Oceans, Climate Change and the Carbon Cycle

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Atmospheric and Oceanic Sciences

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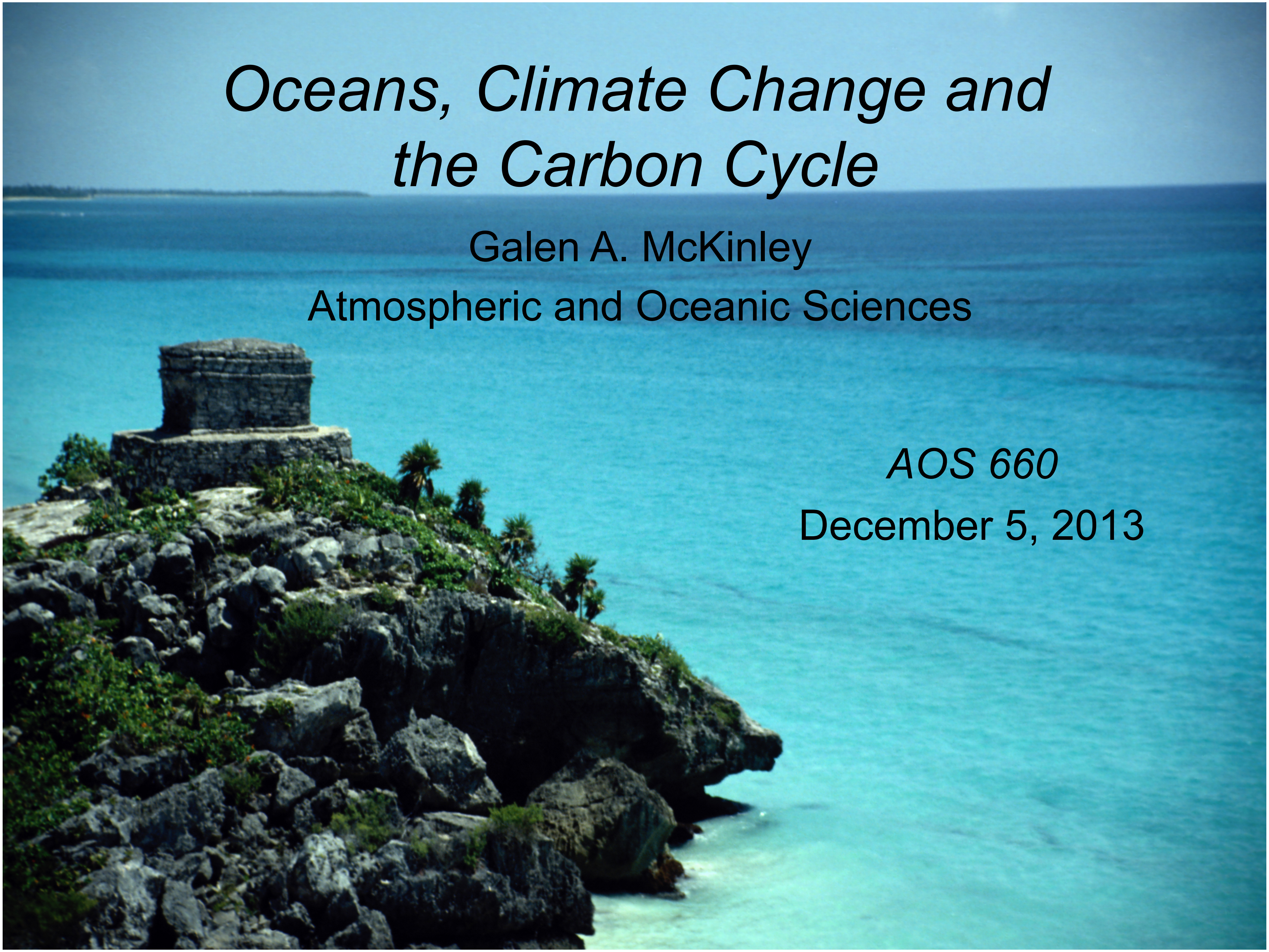

Oceans role in a changing world

- Oceans significantly damp global surface temperature rise driven by the anthropogenically-enhanced greenhouse effect by
  - Absorbing heat
  - Absorbing carbon

Oceans role in a changing world

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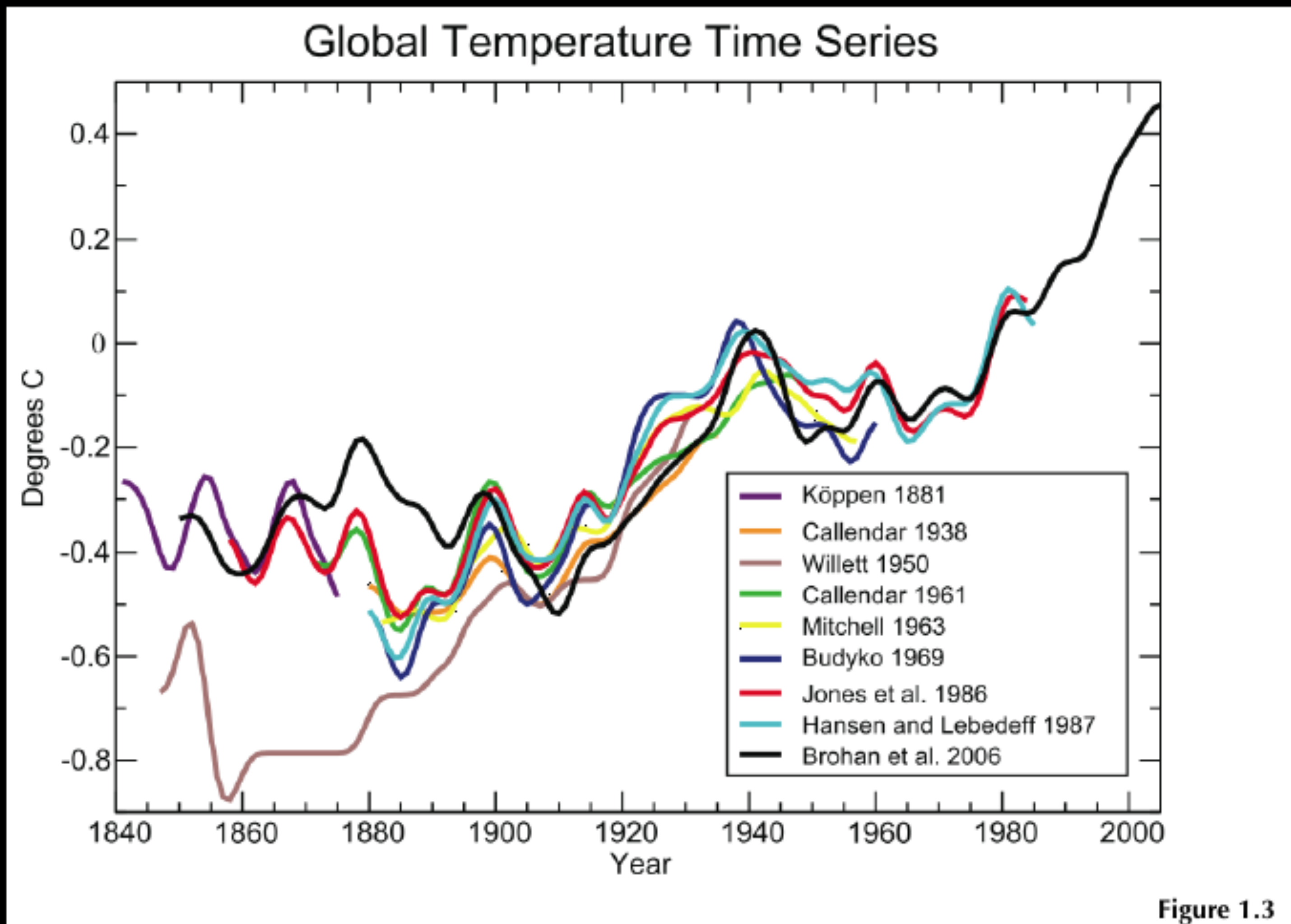
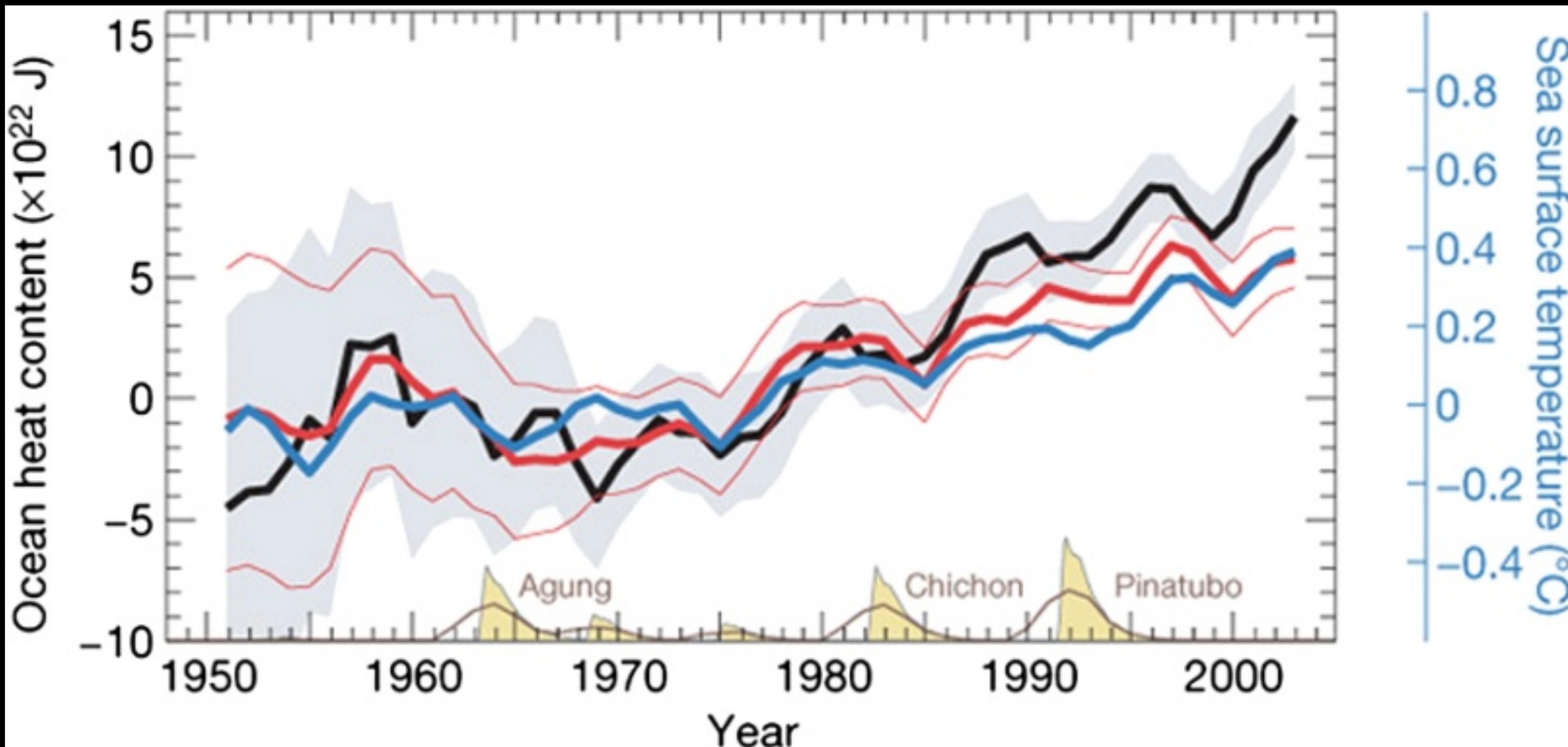
Climate is warming



IPCC AR4

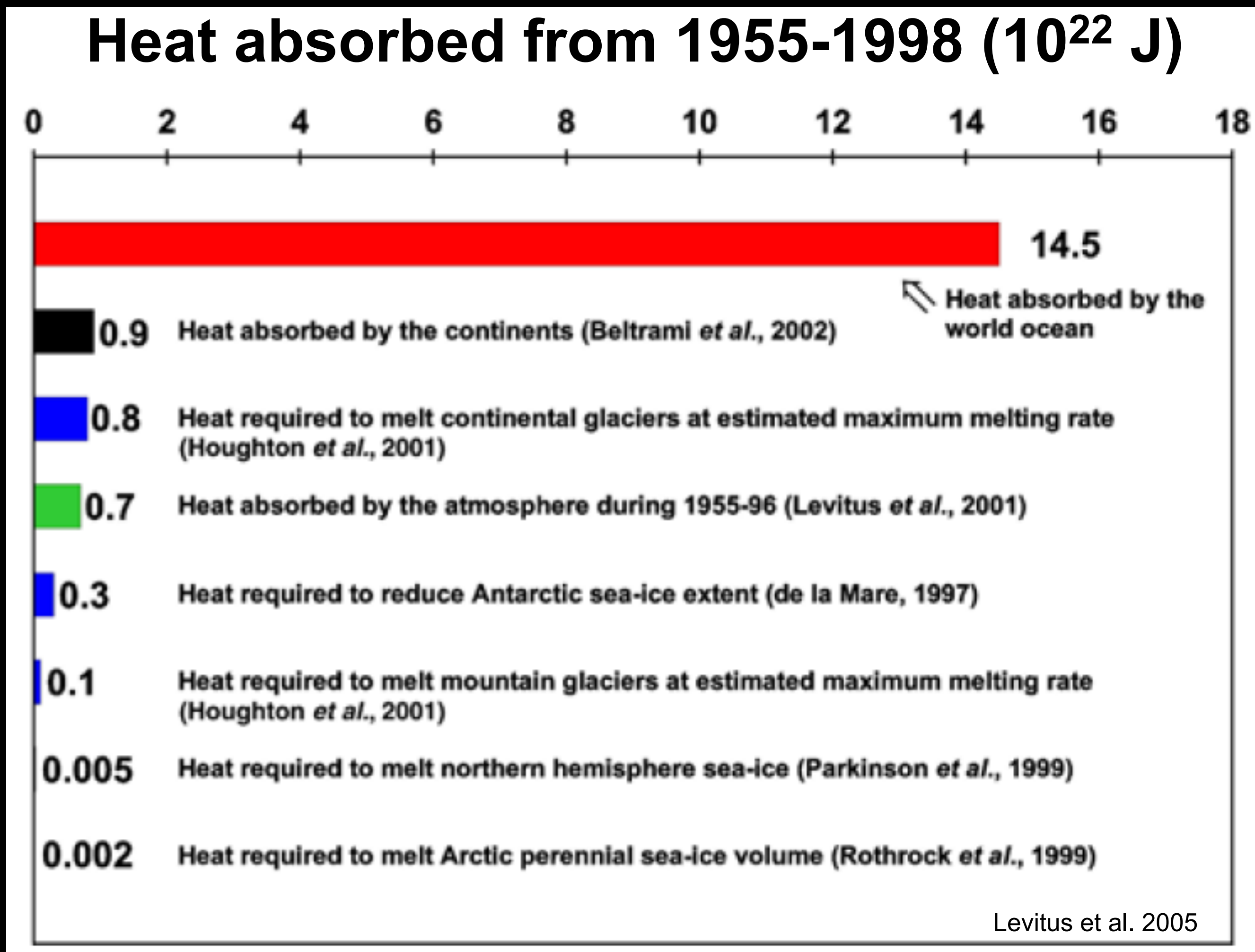
The ocean is warming, too

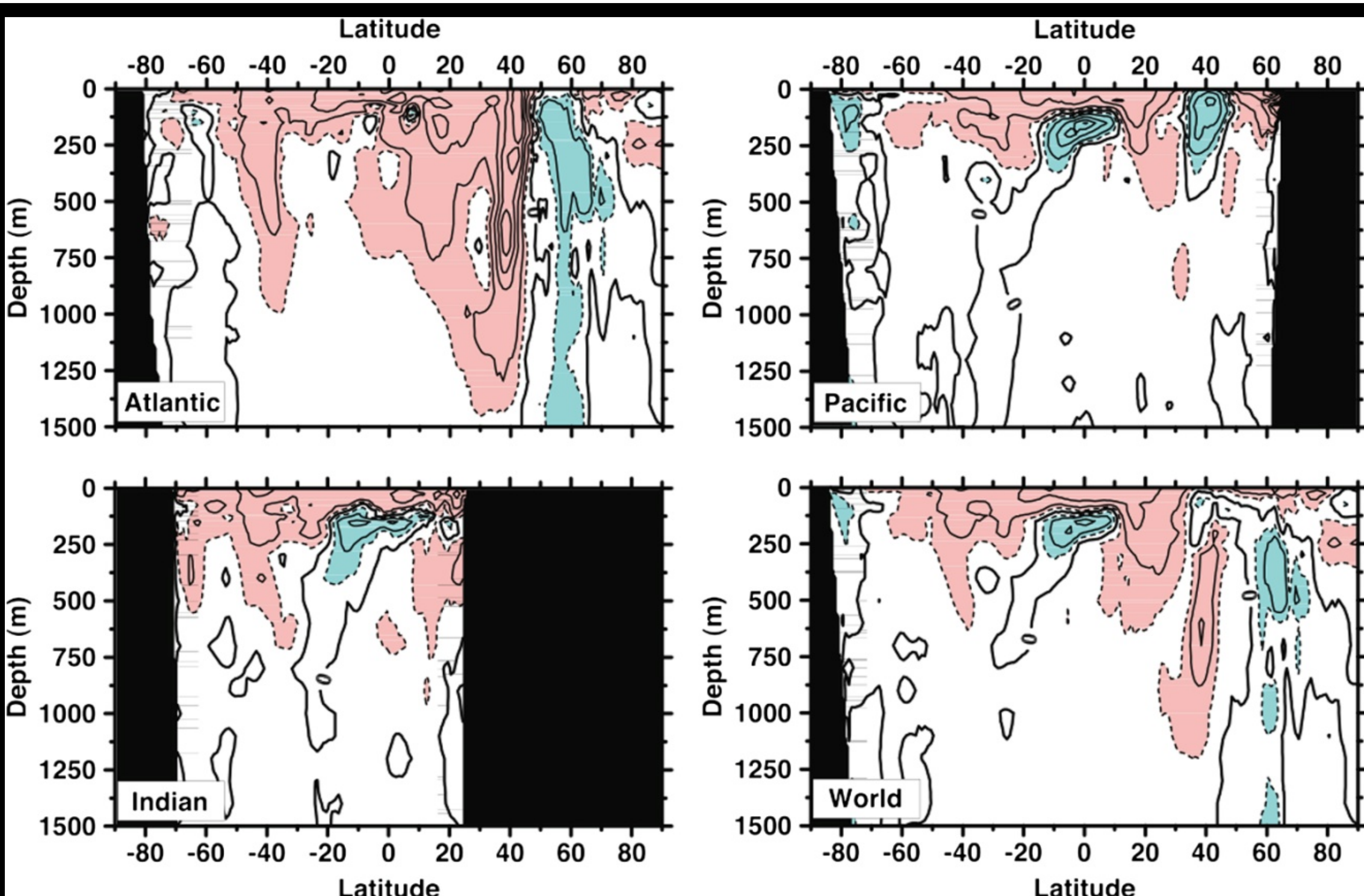


Global ocean heat content change (×10^{22} J) for the upper 0–700 m (black), 0–100 m (red), and SST change (blue). One standard deviation of error is indicated in gray (for 0–700 m) and thin red lines (for 0–100 m). The optical thickness of the stratosphere is indicated at the bottom,
with three major volcanoes labeled.*Source: From Domingues et al. (2008).*

FIGURE S15.17

The ocean is taking up most of the heat going into the climate system





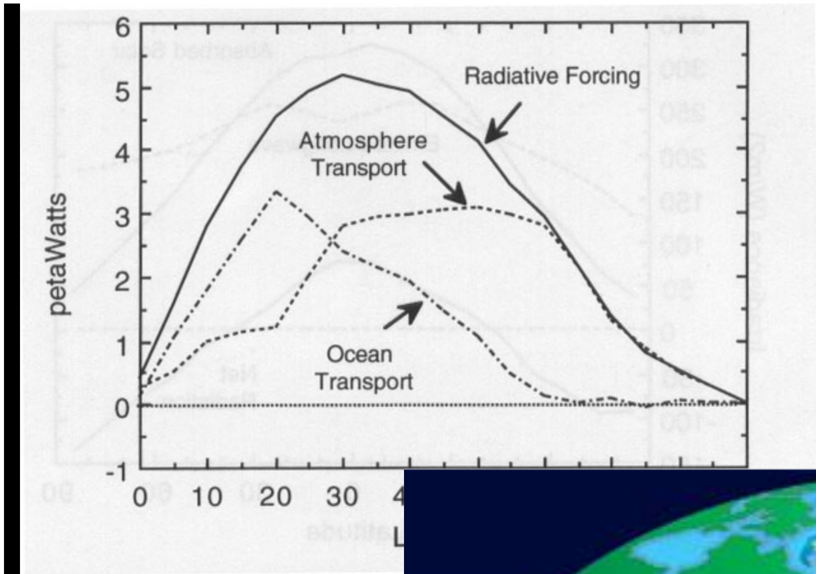
Zonally averaged linear temperature trend for 1955 to 2003 (contour interval of 0.05°C per decade) for the world ocean. Pink: increasing trend. Blue: decreasing trend. *Source: From the IPCC AR4, Bindoff et al., 2007; Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 5.3. Cambridge University Press.*

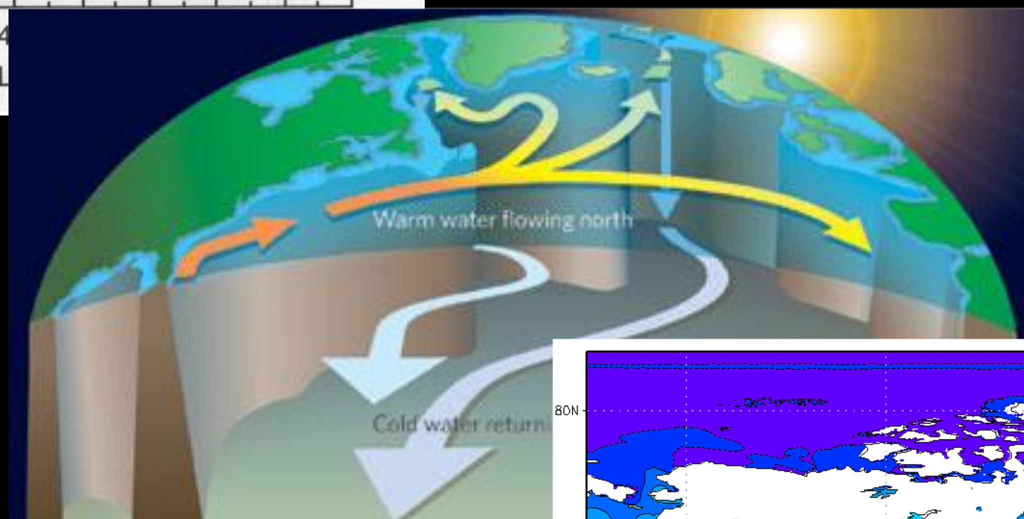
TALLEY

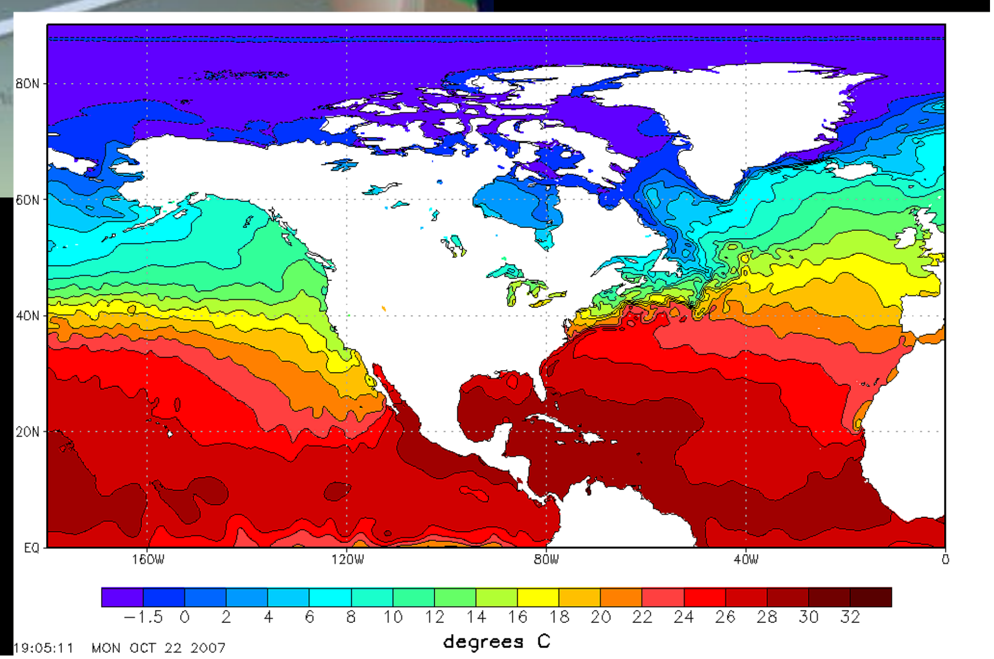
FIGURE S15.19

How else is the ocean responding to warming?

Change to ocean northward heat flux?

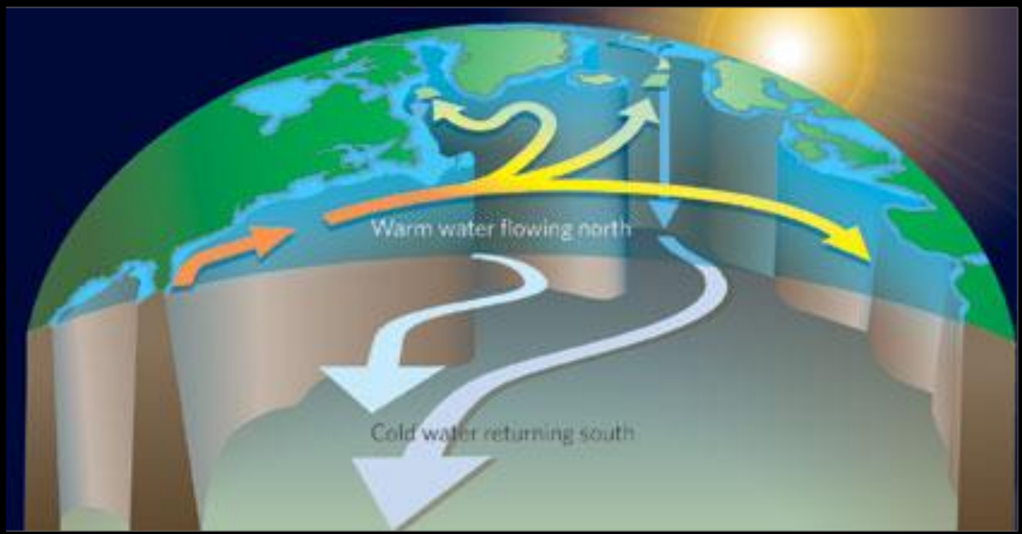






Warming to cause ice age?

Slowing of the Atlantic meridional overturning circulation at 25° N, Bryden et al. 2005 (Nature)



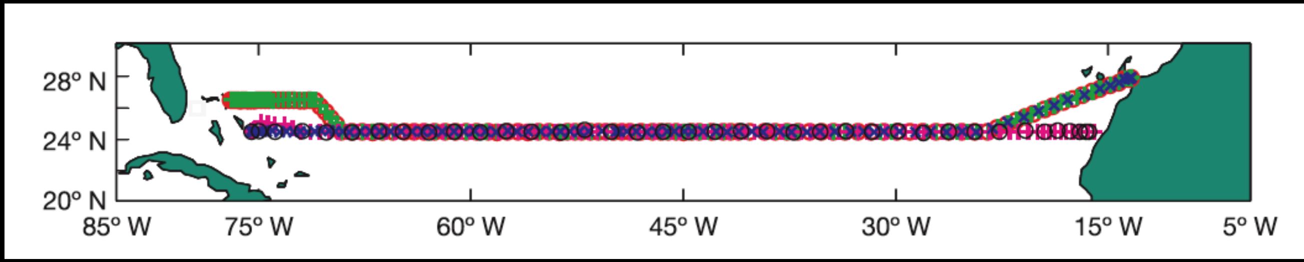
"the Atlantic meridional overturning circulation has slowed by about 30 per cent between 1957 and 2004."

<u>22.9 Sv in 1957 to 14.8 Sv in 2004</u>

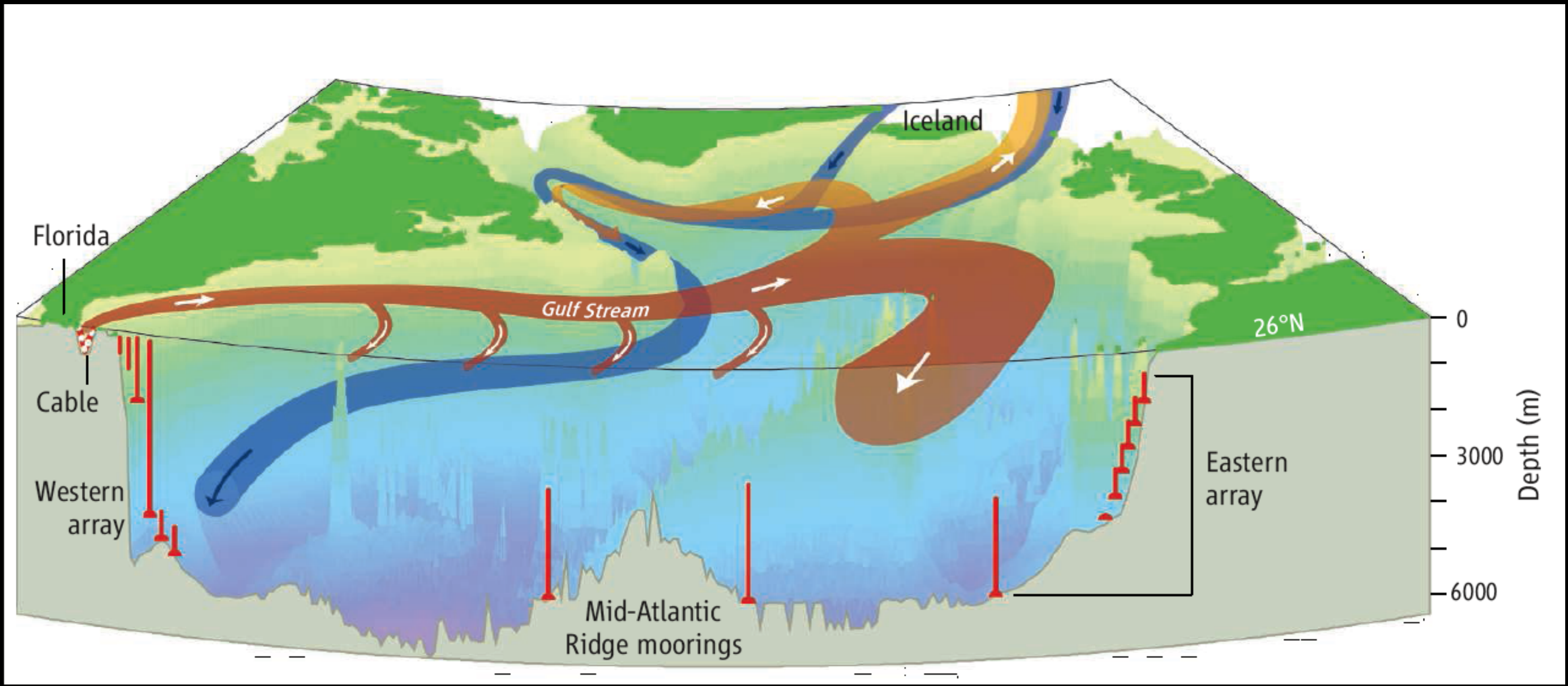
1 Sv = 10^6 m^3/s

Is the data sufficient?

Once in each of 1957, 1981, 1992, 1998, 2004



Temporal variability of the Atlantic Meridional Overturning Circulation at 26.5° N,
Cunningham et al. 2007 (Nature)

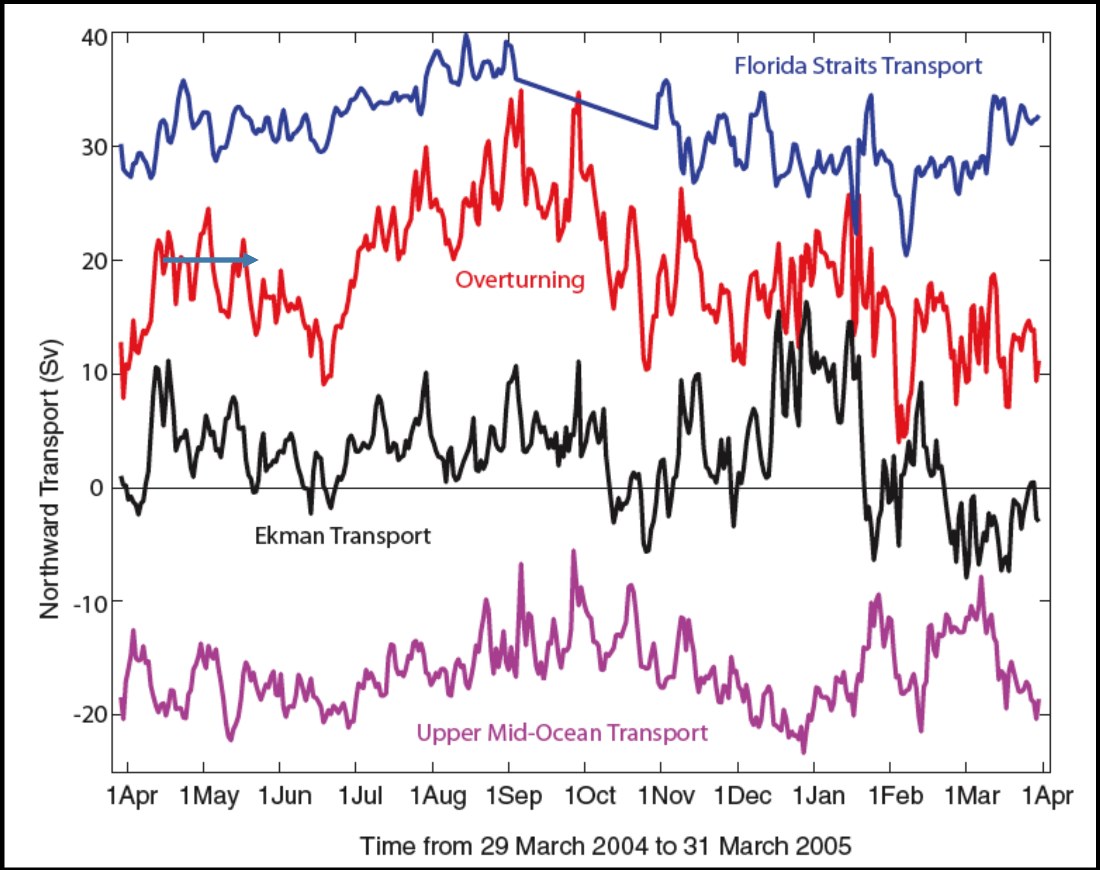


Temporal variability of the Atlantic Meridional Overturning Circulation at 26.5° N, Cunningham et al. 2007 (Nature)

Overturning varies from 4.0 to 34.9 Sv in 1 year!

Previously-reported trends are not clear

Now believe need 20-30 years of continuous observation to detect a trend



Oceans and heat

- Oceans store and move a lot of heat

- Oceans warming with global warming

- Trends in equator to pole heat transport due to change in circulation?
  - Observations can’t yet distinguish trends

Oceans role in a changing world

- Oceans significantly damp global surface temperature rise driven by the anthropogenically-enhanced greenhouse effect by
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Carbon cycle

- Carbon and Climate
- Current questions and methods in global carbon cycling
- Ocean carbon fluxes
  - Ocean acidification
  - Flux variability and trends
  - Coastal and inland waters

Carbon Cycle outline

- Carbon and Climate
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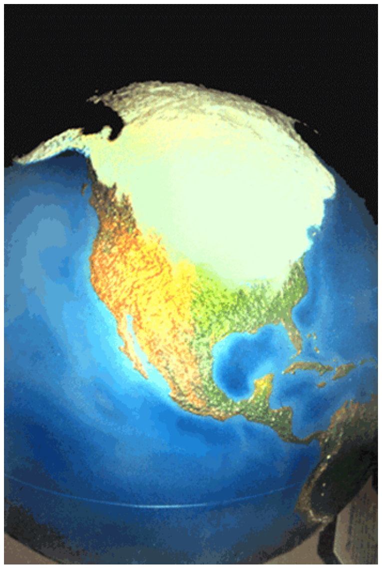
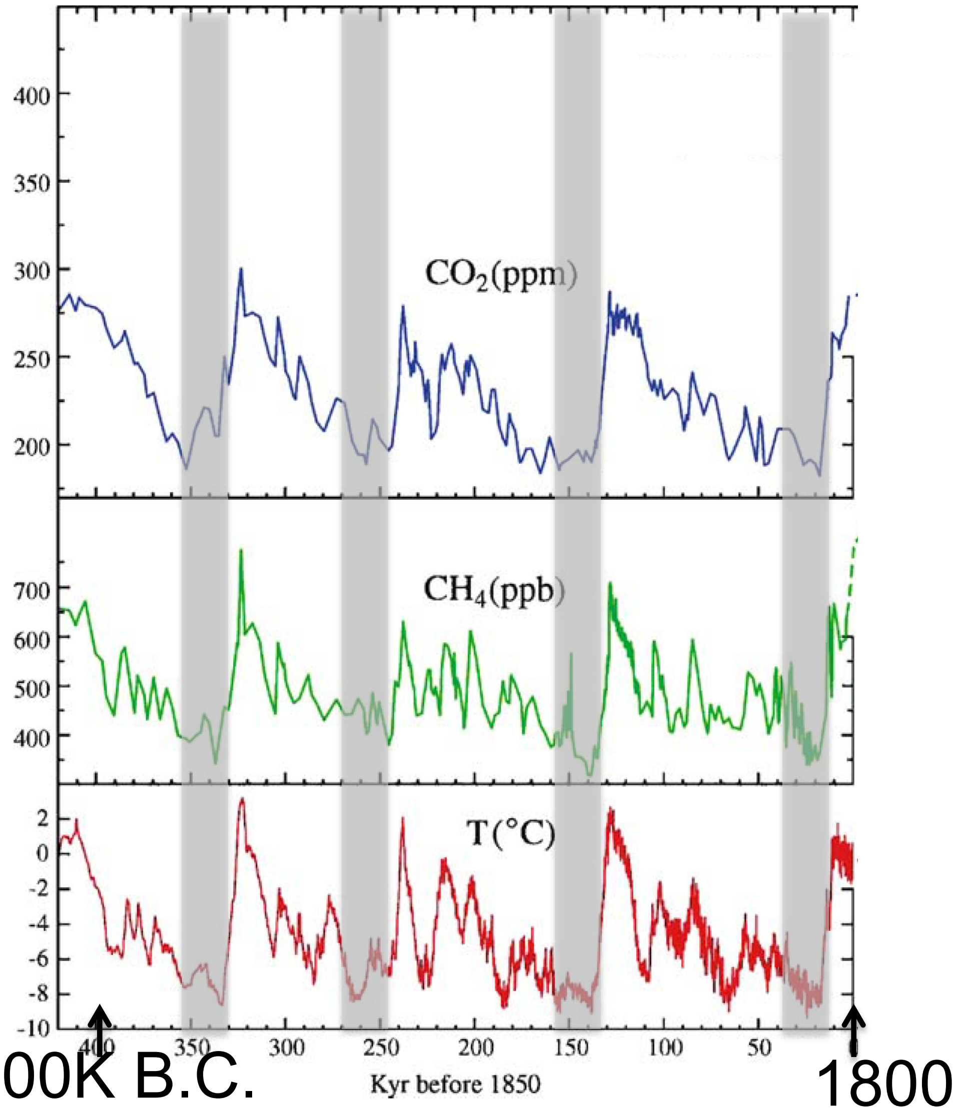
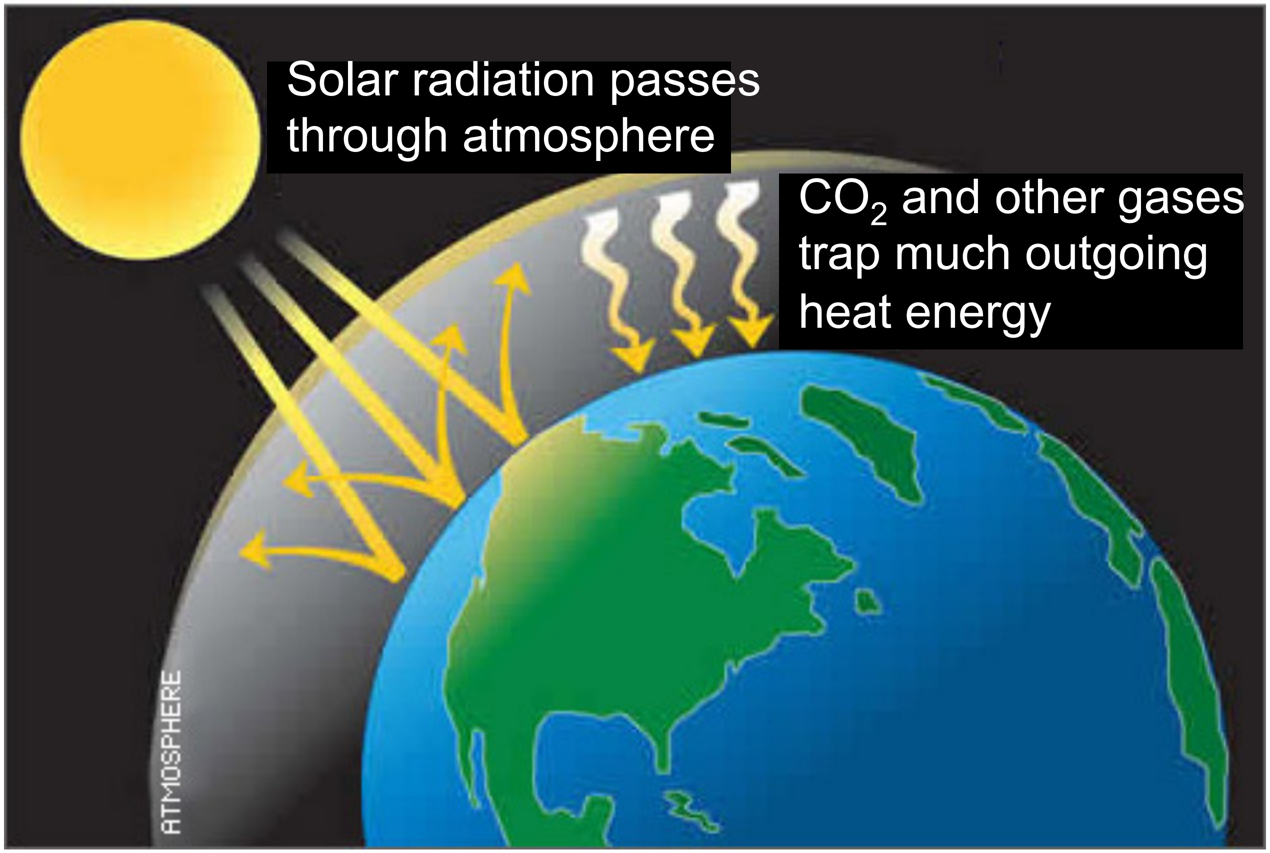
Carbon and Climate are linked through the ages



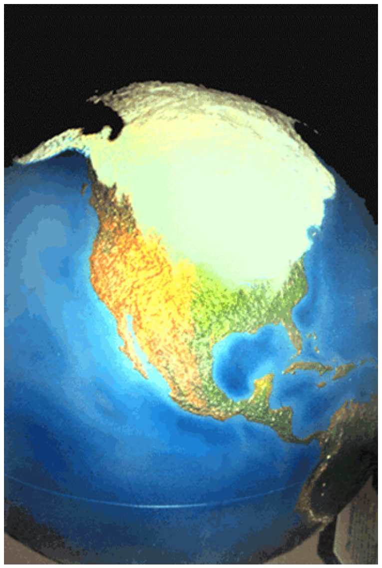
At glacial maxima



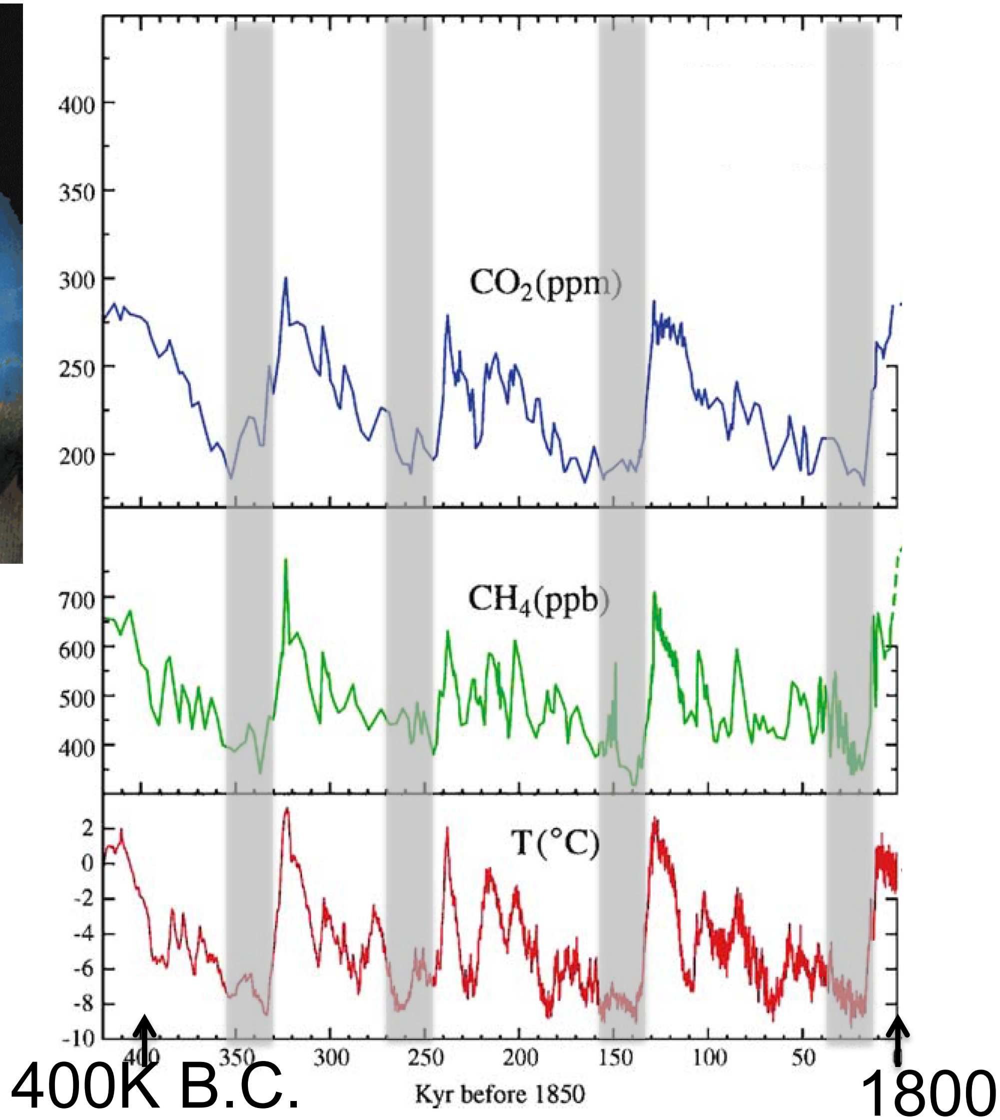
Greenhouse Effect



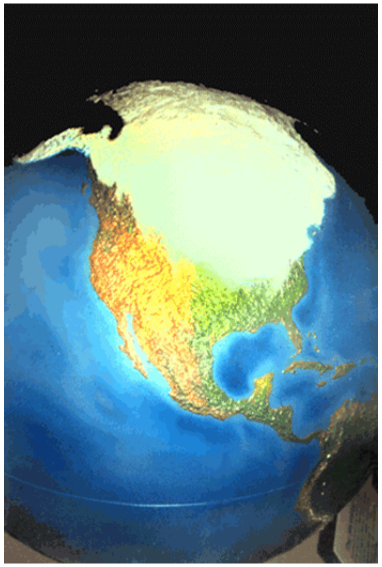
Carbon and Climate are linked through the ages



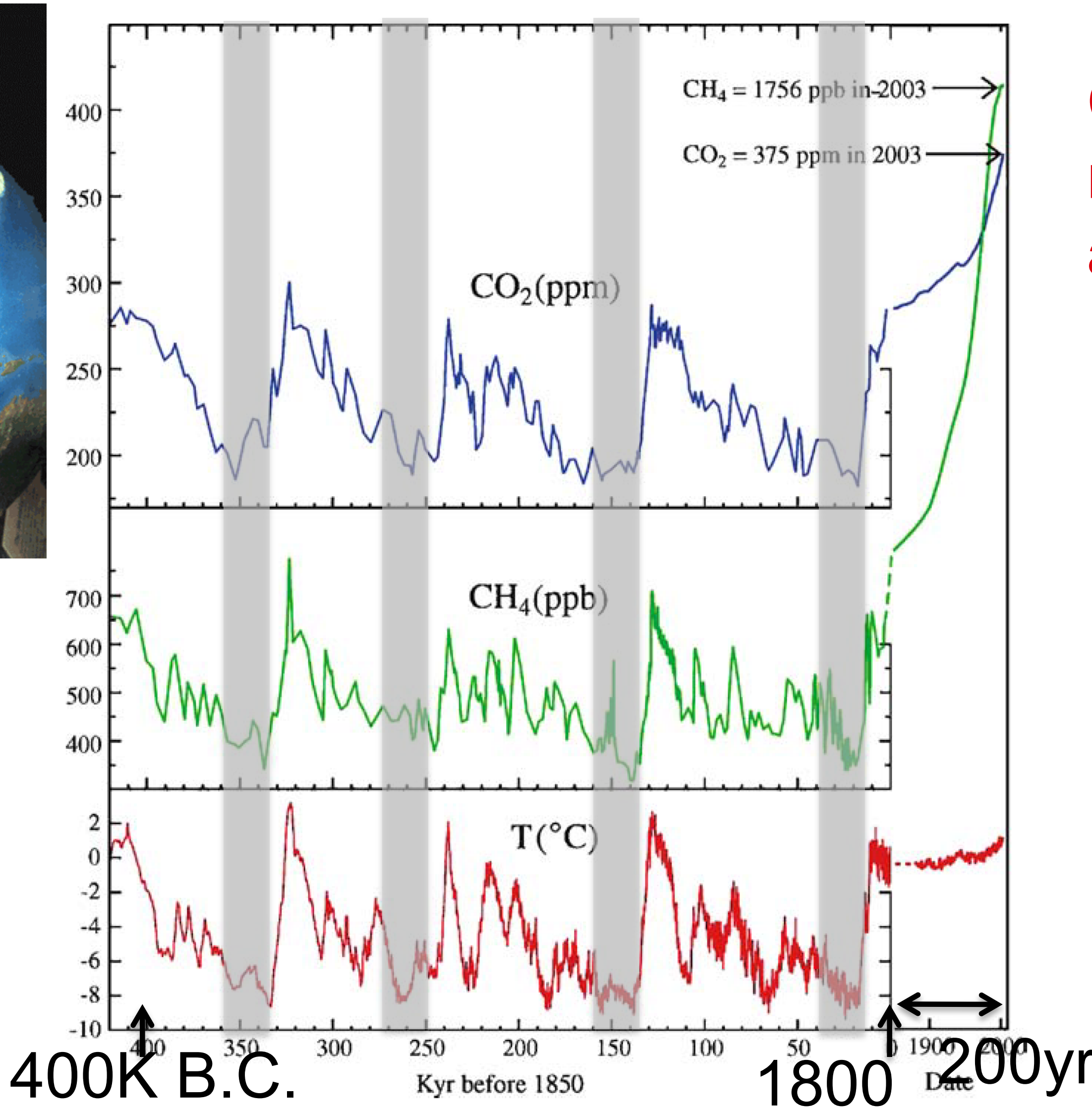
At glacial maxima



Carbon and Climate are linked through the ages



At glacial maxima

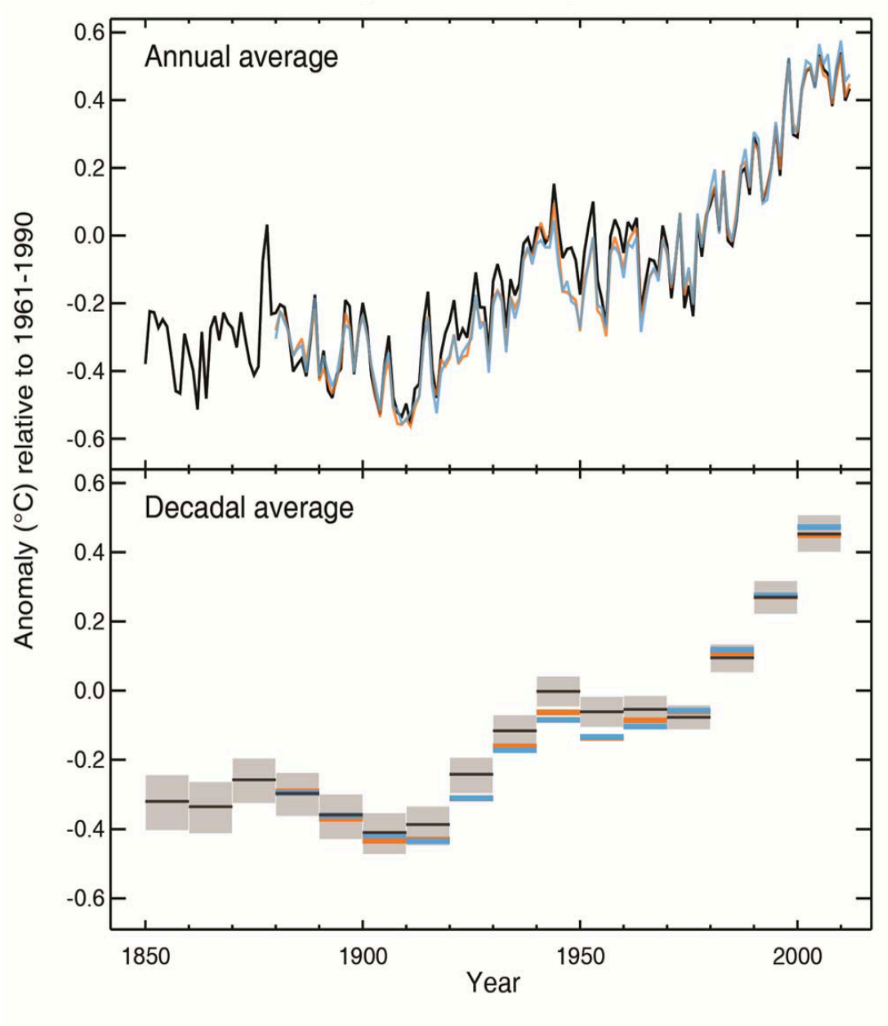


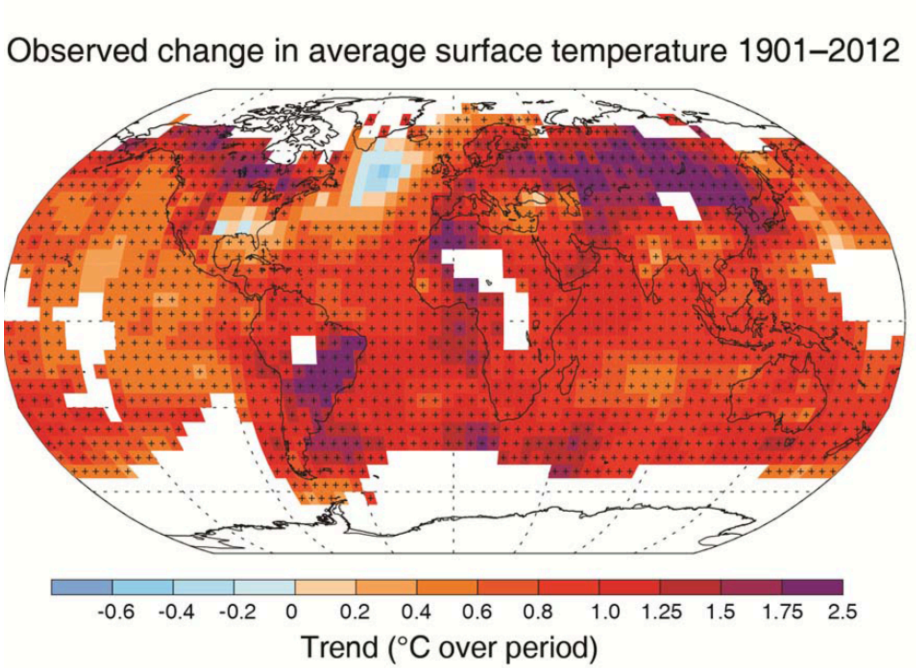
Current modifications are huge

Warming

"The globally averaged combined land and ocean surface temperature data .. show a warming of 0.85 [0.65 to 1.06]°C, over the period 1880–2012" IPCC AR5 WG1 2013

Global Temperature Anomaly 1850-2012





IPCC AR5 WG1 Figure SPM.1

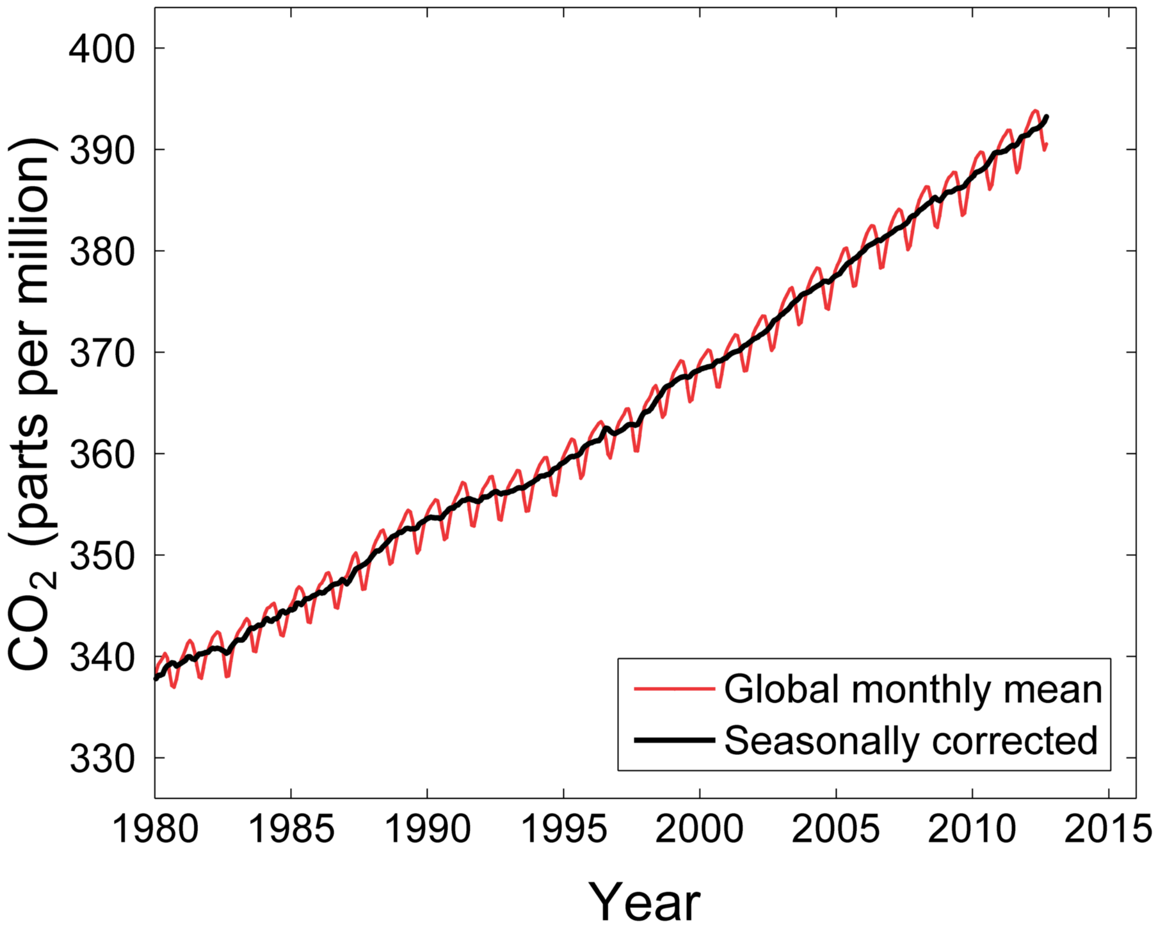
“Human influence on the climate system is clear.

This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system.”

IPCC AR5 WG1 2013

Atmospheric Concentration 2011

The pre-industrial (1750) atmospheric concentration was 278ppm
This has increased to **390ppm in 2011**, a 40% increase.



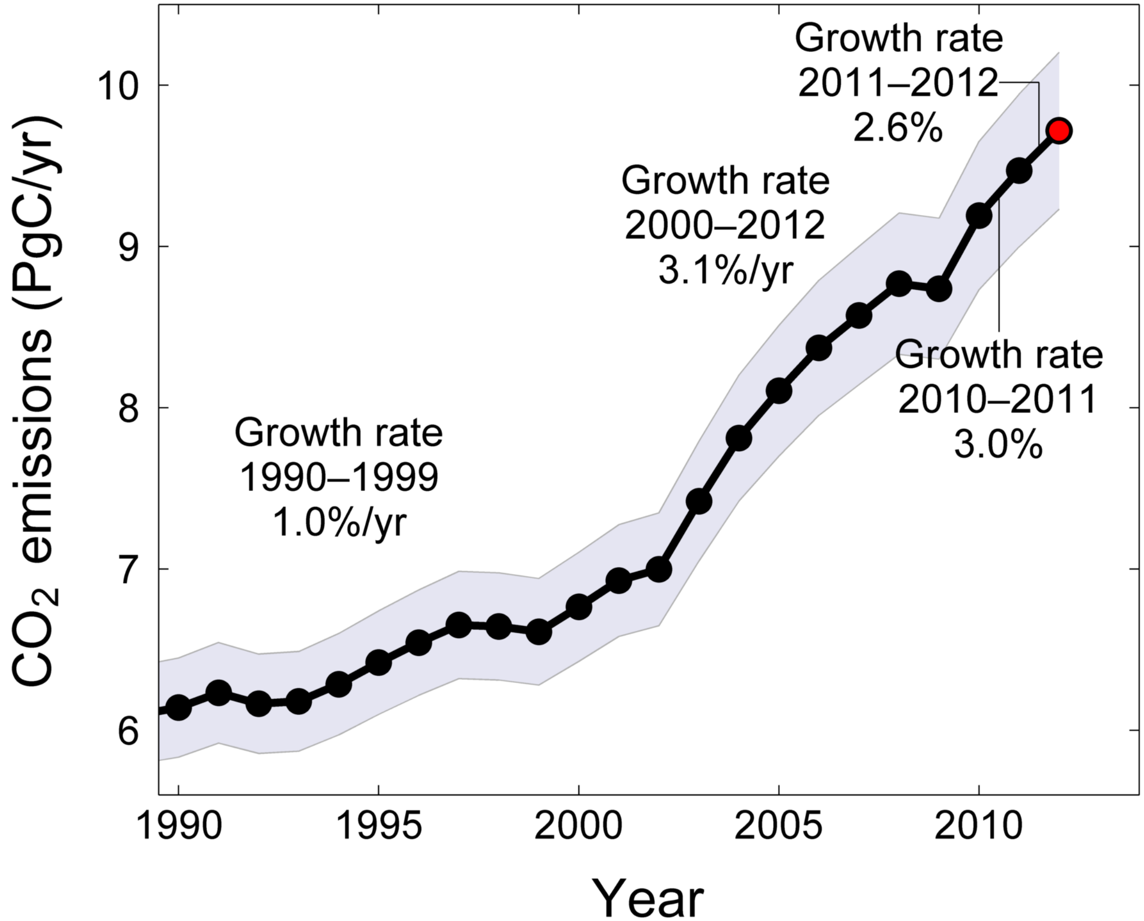
"Seasonally corrected" is a moving average of seven adjacent seasonal cycles

Source: NOAA/ESRL; Global Carbon Project 2012

Fossil and Cement Emissions 2011

Global fossil and cement emissions: 9.5±0.5PgC in 2011, 54% over 1990

Projection for 2012: 9.7±0.5PgC, 58% over 1990

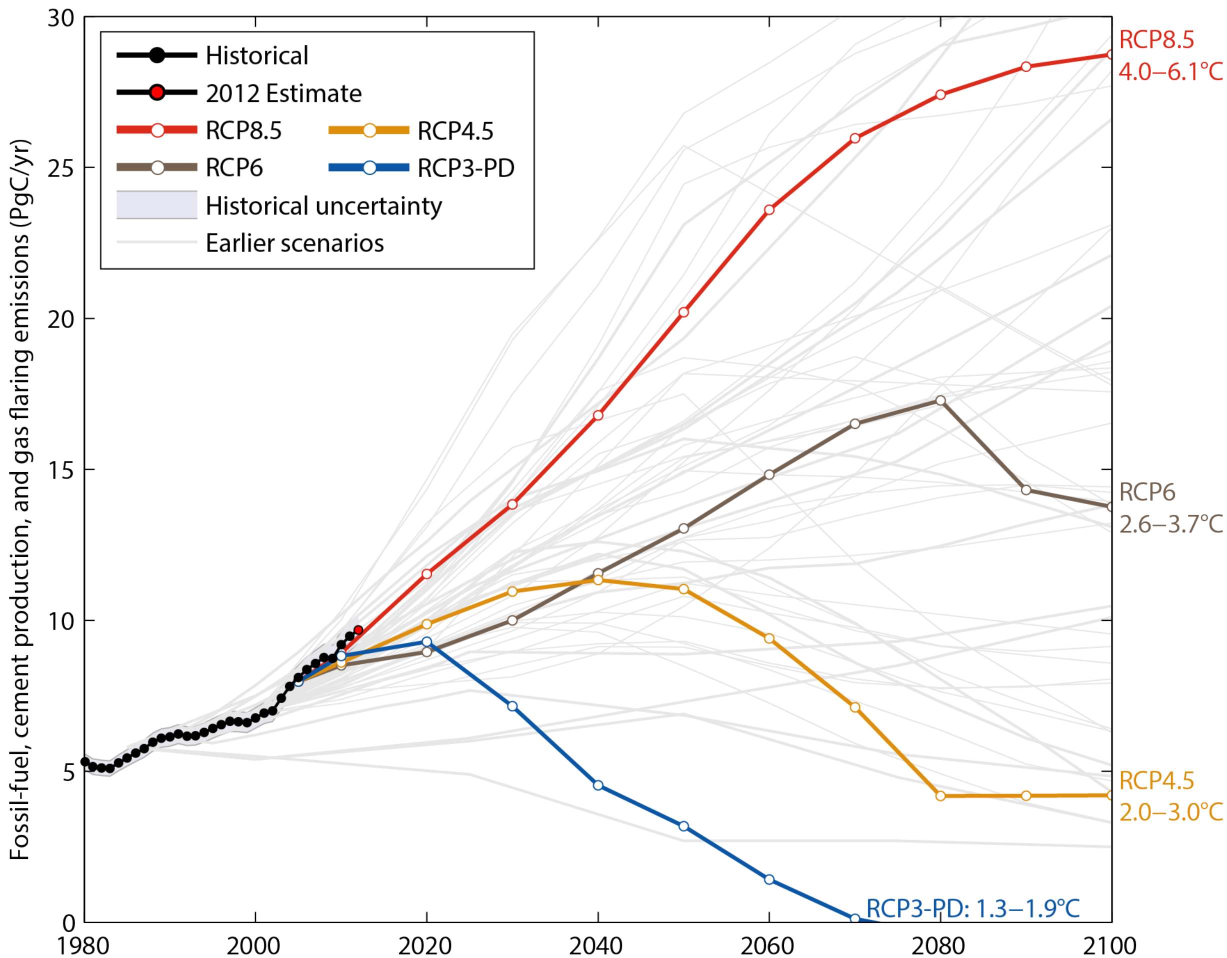


Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

Source: Peters et al. 2012a; Le Quéré et al. 2012; CDIAC Data; Global Carbon Project 2012

Observed Emissions and Emission Scenarios

Emissions are heading to a 4.0-6.1ºC “likely” increase in temperature
Large and sustained mitigation is required to keep below 2ºC

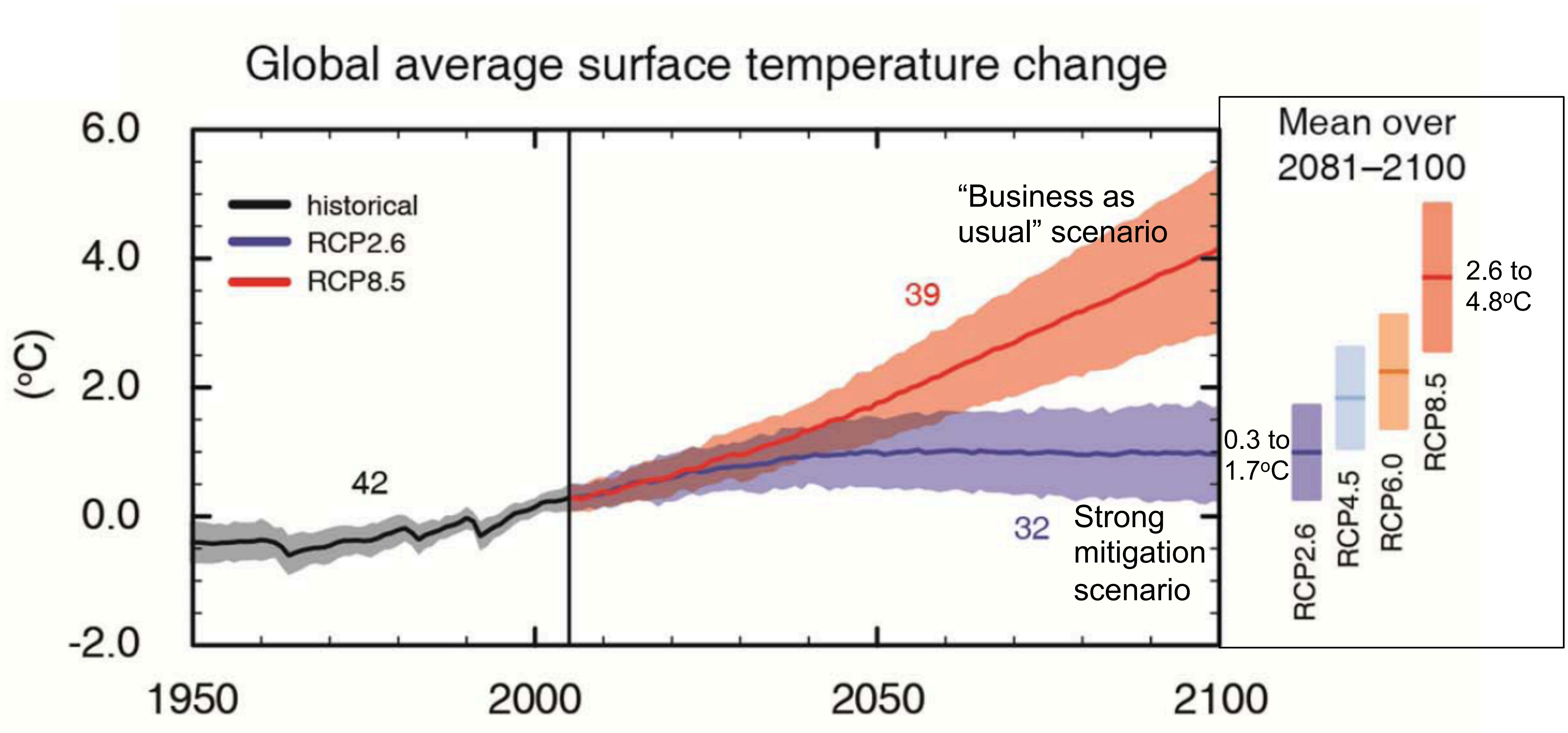


Linear interpolation is used between individual datapoints

Source: Peters et al. 2012a; Global Carbon Project 2012;

Temperature projections with climate models

changes relative to 1986-2005



IPCC AR5 WG1 Figure SPM.7, scenario labels added

"Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to *likely* be in the ranges… 0.3°C to 1.7°C (RCP2.6)… 2.6°C to 4.8°C (RCP8.5)" IPCC AR5 WG1 2013

Fate of Anthropogenic CO_2 Emissions (2002-2011 average)

8.3±0.4 PgC/yr 90%

1.0±0.5 PgC/yr 10%

+

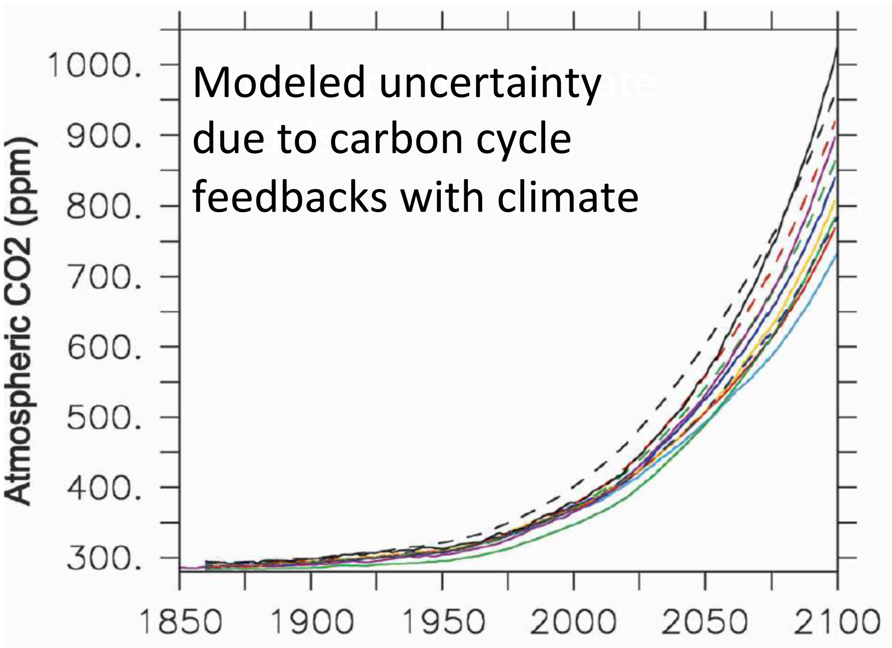
4.3±0.1 PgC/yr
46%

2.6±0.8 PgC/yr
28%
Calculated as the residual of all other flux components

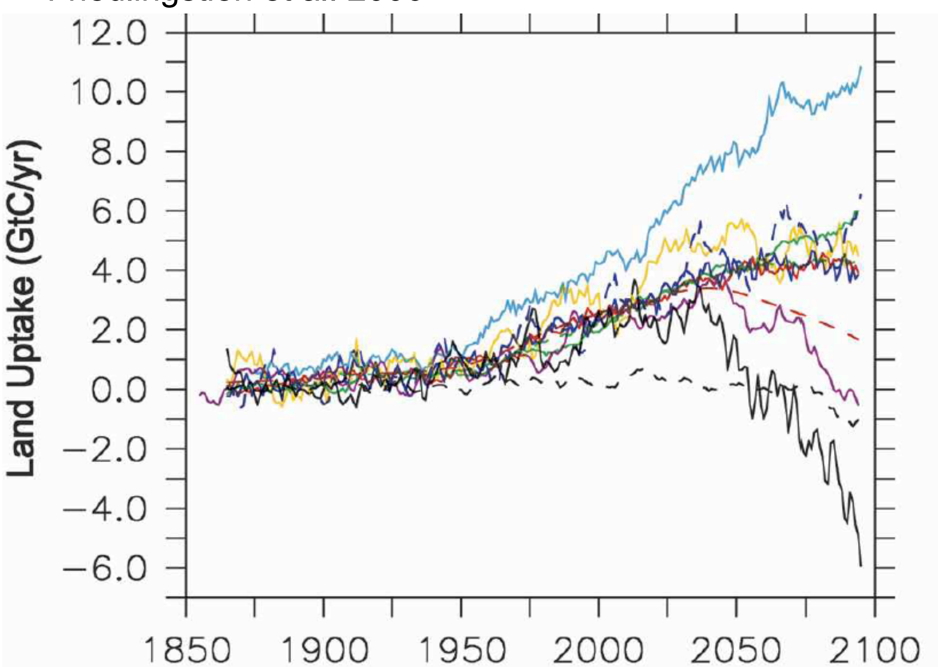
26%
2.5±0.5 PgC/yr

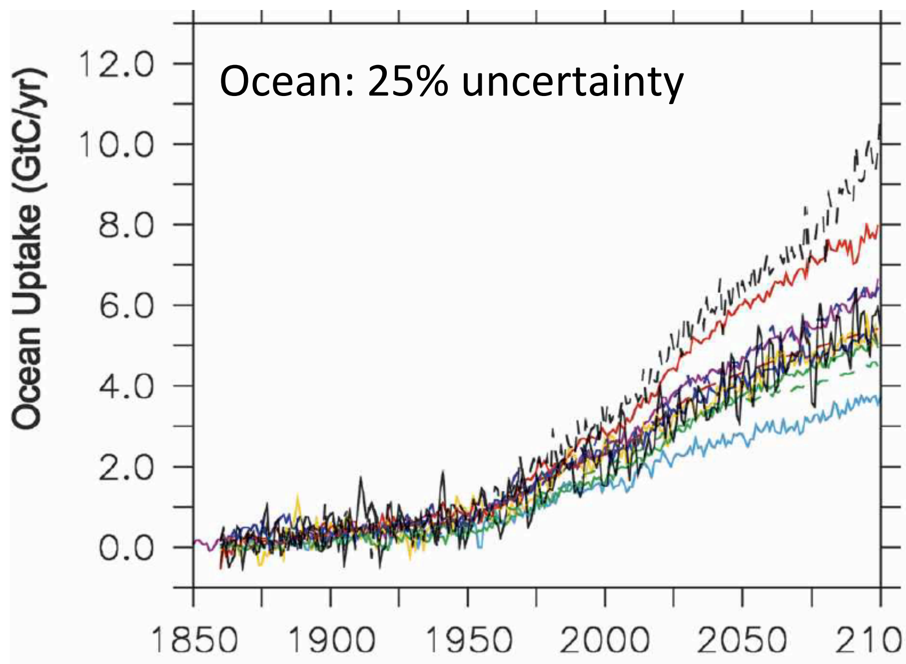
Source: Le Quéré et al. 2012; Global Carbon Project 2012

Future atmospheric CO_2?



Friedlingstien et al. 2006





Carbon cycle outline

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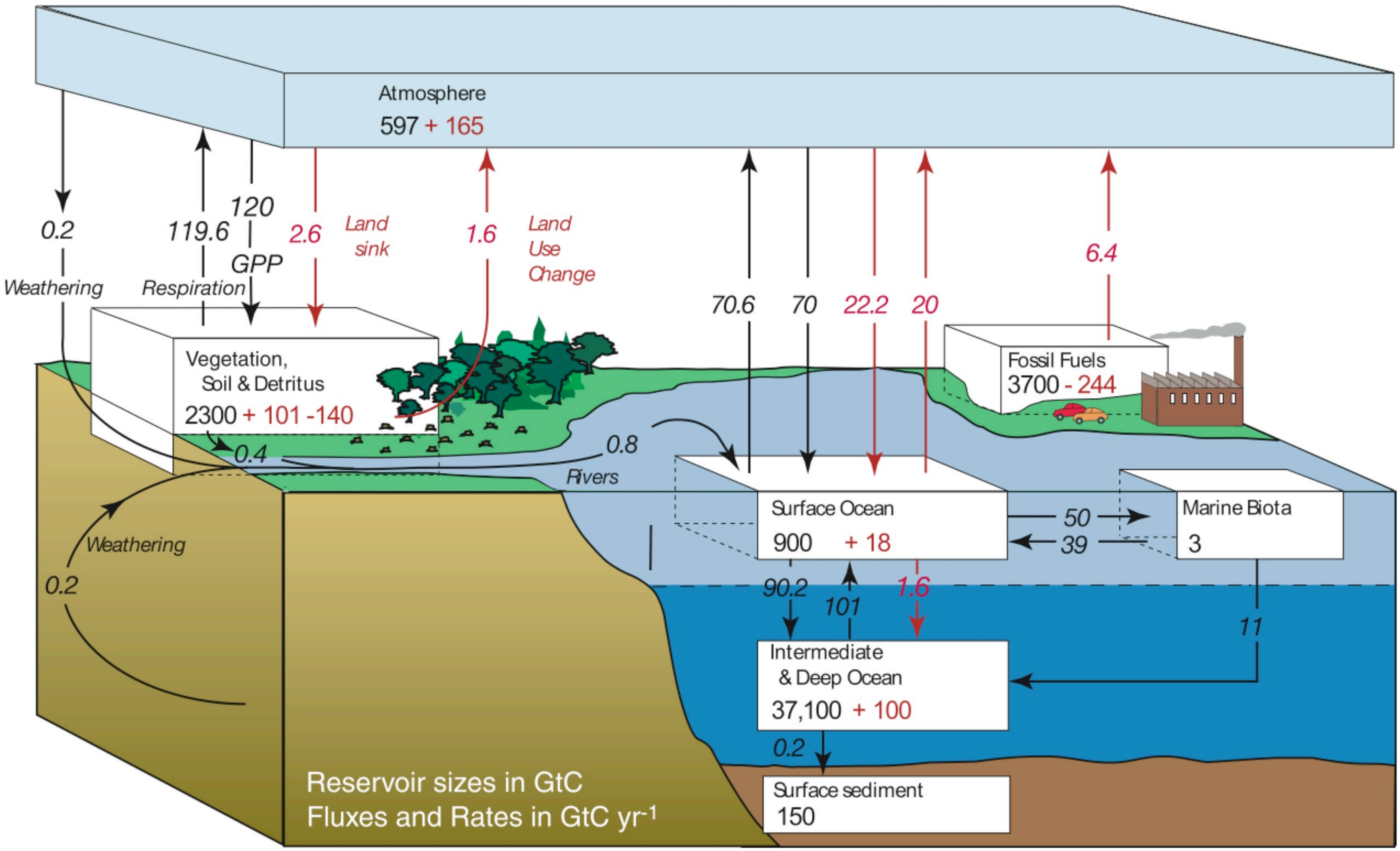
Current questions driving carbon cycle research

- Quantification of fluxes?
  - Can we observe change?
- Mechanisms of natural carbon cycling?
  - Response to changing climate?
- Can we verify carbon treaties?

The global carbon cycle



Some processes fast (month-yr), others thousands of years

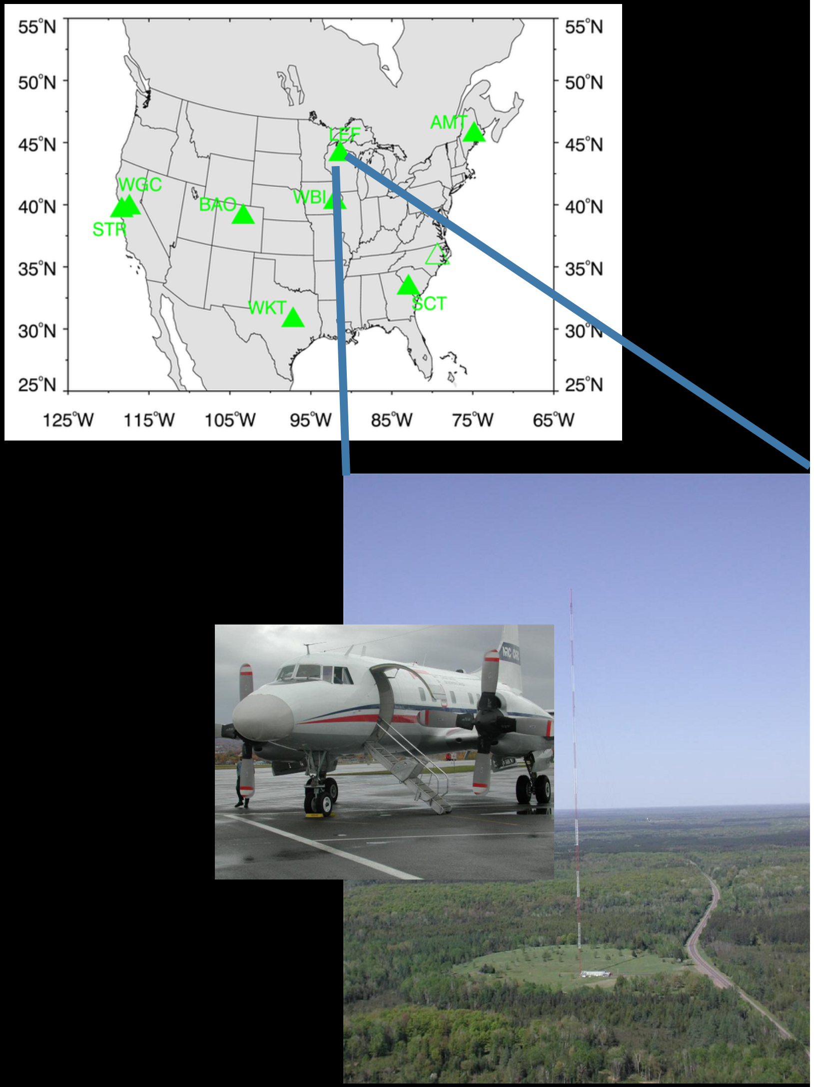
On average, CO_2 lifetime in atmosphere = 100 yrs+

Figure 7.3

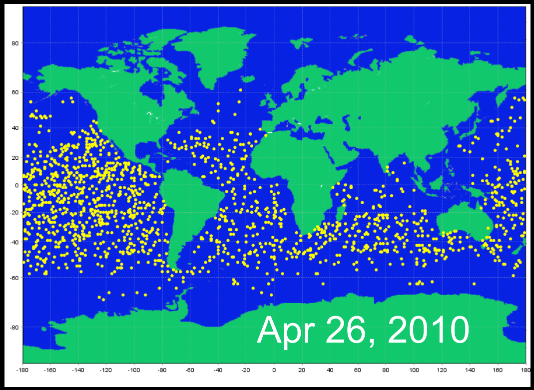
Direct Observations

Survey Cruises, Volunteer Ships

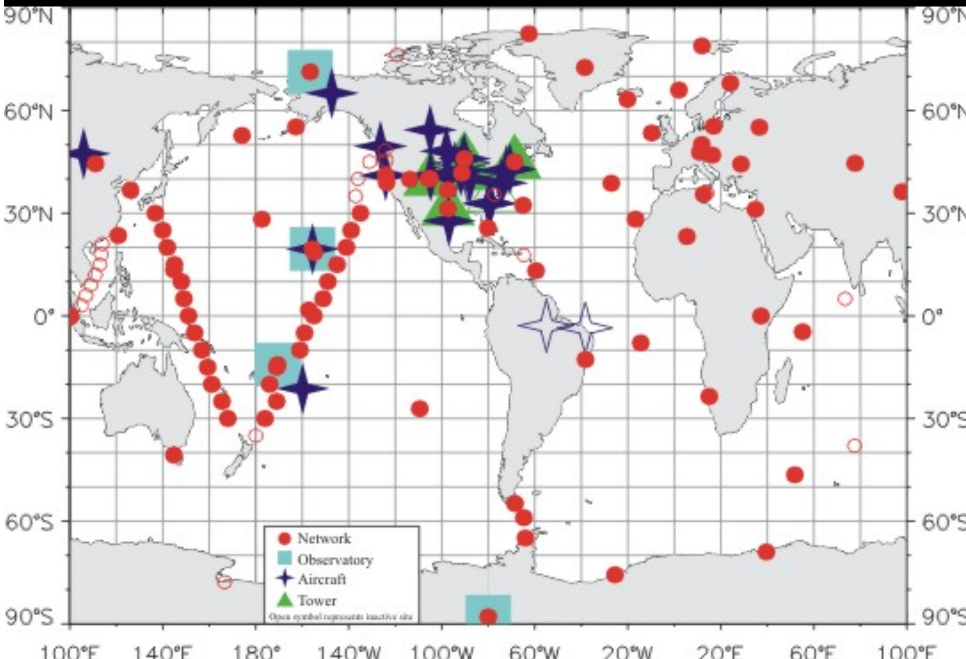
In-situ observations

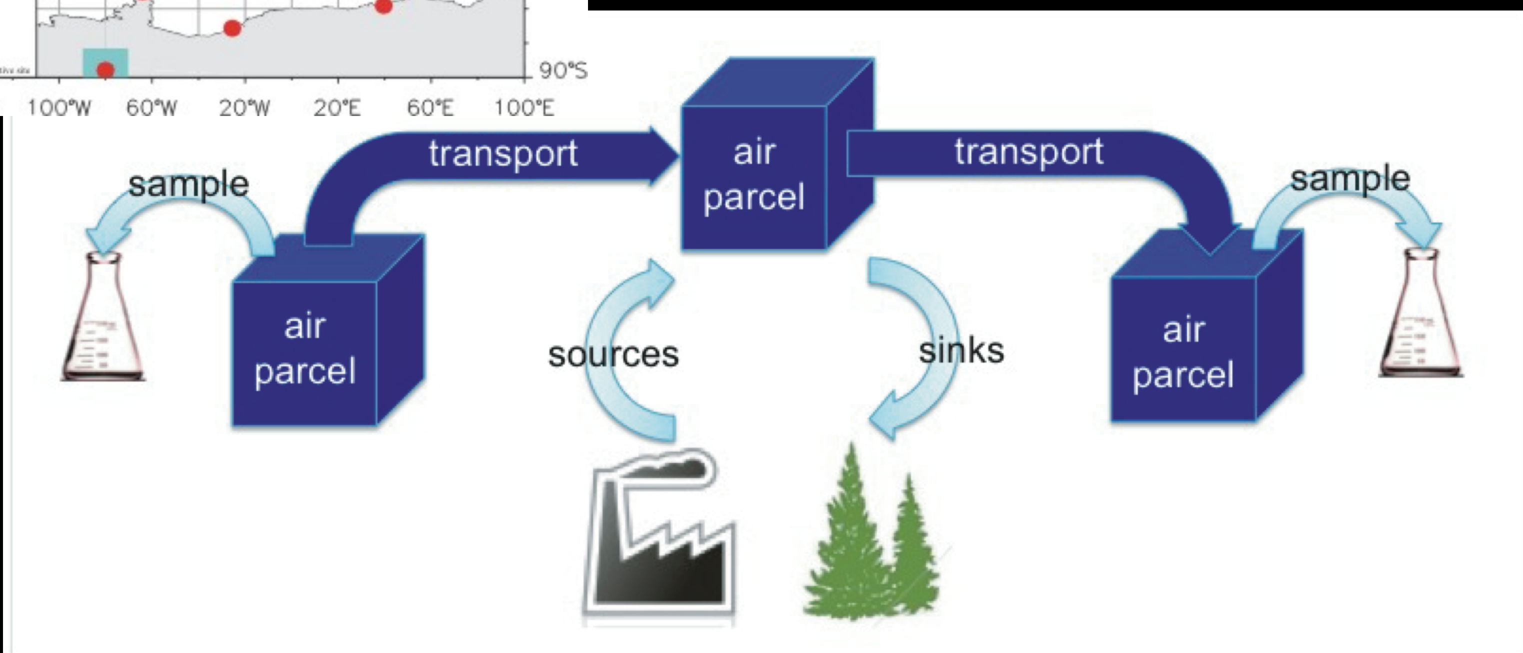


Autonomous

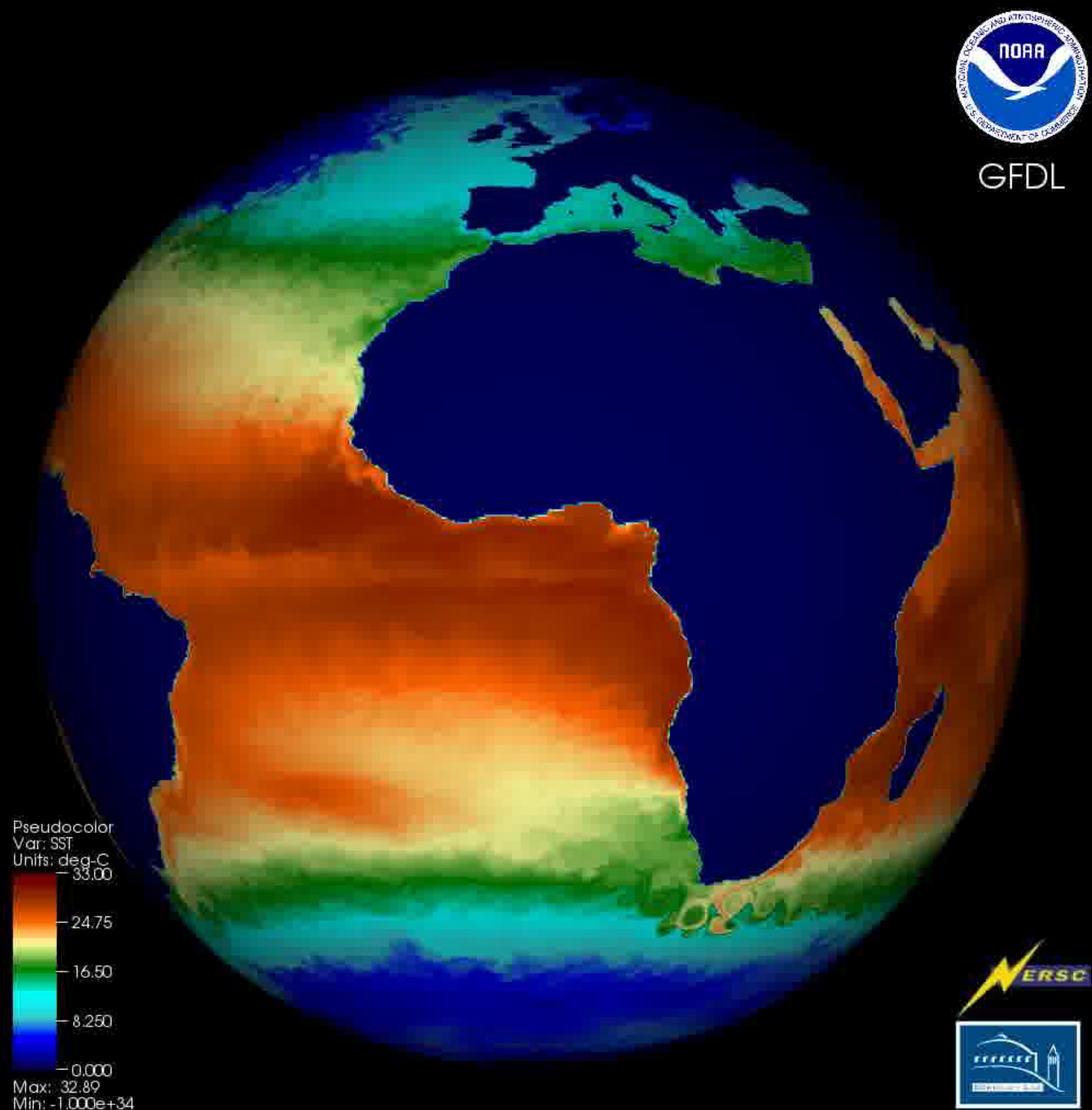


Atmospheric Data + Reverse Transport = Inverse Model for surface CO_2 flux





Forward Models = Numerical codes for Physical - Chemical - Biological interactions



+ biology + chemistry = Carbon Cycle

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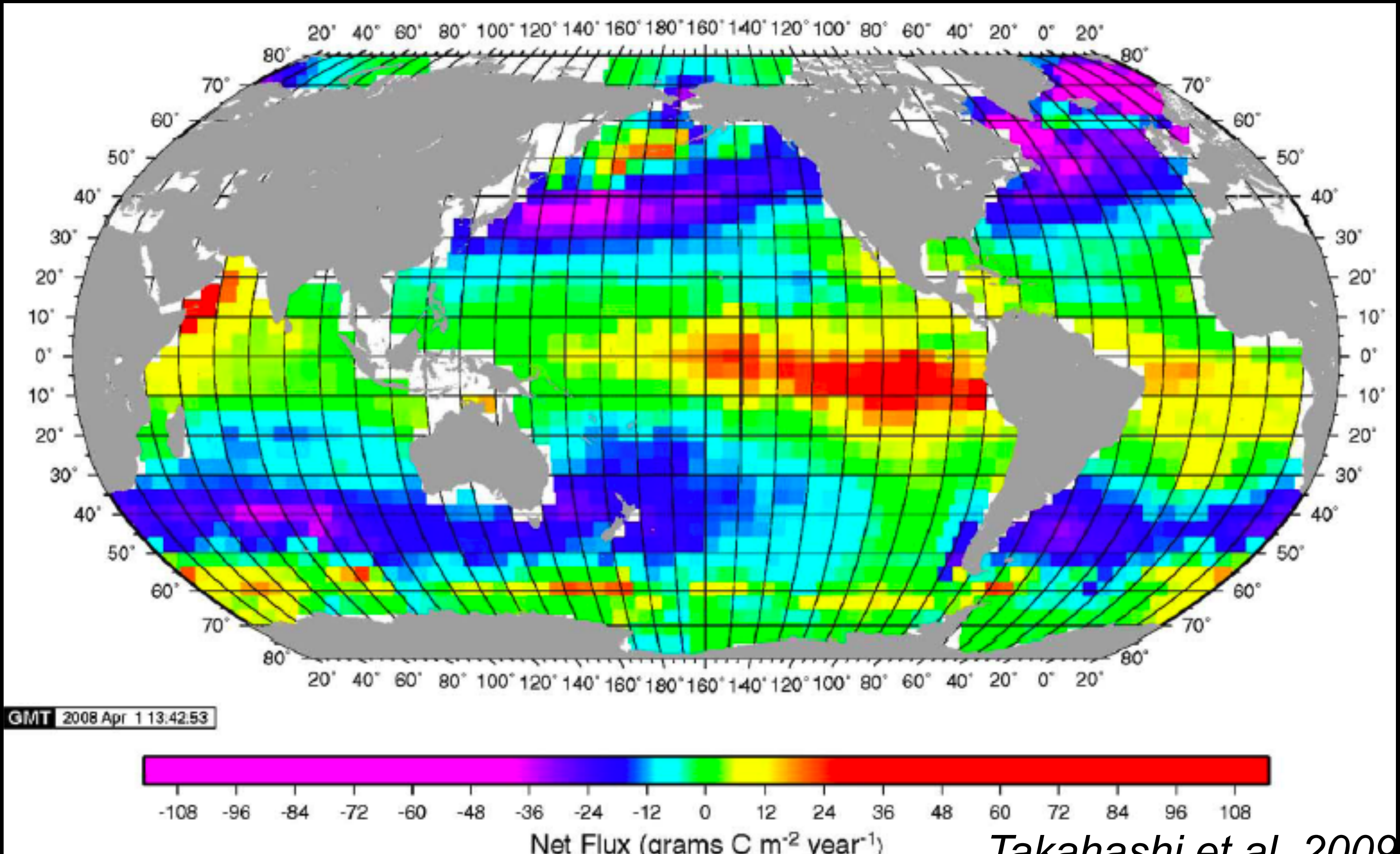
Mean sea-to-air carbon flux
CO_2 flux α ($pCO_2^{atm} - pCO_2^{s.ocean}$)

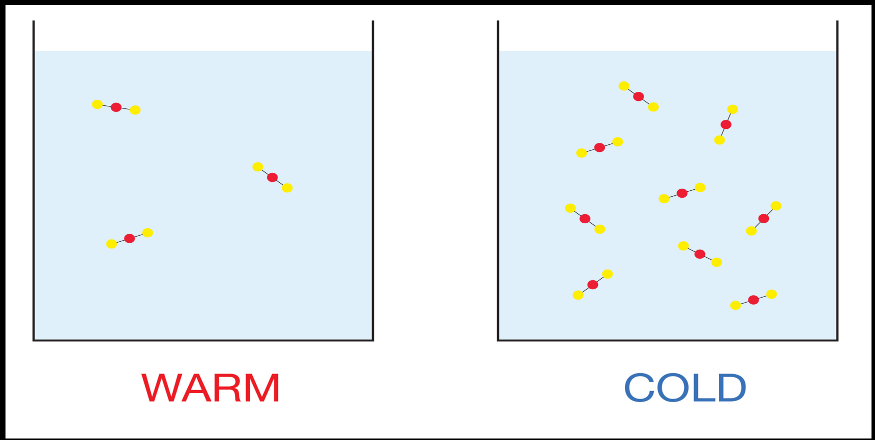


Takahashi et al. 2009

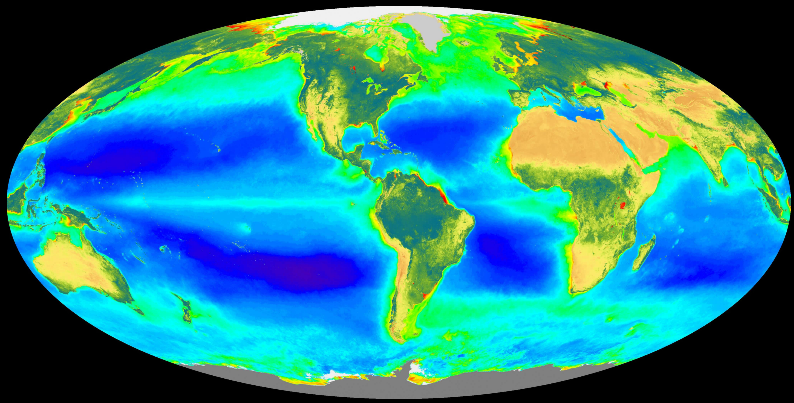
- Pattern dominated by $pCO_2^{s.ocean}$

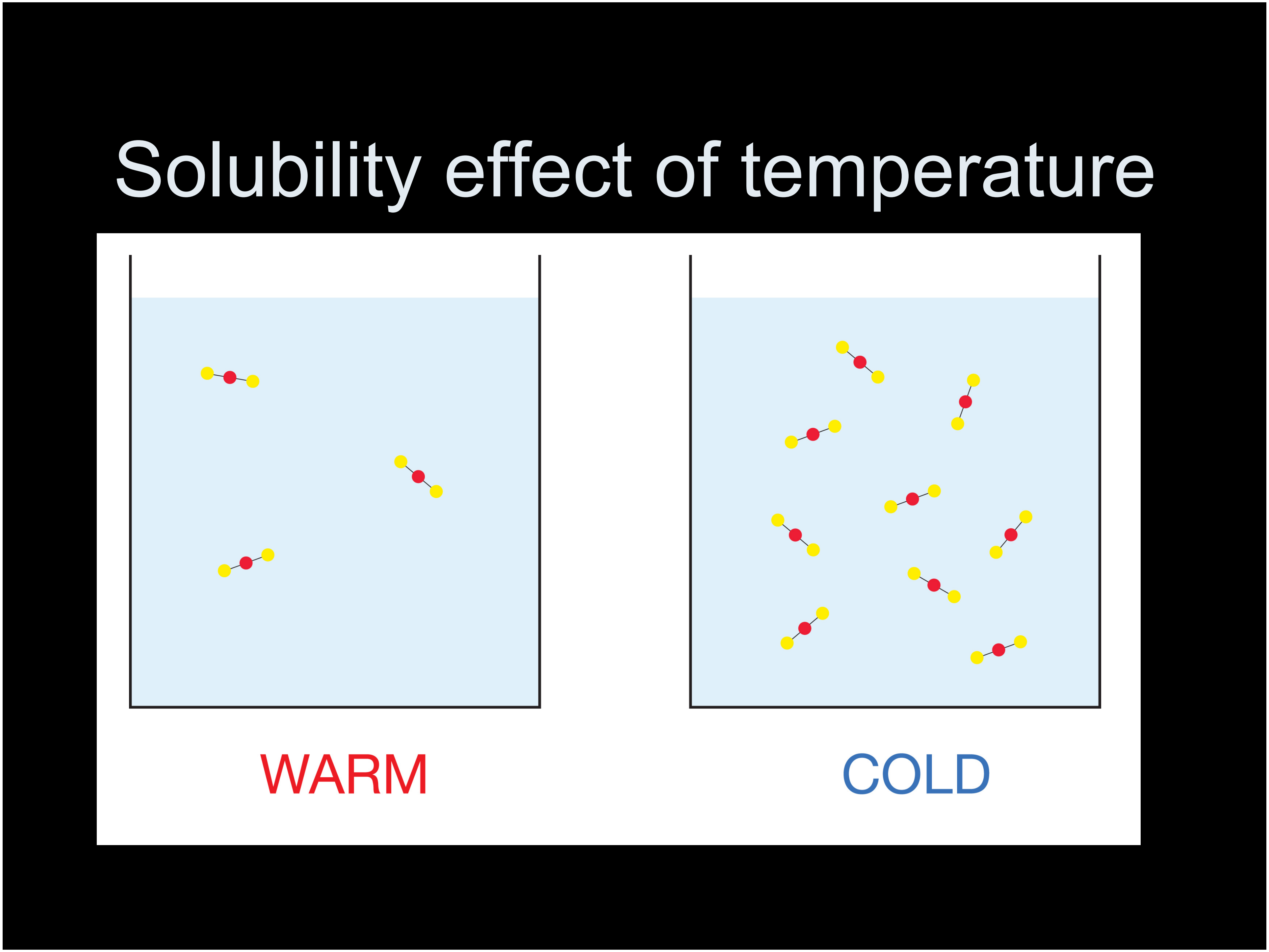
Air-sea CO_2 fluxes caused by

- Solubility effects

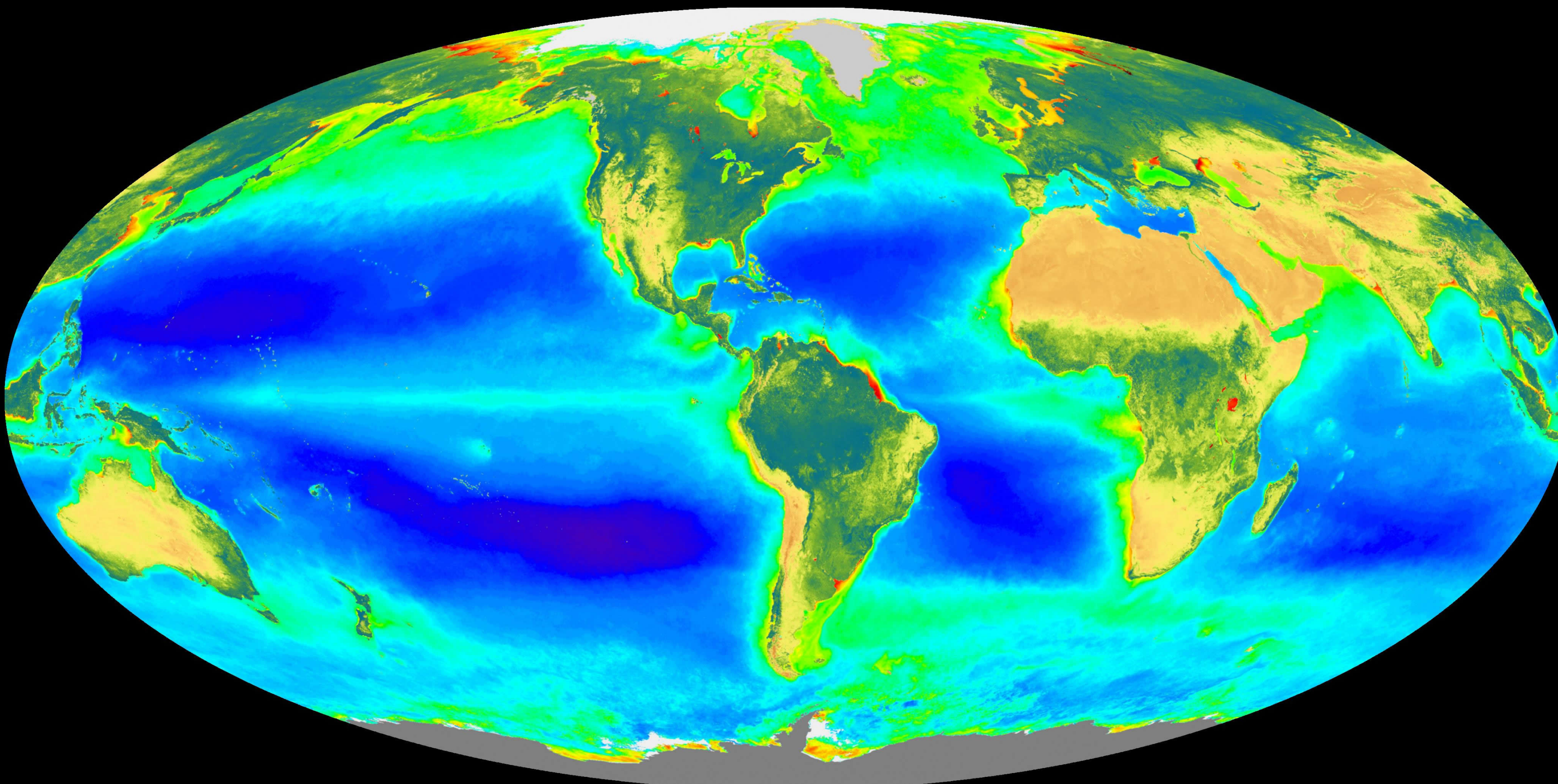


- Biological effects

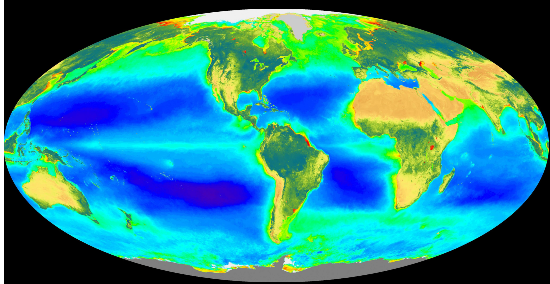


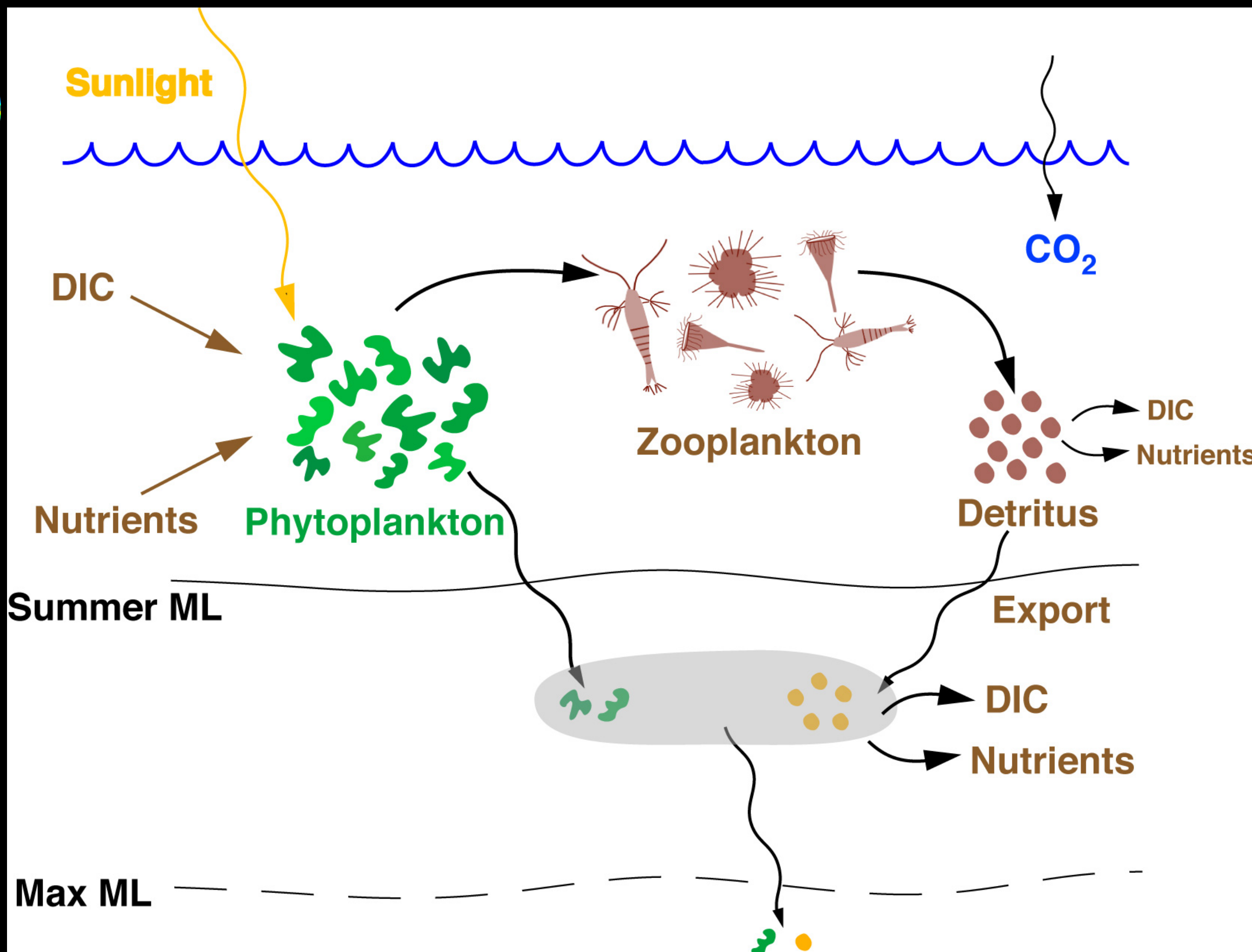

Solubility effect of temperature
WARM
COLD

Biological effect

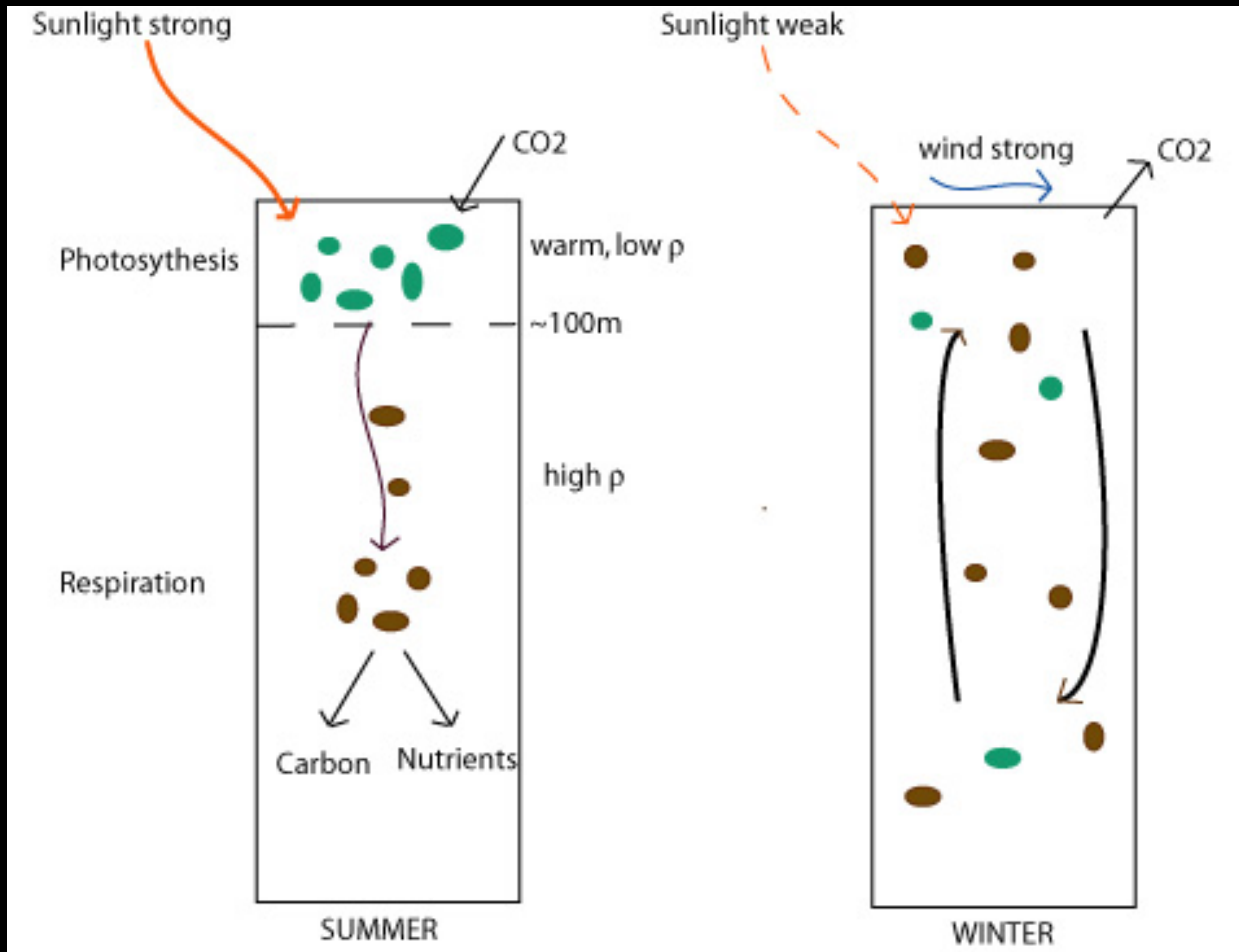


Biological effect

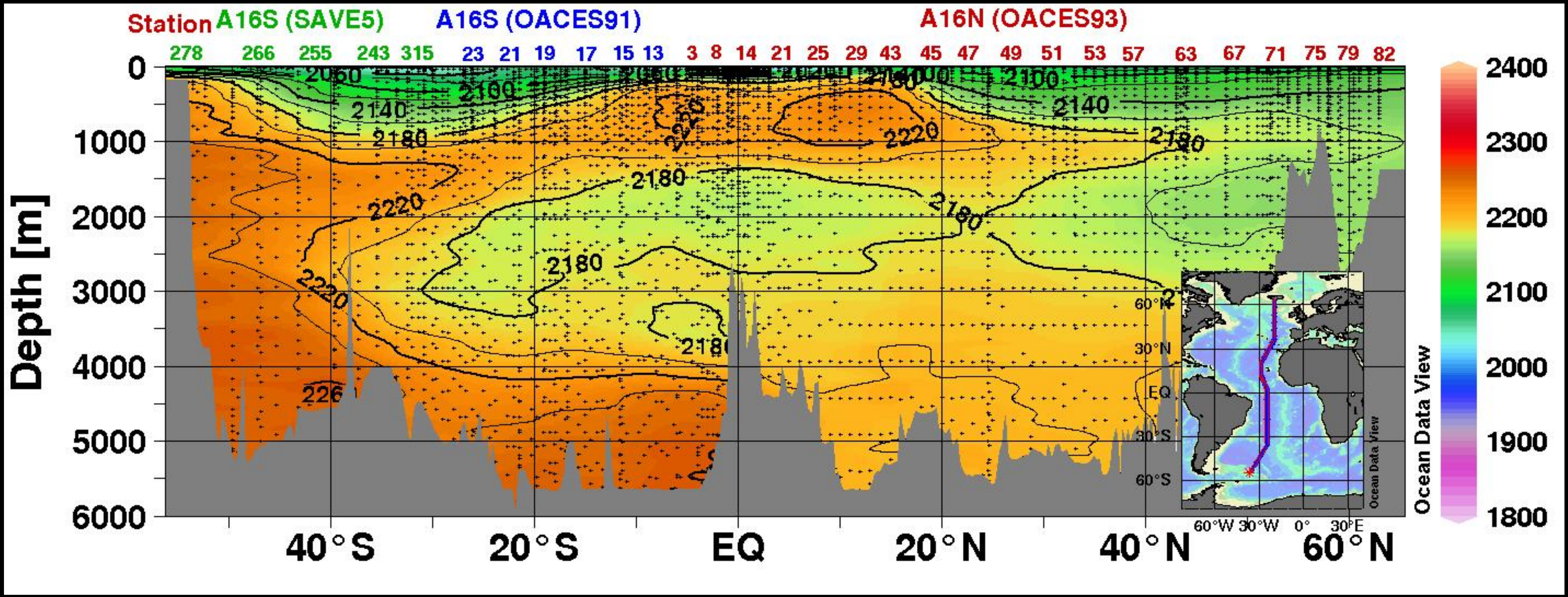




Seasonal cycle due to convection and biology

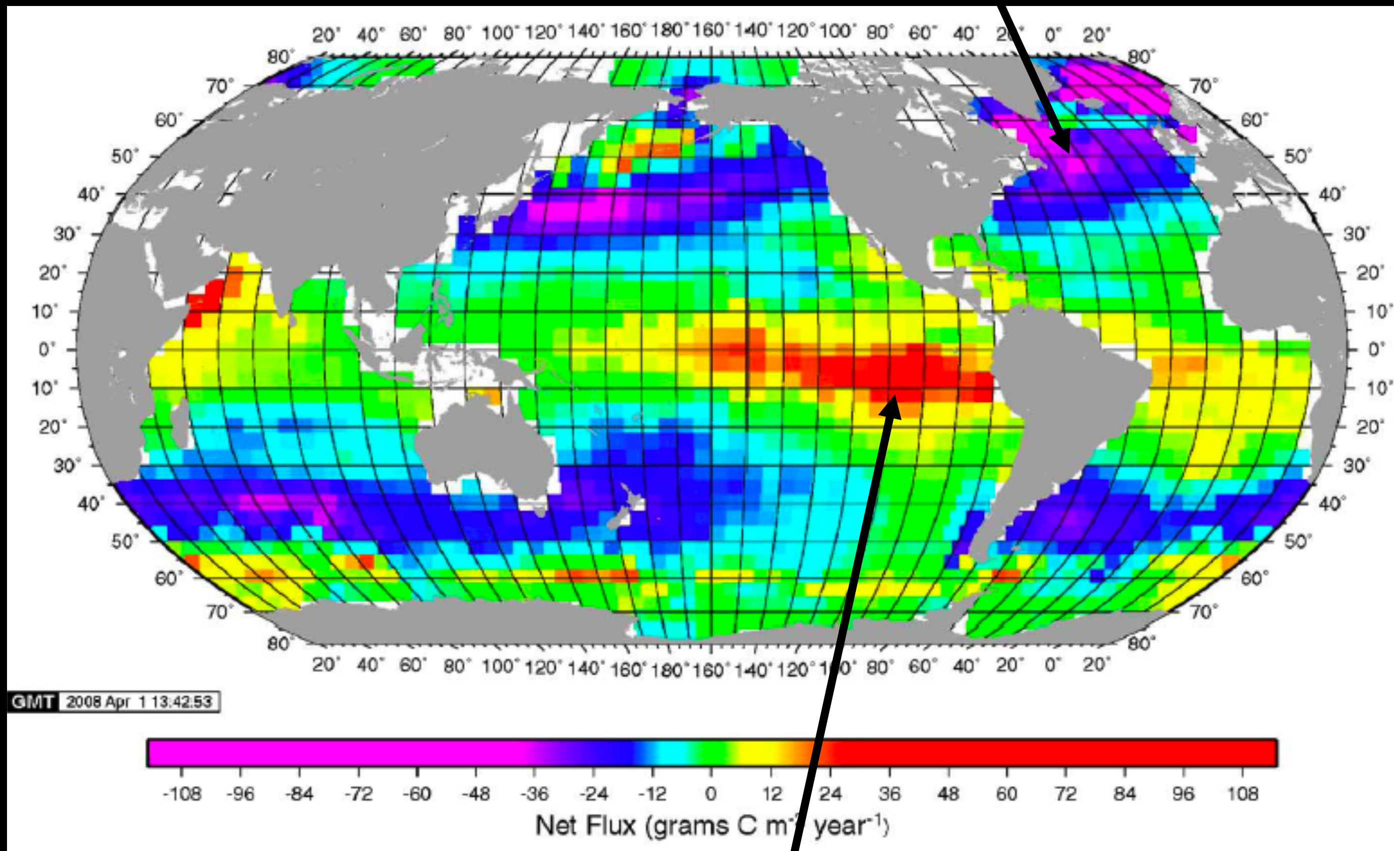


Dissolved inorganic carbon observed from Iceland to the Southern Ocean



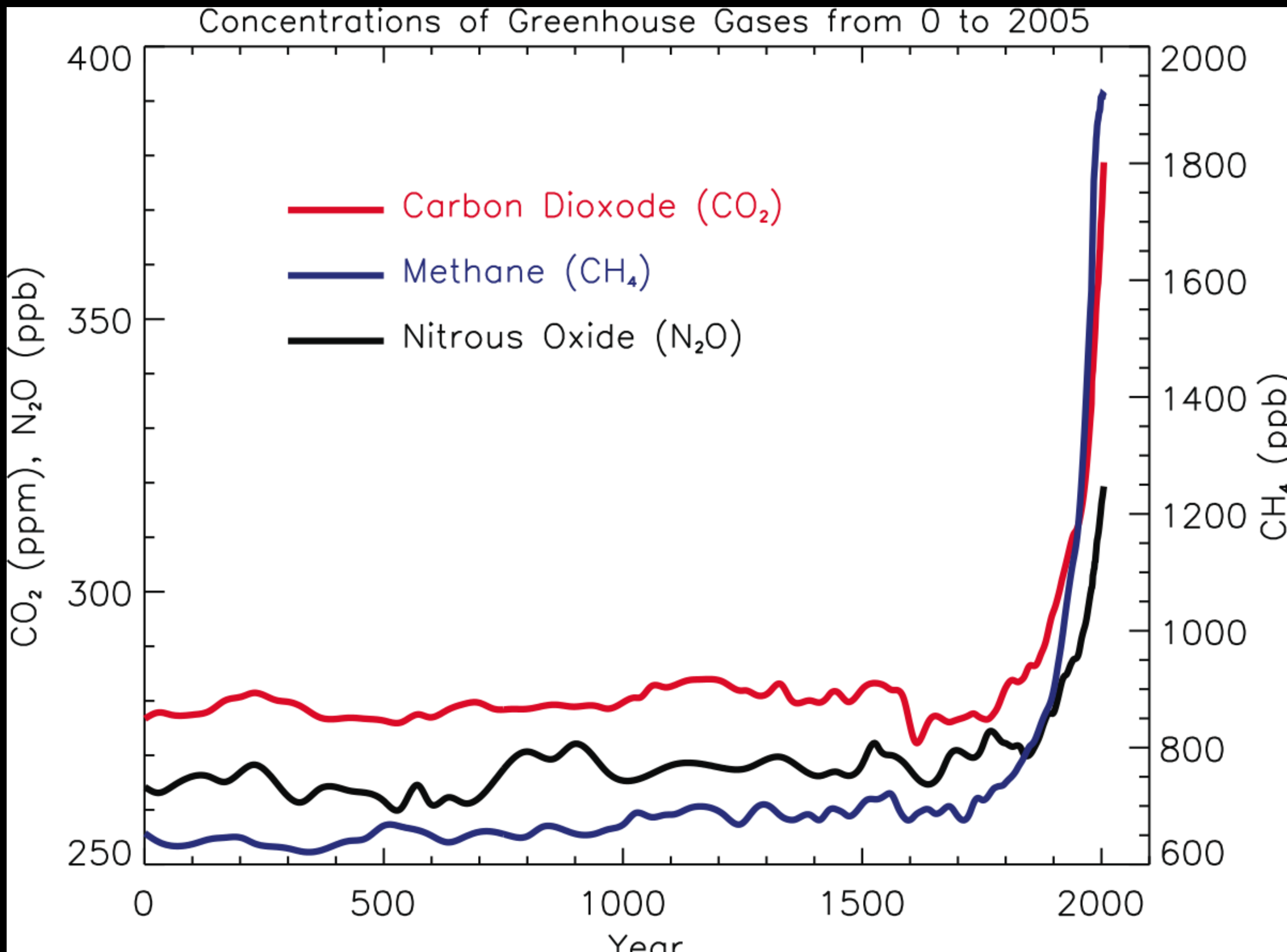
(1) Cooling of northward flowing waters

(2) High biological productivity

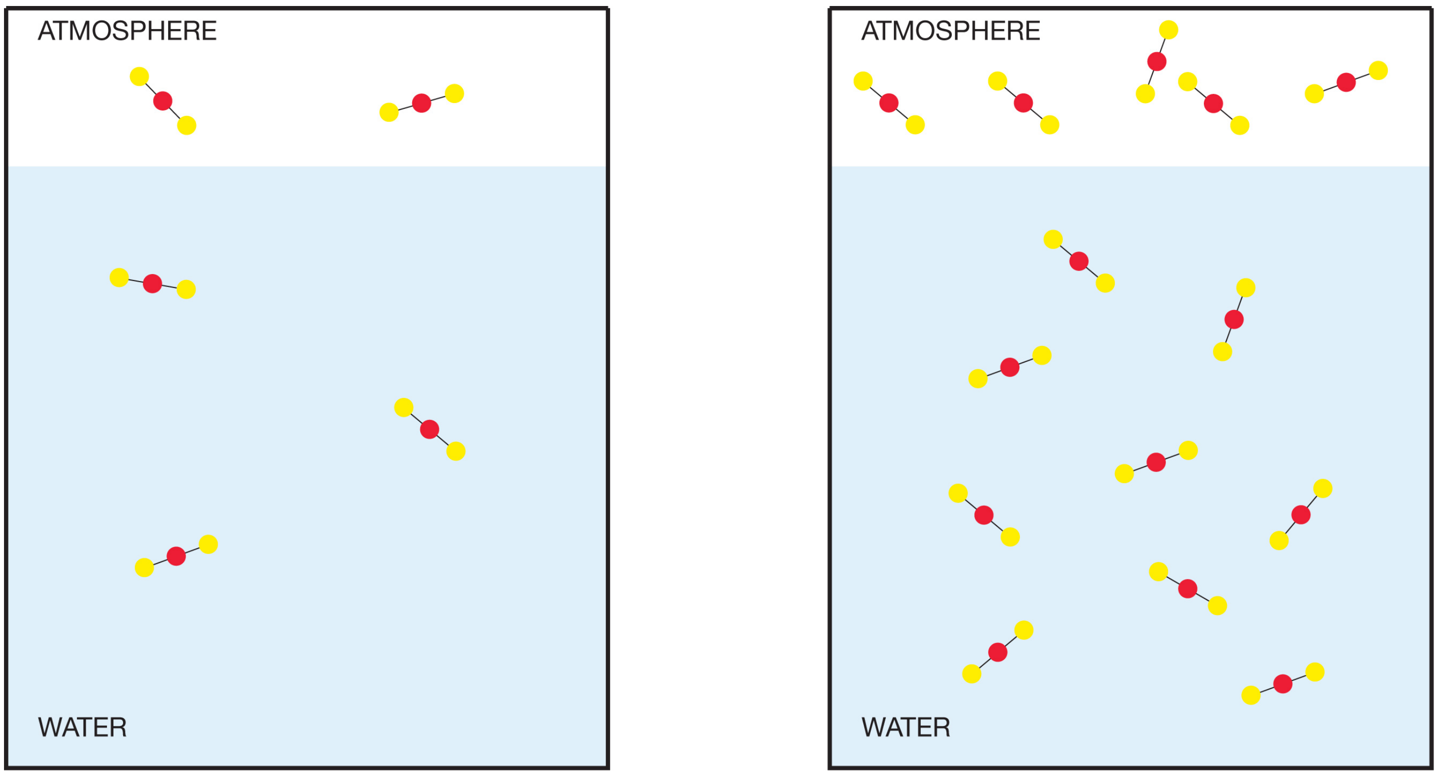


Upwelling drives return of cold and carbon-enriched deep waters to surface

Carbon dioxide is increasing in the atmosphere



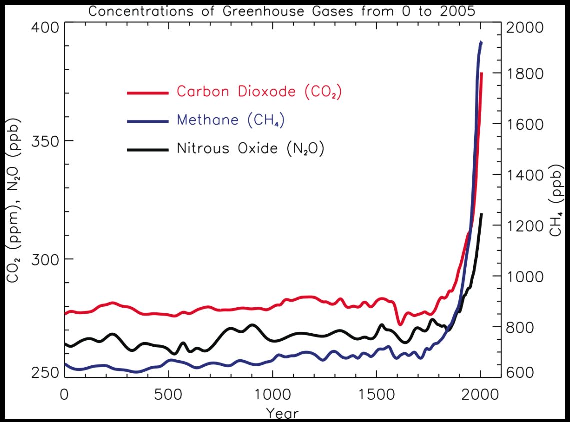
Increased atmospheric pCO_2 drives carbon into the ocean



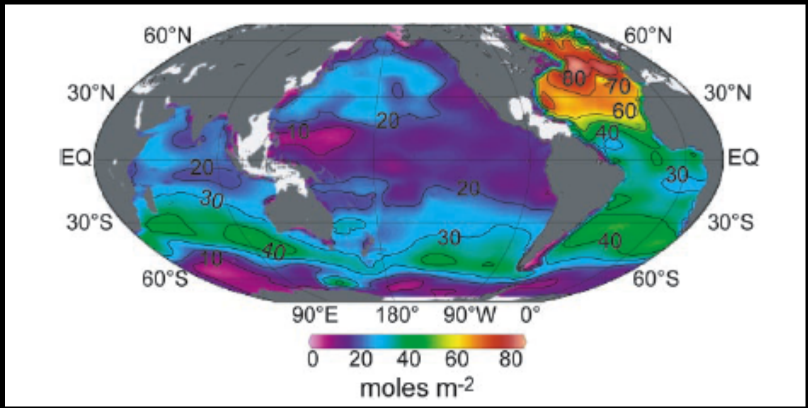
How much carbon has the ocean absorbed since 1800?

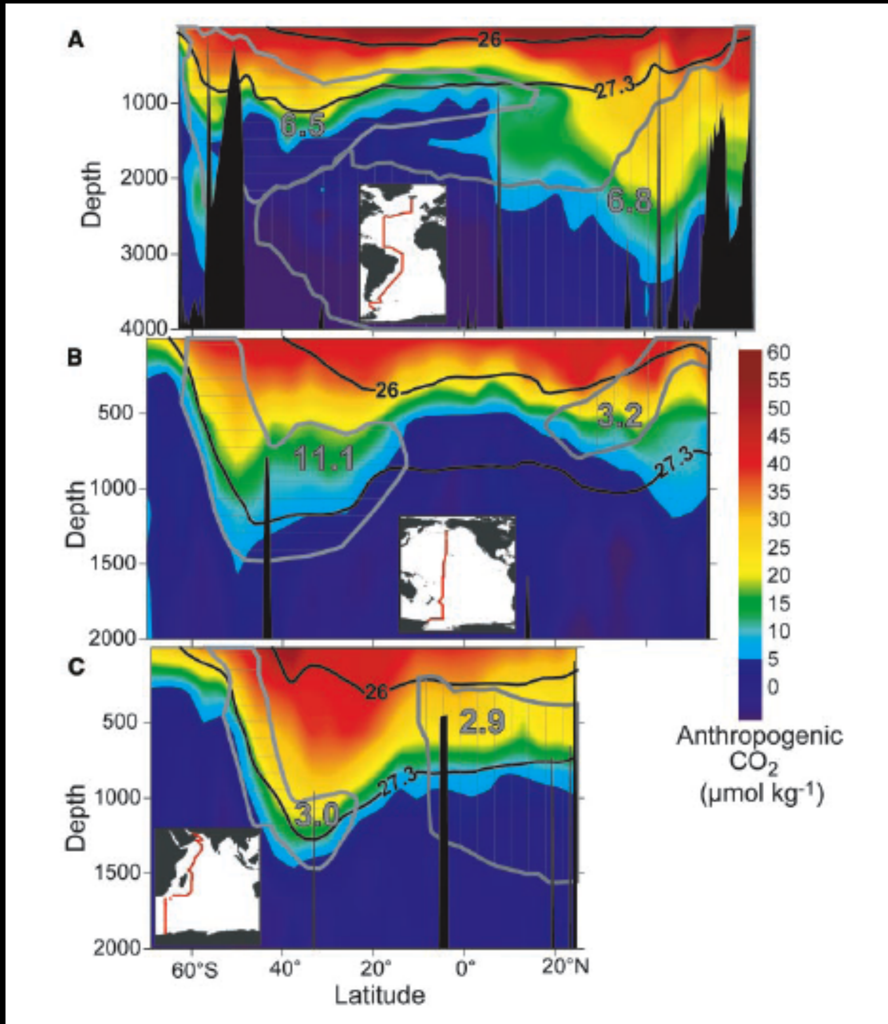
How much carbon has the ocean taken up?

- Observe carbon concentration throughout the ocean
- Assume constant biology over last 200 years
- Calculate the additional carbon put into the ocean due to increasing atmospheric pCO_2



Total ocean anthropogenic CO_2 uptake (1800-1994)



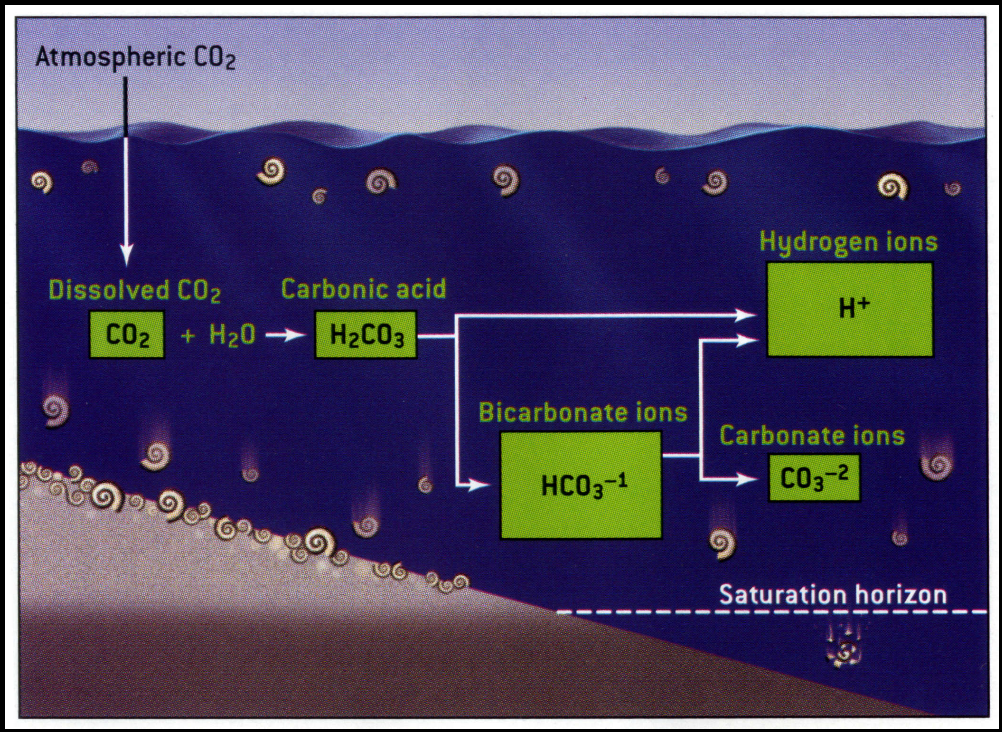


Ocean has taken up 48% of the total fossil fuel carbon

Sabine et al. 2004

This uptake has an impact.

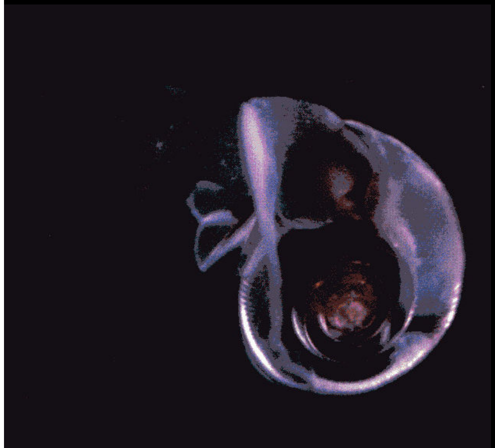
Ocean Acidification:
$CO_2 + H_2O$ = CARBONIC ACID



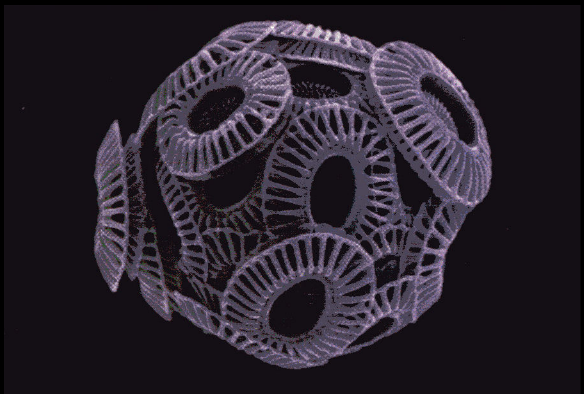
Carbonic acid lowers pH (increases H^+)

Due to anthropogenic CO_2 emissions since 1800, ocean pH has already declined 0.3 units = 30% increase in H^+

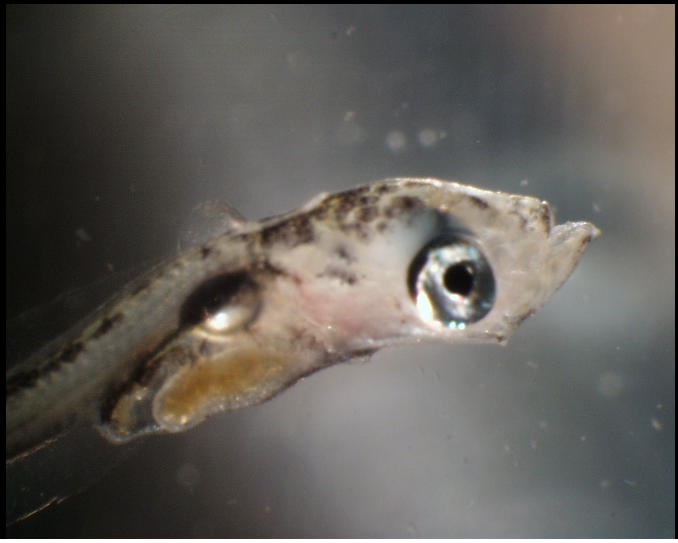
Many organisms make hard parts of $CaCO_3$, which dissolves in acid



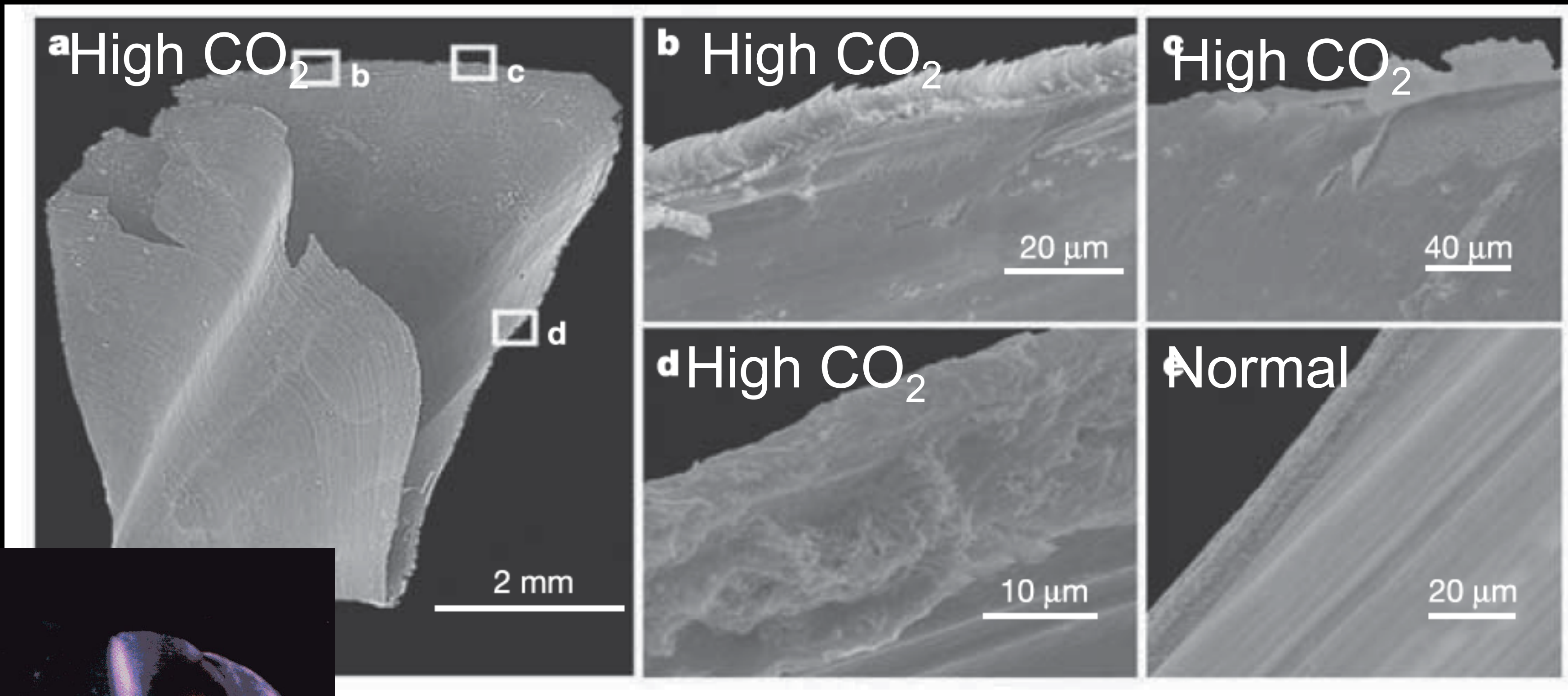
Pteropod (*Limacina helicina*)

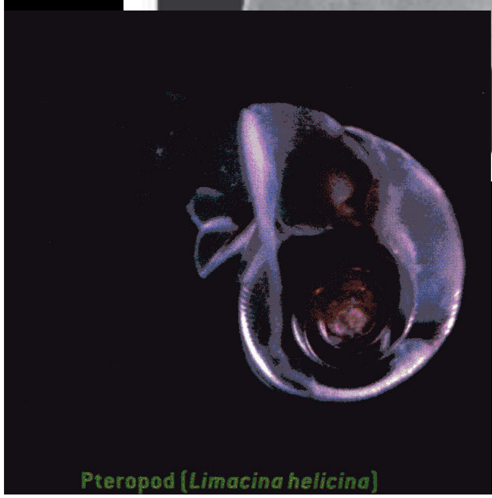


Coccolithophorid (*Emiliania huxleyi*)

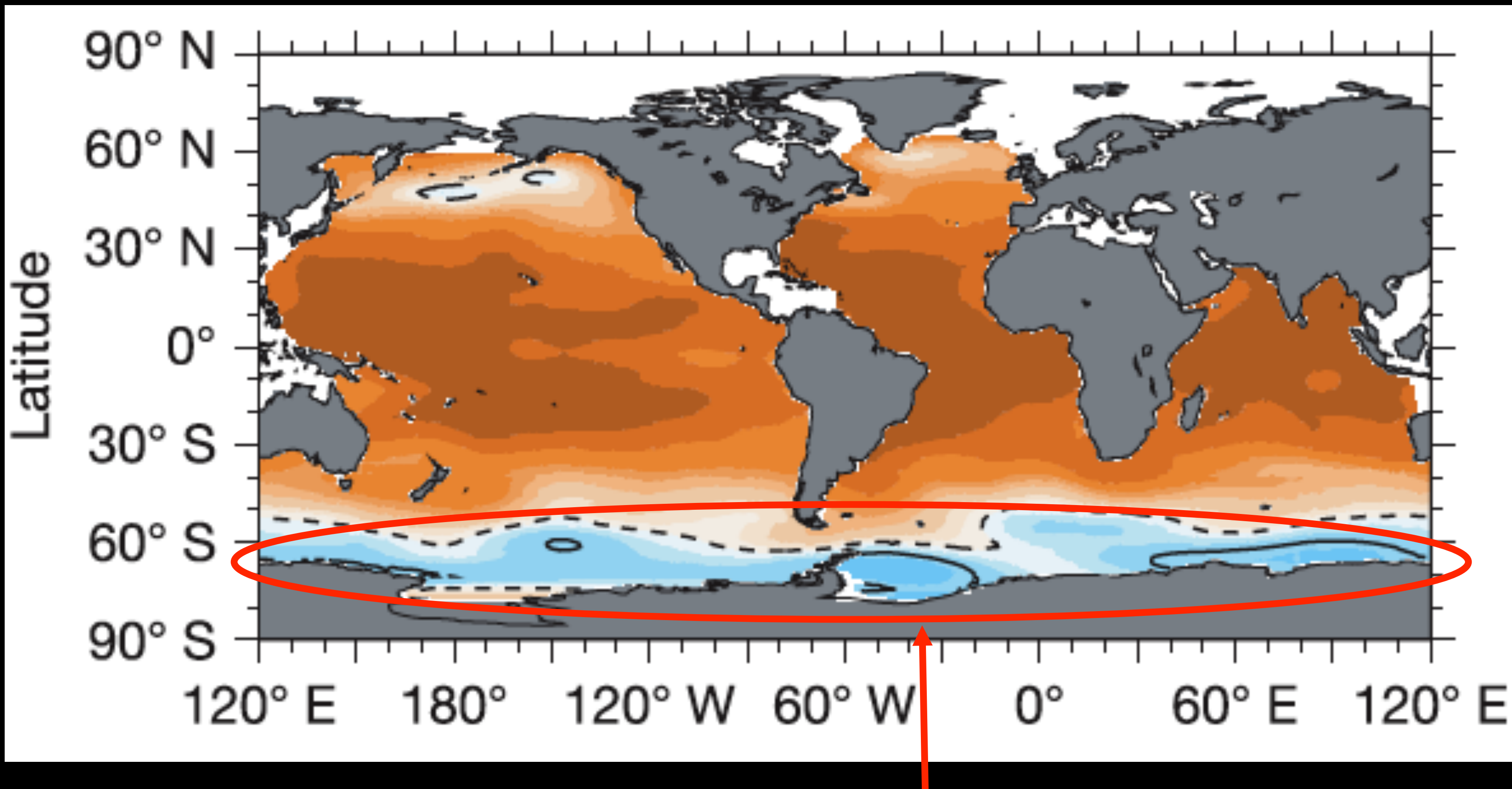


Corrosion of pteropods after 48 hours is high CO_2 water





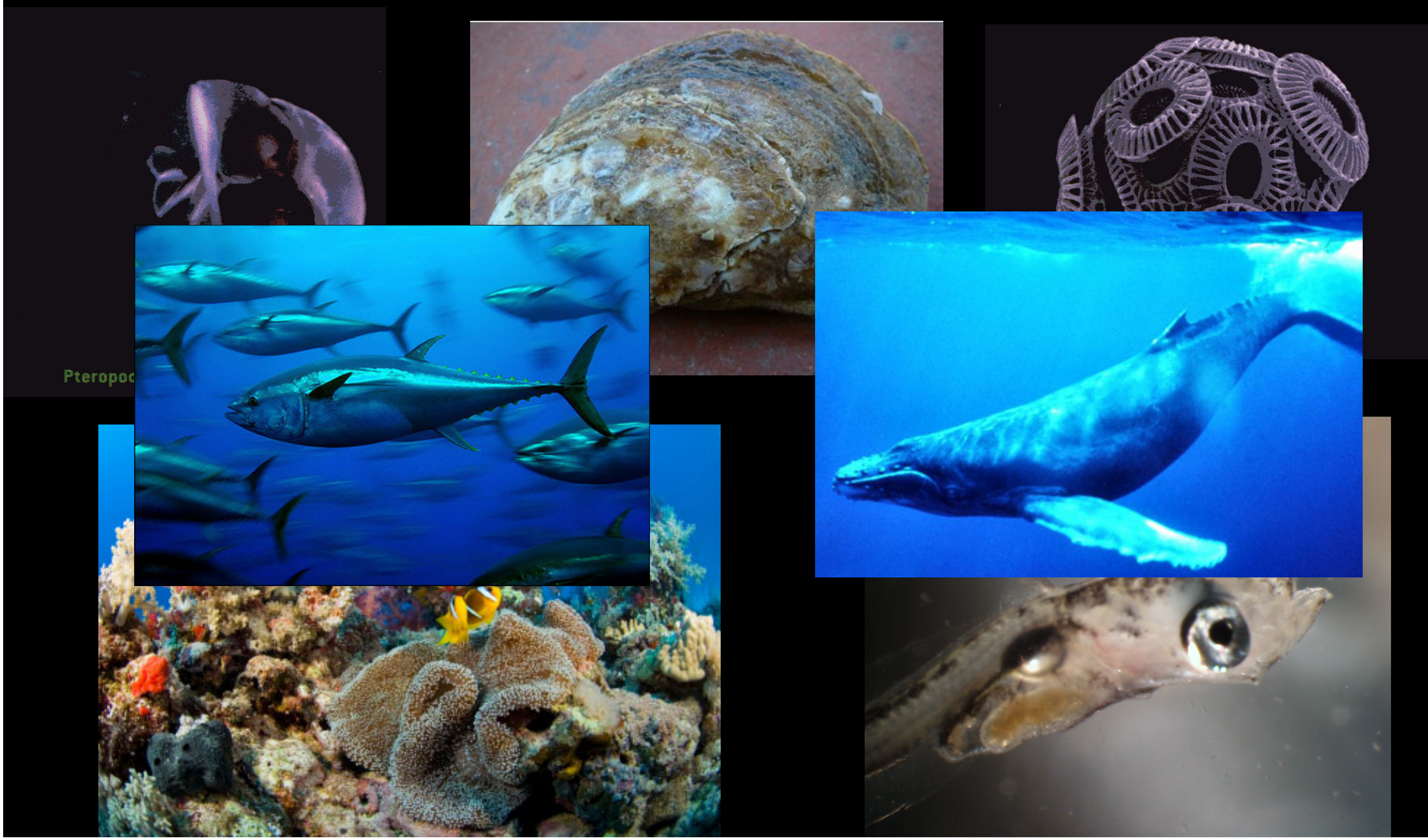
Projection for 2100



Southern Ocean becomes corrosive to $CaCO_3$

Impacts likely before – some observed already

Ecosystem-wide impacts?

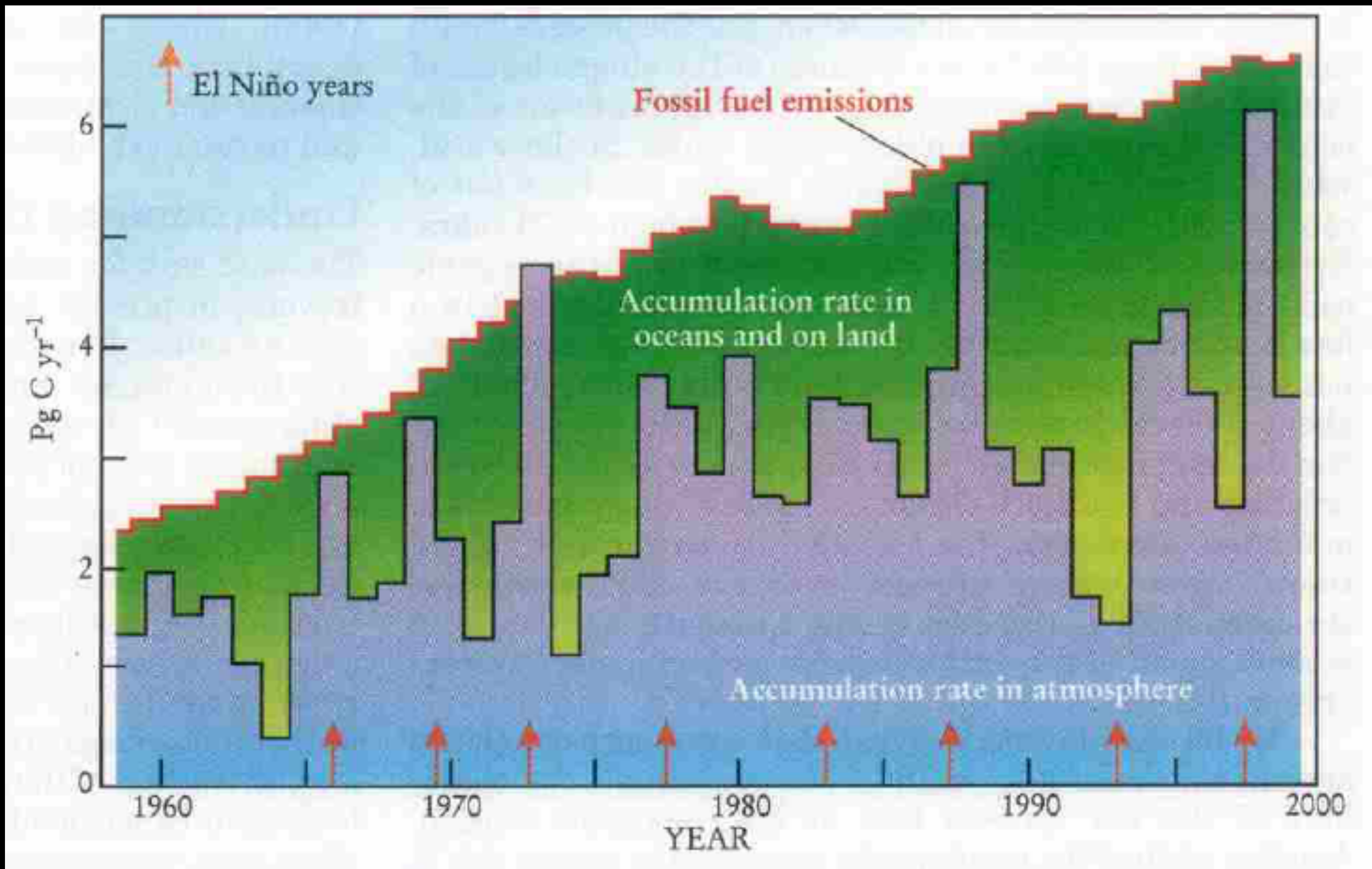


Governmental Responses to Ocean Acidification

- Major reports
  - first - Royal Society in 2005
  - latest - National Research Council, 22 April 2010
- Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009 - ~$100M
- Senate Hearings: June 2008, April 2010

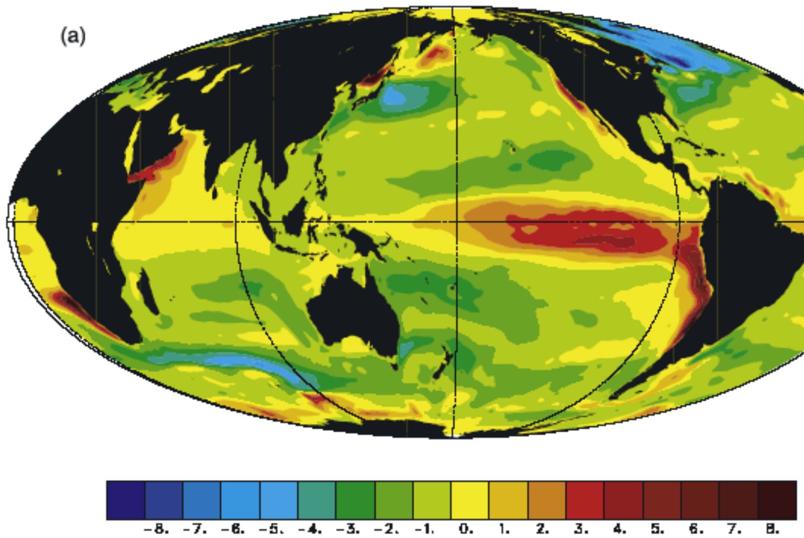
Learn more :
http://www.whoi.edu/OCB-OA

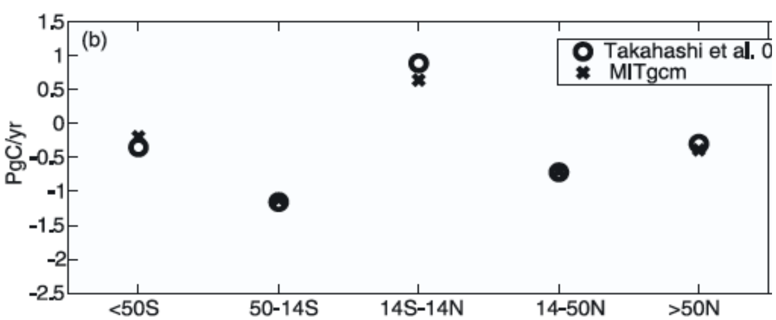
Variability in the air-sea CO_2 flux

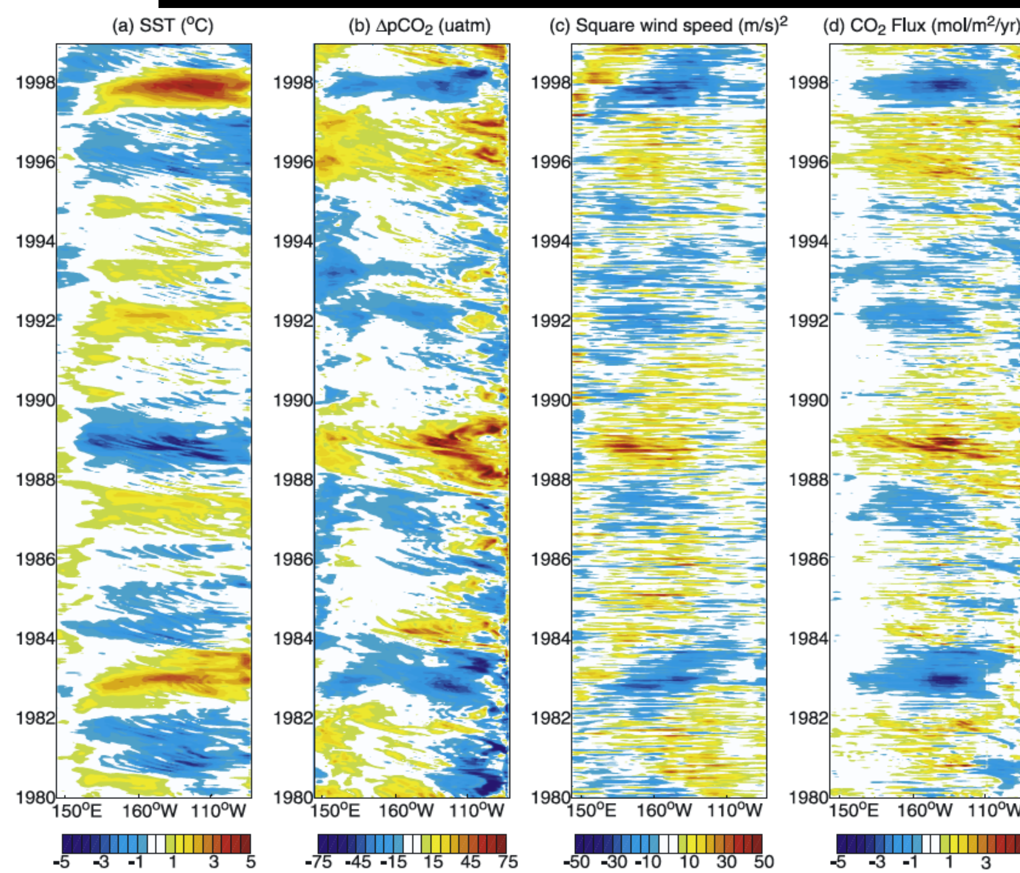


Sarmiento and Gruber 2002

Interannual variability dominated by El Nino / Southern Oscillation cycle

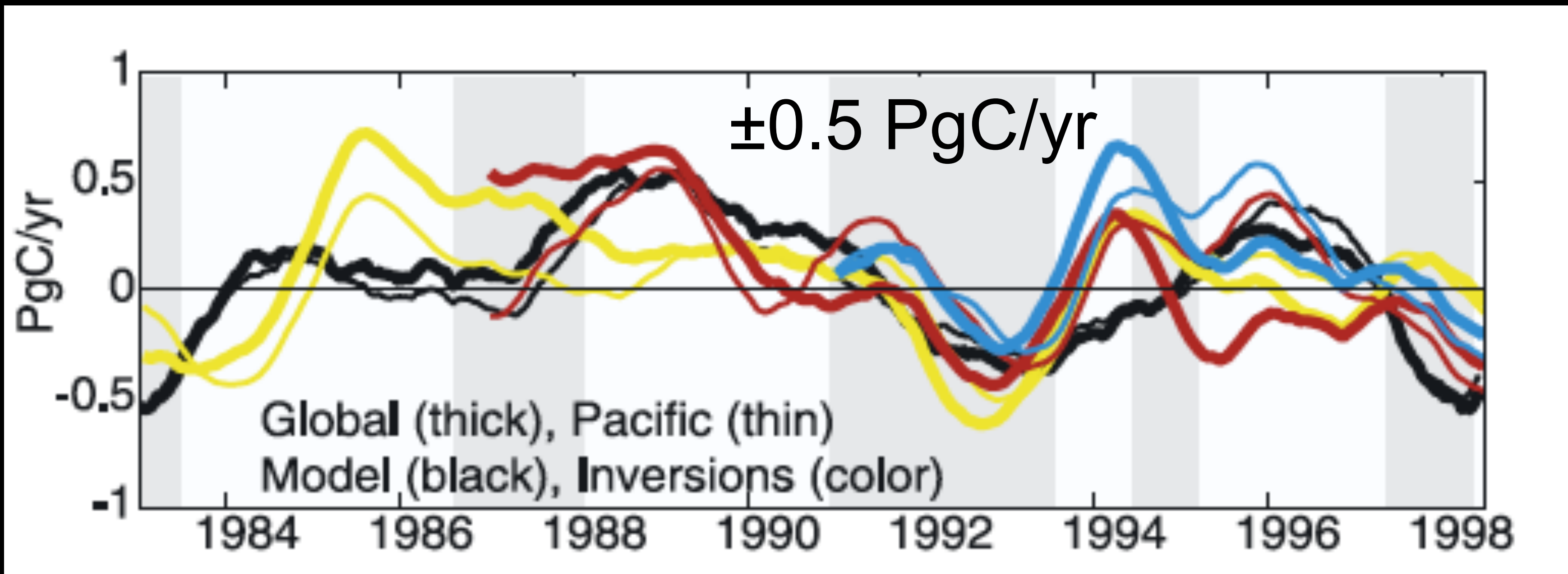




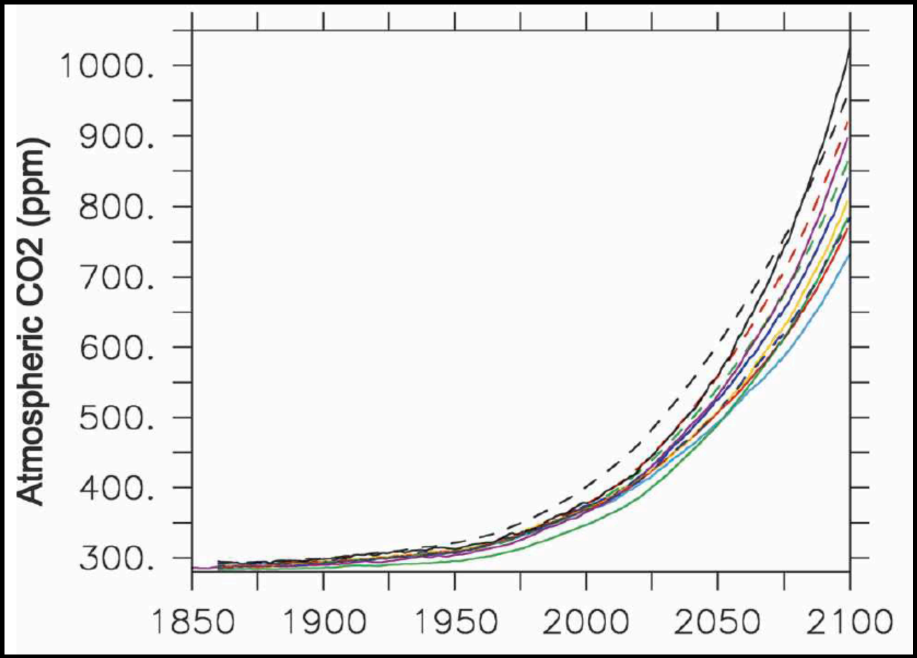


McKinley et al. 2004a

Forward models and inversion of Rodenbeck et al. (2003) agree

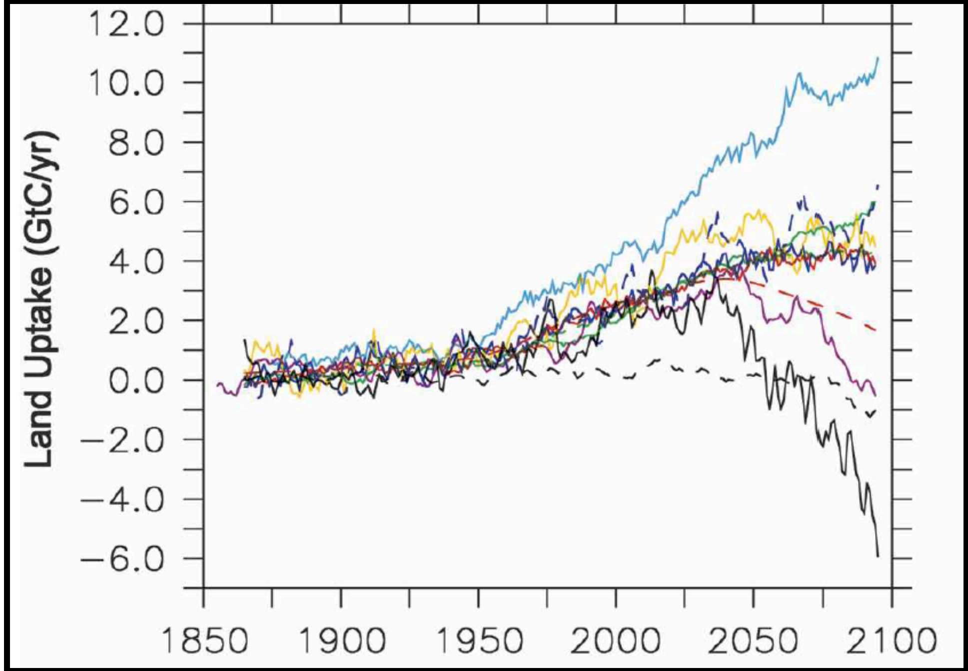


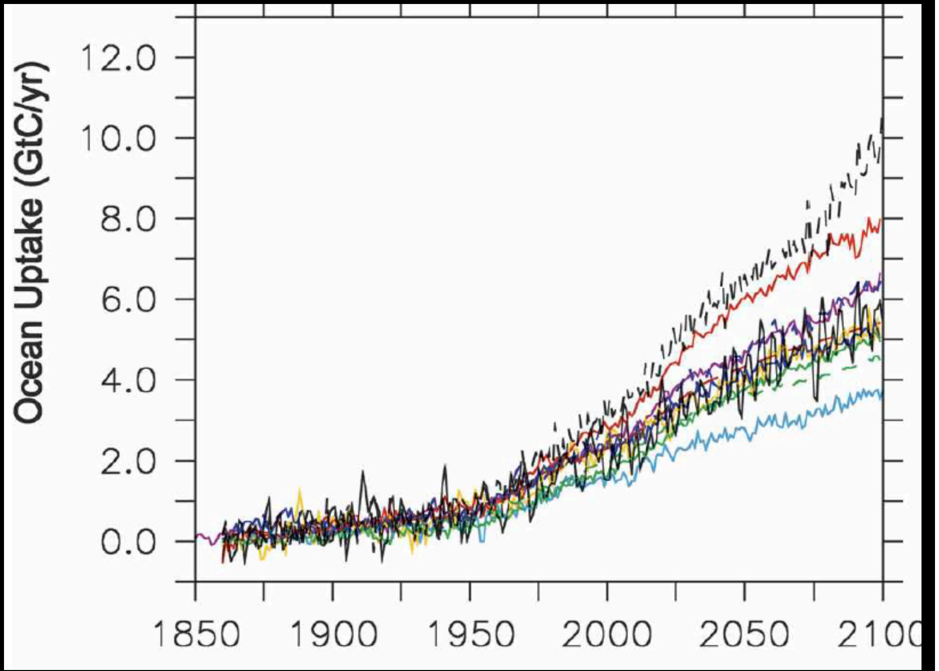
McKinley et al. 2004b



Future atmospheric CO_2?

Friedlingstien et al. 2006





Are trends already detectable?

Reduction in fraction stored in the ocean
(Canadell et al. 2007)

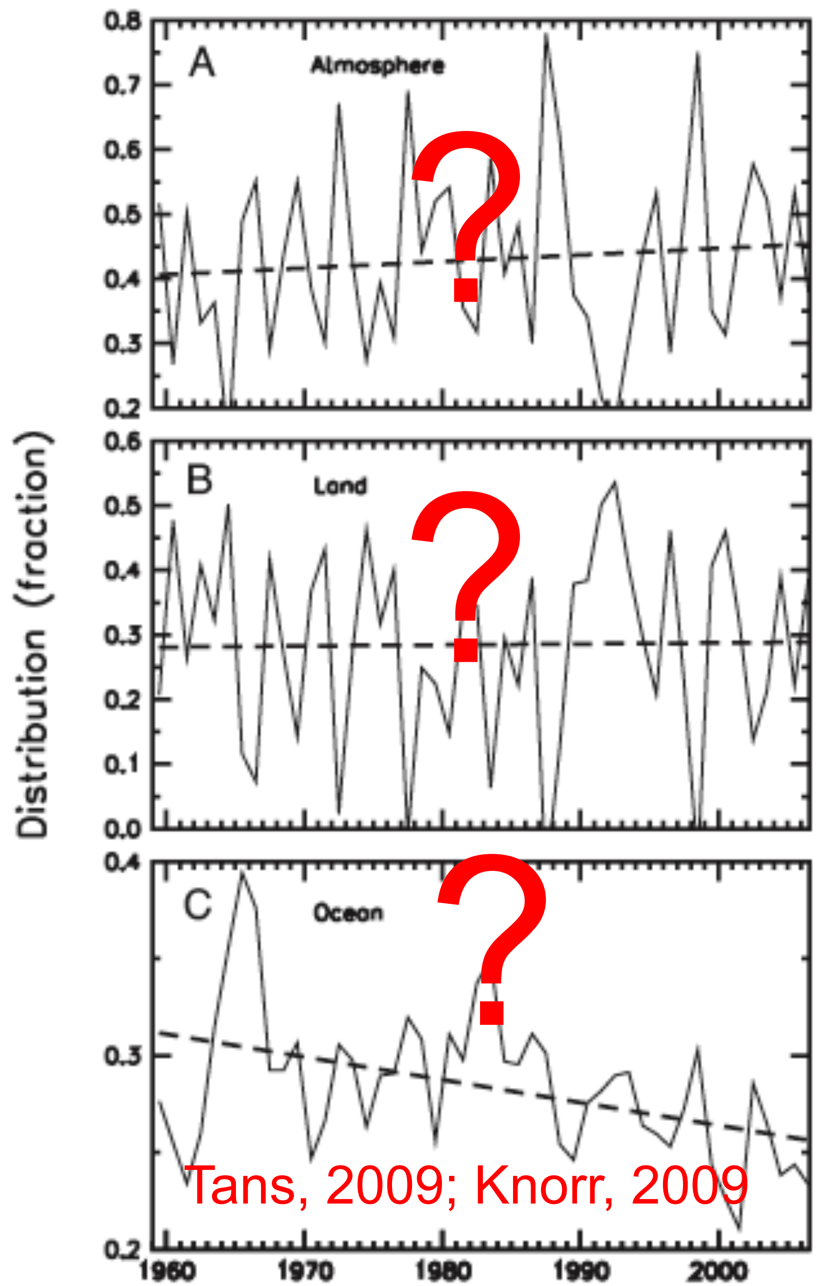
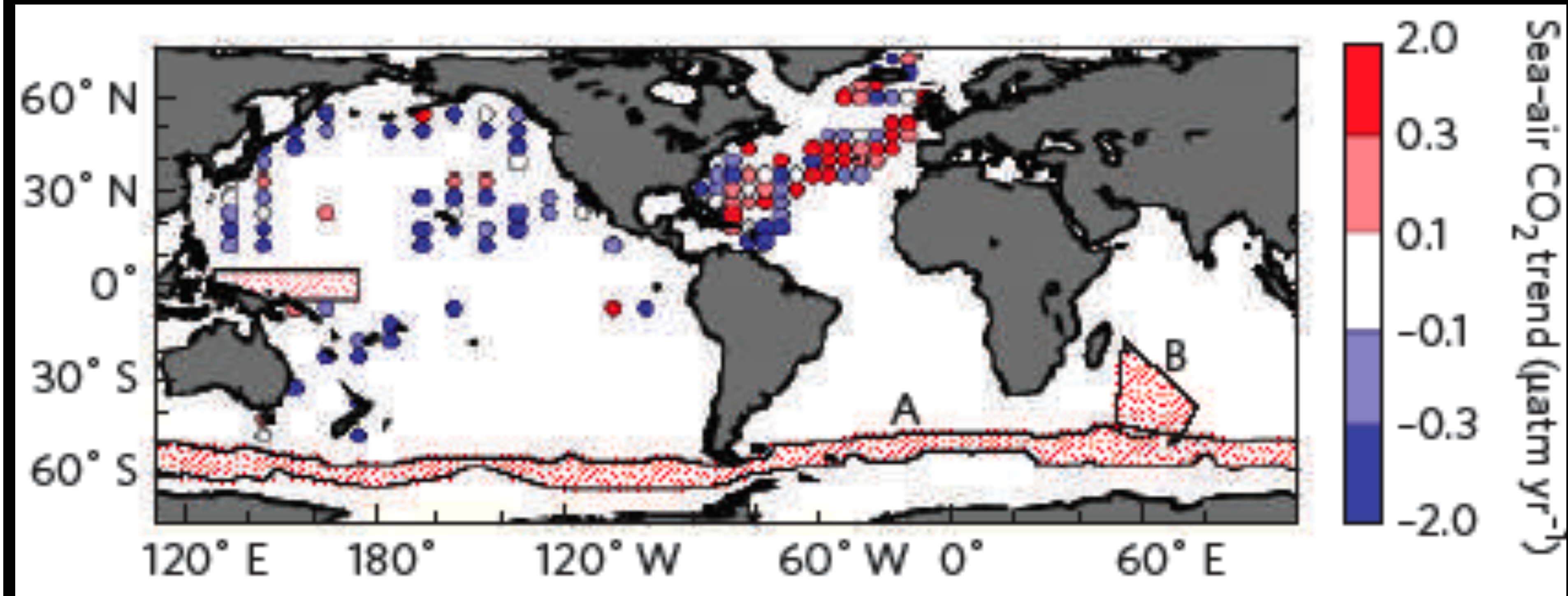


Fig. 2. Fraction of the total emissions (F_{Foss} + F_{LUC}) that remains in the atmosphere (*A*), the land biosphere (*B*), and the ocean (*C*).

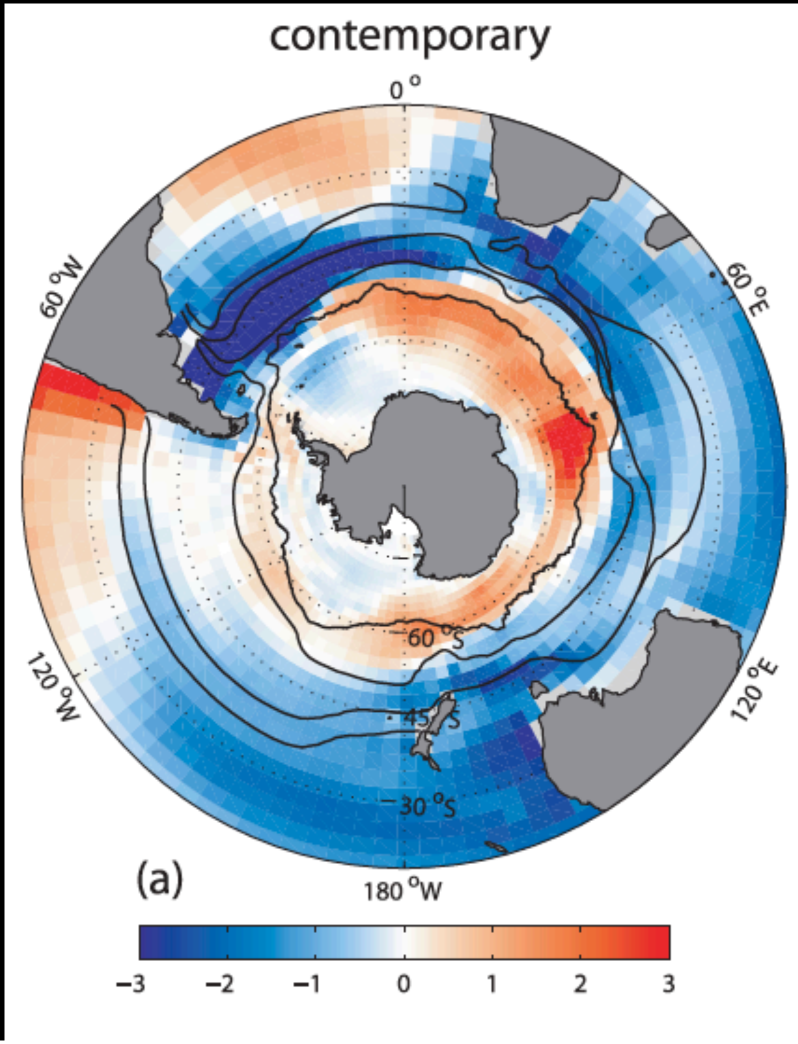
Regional Trends in Ocean?



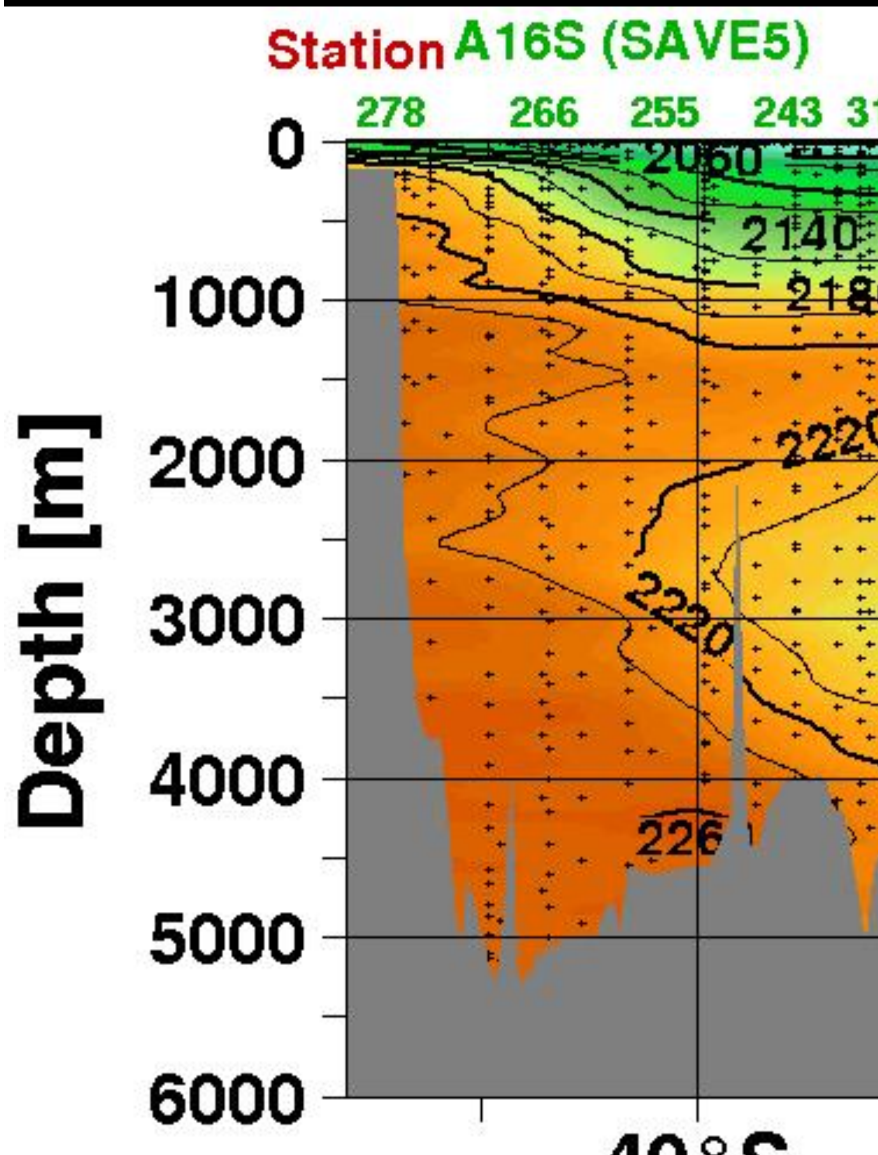
LeQuéré et al. 2009

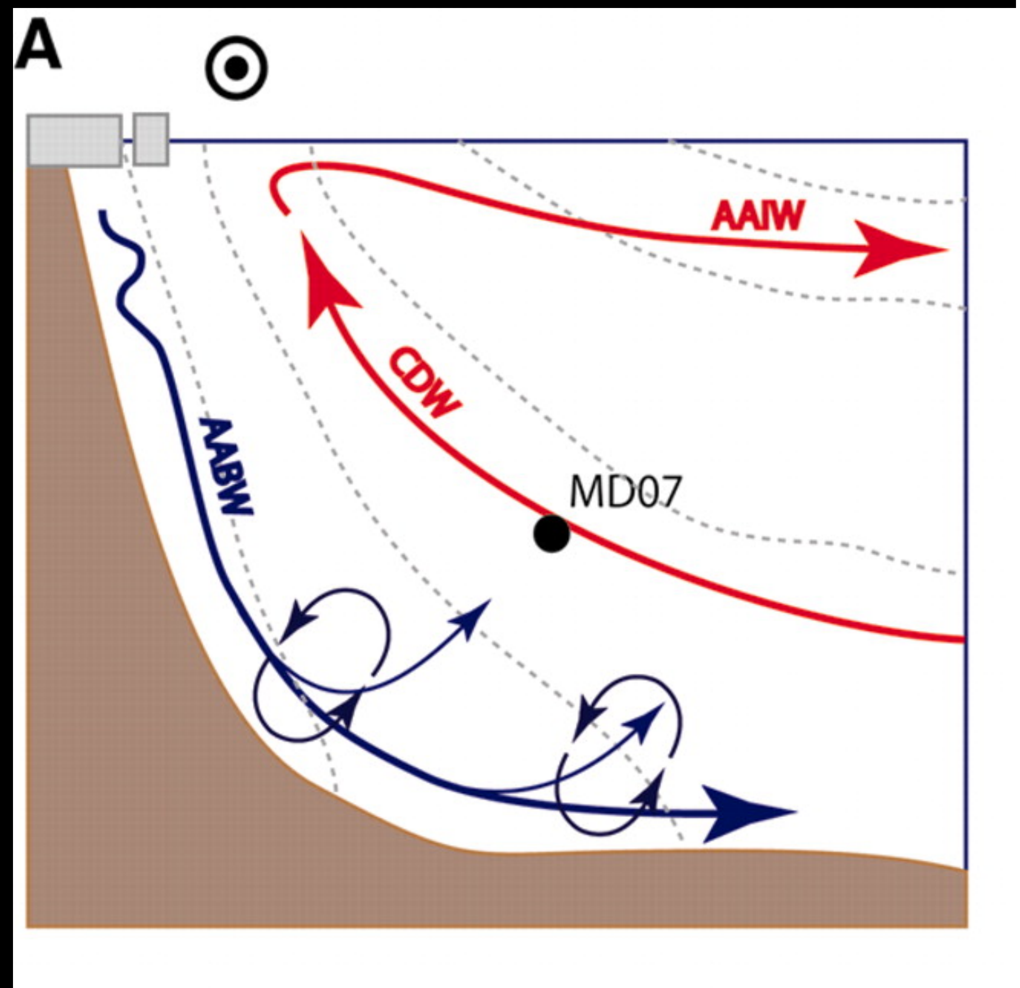
Southern Ocean Trends?

Carbon goes both out and in in Southern Ocean

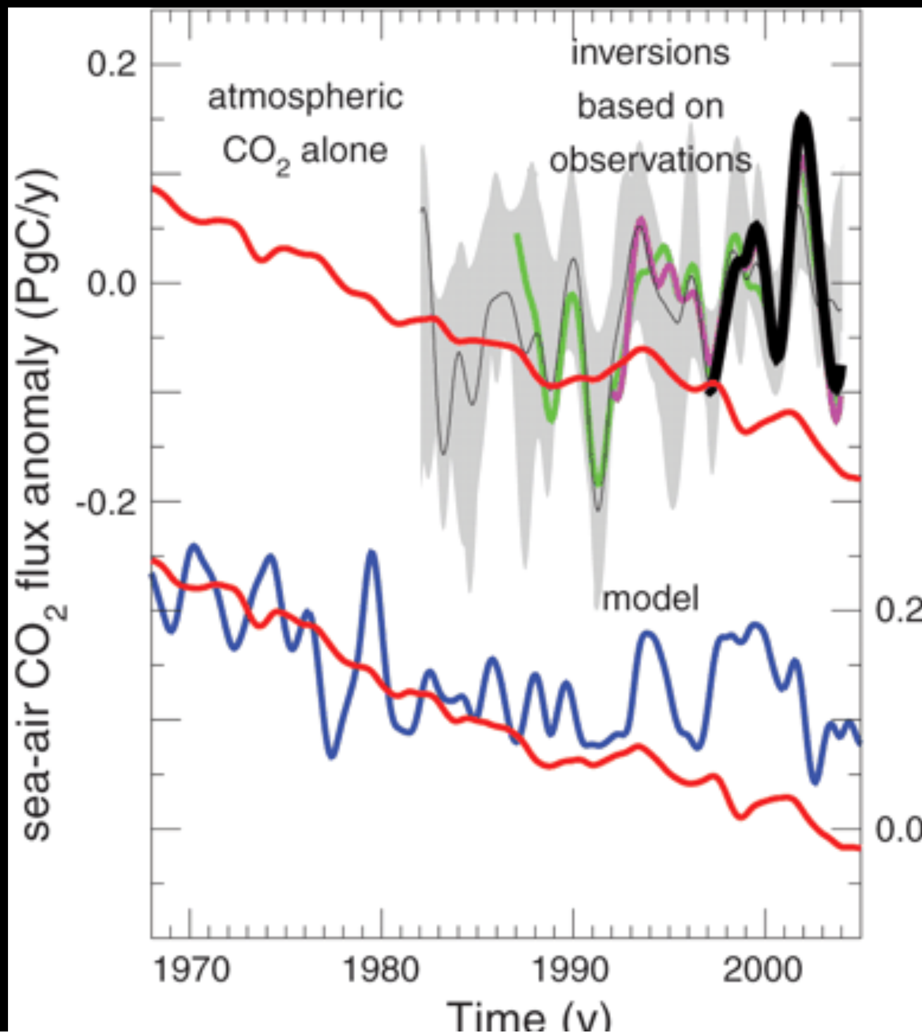


Lovenduski et al. 2007


Station A16S (SAVE5)
278
266
255
243
0
1000
2000
3000
4000
5000
6000
Depth [m]
2060
2140
2220
2220
226
40°S

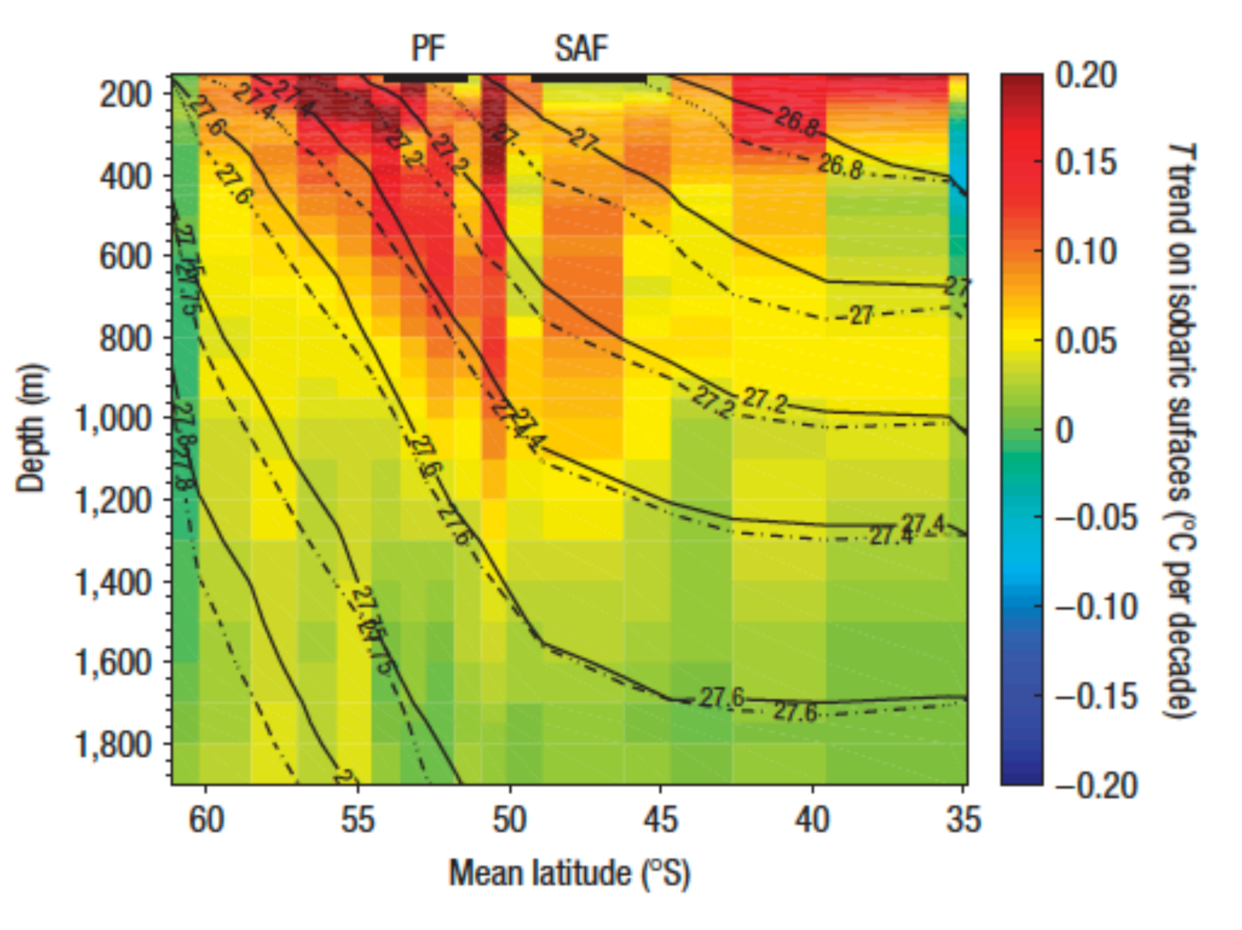

A
AAIW
CDW
AABW
MD07

Coarse models suggest that increasing winds (due to climate change) have already increased outgassing of natural carbon, reducing net sink



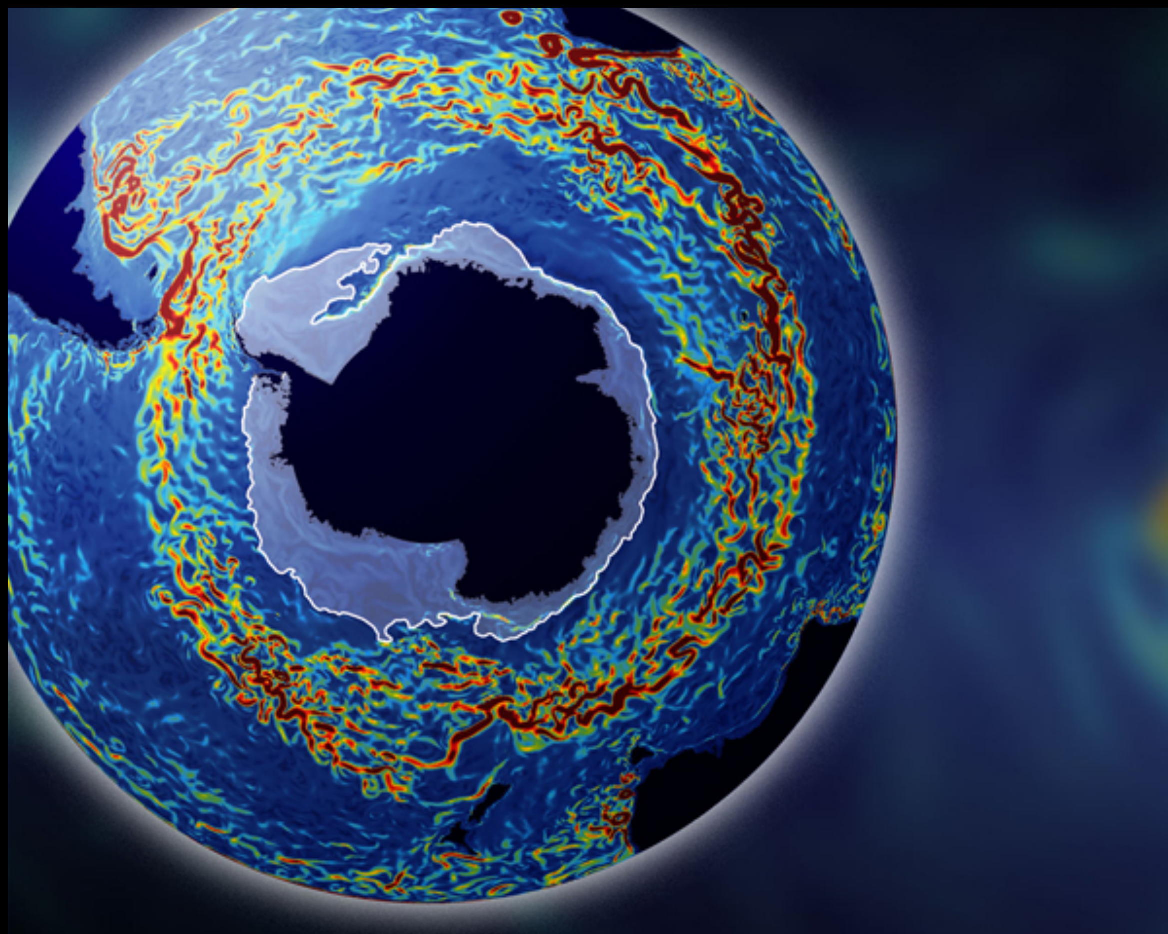
LeQuere et al. 2007

Coarse models may not get physics right. Data show isopyncal slope unchanged = evidence for no ventilation increase



Boning et al. 2008

Eddy Resolving Simulation May 12, 2006 (red=fast)



Mazloff, 2008

Eddy resolving model indicates EKMAN drives anthropogenic CO_2 uptake variations within the year, and thus long-term variation in winds may actually be of importance

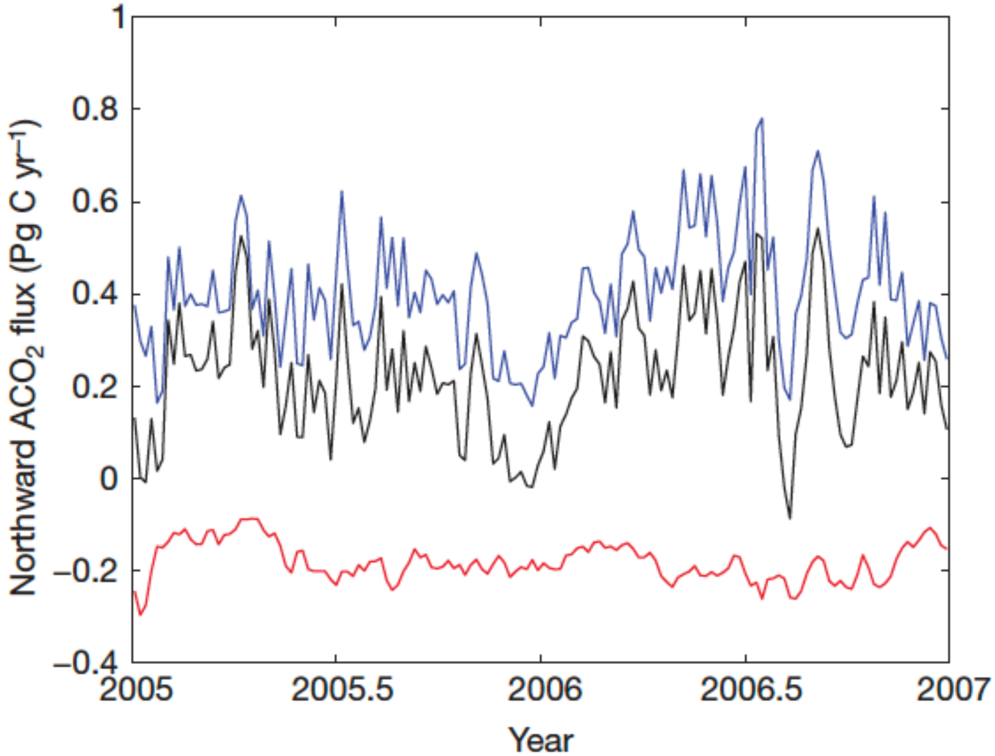


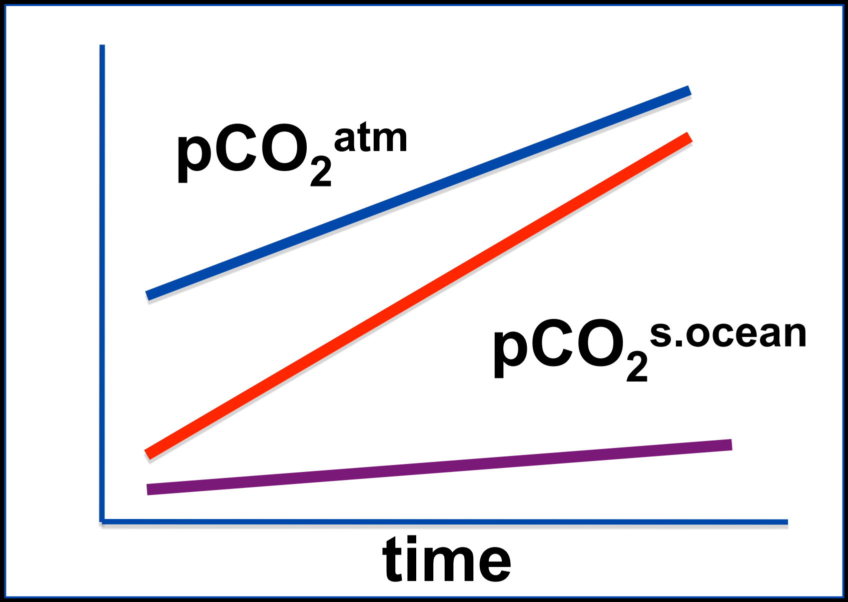
Figure 3 | Variability of anthropogenic carbon transport. Time series of northward cross-frontal ACO_2 flux: zonal-mean (blue), eddy (red) and net (black) transport. The zonal and temporal mean was calculated along the position of the APF for the 2-yr simulation period.

Ito et al. 2010

In the complex Southern Ocean, with limited data, the links of physical change to carbon change are still under debate

North Atlantic Trends?

Comparing pCO_2 trends:
CO_2 flux α ($pCO_2^{atm} – pCO_2^{s.ocean}$)



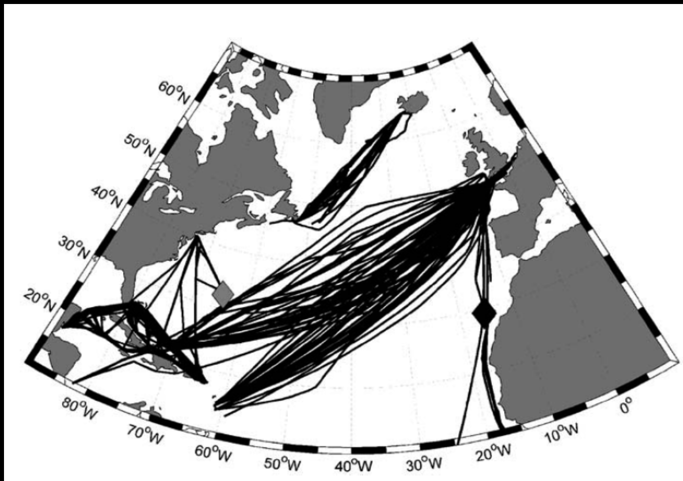
$dpCO_2^{s.ocean}/dt$ >
$dpCO_2^{atm}/dt$

DECLINING SINK

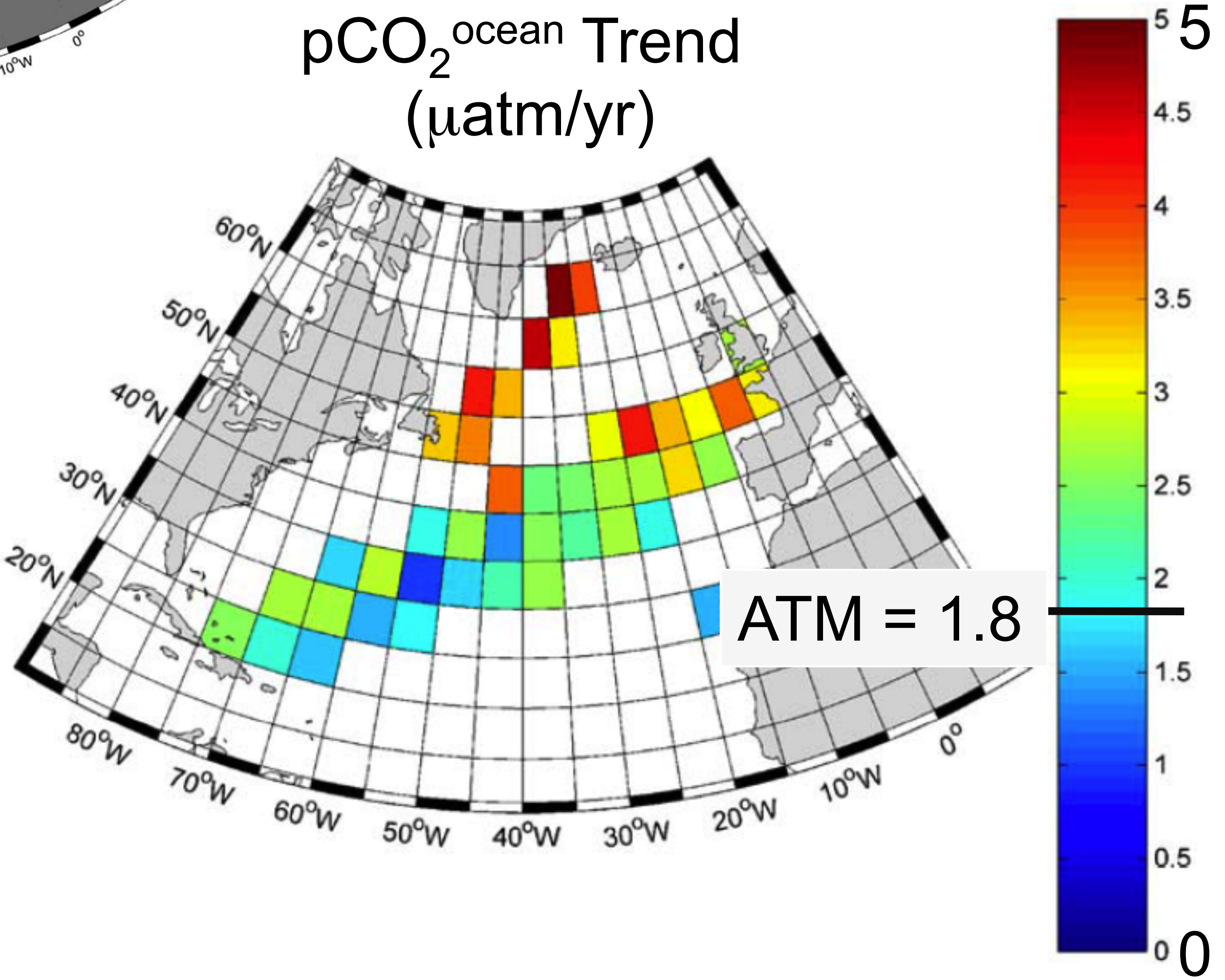
$dpCO_2^{s.ocean}/dt$ <
$dpCO_2^{atm}/dt$

INCREASING SINK

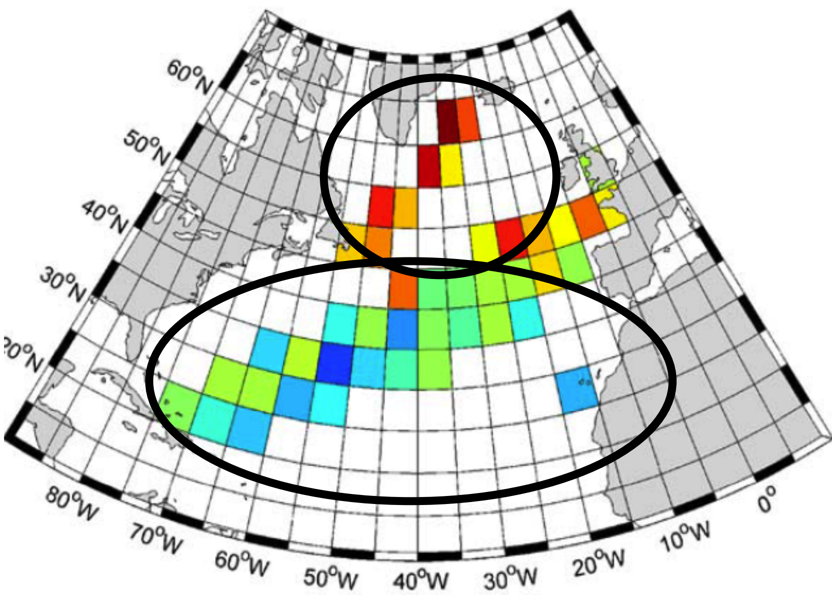
VOS datasets, linear pCO_2 trend 1990-2006 (*Schuster et al. 2009)*

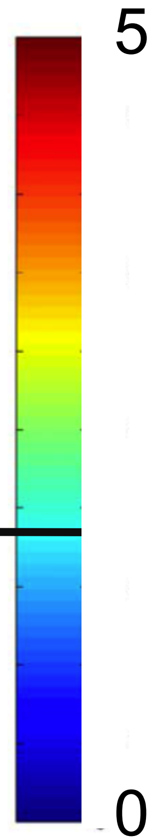


Data of
Corbiere et al. 2007
Shuster & Watson 2007
Bates 2007
Olsen et al. 2004
Santana-Casiano et al. 2007



Observed 1990-2006



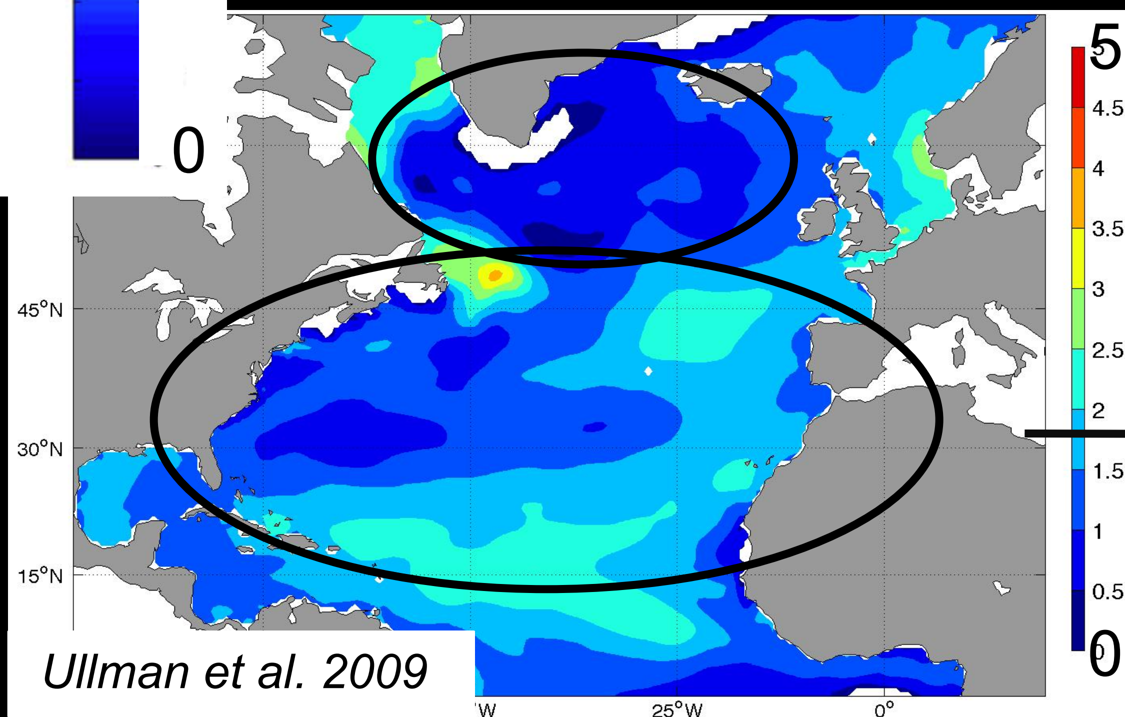


Schuster et al. 2009

pCO_2^{ocean}

(µatm/yr)

Modeled, 1992-2006

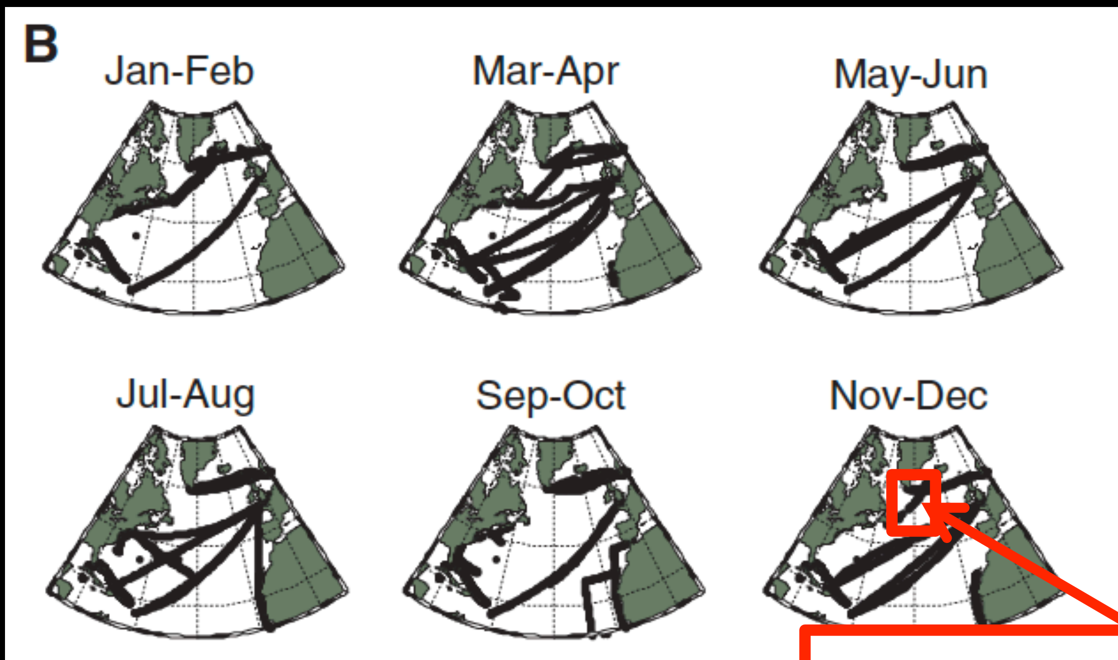


Ullman et al. 2009

Generally consistent <45N, but inconsistent >45N

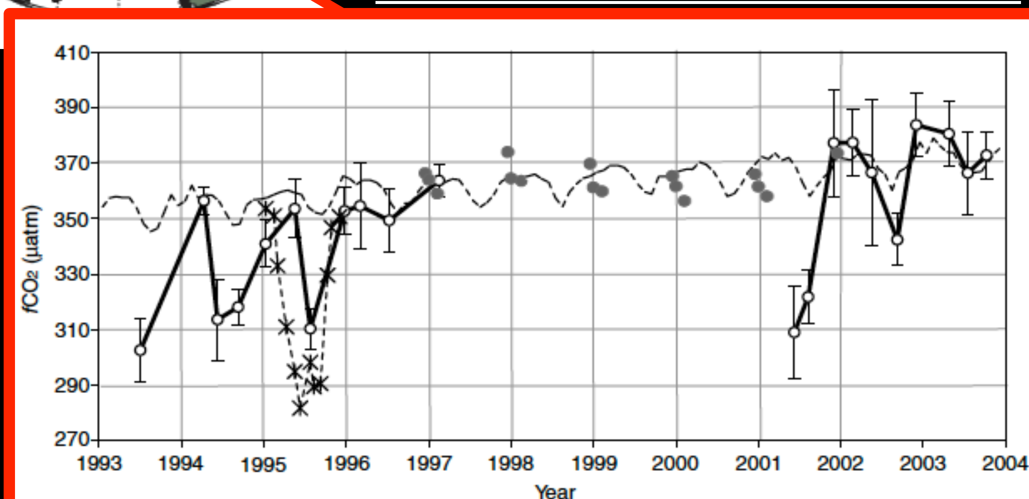
VOS data coverage poor

2005 – A good year



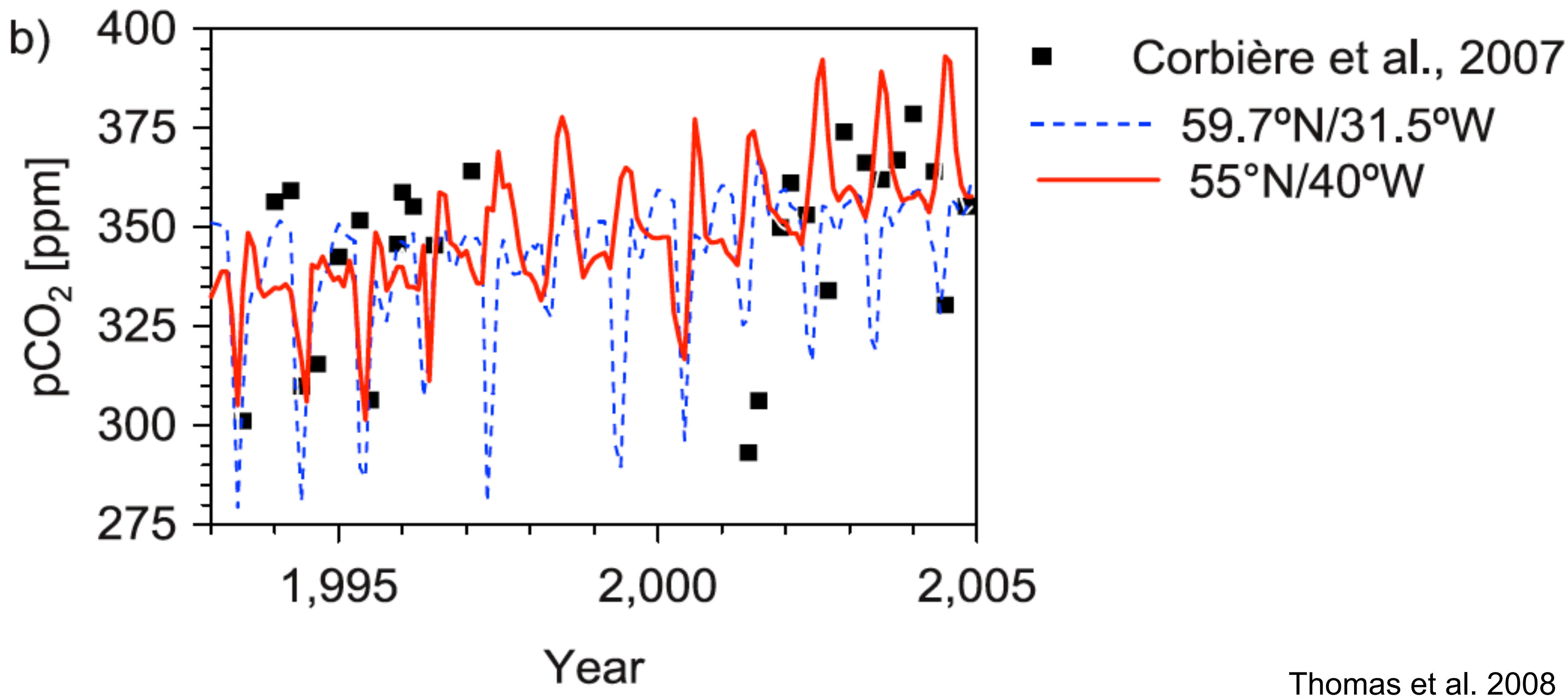
Watson et al. 2009

Iceland to Newfoundland



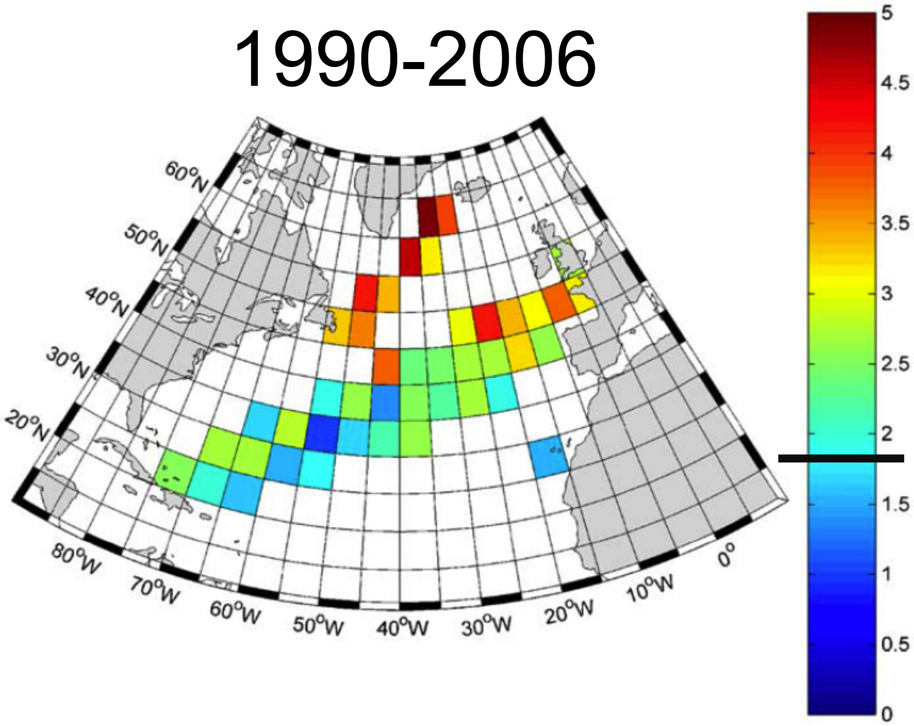
Corbiere et al. 2007

Models are imperfect



Thomas et al. 2008

1990-2006



Different timeframes, different datasets

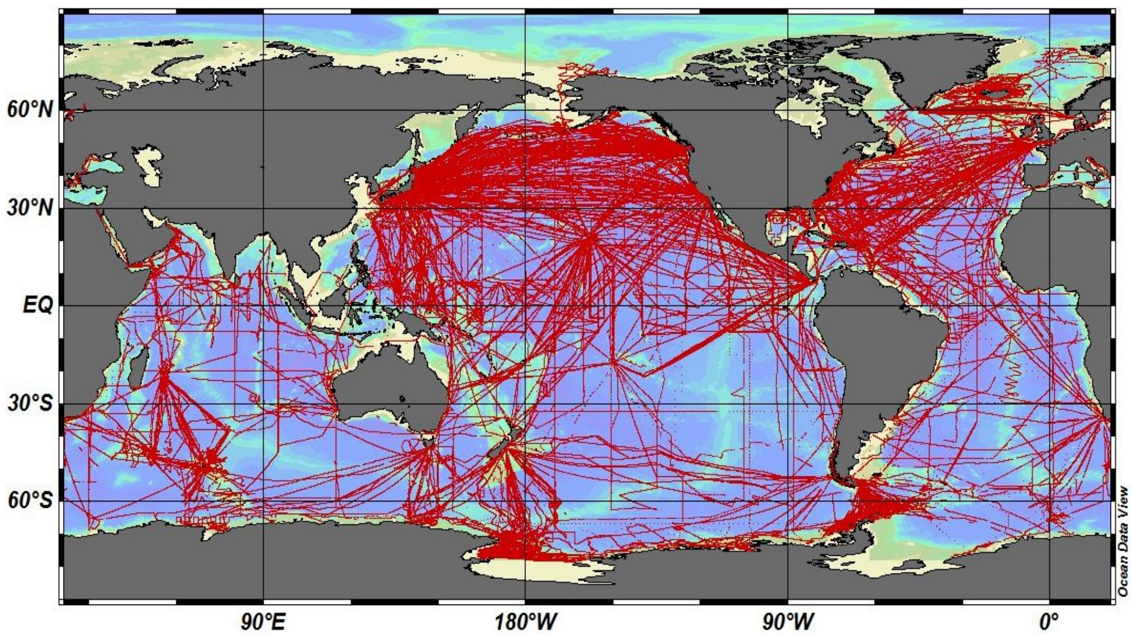
1981-2007

LeQuéré et al. 2009 using data of Takahashi et al. 2009

Observed North Atlantic pCO_2 trends

Takahashi et al. 2010 in-situ pCO_2 database

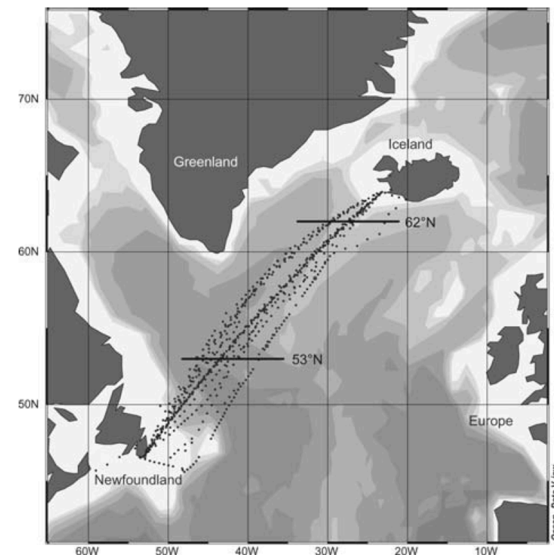
released on CDIAC website



-Over 4.5 million data points globally

-Over 1 million in the North Atlantic

SURATLANT dataset
Calculated pCO_2
(1993-2007)



Corbiere et al. 2007

Step 1: Calculate monthly means for 1°x1° gridcells

Biomes

- Divide ocean based on physical and biological characteristics (as done in Sarmiento et al 2004)
- Selection criteria includes SST, max MLD, and chlorophyll-a climatologies

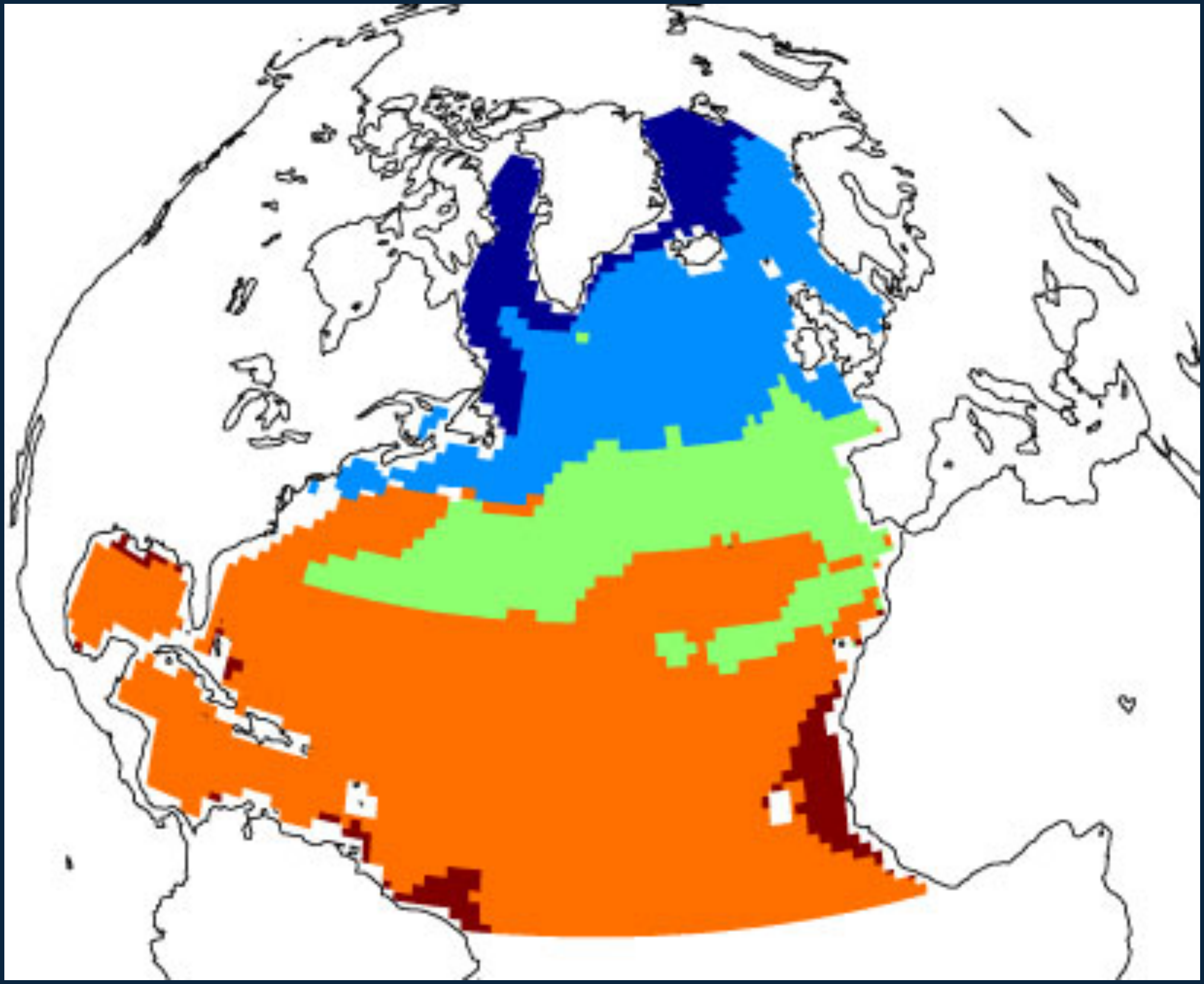
Marginal Sea Ice (ICE)

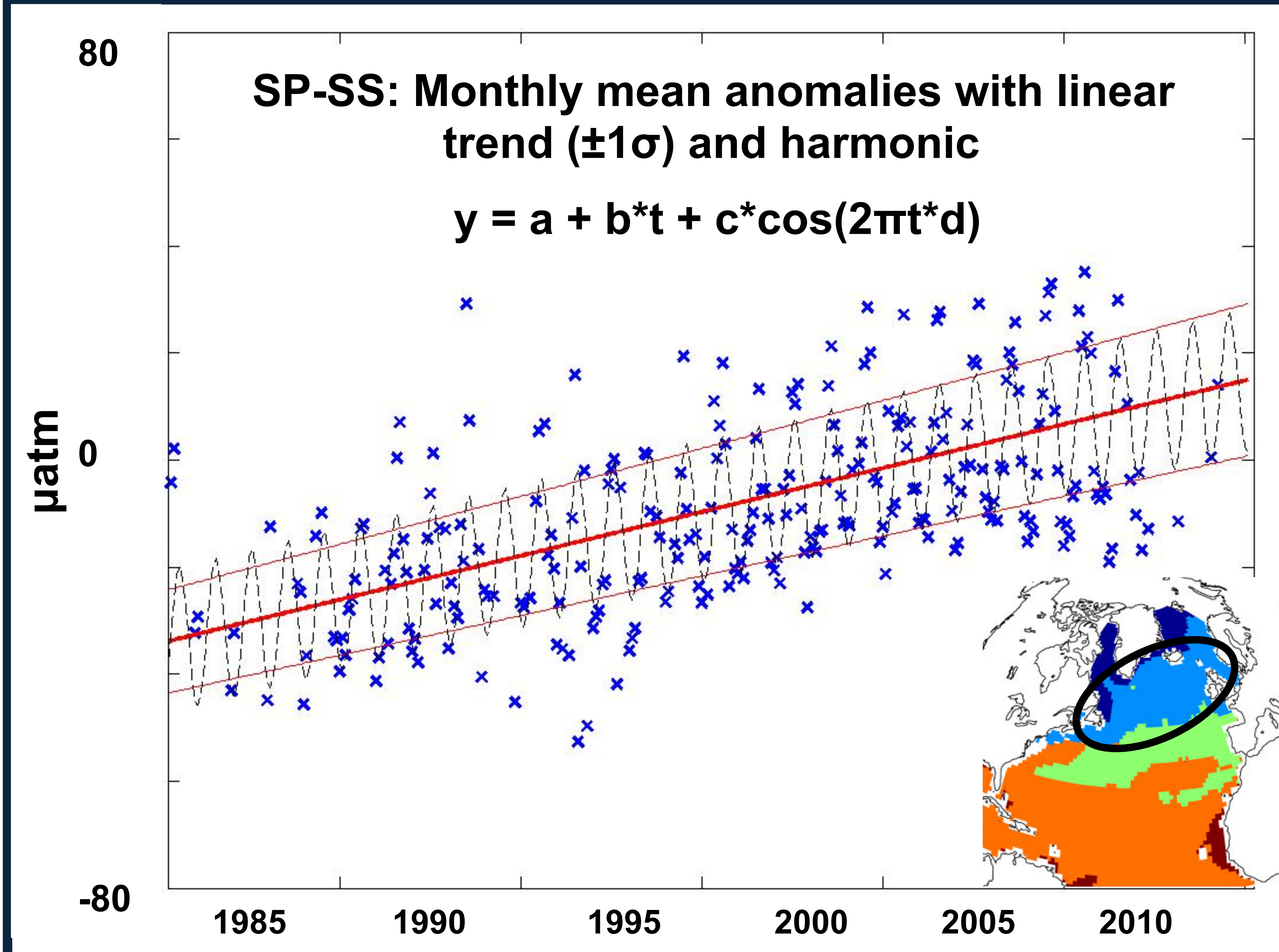
Subpolar (SP-SS)

Seasonally Stratified Subtropical (ST-SS)

Permanently Stratified Subtropical (ST-PS)

Low-Latitude Upwelling (LLU)

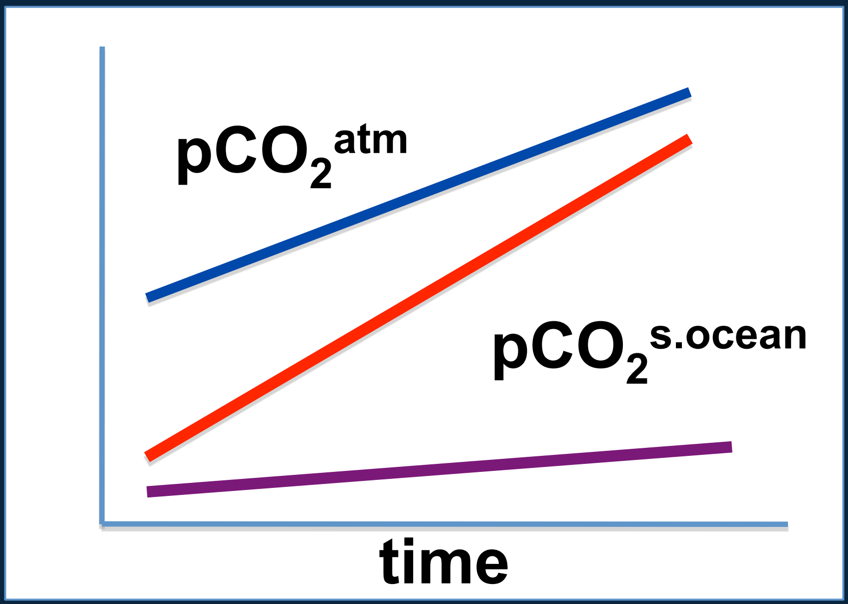



SP-SS: Monthly mean anomalies with linear trend (±1σ) and harmonic
y = a + b*t + c*cos(2πt*d)
80
0
-80
µatm
1985
1990
1995
2000
2005
2010

Results of Data Analysis

1993-2005 (decadal)

1981-2009 (multi-decadal)



$dpCO_2^{s.ocean}/dt$ > $dpCO_2^{atm}/dt$

DECLINING SINK

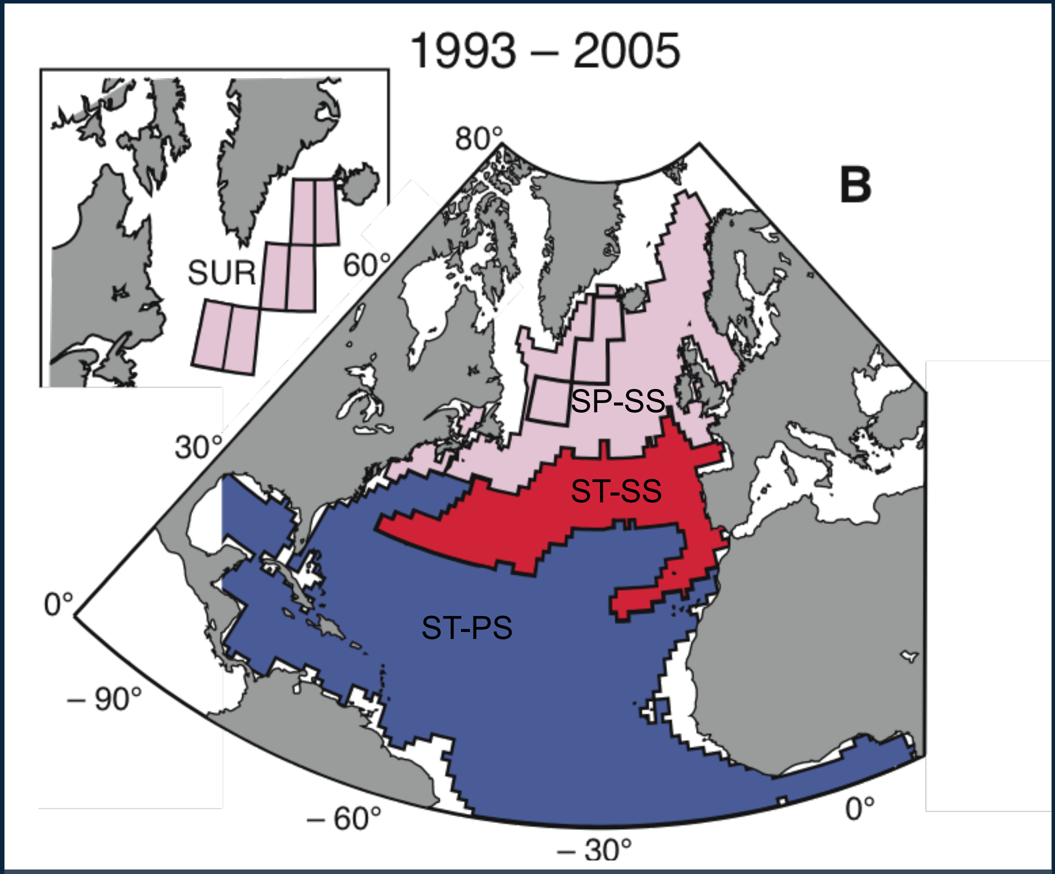
$dpCO_2^{s.ocean}/dt$ < $dpCO_2^{atm}/dt$

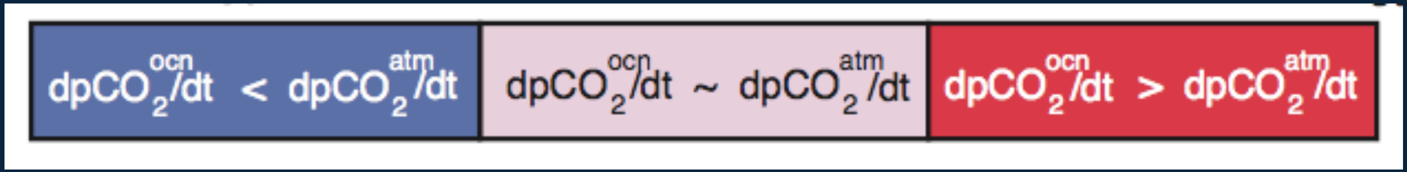
INCREASING SINK

Compare calculated pCO_2 trends to atmospheric trends to determine if carbon sink is changing with time

Trend in pCO_2^{ocean} compared to pCO_2^{atm}

Decadal:
1993-2005

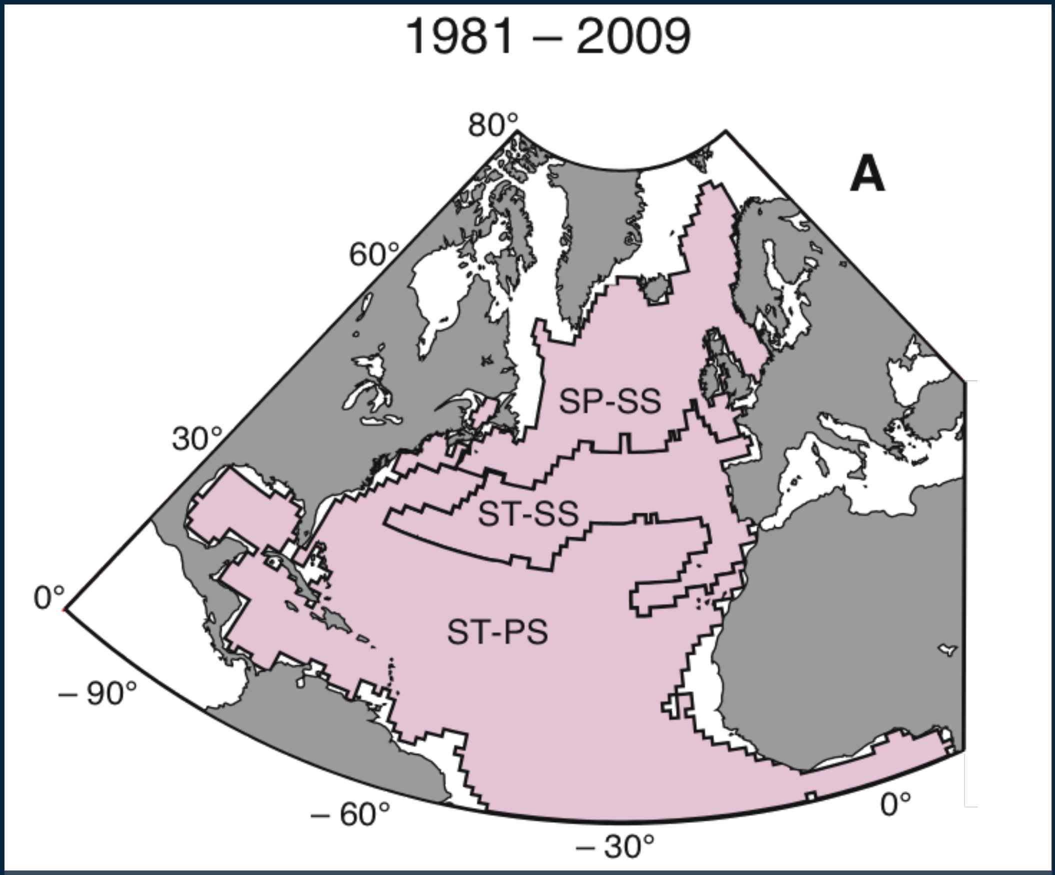


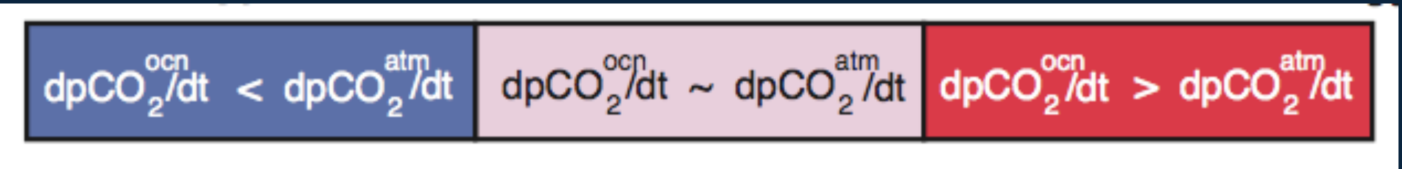


increasing sink | steady | decreasing sink

Trend in pCO_2^{ocean} compared to pCO_2^{atm}

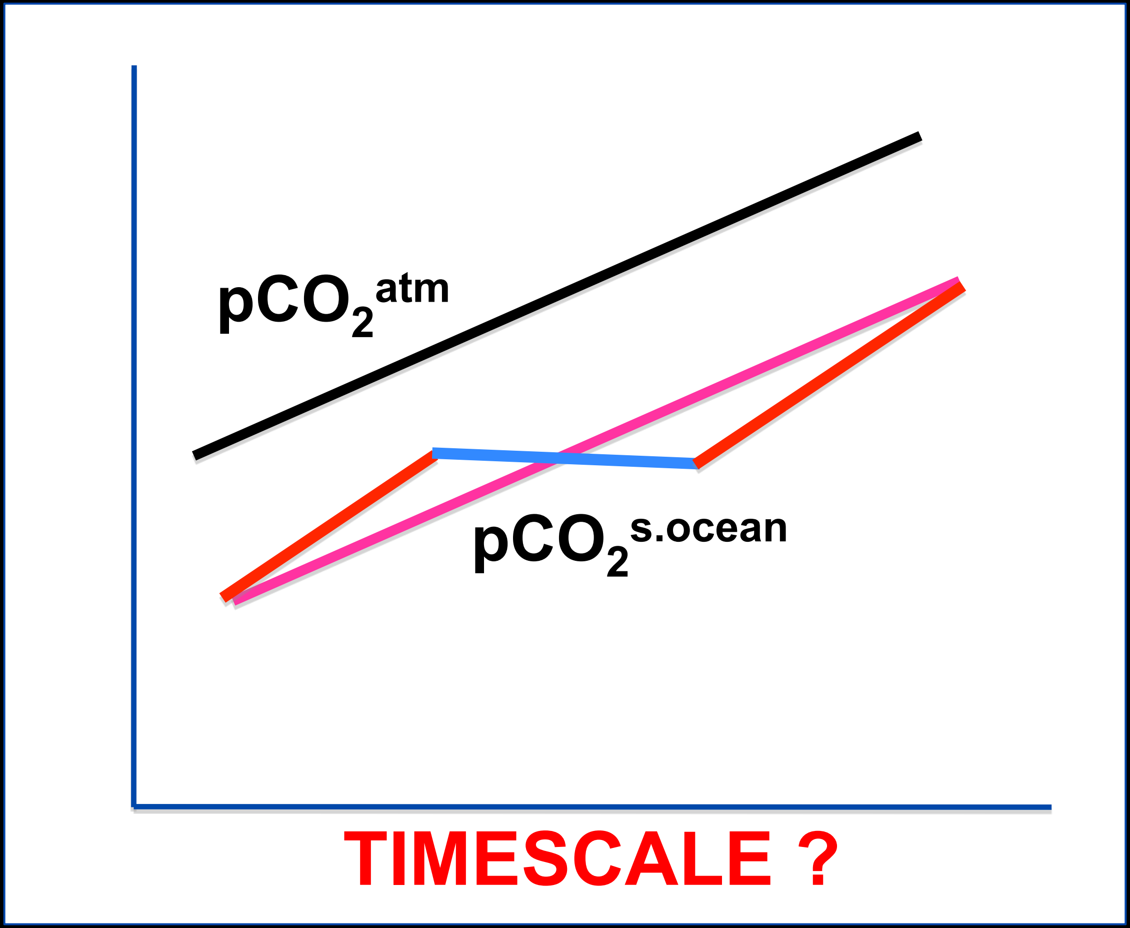
Multi-decadal:
1981-2009

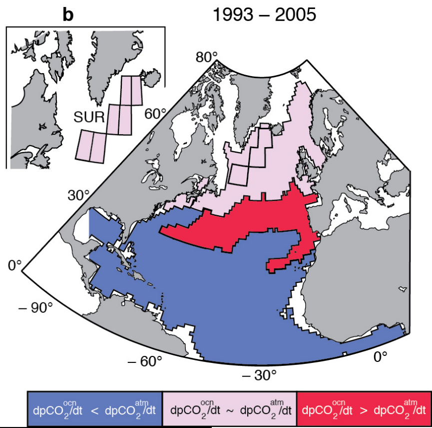




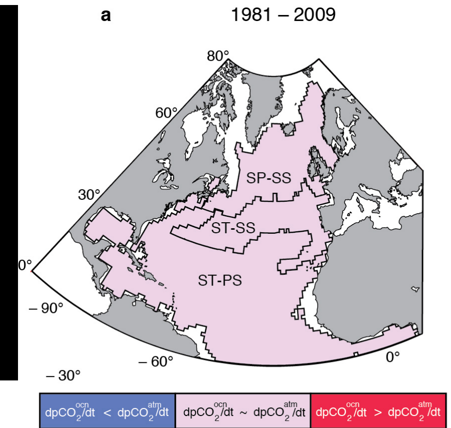
increasing sink | steady | decreasing sink

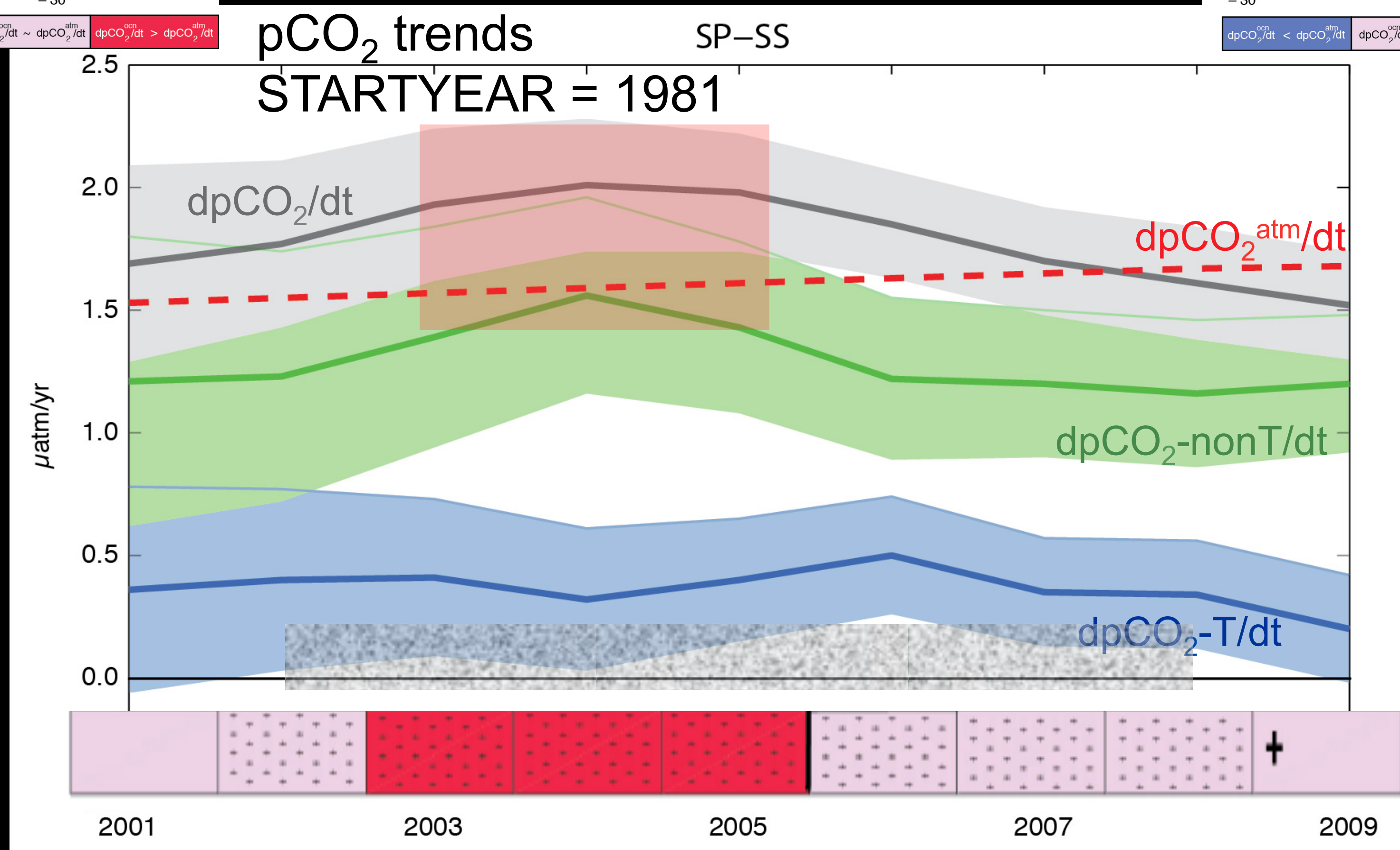
On what timescale does the ocean follow the atmosphere?





Evaluate transition from decadal to multidecadal

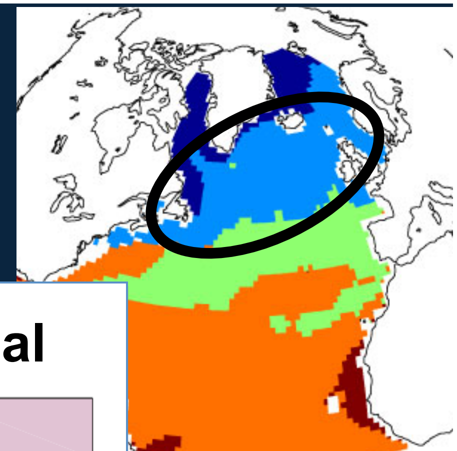


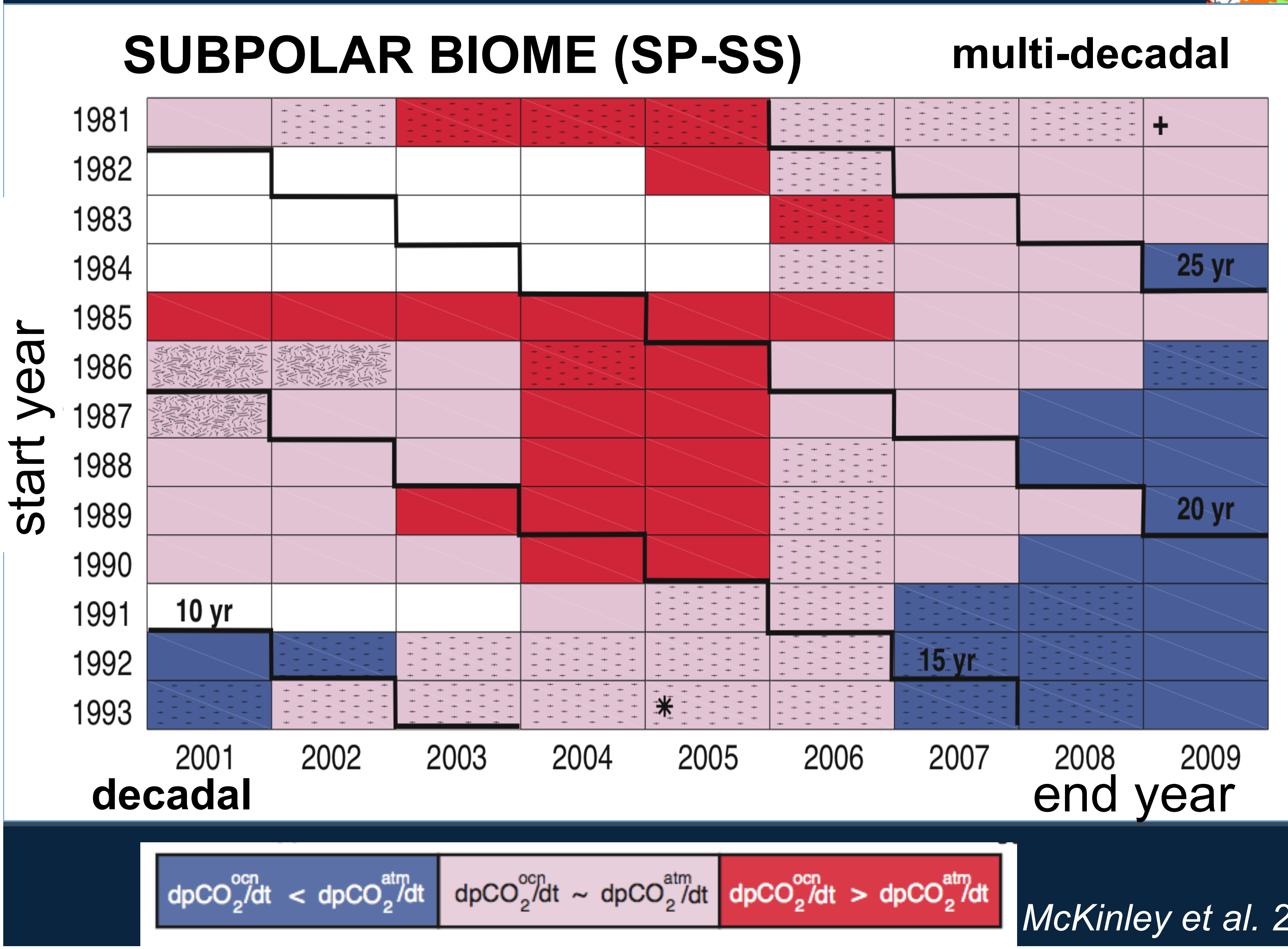


ENDYEAR

Considering varying timescales

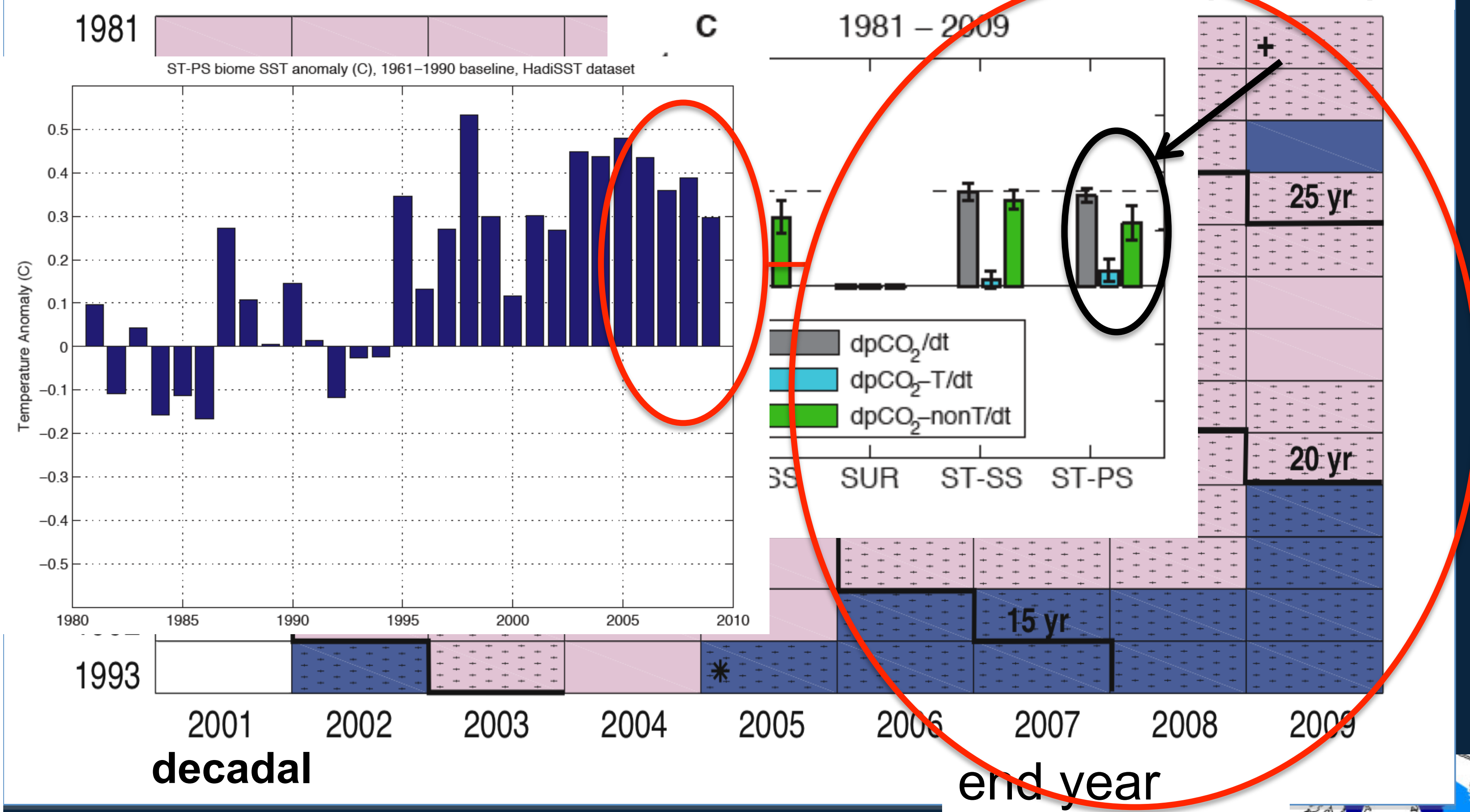
Dotted = warming influence significant

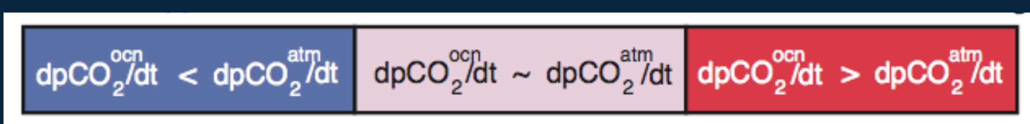


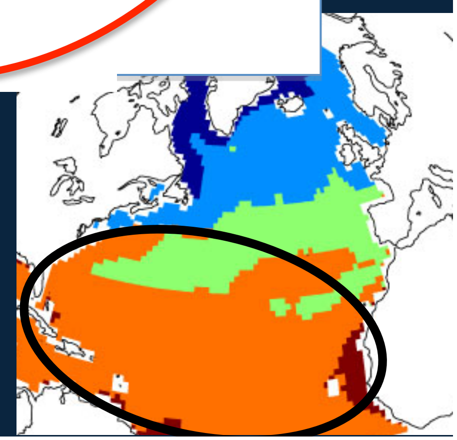


McKinley et al. 2011

SUBTROPICAL PERMANENTLY STRATIFIED (ST-PS)







McKinley et al. 2011

Conclusions: N. Atlantic Trends

- Data are sufficient to estimate biome-scale trends, with 1σ confidence
  - More data will increase confidence
- North of 30^{o}N, anthropogenic carbon accumulation is best explanation for $pCO_2^{s.ocean}$ trends beyond 25 years
- South of 30^{o}N, evidence that warming has damped carbon uptake since 2006

Conclusions

- Quantifying the open ocean carbon cycle
  - Mean sources and sinks can be partitioned
  - Some year-to-year variability can be explained
  - Distinguishing variability from long-term trends is critical
    - Subtropical N. Atlantic solubility feedback, reducing sink, is increasingly clear
- Research is limited by both data and process understanding