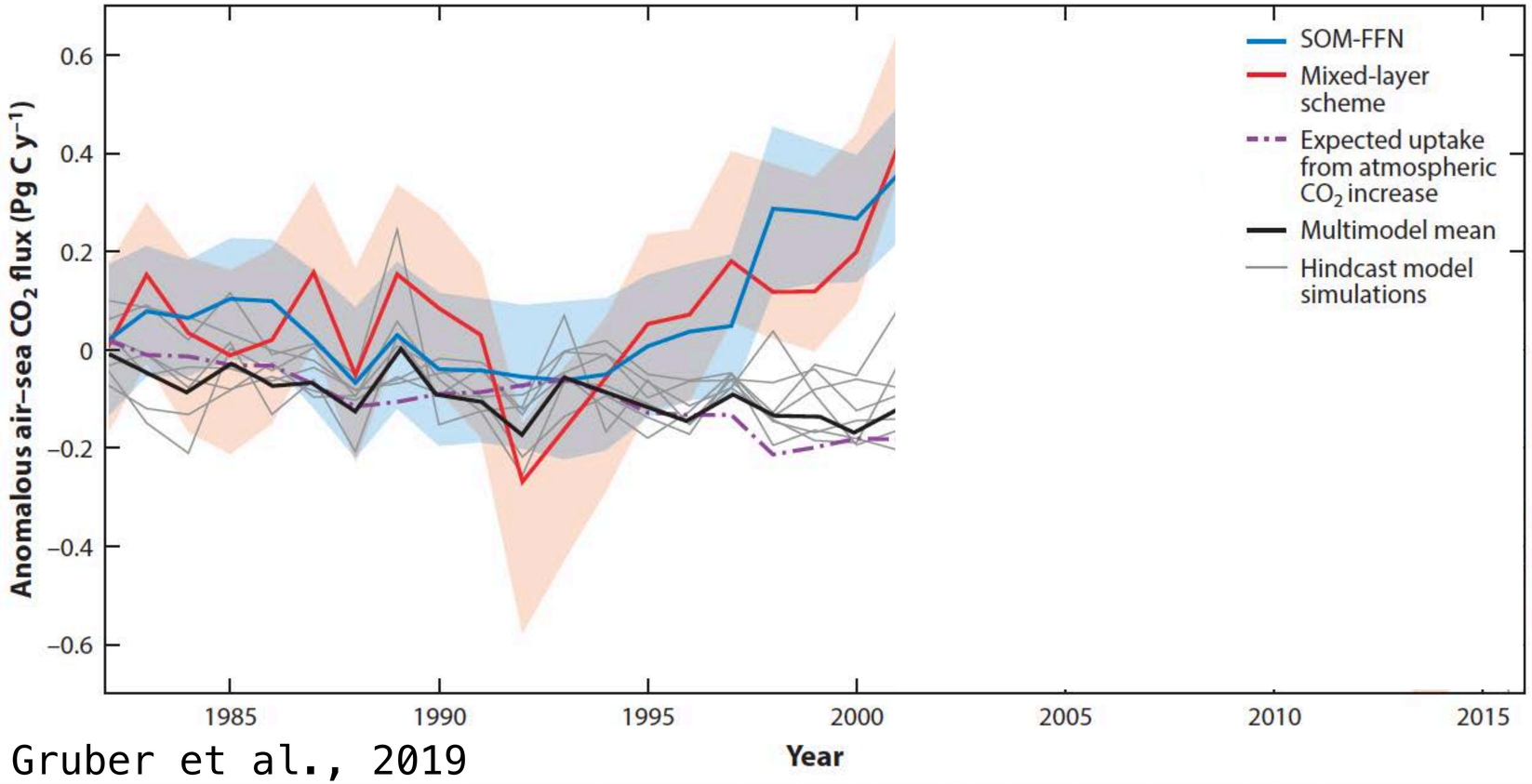
Gruber et al., 2019

- Westerly winds intensification
- Stronger Ekman transport / upwelling
- Enhanced CO2 outgassing

CO2 flux SO, decadal variability

"by 2012 the Southern Ocean had regained its expected strength"

Landschützer et al., 2016



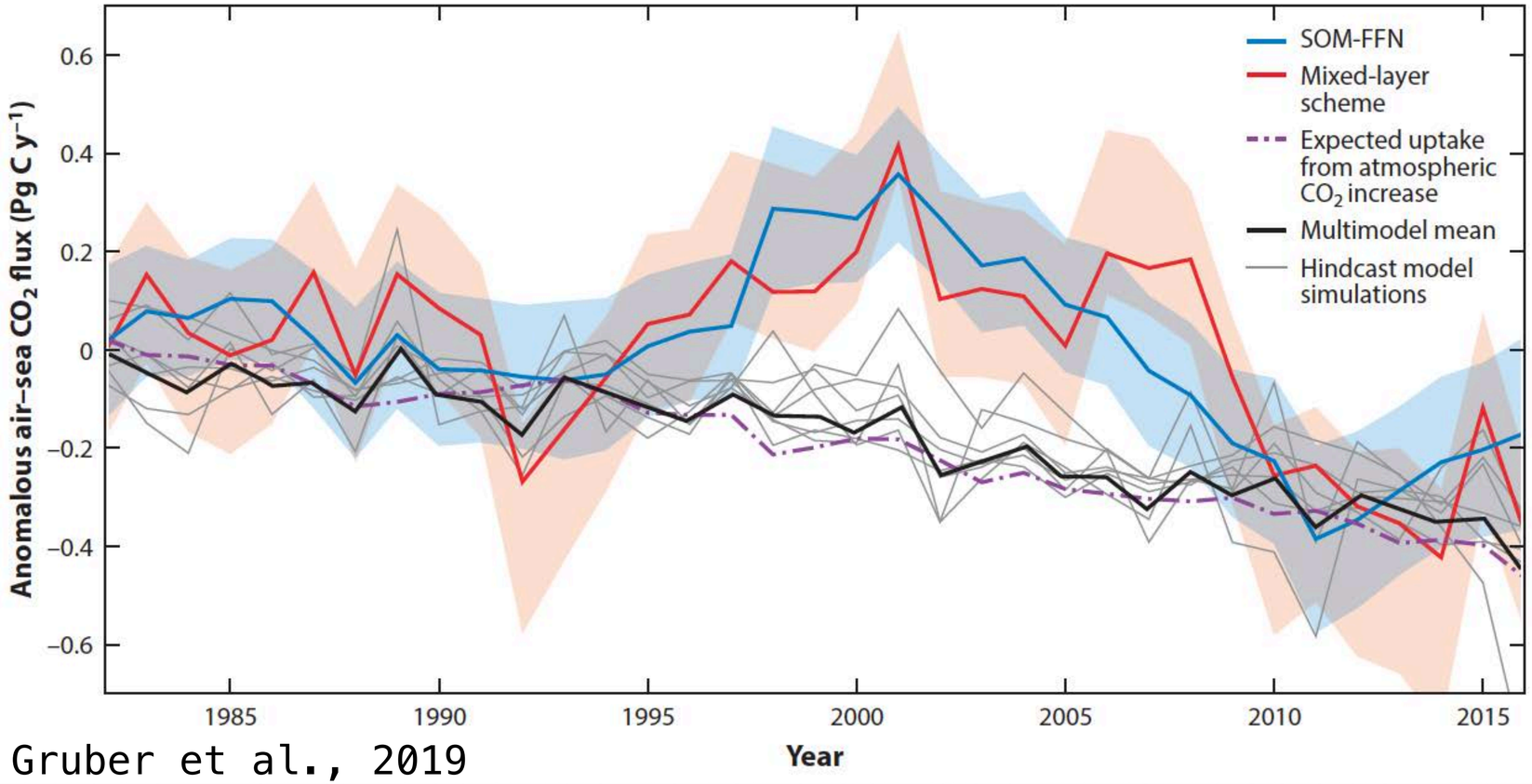
Gruber et al., 2019

What are drivers?

CO2 flux SO, decadal variability

"by 2012 the Southern Ocean had regained its expected strength"

Landschützer et al., 2016

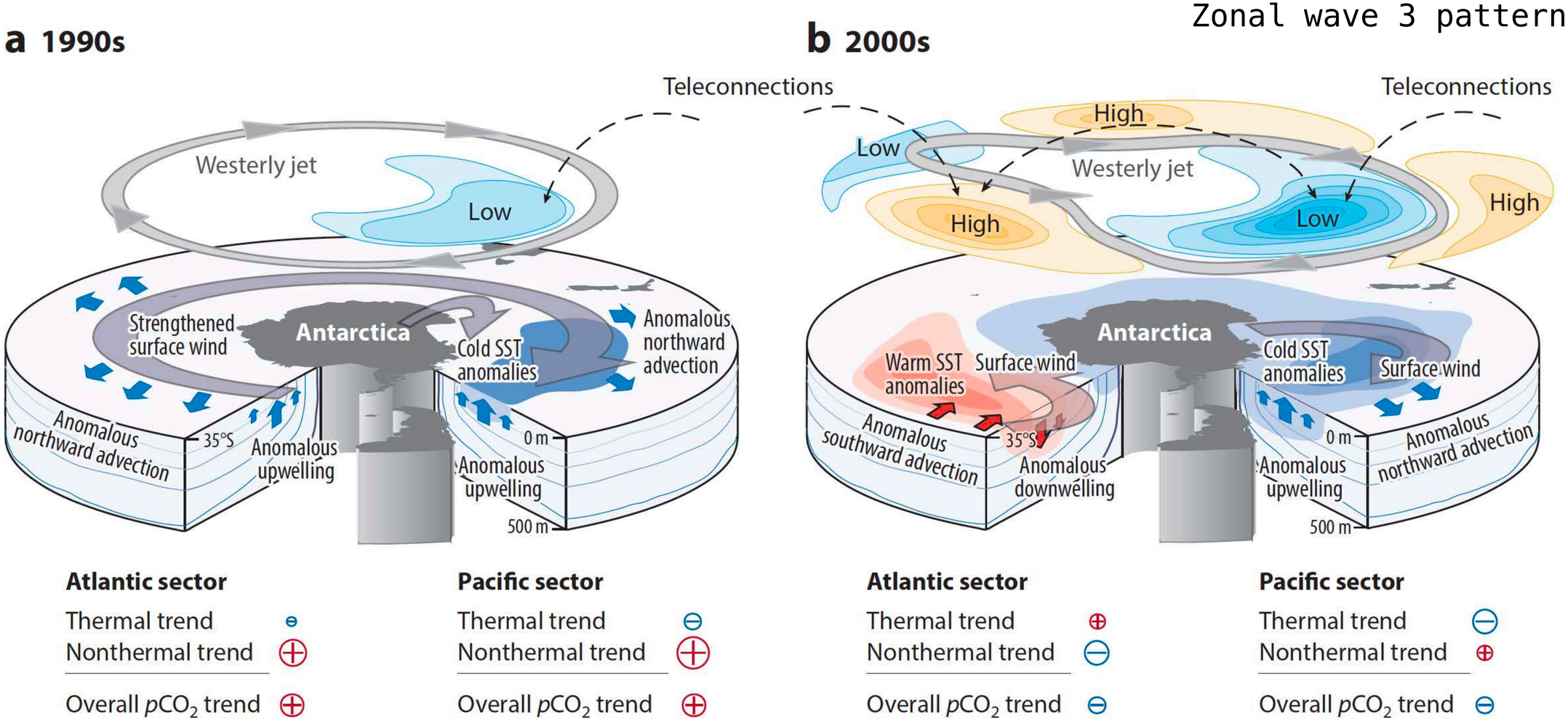


Gruber et al., 2019

What are drivers?

CO2 flux SO, decadal variability

Zonal wave 3 pattern

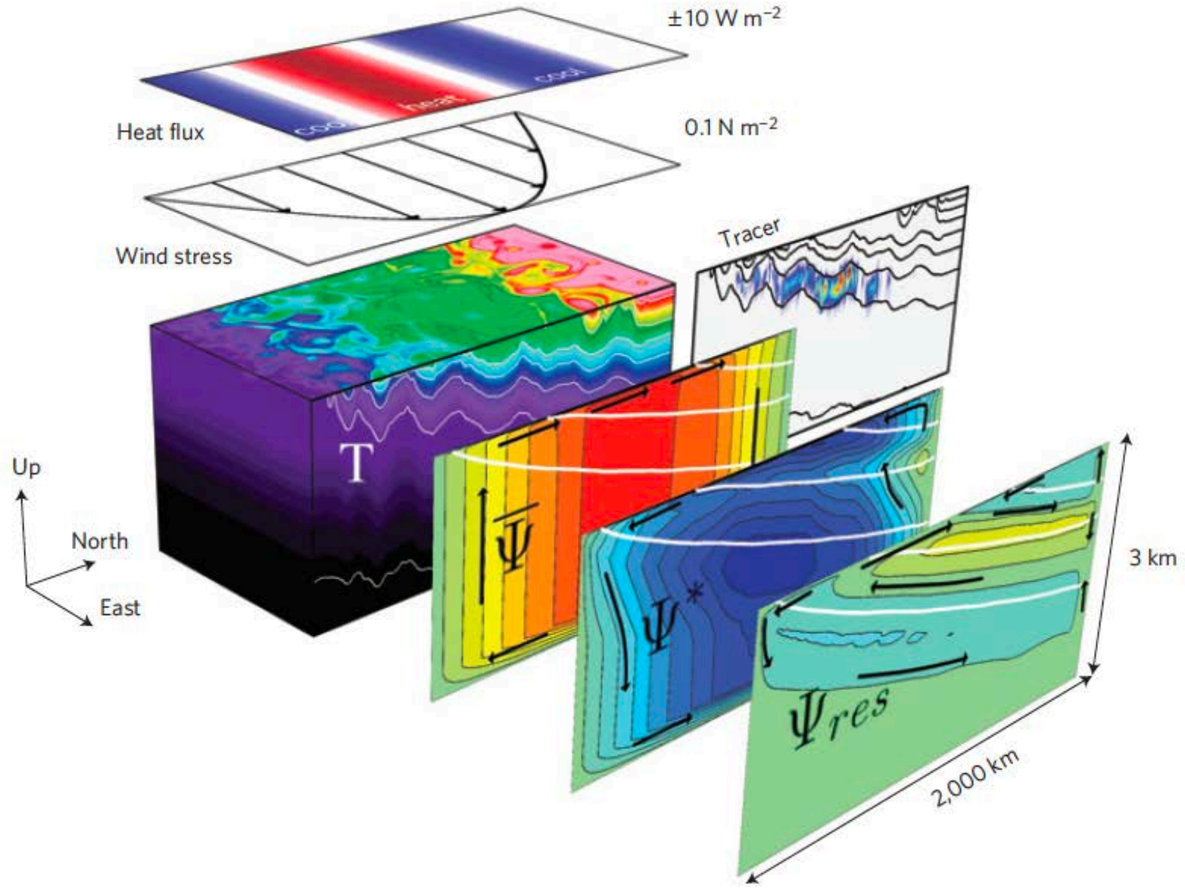


Atlantic sector		Pacific sector	
Thermal trend	⊖	Thermal trend	⊖
Nonthermal trend	⊕	Nonthermal trend	⊕
Overall pCO_2 trend	⊕	Overall pCO_2 trend	⊕

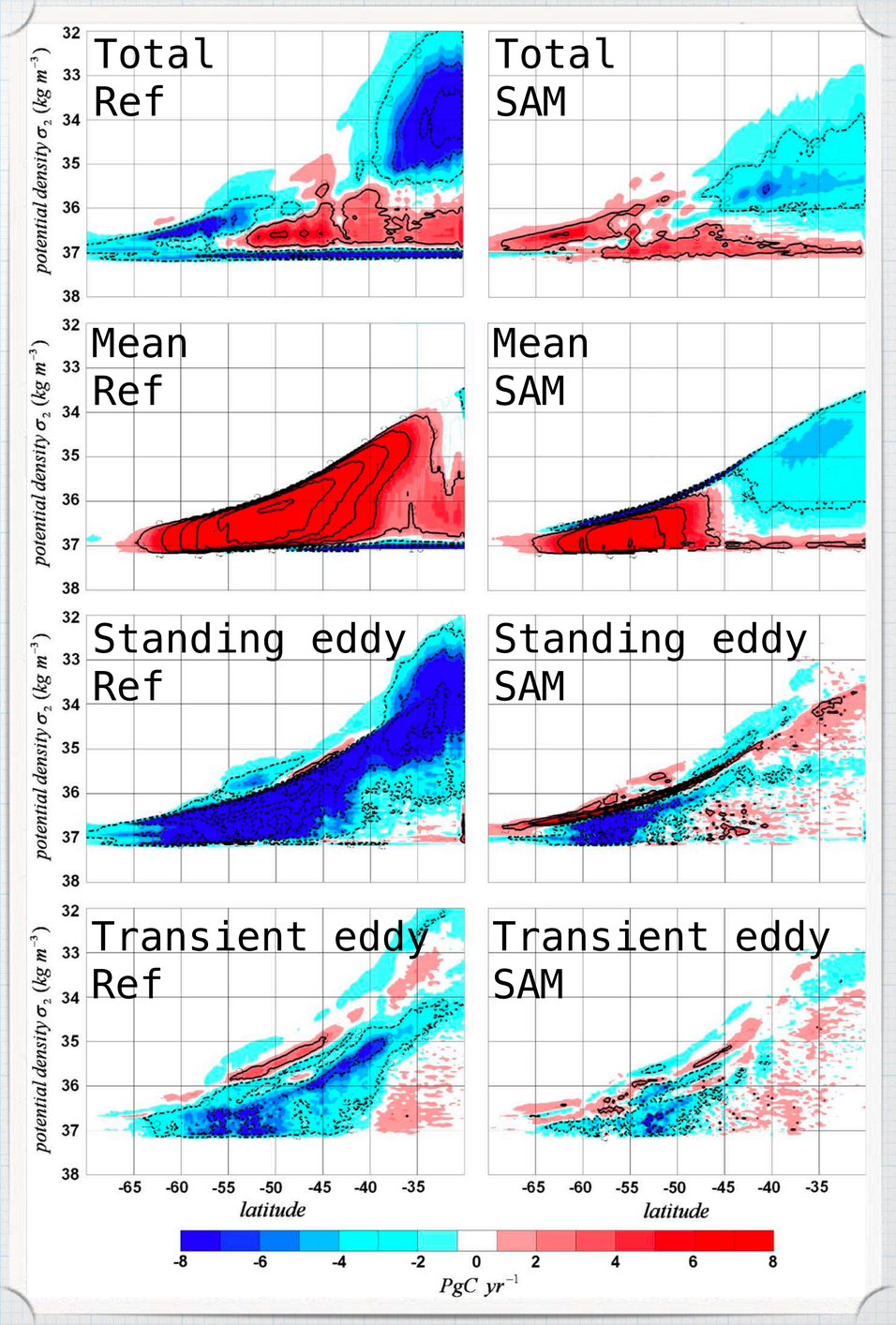
Atlantic sector		Pacific sector	
Thermal trend	⊕	Thermal trend	⊖
Nonthermal trend	⊖	Nonthermal trend	⊕
Overall pCO_2 trend	⊖	Overall pCO_2 trend	⊖

Gruber et al., 2019

Eddy compensation



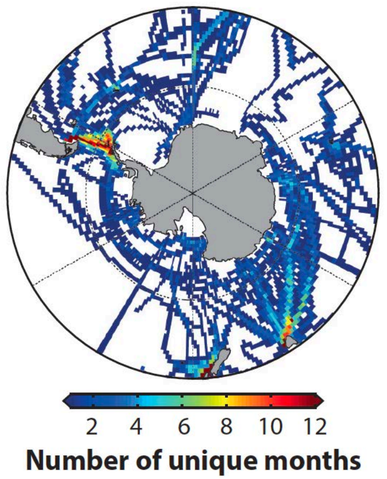
Marshall and Speer, 2012



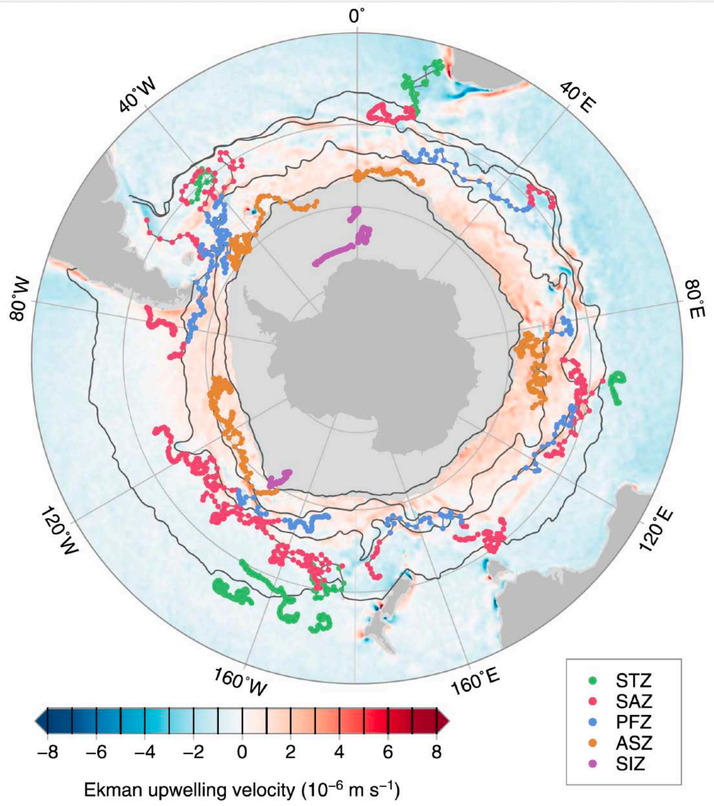
Dufour et al., 2013

New observations

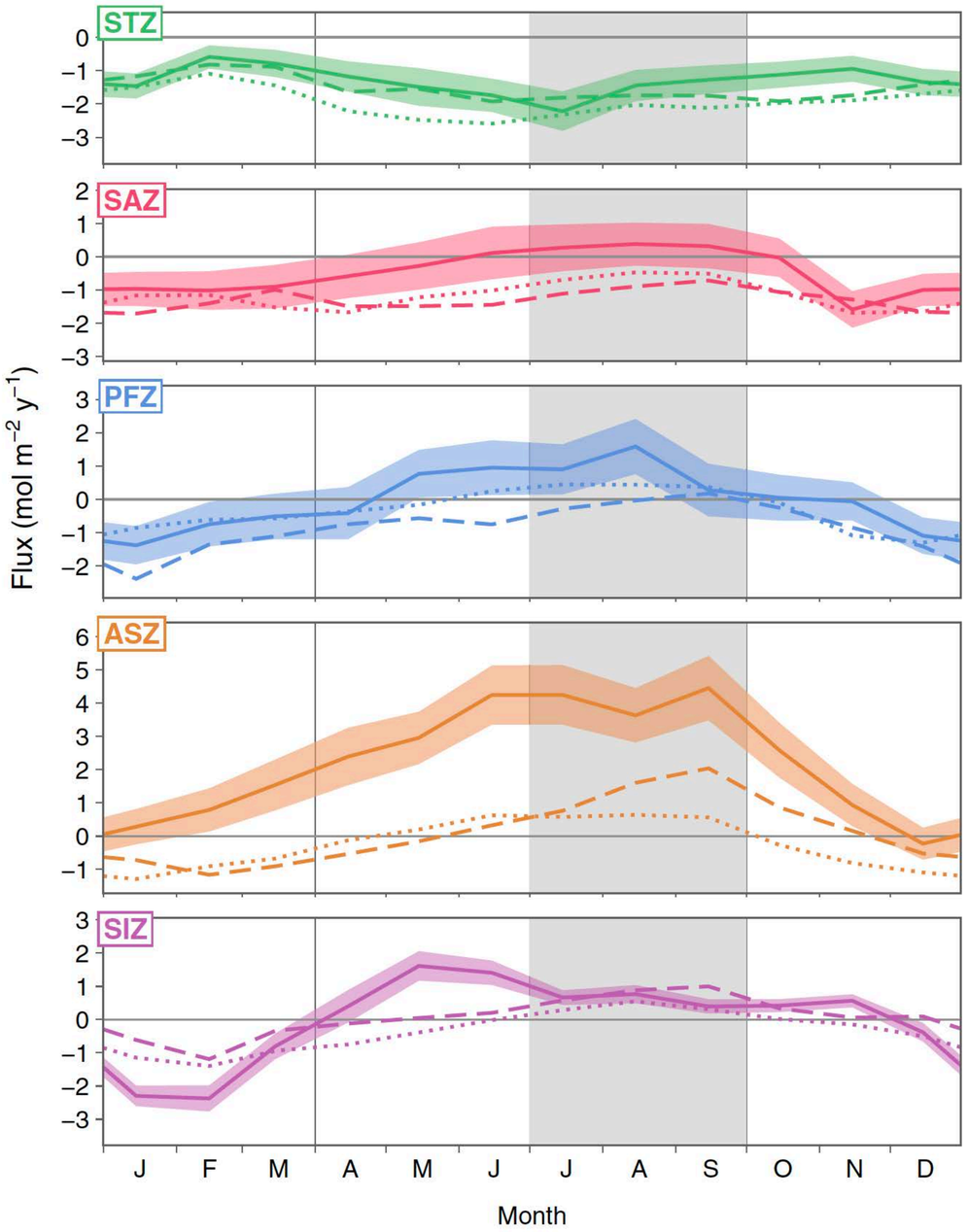
Gruber et al., 2019



SOCCOM | *Unlocking the mysteries of the Southern Ocean*



Gray et al., 2018



Challenges

- More observations are required (especially in the Southern Ocean and subsurface).
- How the CO_2 flux is modified by the changes in the ocean general circulation?
- Modeling effort to simulate CO_2 flux (especially in the Southern Ocean)
- A better understanding of the CO2 in a coupled system (atmosphere/ocean/sea-ice/land system)