2018 International AMOC Science Meeting | US-CLIVAR

Feedbacks between the AMOC and the carbon cycle: a present and future perspective

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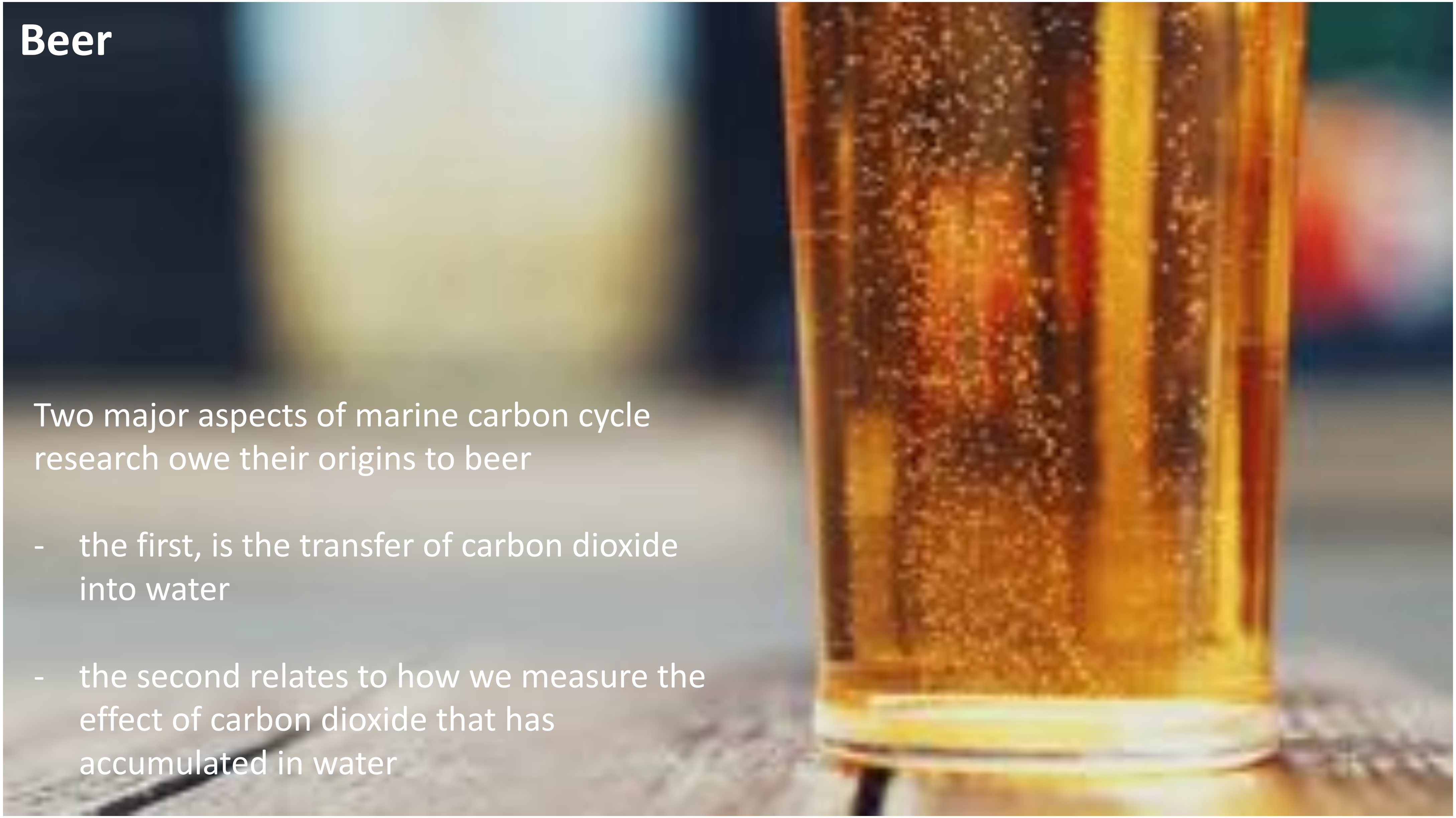
SUMMARY – AMOC-Carbon – a review

- Introduction to the carbon cycle and its drivers
- Current knowledge of how it relates to the overturning circulation
- The carbon cycle into the future



Beer

Two major aspects of marine carbon cycle research owe their origins to beer

- the first, is the transfer of carbon dioxide into water

- the second relates to how we measure the effect of carbon dioxide that has accumulated in water

Beer

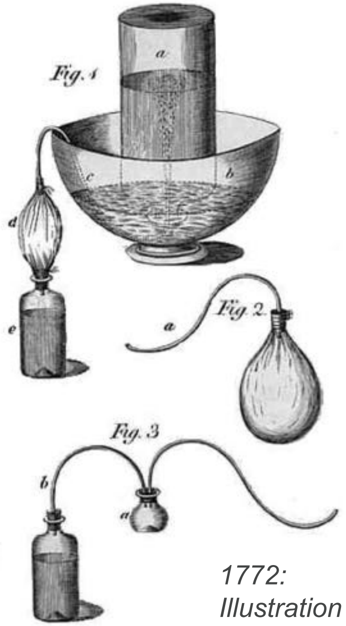
1. Getting CO_2 into water:

Require [atmospheric CO_2] > [water CO_2]

Joseph Preistley FRS 1733-1804
English theologian, natural philosopher, chemist and political theorist, discovered dephlogisticated air (oxygen)

In 1767, first to artificially carbonate water by hanging a filled vessel over a fermentation vat at a brewery in Leeds, UK (fermentation vats naturally give off CO2 in the process of converting sugars into low alcohol).

Followed it up with *"Impregnating Water with Fixed Air", 1772,* chemical carbonation by dripping vitriol (sulfuric acid) into powdered chalk (calcium carbonate) producing CO_2 gas, that was then infused into agitated water



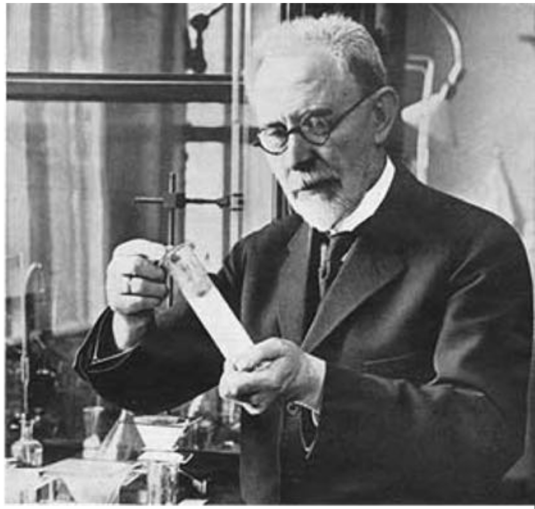
1772: Illustration from Directions for Impregnating Water with Fixed Air by Joseph Priestley

Didn't market the process commercially, but gave the method / ingredients to Captain James Cook on his 2nd Pacific voyage, in hope of its ability to alleviate scurvy.

Method picked up by Jacob Schweppe, who simplified it and did quite well out of it

Beer

2. Measuring the effect of CO_2 in water:



Søren P. L. Sørensen created the pH scale in 1909 whilst working at the Carlsberg Laboratory in Copenhagen, Denmark.

Studied the effect of ion concentration on proteins and enzymes, and because the concentration of hydrogen ions was particularly important,

Introduced the pH-scale as a simple way of expressing it, and two new ways of measuring acidity, based on electrode potentiometry and colorimetry, both still used to this day

pH Sensors

Commercially available for measuring seawater pH down to 0.004 pH units

Colorimetry

e.g. Sunburst Submersible Autonomous Moored Instrument (SAMI)-pH

Electrode potentiometry

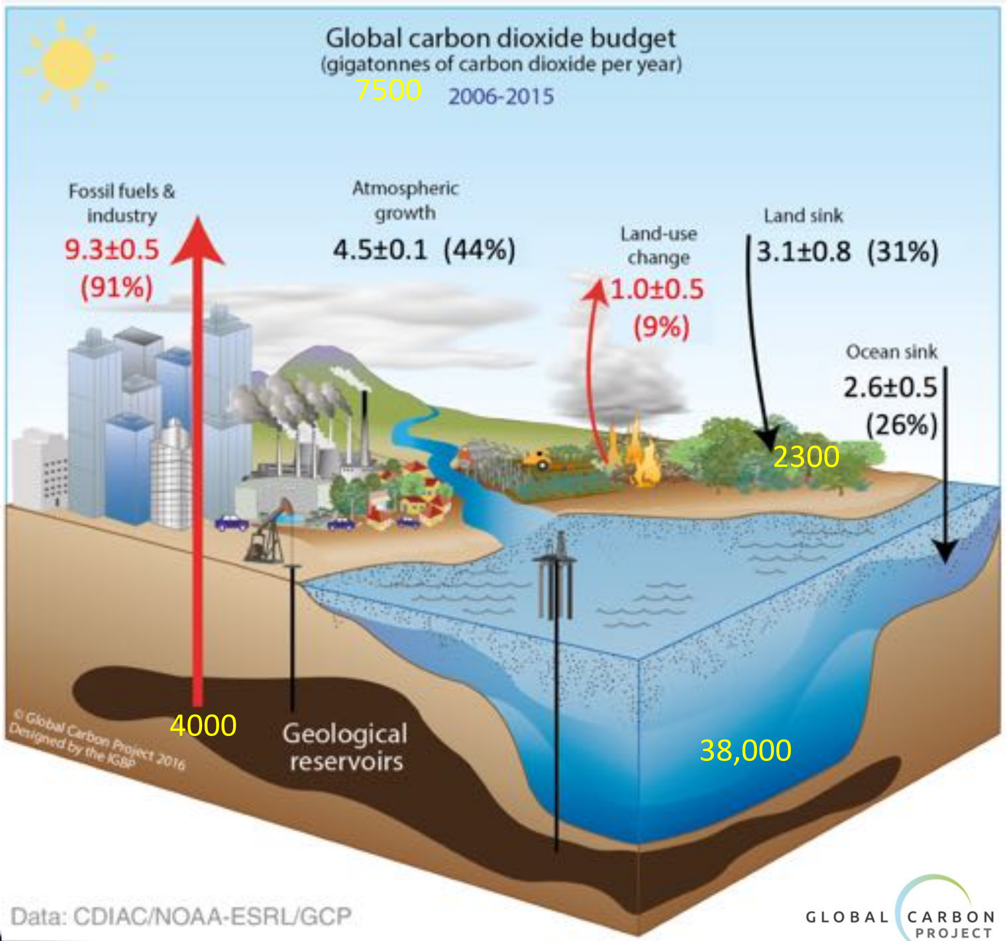
e.g. Sea Bird SeaFET Ion Sensitive Field Effect Transistor pH sensor

Beer

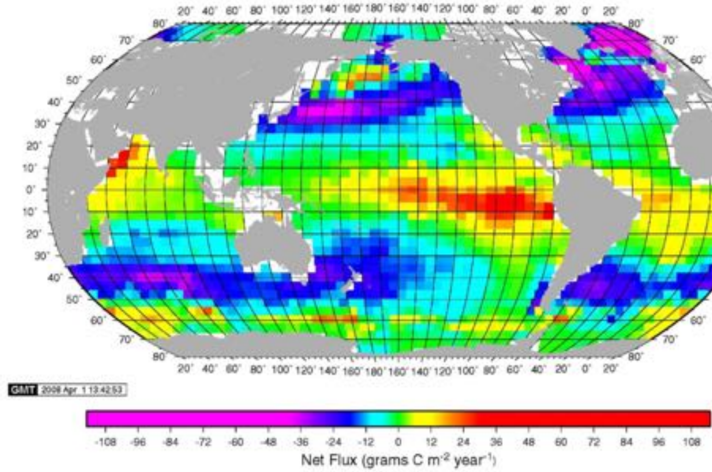
A third aspect relates not to the origins but to the future of the marine carbon cycle

- The outgassing of carbon dioxide from the liquid as the water slowly warms ups

Carbon dioxide

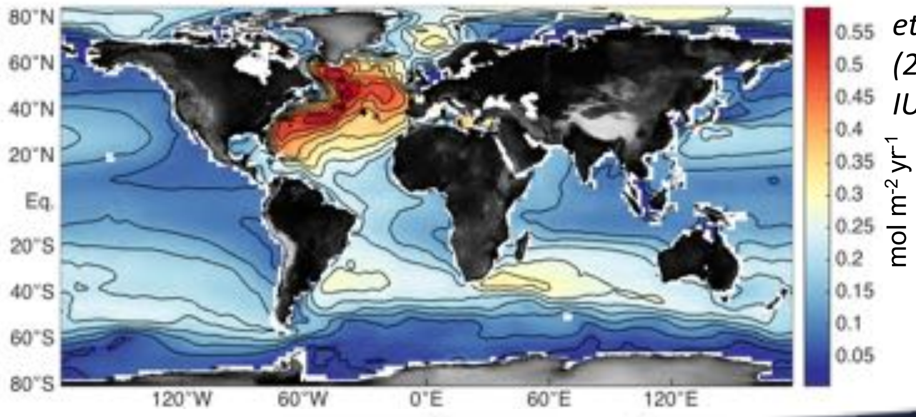


Annual flux of contemporary CO_2



Takahashi et al (2009) DSR

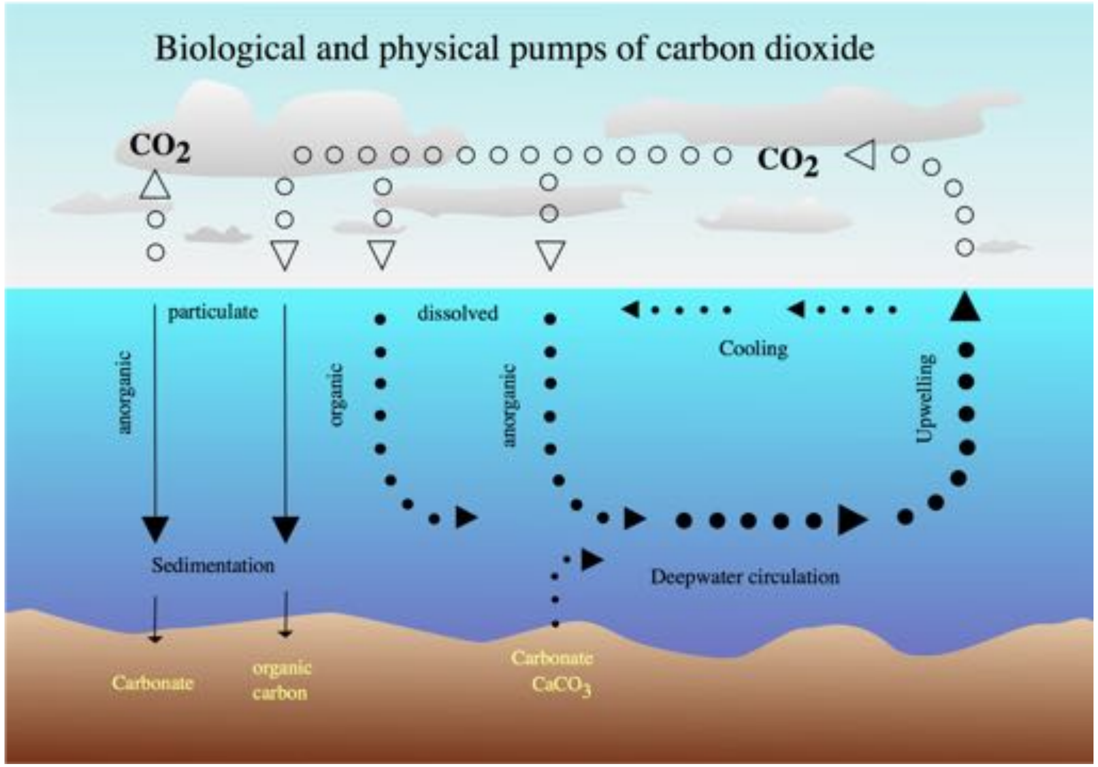
Column inventory of anthropogenic carbon



Brown et al (2016) IUCN

What are the drivers of the ocean CO_2 sink?

- Heat fluxes – cooling / warming of surface waters drives CO2 uptake / outgassing through impact on CO_2 solubility **(AMOC)**
- Biological production and the drawdown in carbon concentrations associated with this
  - Nutrient supply that sustains biological production **(AMOC)**
- Ocean Circulation
  - Transport of recently ventilated waters high in anthropogenic carbon to depth **(AMOC)**
  - Transport of old waters high in natural / remineralised carbon and nutrients to the surface **(AMOC)**
- Wind regime – speed of air-sea CO_2 transfer related to wind strength

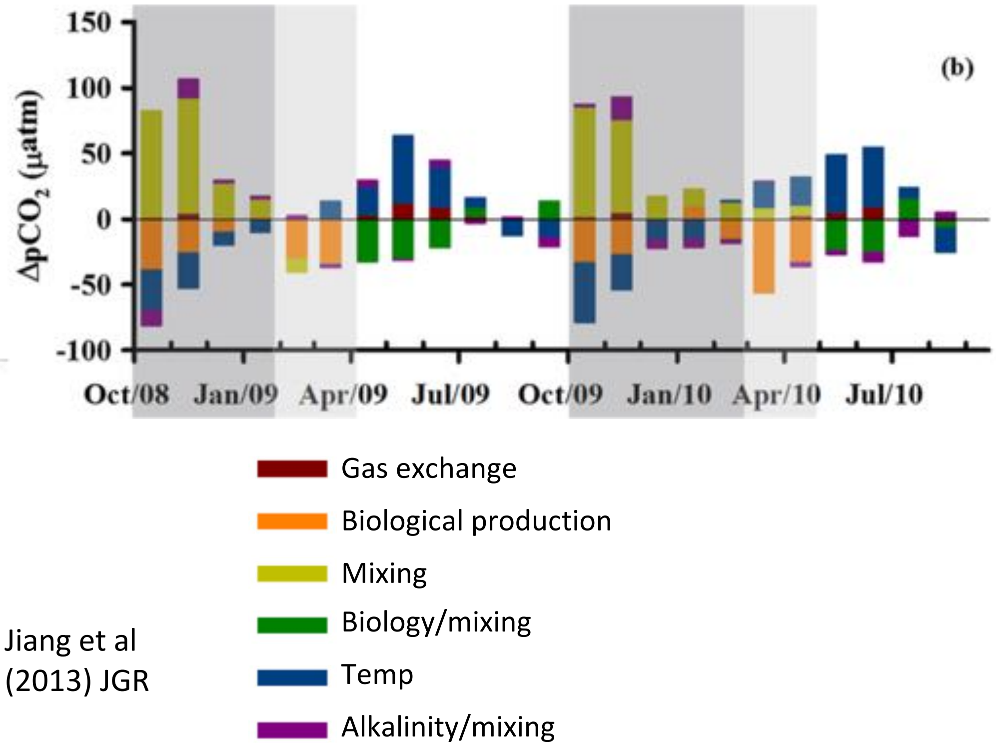


Ocean CO_2 sink currently a delicate balance between speed at which CO_2 enters the ocean, & speed at which it is removed from the surface -> substantial variability

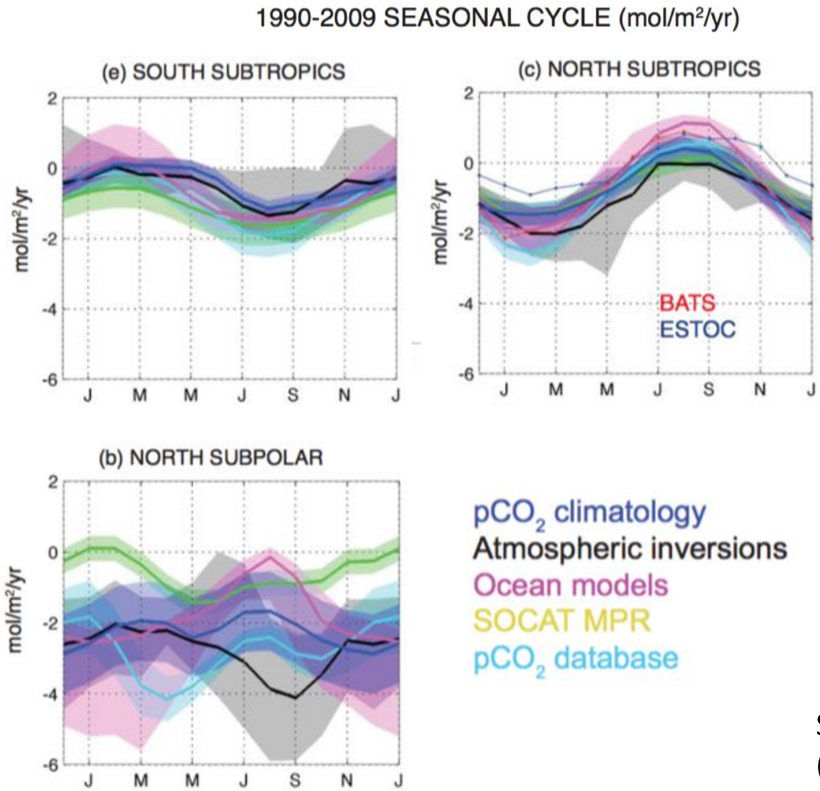
What are the drivers of the ocean CO_2 sink?

NORTH ATLANTIC

Variability in seasonal ΔpCO_2 amplitude, and continuing disagreement between different methods for constraining the seasonal CO_2 cycle



Jiang et al (2013) JGR



Schuster et al (2013) BG

What are the drivers of the ocean CO_2 sink?

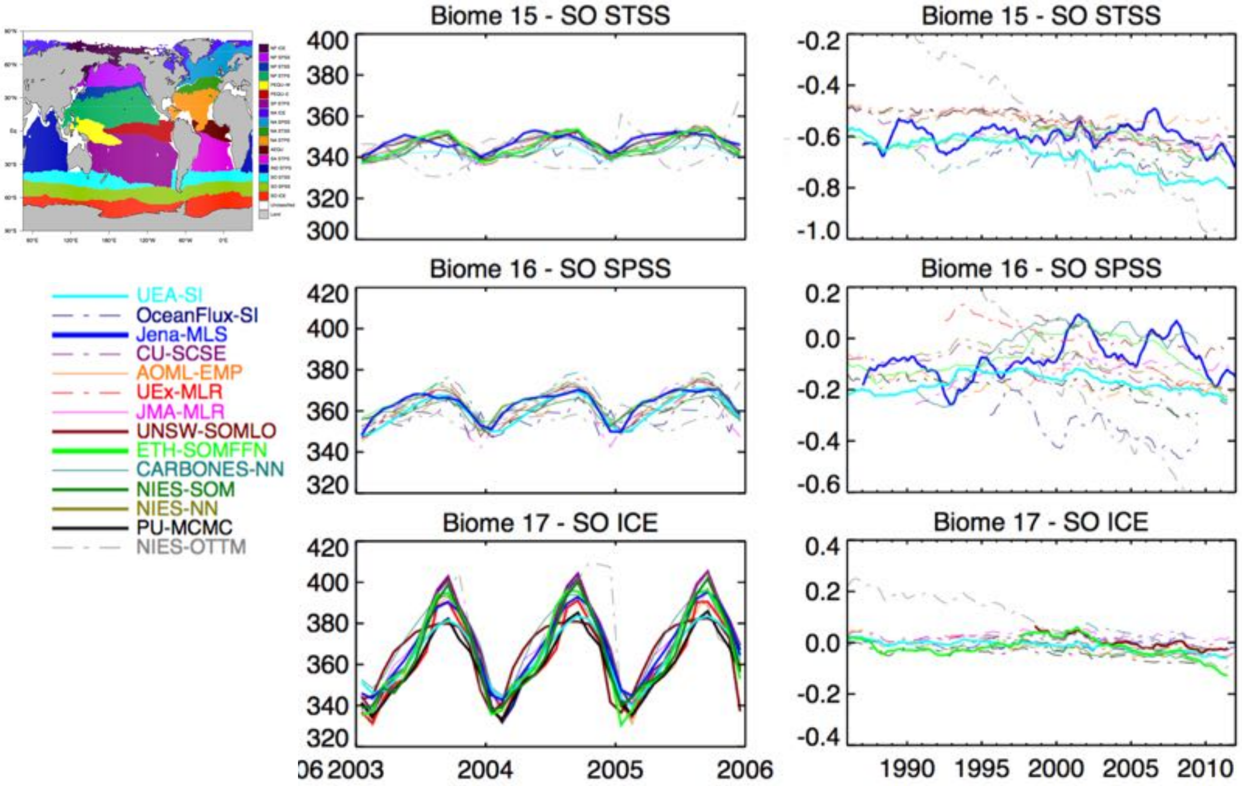
Variability in seasonal ΔpCO_2 amplitude, and continuing disagreement between different methods for constraining the seasonal CO_2 cycle

Observations

2003-2005 SSpCO_2

Mapping

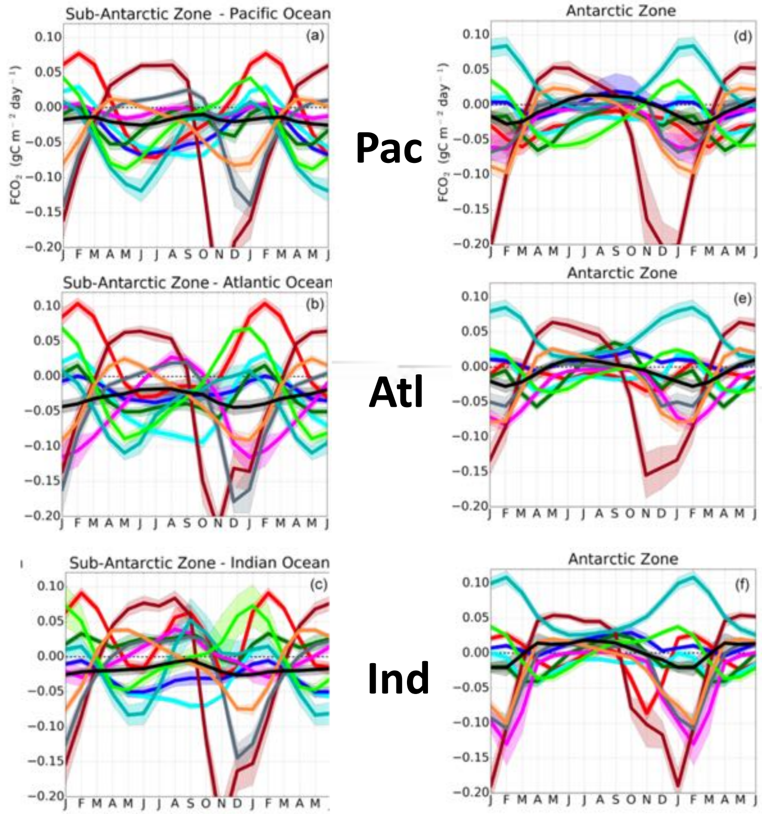
Interannual flux variation



SOUTHERN OCEAN

Models

SEASONAL CYCLE IN SEA-AIR CO2 FLUX

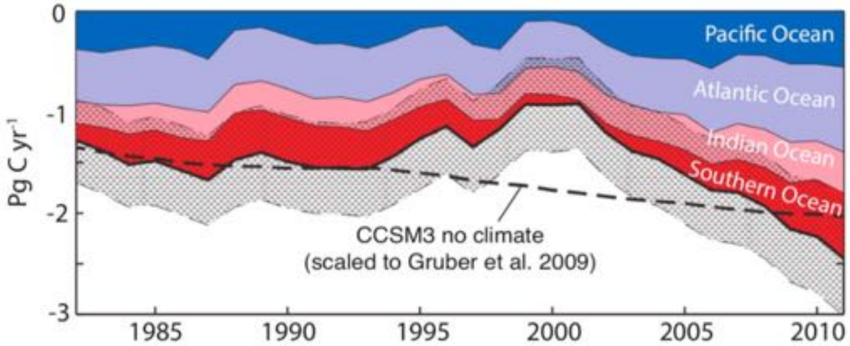


Mongwe et al (2018) BG

Understanding drivers of flux variability and trends key to predicting future response

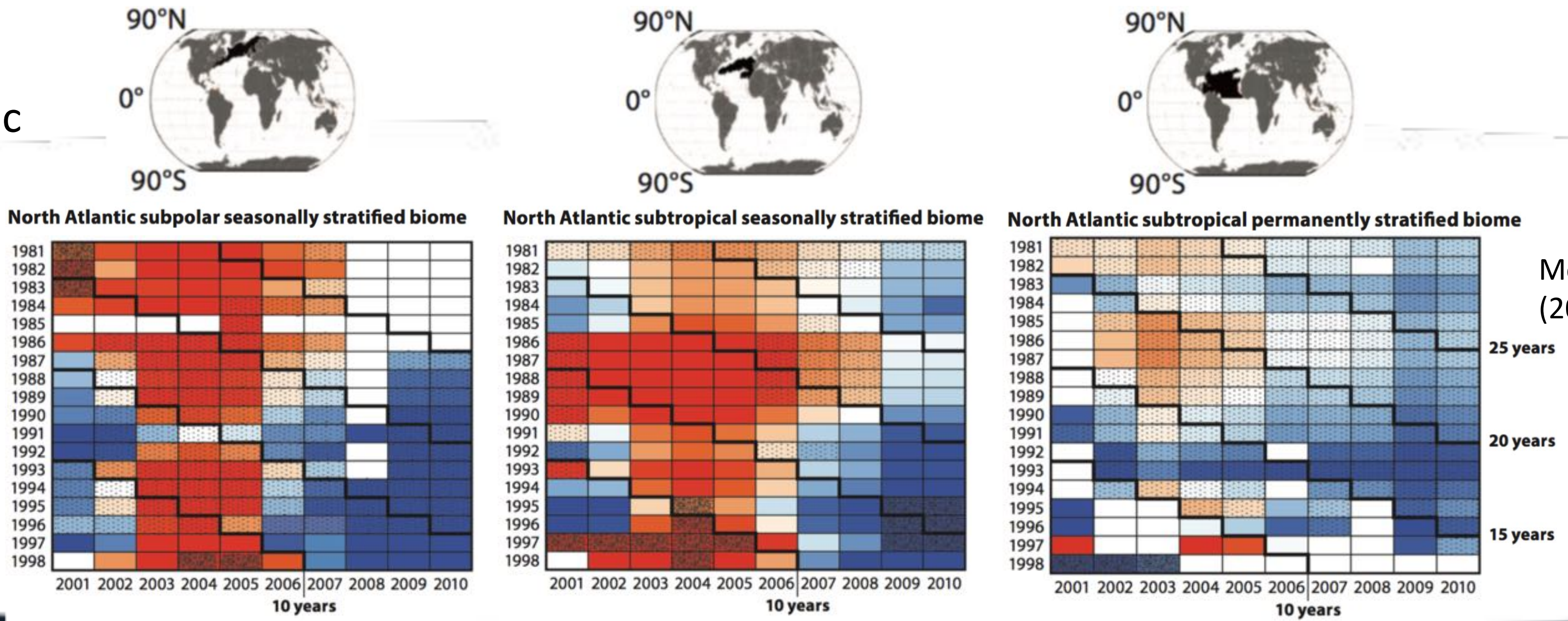
Carbon dioxide fluxes

Substantial interannual variability in air-sea CO_2 fluxes



Landschutzer et al (2016) GBC

Variability in regional Atlantic decadal trends

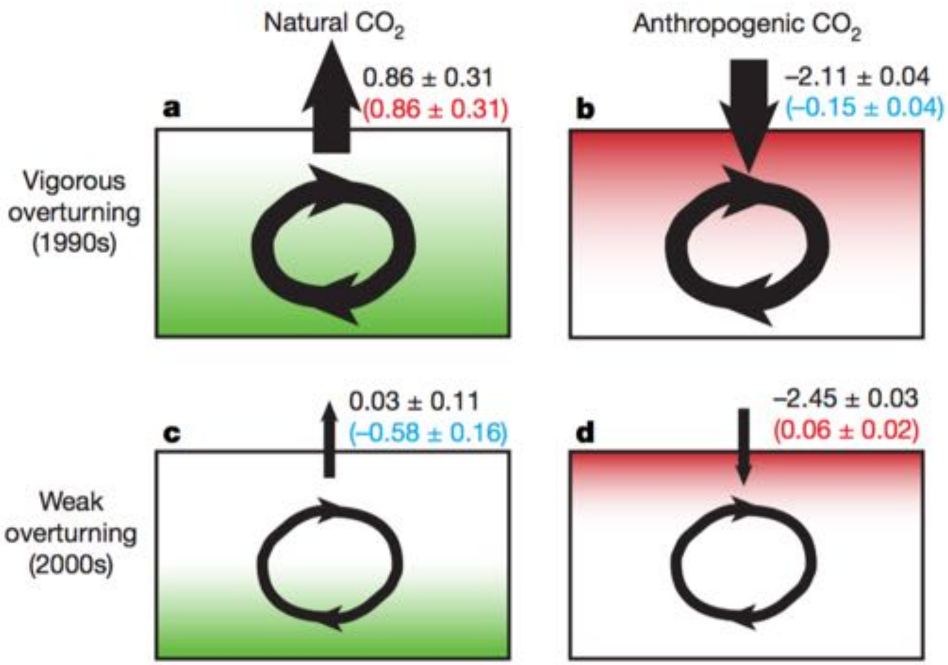


McKinley et al (2017) AnnRev

Carbon dioxide fluxes linked to ocean overturning

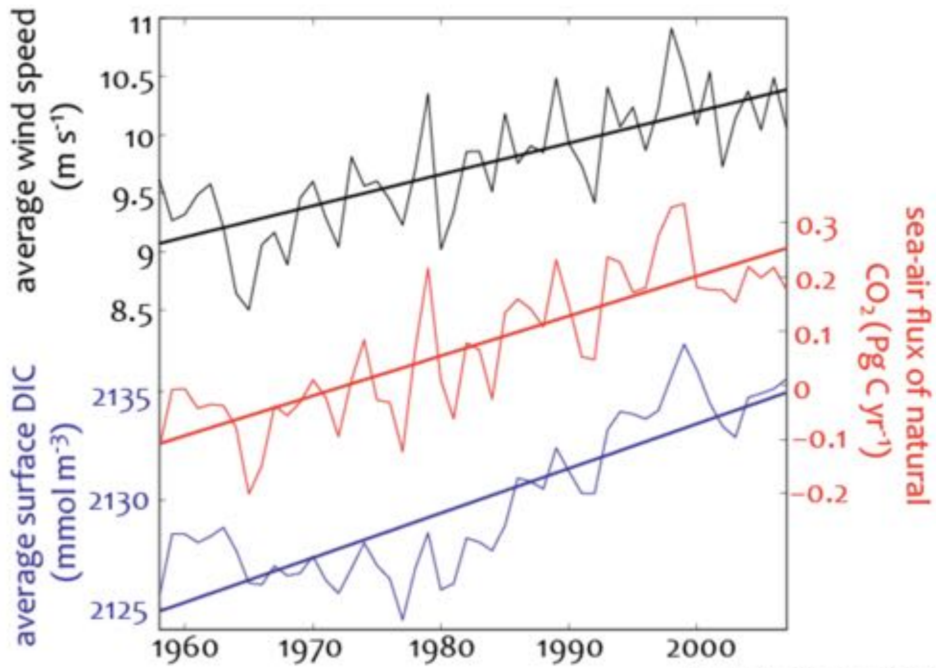
Decadal variability in air-sea CO_2 fluxes linked to circulation variability, itself possibly linked to wind

Ocean inversion from observations



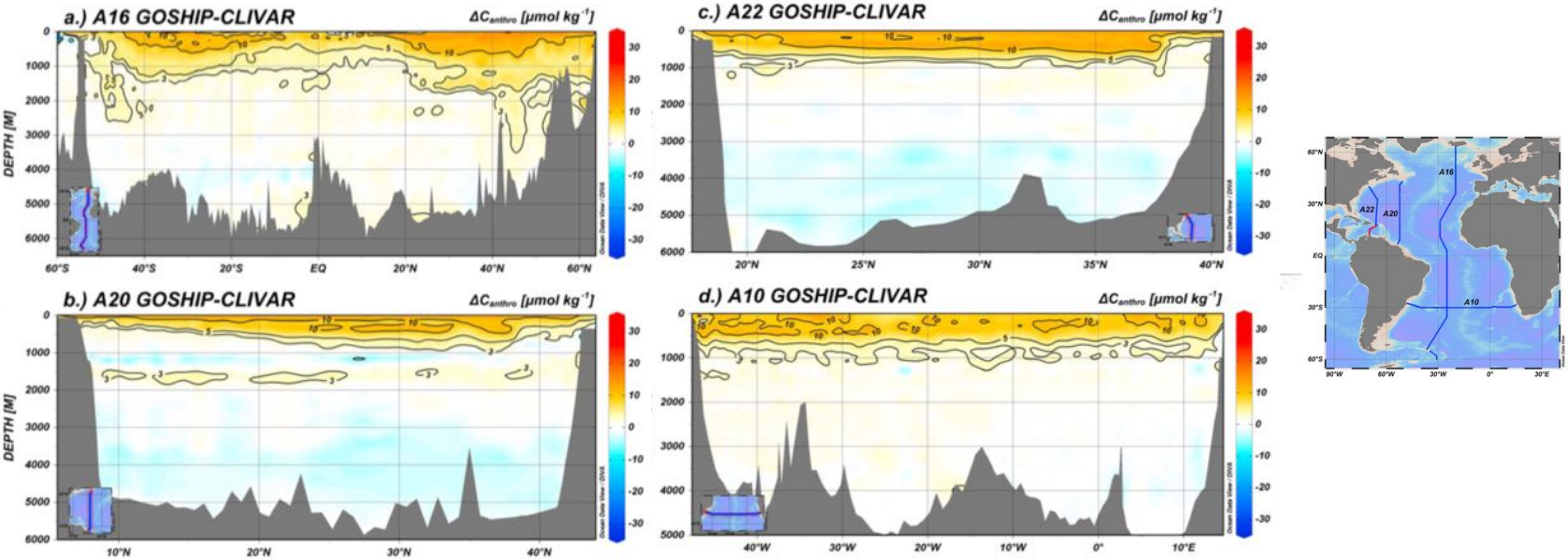
DeVries (2017) Nature

Hindcast model



Lovenduski et al. (2013)

The 'other' CO_2 problem - Ocean acidification



Woosley & Wanninkhof (2016)

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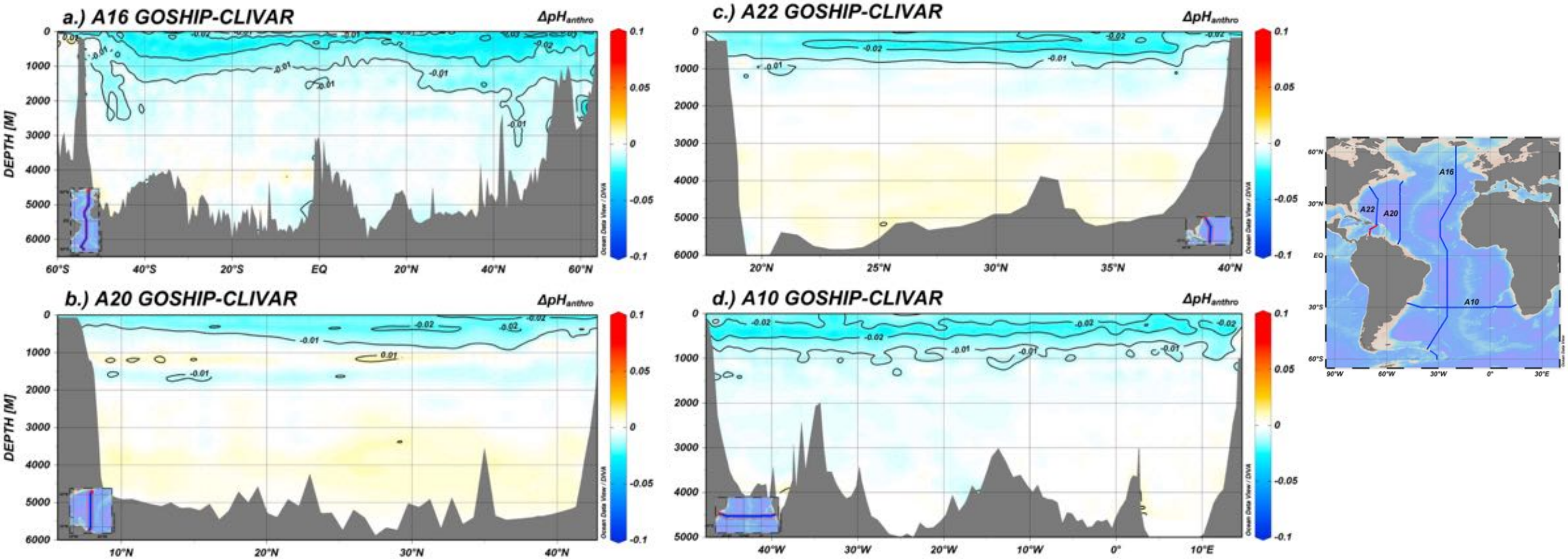


Woosley & Wanninkhof (2016)

AMOC CO_2 feedbacks: present

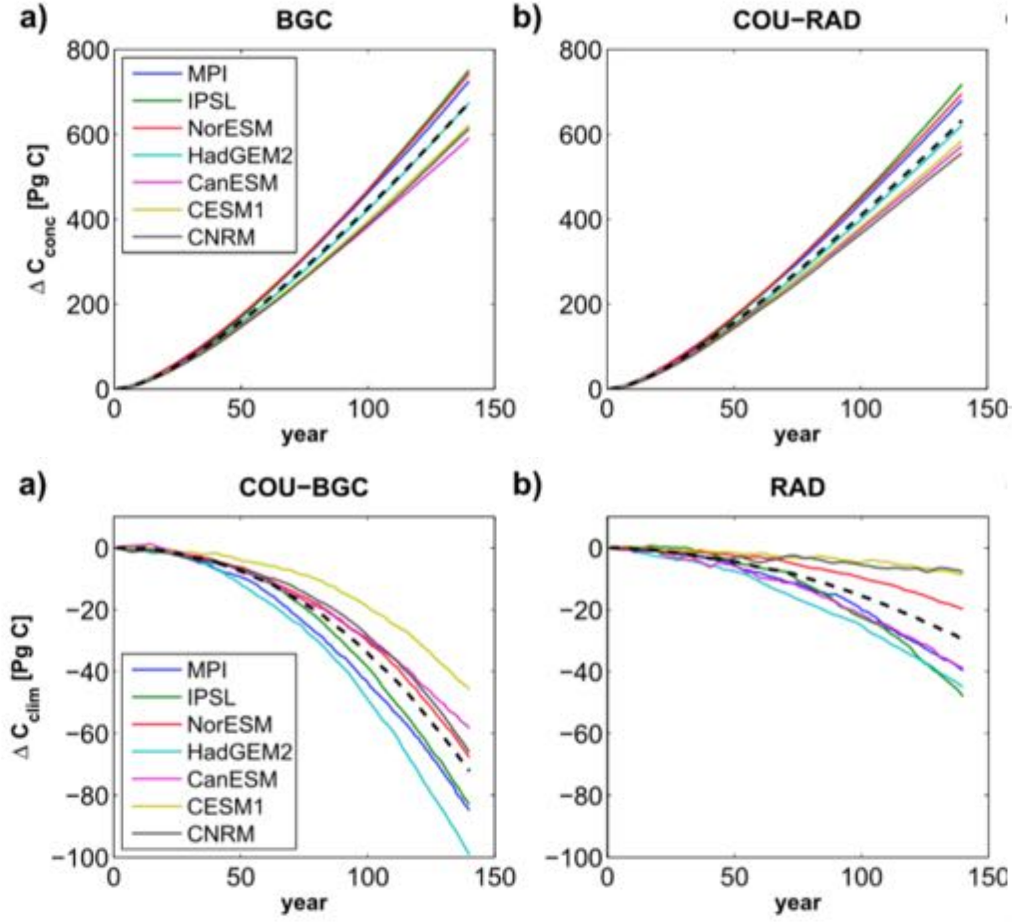
- Decadal variability in upper ocean overturning linked to variability in global air-sea CO_2 fluxes, predominantly through impacts on natural carbon system
- Regionally the co-variability is not as clear-cut
- In Atlantic, AMOC directly related to regional ocean carbon transport, and capacity of system to uptake additional CO_2 from the atmosphere
- Short-term AMOC variability can directly impact biological system through vertical nutrient supply, and carbon drawdown associated with enhanced export production
- Ocean acidification being propagated into deep waters by AMOC

AMOC CO_2 feedbacks: future impacts CMIP5 - global

COU = fully coupled climate carbon
BGC = Increasing atmospheric pCO_2, no radiative effect
RAD = preindustrial atmospheric CO_2, yes radiative effect

Change in carbon inventory

Carbon release due to carbon-climate feedback



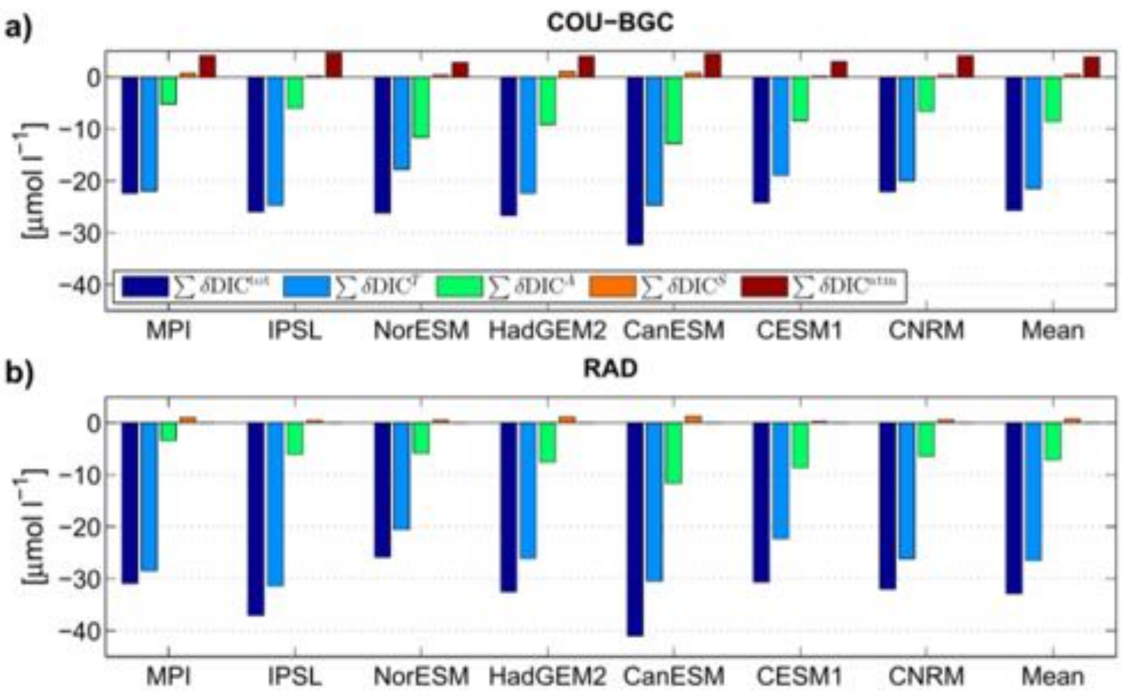
COU undergoes:

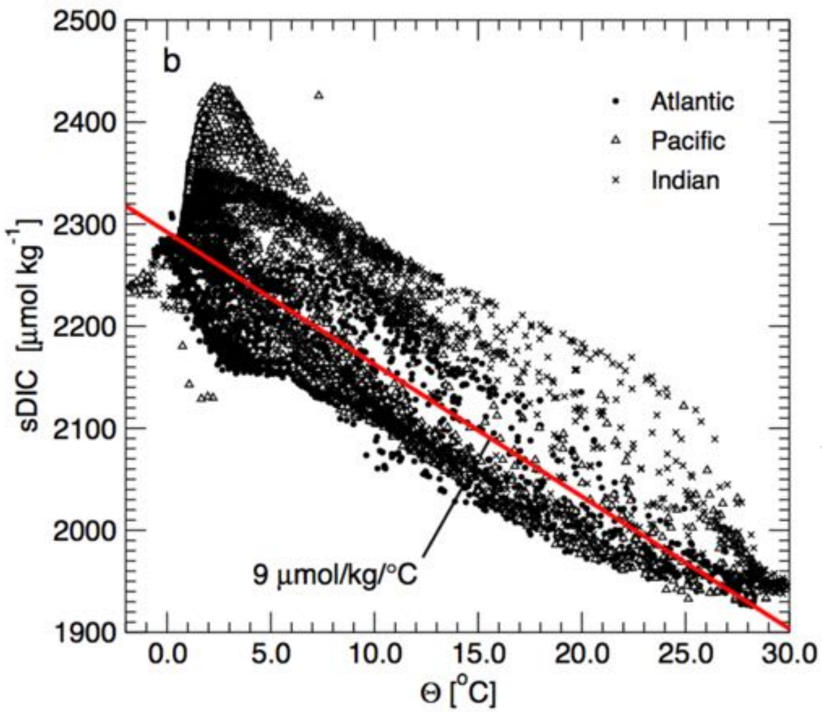
- Higher ocean heat content
- Higher stratification (lower MLDs)
- Arctic and Antarctic sea ice loss
- Slowdown in AMOC

Schwinger et al (2014)

CMIP5 – feedbacks on surface carbon concentrations

Total decrease in surface DIC concentration due to climate change



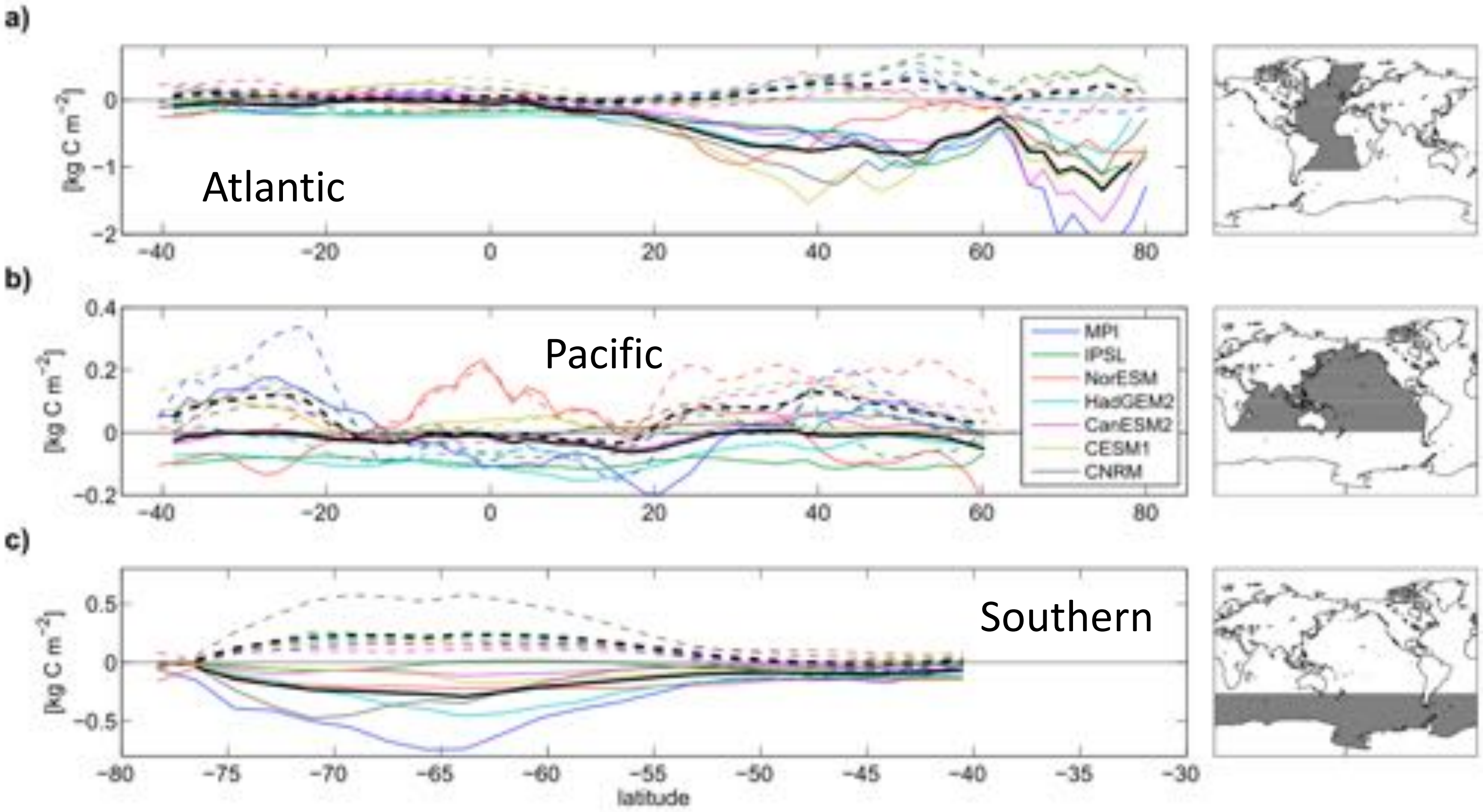


Total | Temperature (solubility) | Alkalinity | Salinity | Atmospheric CO_2

Sarmiento & Gruber (2006)

Schwinger et al (2014)

CMIP5 – feedbacks on deep carbon concentrations >500m



Schwinger et al (2014)

Carbon-climate feedbacks in presence (solid) and absence (dashed) of increasing atmospheric CO_2

Regions where overturning circulation is prominent show greatest response

AMOC slowdown leads to less anthropogenic CO_2 to be transported to depth, but also less natural CO_2 to be outgassed

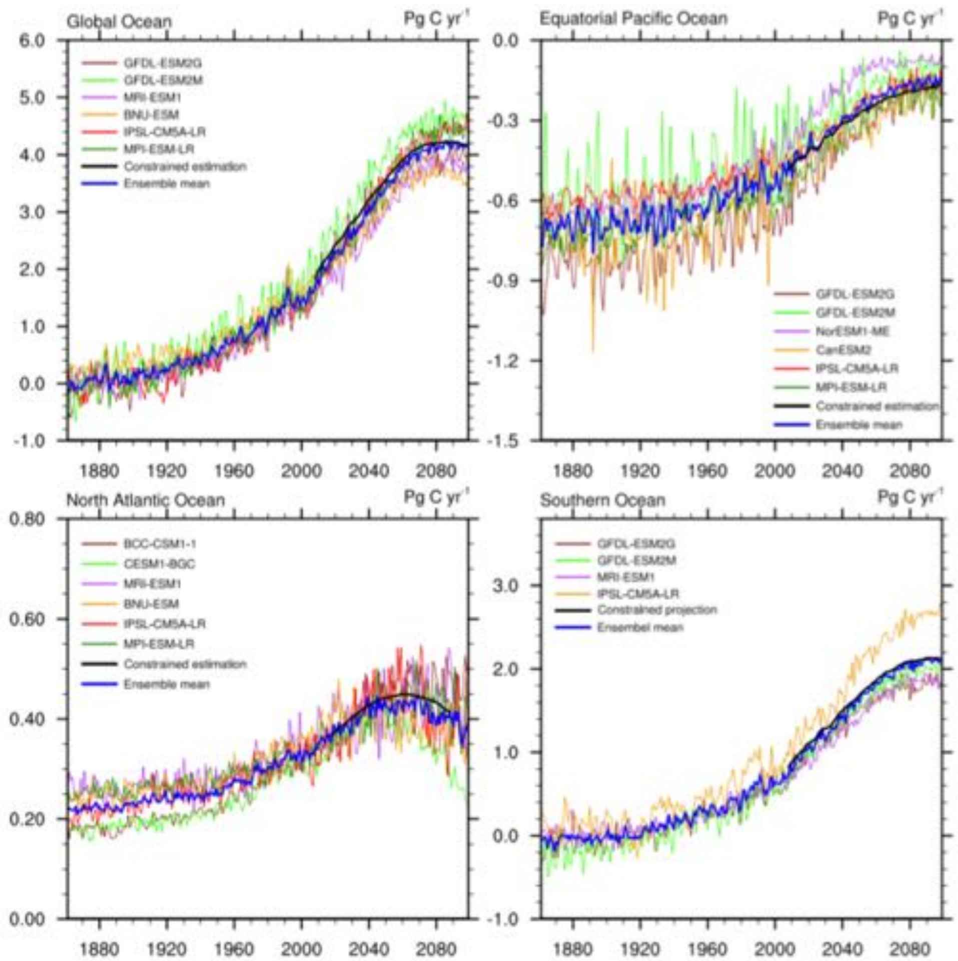
AMOC CO_2 feedbacks: future impacts on air-sea CO_2 fluxes CMIP5

Historical and projected air-sea CO_2 fluxes

Carbon response to higher ocean heat content, increased stratification (lower MLDs), Arctic and Antarctic sea ice loss, slowdown in AMOC

- Increases in CO_2 uptake by the ocean to stop by 2070
- Carbon uptake in the North Atlantic Ocean is predicted to continuously increase until 2040, remain stable between ~2040 and 2070, then rapidly decrease after 2070

Wang et al (2016)

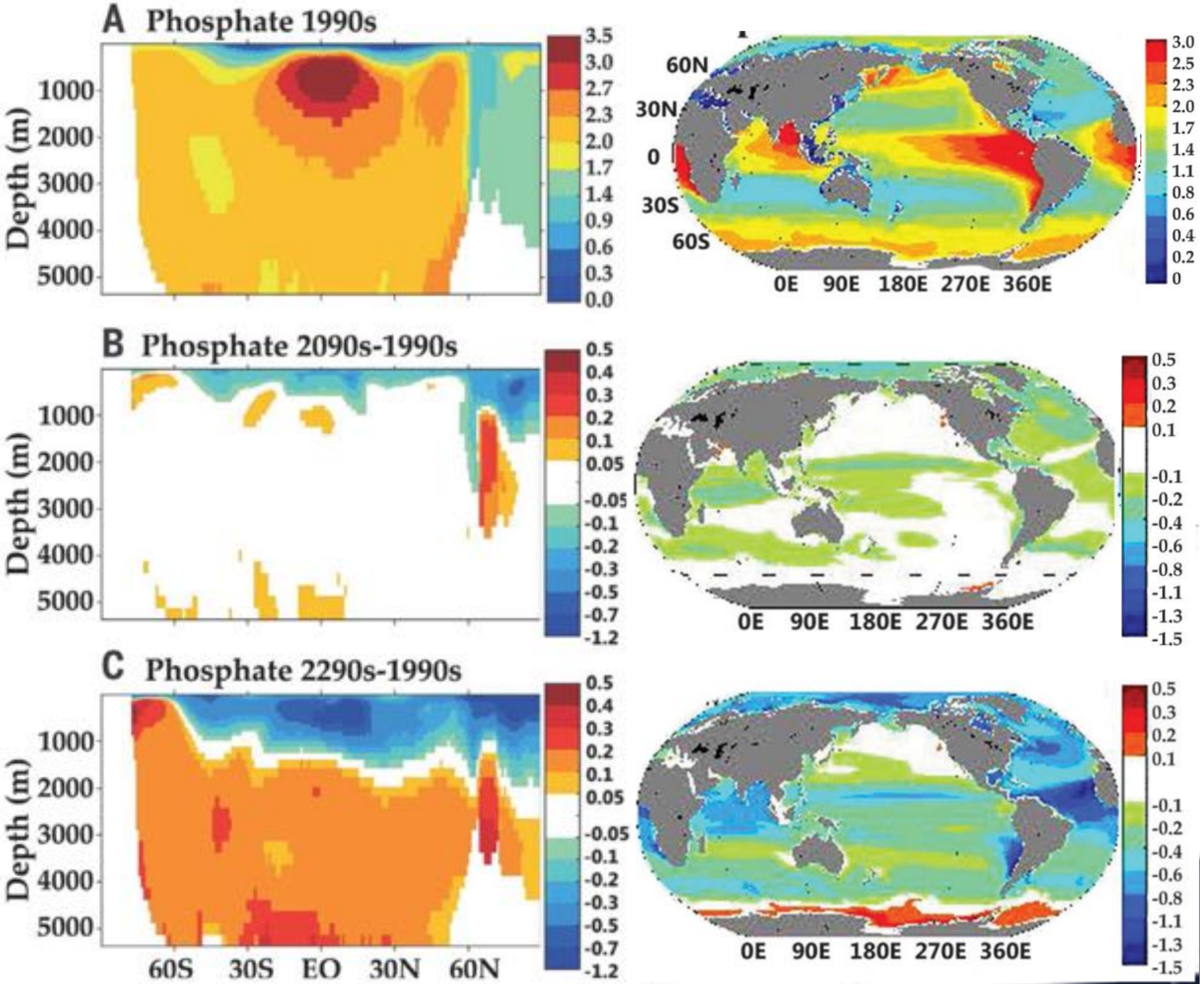


AMOC CO_2 feedbacks: nutrients

Biological productivity in the North Atlantic is sustained by nutrients entrained and subducted in the Southern Ocean, and transported northwards as part of the AMOC.

If the rate at which nutrients are supplied to the surface layer becomes slower than the rate at which they are exported through production, then nutrients will be steadily stripped from the surface and accumulate at depth, trapping them in the deep ocean.

This may lead to increased nitrogen fixation, production of N_2O (GHG), and expansion of deoxygenation zones with substantial impacts on ecosystems

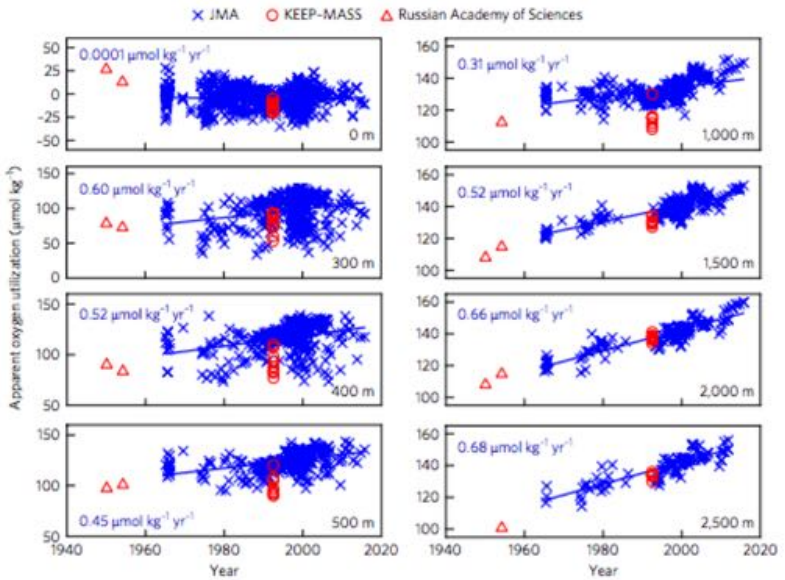


AMOC CO_2 feedbacks: reduced ventilation leading to deep acidification

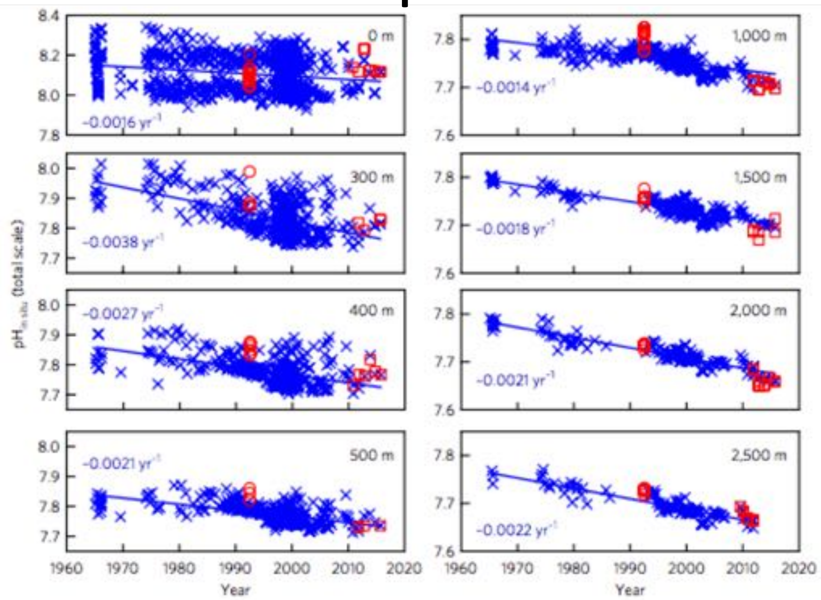
An additional consequence of this will be enhanced acidification at depth, as greater organic decomposition leads to the addition of carbon to deep waters.

Chen et al (2018)

AOU



pH



Sea of Japan – reduced ventilation between 1965 and 2015 has increased AOU throughout the water column and increased pH. pH at 2500m has decreased 25% quicker than at surface, which has been tracking atmospheric increase

AMOC CO_2 feedbacks: export of acidified waters to depth

Perez et al (2018)

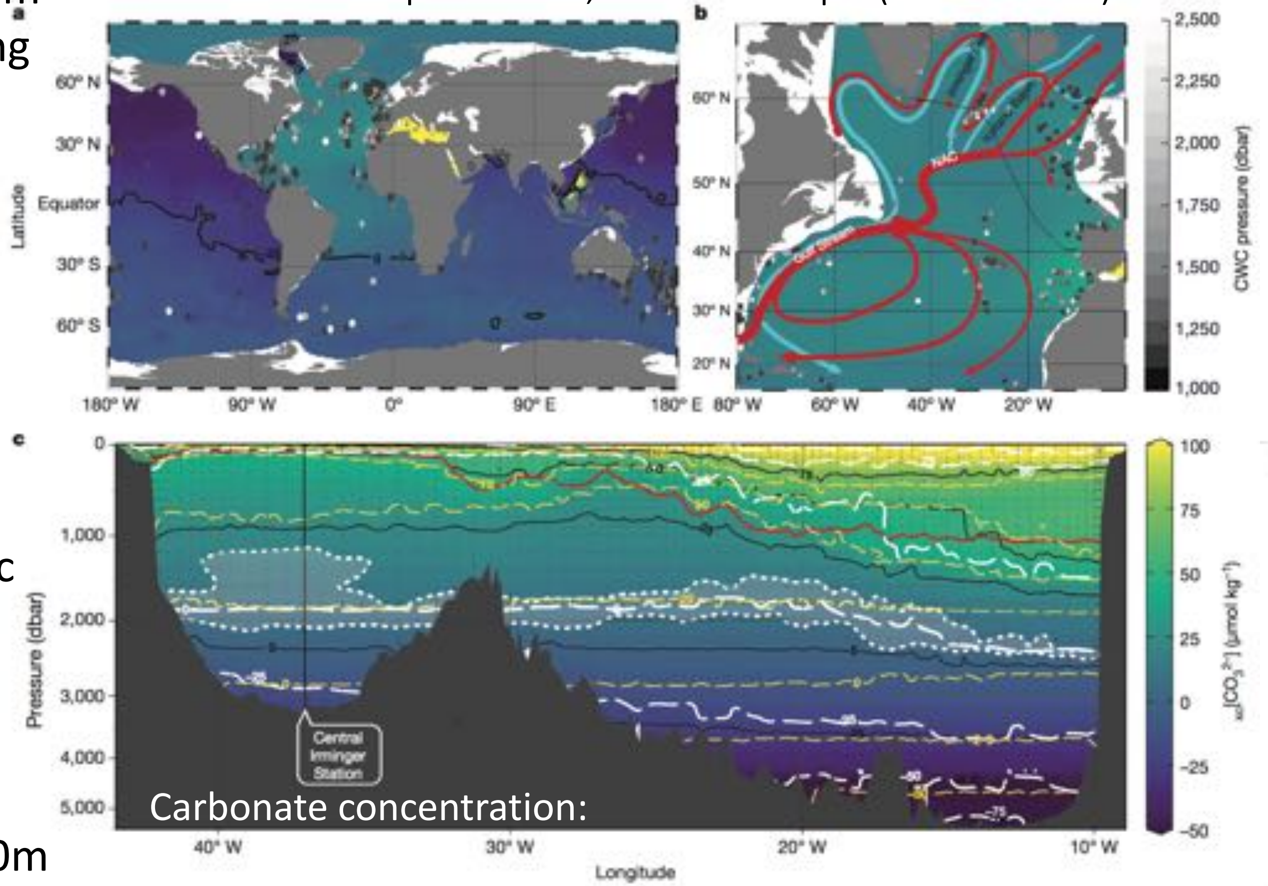
Cold water coral (CWC) reefs are "ecosystem engineers" acting as breeding and spawning grounds for multiple species of fish, many economically important

95% of CWC located above aragonite saturation horizon, below which their skeletons would begin to crumble and dissolve.

North Pacific ASH is shallower than Atlantic

Overturning circulation is transporting carbonate-depleted waters to depth. Predicted that in 30 years if business-as-usual, Atlantic AZH will shoal by 1000-1400m

Location & depth of CWCs, colour=ASH depth (dark = shallow)



Carbonate concentration:

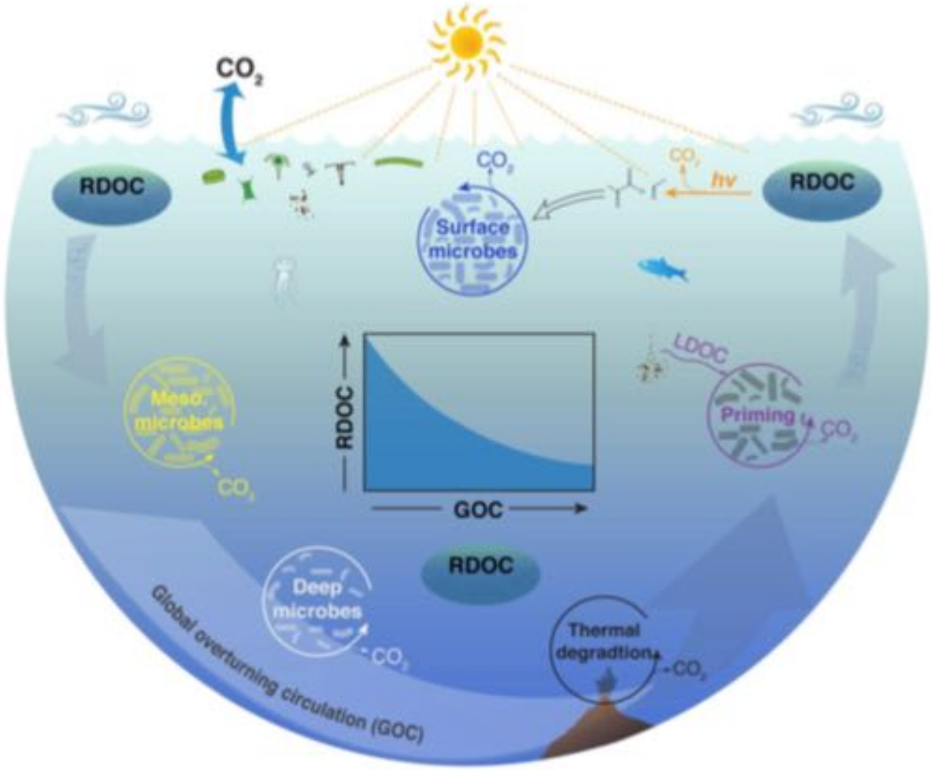
preindustrial = yellow, modern = black, white = atmos CO_2 @520ppm

AMOC CO_2 feedbacks: future impacts on air-sea CO_2 fluxes
Organic carbon

Refractory Dissolved Organic Carbon (RDOC) is complex, long-chain organic material that exists in the ocean for millenia due to its resistance to degradation, and it is a vast reservoir of carbon (~660 PgC)

Can survive multiple circuits of the Global Overturning Circulation (GOC), but is eventually converted to soluble form by microbial / photic processes at the surface or thermal degradation at hydrothermal vents

Slowdown in AMOC could thus be a negative feedback on atmospheric CO_2, as less refractory DOC is delivered to these locations



Shen & Benner (2018)

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AMOC CO_2 feedbacks: future impacts summary

AMOC and the carbon cycle are intimately related

Increased ocean heat content will make seawater less soluble to CO_2 causing substantial outgassing of natural carbon

Increased stratification and AMOC slowdown could have multiple feedbacks:

- Less carbon transported to depth, reducing uptake from atmosphere as high concentrations remain at surface
- Inorganic nutrient and refractory organic matter trapping in deep waters as supply to surface / productive regions diminishes, impacting ecosystems dependent on such production, and leading to Increased acidification at depth

But stable AMOC will enable high anthropogenic carbon / low carbonate ion waters to be exported to depth, leading to shoaling of aragonite saturation horizon

Thanks to funders, NERC LTS programmes ORCHESTRA & CLASS, and projects RAGNARoCC, NE/P021247/1; ABC-Fluxes, NE/M005046/1; TICTOC, NE/P019293/1; SONATA, NE/P021417/1