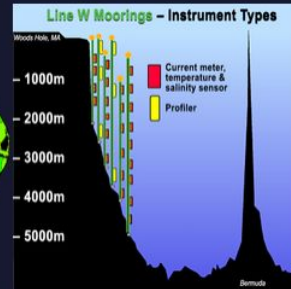
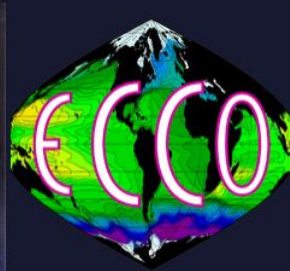


State of the Science Large-scale Ocean Physics



Geoffrey (Jake) Gebbie, WHOI
Hydrosphere PI Meeting
September 1, 2026

ECCO- Estimating the Circulation and Climate of the Ocean



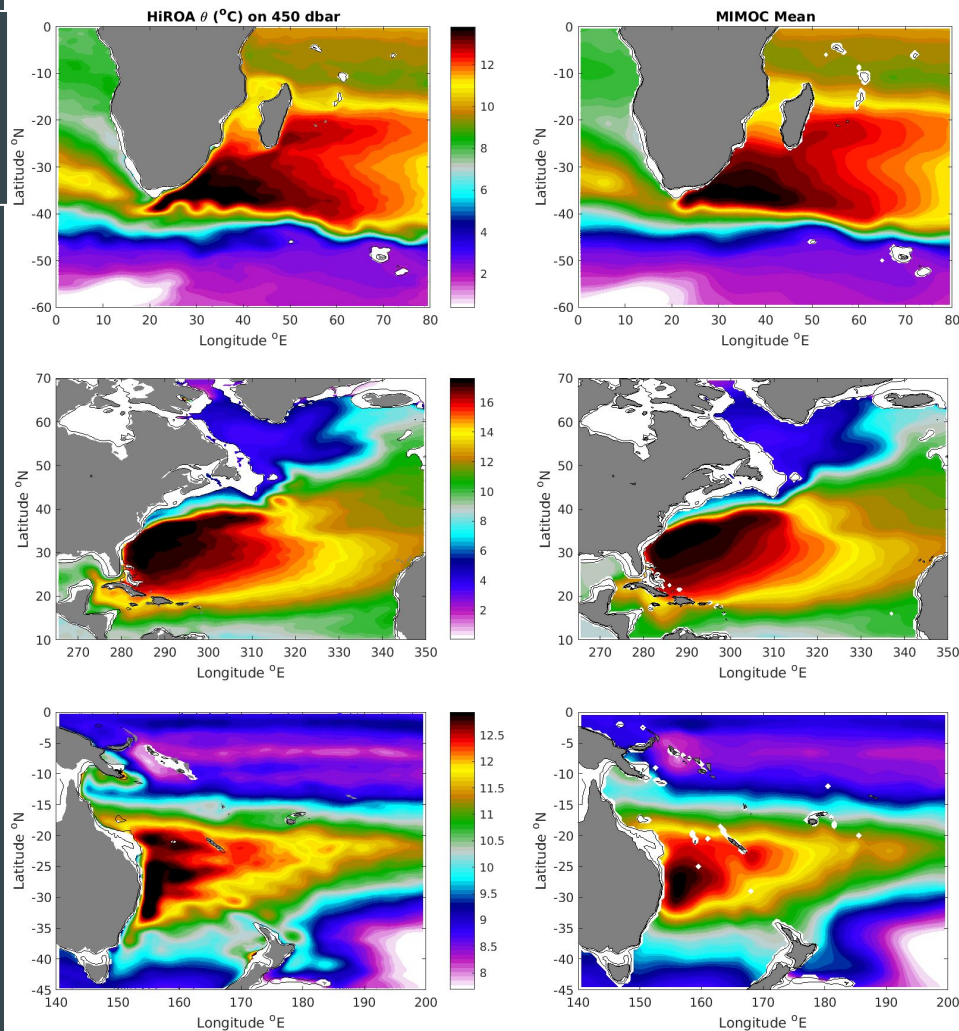
LEFT TO RIGHT: Argo drifter; artist's depiction of the Jason-3 and QuikSCAT satellites in Earth's orbit; ECCO logo; and diagram representing the Line W moorings. (Sources: Univ. of California, San Diego; NASA; ECCO consortium; Woods Hole Oceanographic Institution, WHOI)

e.g., Wunsch and Heimbach 2008, Forget et al. 2015, Fenty et al. 2017



Originally Menemenlis et al. 2008

Argo + Altimetric Atlas



MIMOC,
Argo only

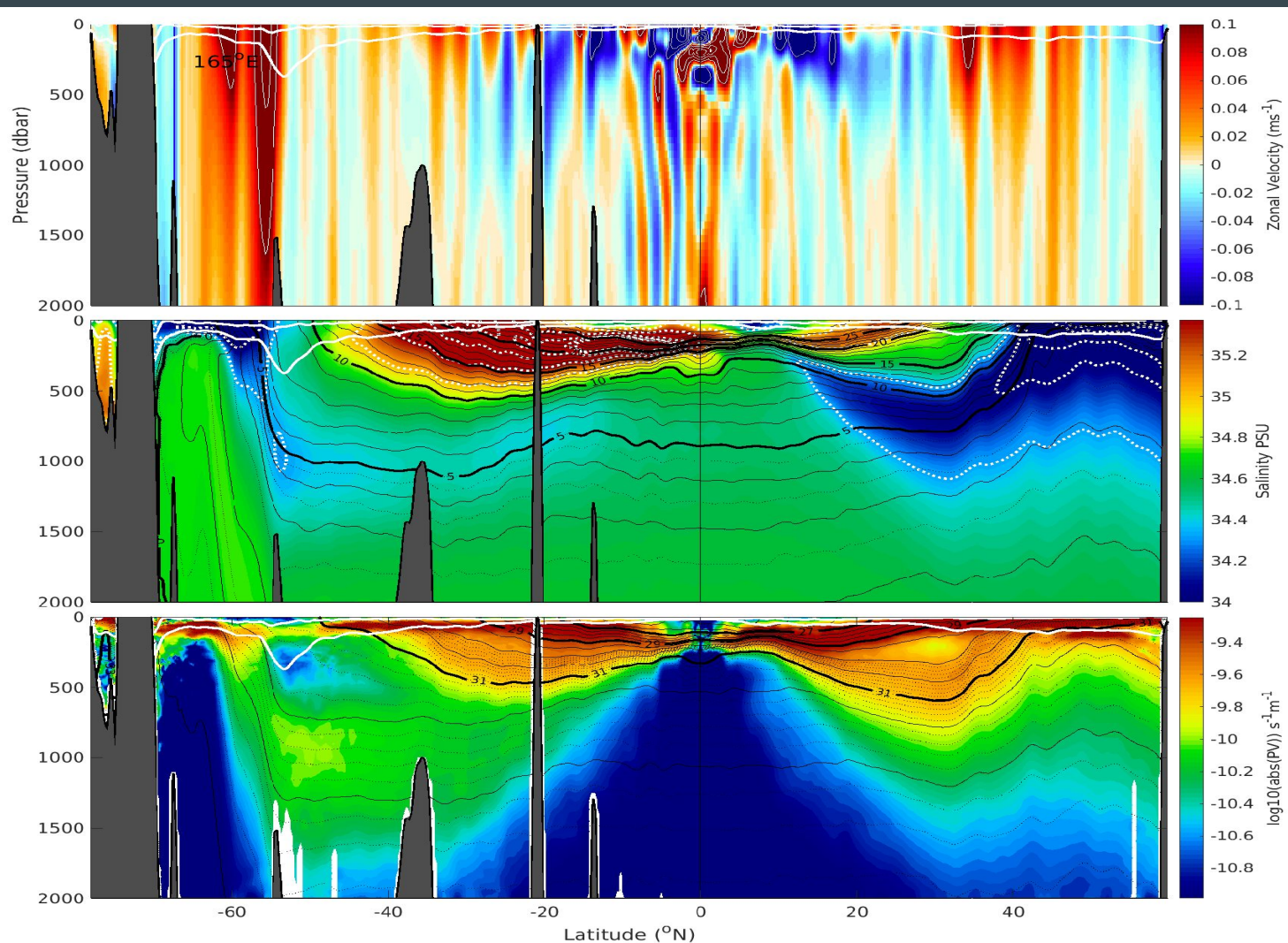
Small-scale
features are nearly
permanent,
blurring the
large-scale and the
mesoscale.

Wijffels, Gebbie, Robbins 2025
Schmidt et al, 2013

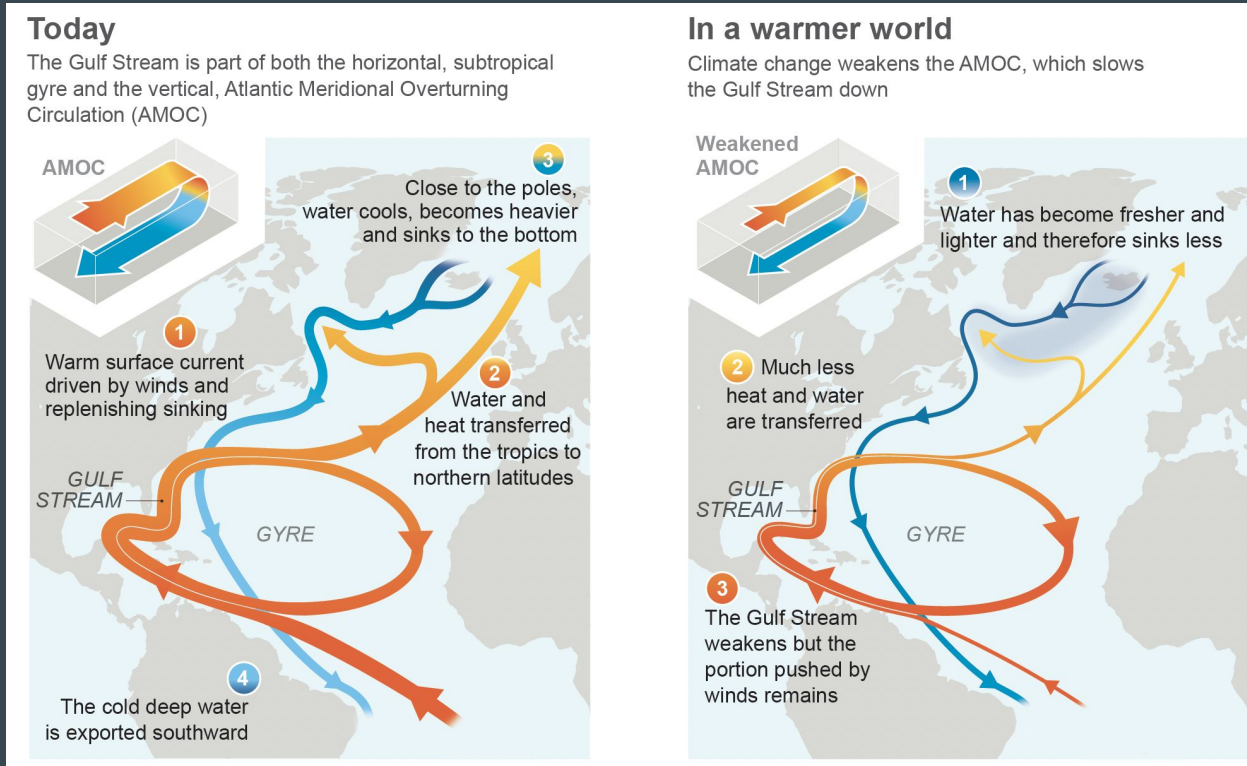
$\theta(^{\circ}\text{C})$ on 450dbar

165°E Western Pacific

- Small scale features persist even in a 20 year climatology
- Deep reaching zonal jets at all latitudes
- Shear signature is evident in wiggles on isotherms



Atlantic Meridional Overturning Circulation (AMOC)



Accumulating (integrating) meridional velocity V zonally coast-to-coast and vertically to depth of max. transport

FINANCIAL TIMES

US COMPANIES TECH MARKETS CLIMATE OPINION WORK & CAREERS LIFE & ARTS HTSI

Climate change **Added**

Global warming threatens collapse of Atlantic currents this century, new study finds

Shutdown of ocean flows would likely lead to more stormy winters and drier summers in Europe



Other signs of global warming include high sea surface temperatures in temperate regions of the northern hemisphere, while sea ice around Antarctica is at an all-time low © Henrik Egede-Lassen

NATIONAL Climate Education Health Innovations Investigations National Security Obituaries S

Ocean system that moves heat gets closer to collapse, which could cause weather chaos, study says

By Seth Borenstein | AP
February 9, 2024 at 4:40 p.m. EST

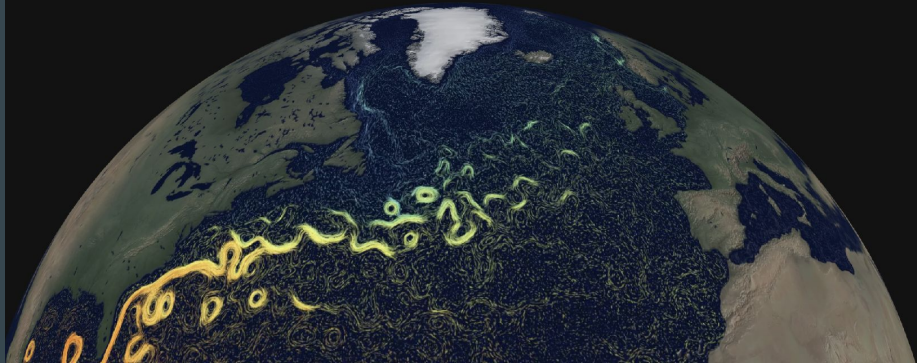


The New York Times

In the Atlantic Ocean, Subtle Shifts Hint at Dramatic Dangers

The warming atmosphere is causing an arm of the powerful Gulf Stream to weaken, some scientists fear.

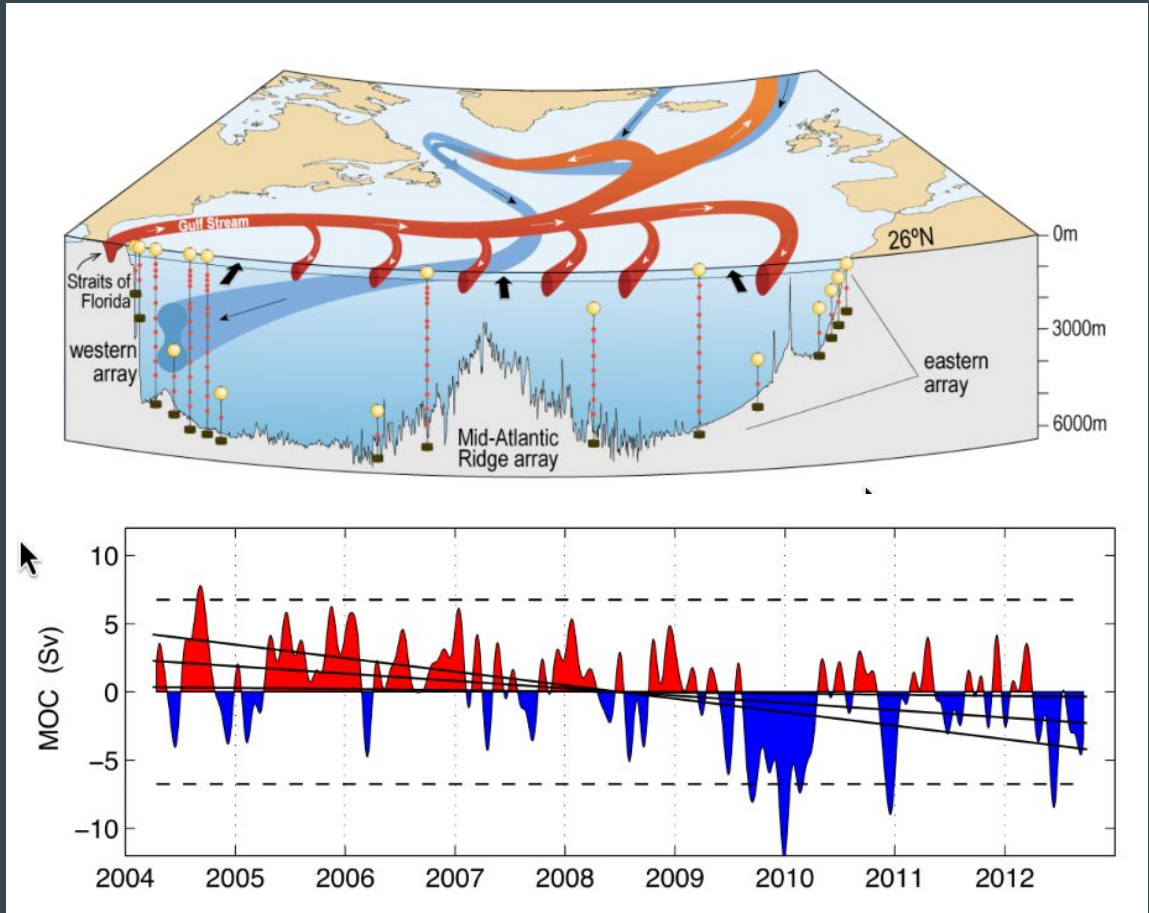
By MOISES VELASQUEZ-MANOFF
and JEREMY WHITE



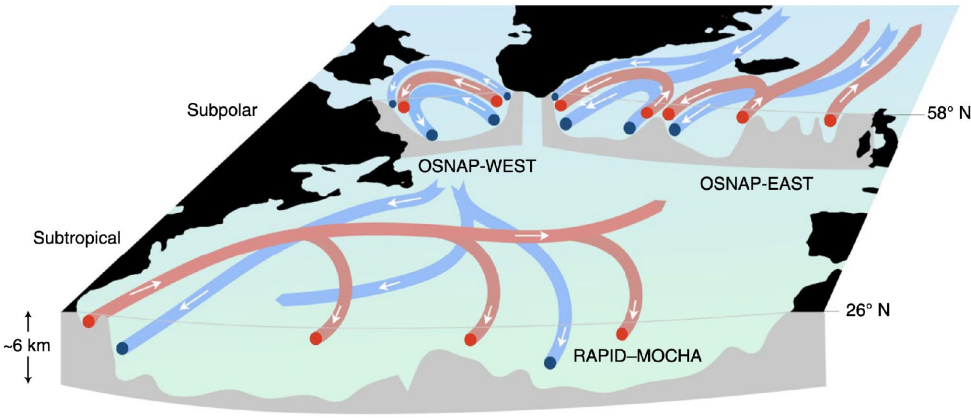
AMOC has already slowed down! (but not how it was expected)

RAPID-MOCHA array

e.g., Smeed et al. 2012

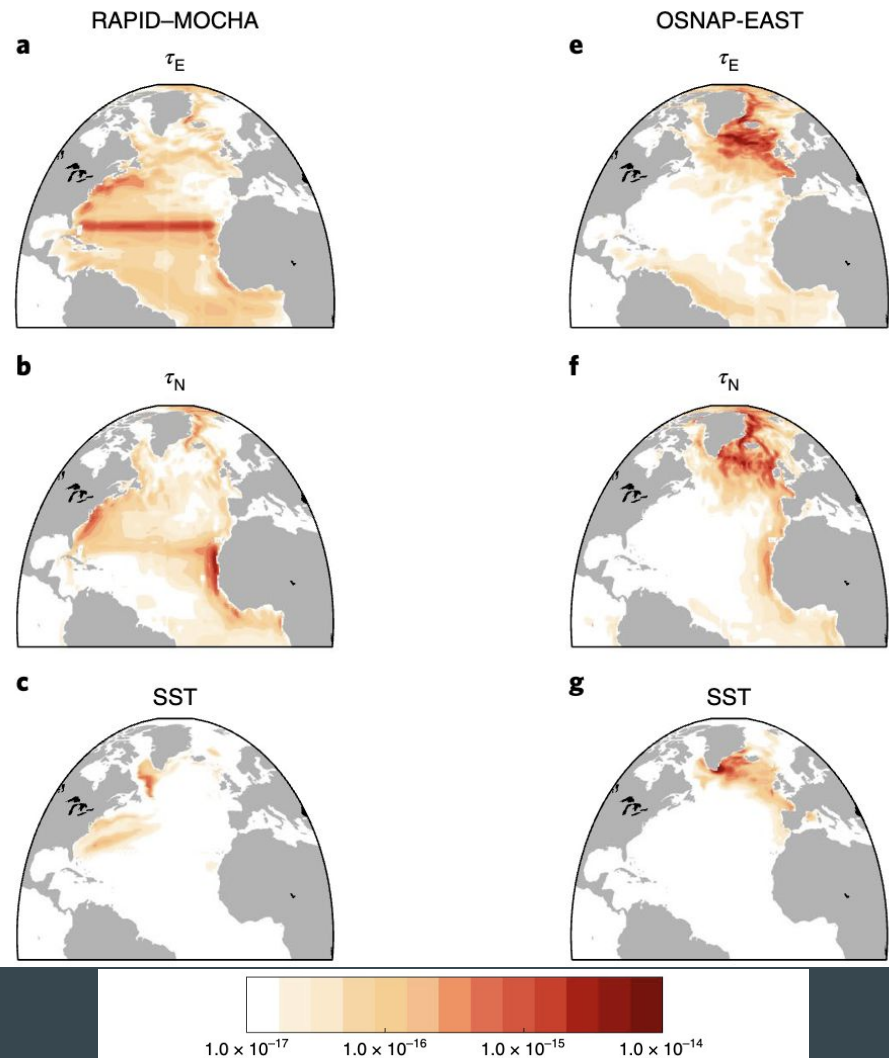


Sources of subtropical and subpolar North Atlantic overturning variability

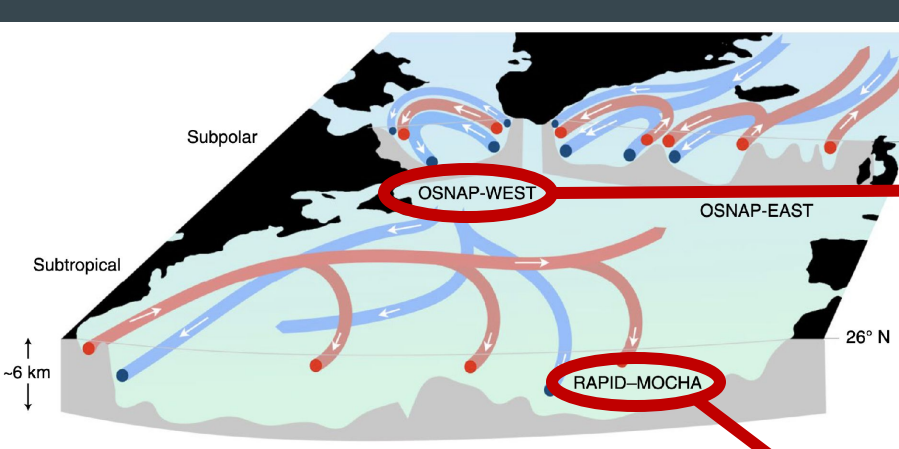


“Backpropagation” in the ECCO system:
forcing influence on AMOC over the period
1992–2015

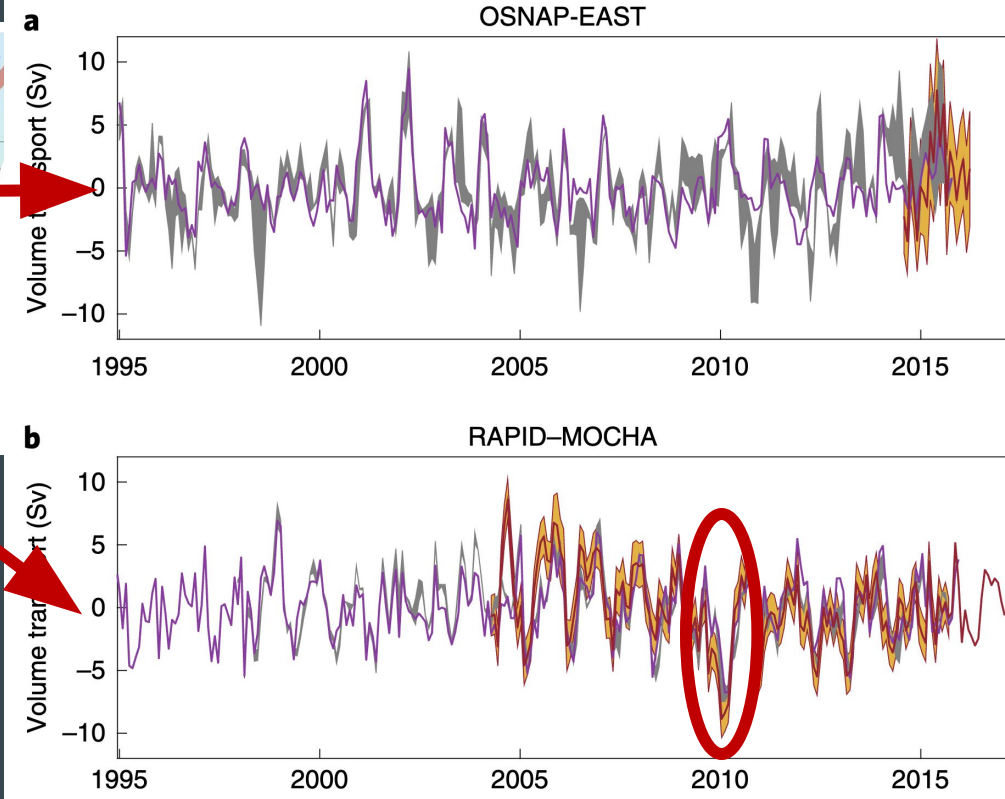
Kostov et al., Nature Geoscience, 2021
Also see Heimbach et al. 2011,
Pillar et al. 2016



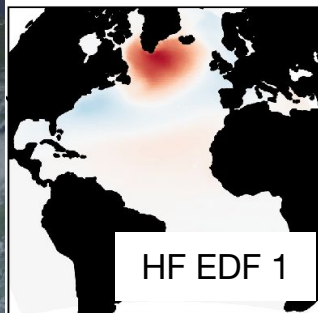
Sources of subtropical and subpolar North Atlantic overturning variability



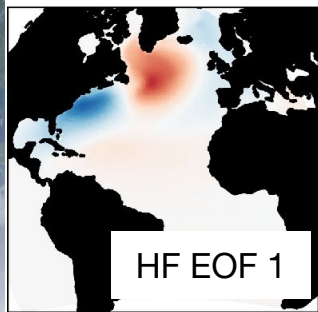
- Reconstruction by convolution of (lagged) sensitivity kernels with surface patterns
- reproduces observed AMOC weakening around 2010!



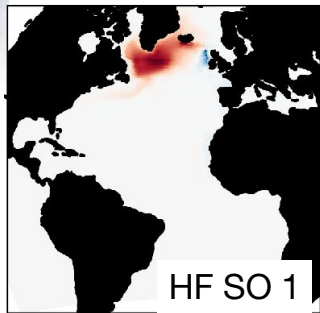
What are the **dominant modes** and **pathways** by which the atmosphere drives **ocean variability**?



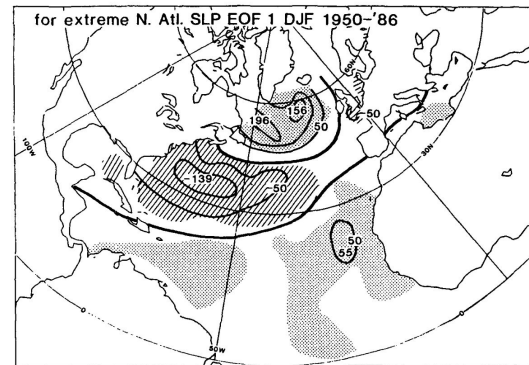
What are the dominant modes of **atmospheric variability**?



What are the most efficient pathways by which variability in an ocean quantity **might be excited**?



The leading EDF has a pattern correlation of 94% with the NAO.



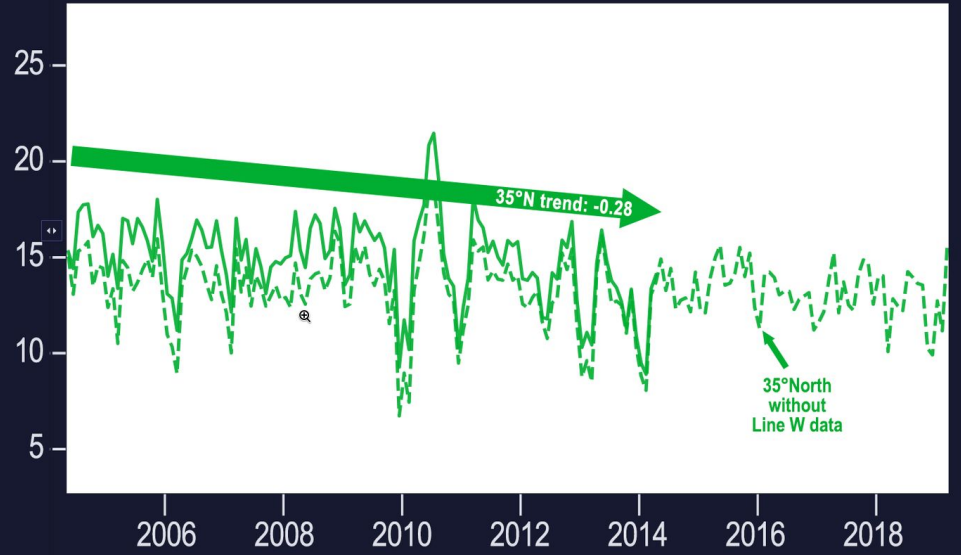
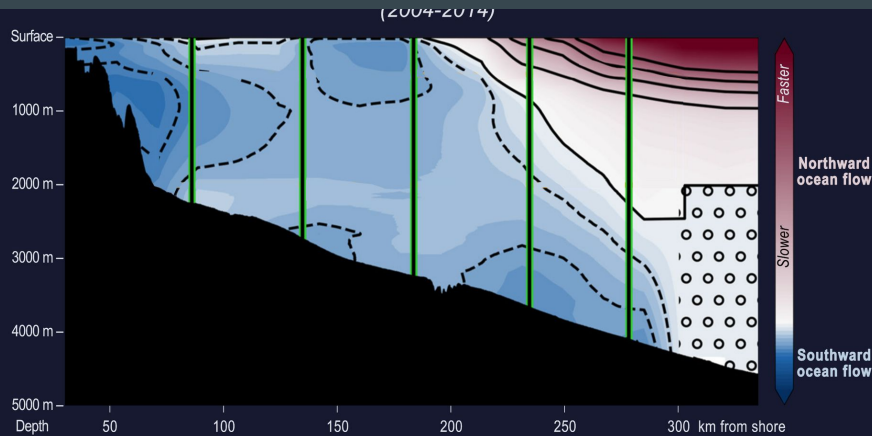
NAO heat flux (Wm^{-2} ; Cayan, 1992)

The leading EOF has a primarily **dipolar** structure.

Local heat fluxes are a leading driver of annually-averaged SPG heat content.

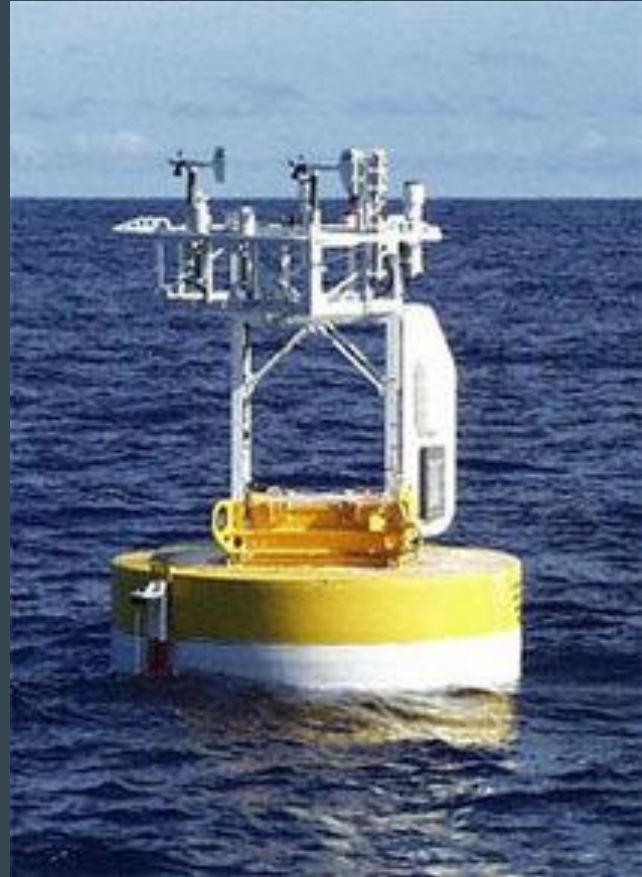
Amrhein et al. 2024

Temporary AMOC decline seen in the deep western boundary current and ECCO, but later recovers.



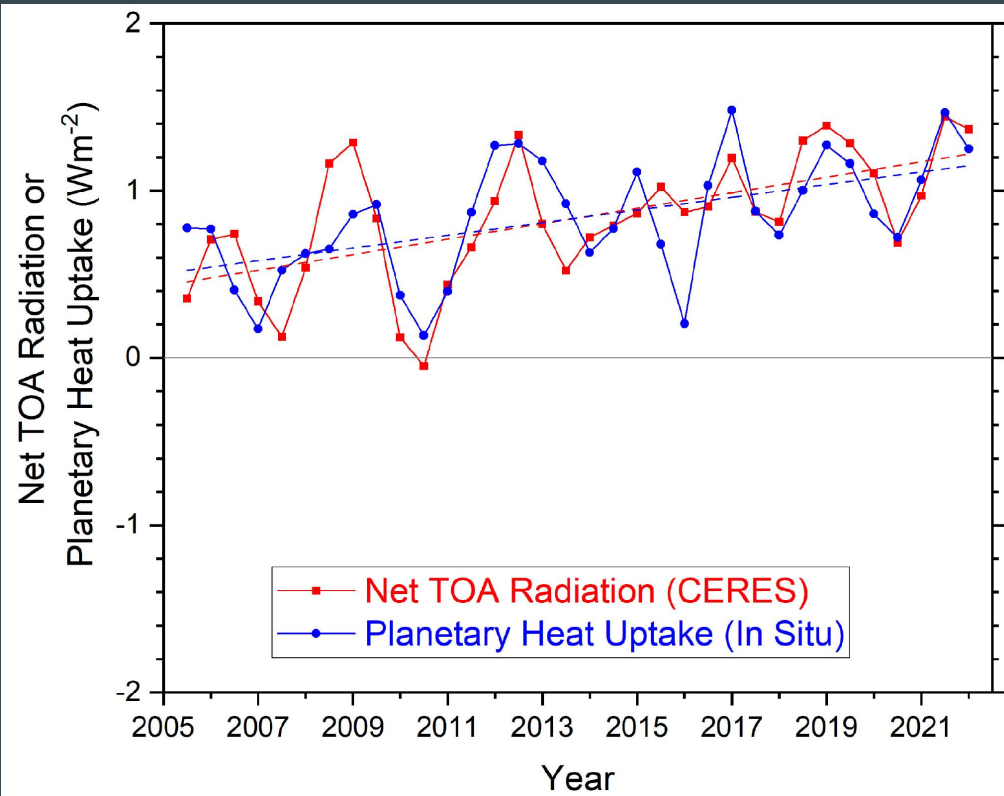
Line W observations AMOC at 35 North
Le Bras et al. 2023

Ocean heat uptake and planetary energy imbalance



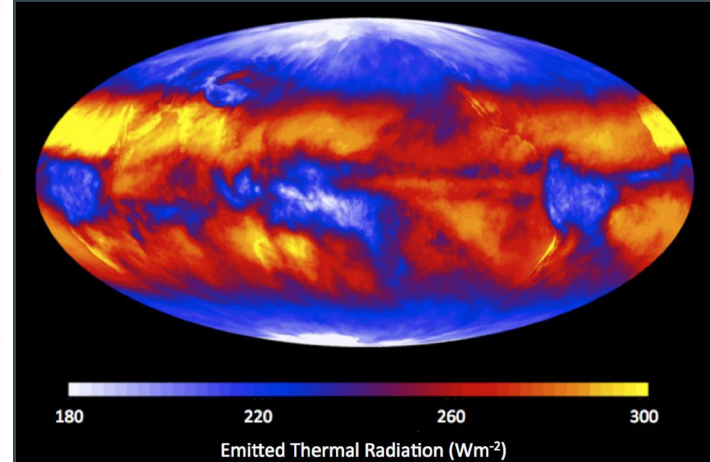
The Earth's net radiative imbalance – 2023 estimate

Schmidt et al., FMARS (2023)



An apparent trend of 0.4 W/m^2 per decade (since 2005)

Clouds and the Earth's Radiant Energy System (CERES)



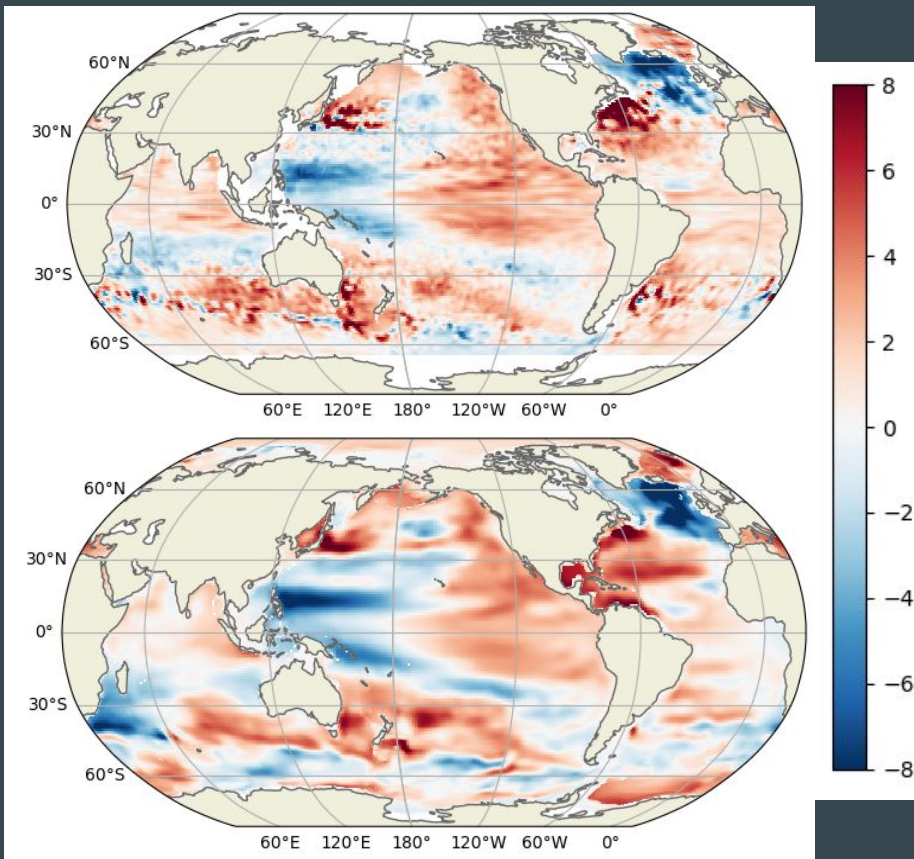
CERES:

6 instruments on
4 satellites (TRMM,
Terra, Aqua, SNPP)

ECCO V4r6 heat and steric height trends: consistent with Argo [0–2000 m]

Ocean Heat Trend (W m^{-2})

Argo



Constraints from altimetry and gravity missions sufficient to fill in gaps in Argo data

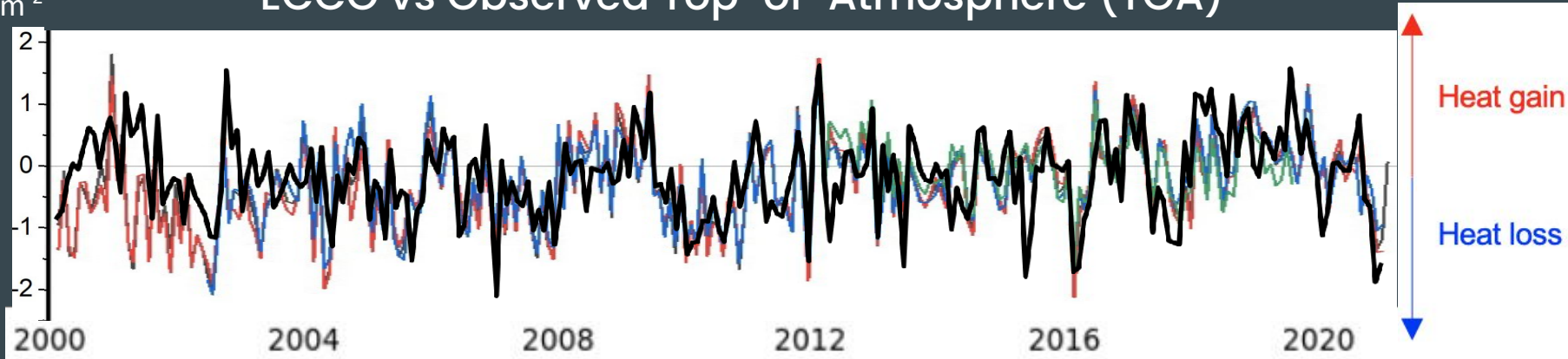
Courtesy Andrew Delman via Patrick Heimbach

ECCO

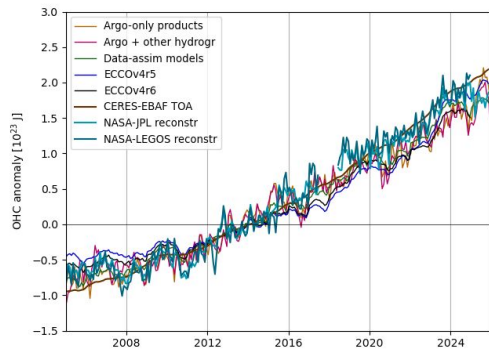
Diagnosing Earth Energy Imbalance and Its Acceleration

Monthly-Mean Global Heat Flux Anomalies ECCO vs Observed Top-of-Atmosphere (TOA)

Wm^{-2}



Global OHC from sat reconstr & other product ensembles,
adjusted from 0-2000 dbar, with 2006-2020 mean removed, no seasonal cycle



— EBAF Ed4.1
— SSF1deg_Terra
— SSF1deg_Aqua
— SSF1deg_SNPP
— ECCO V4r6

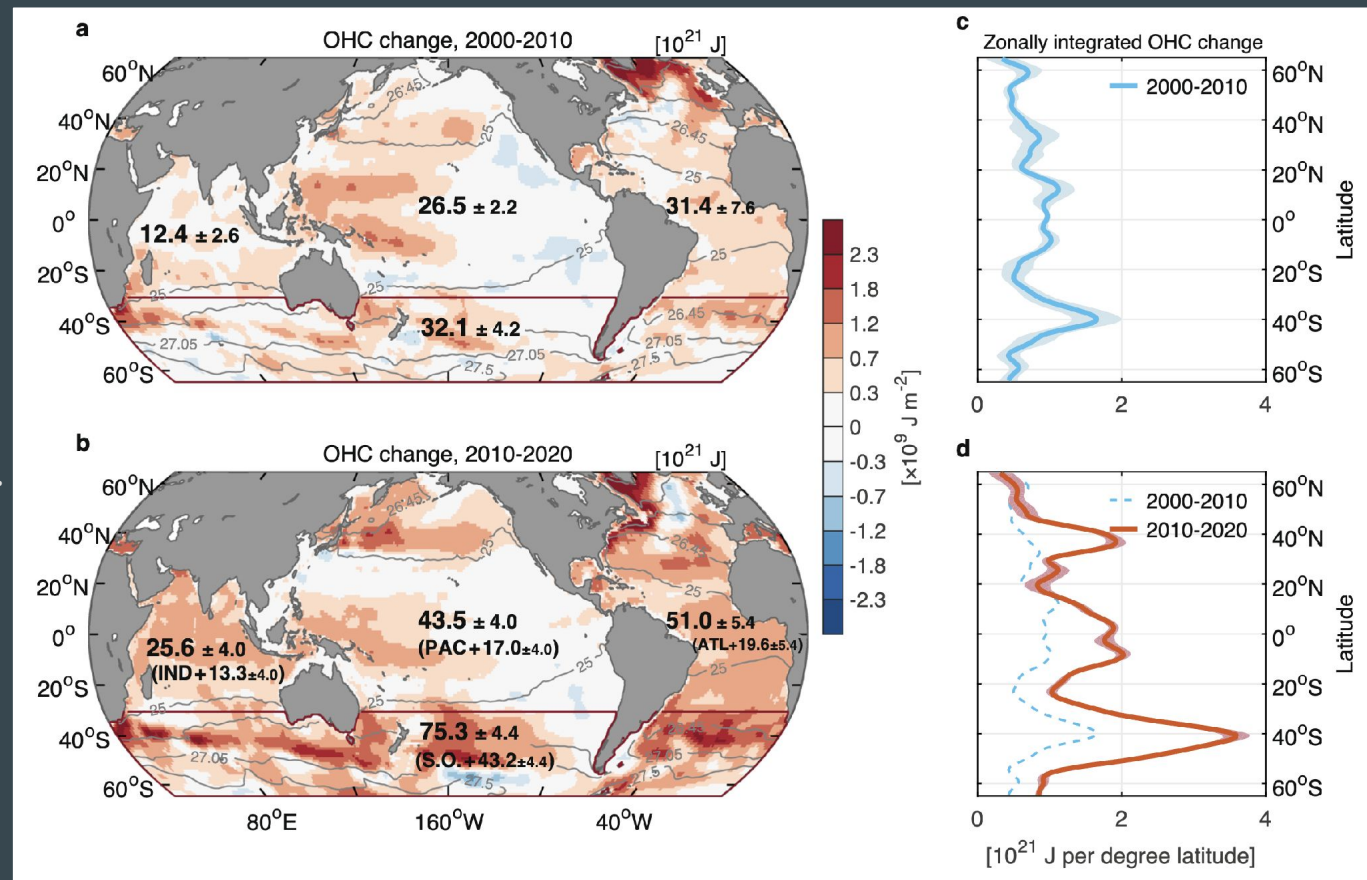
□ Multi-platform CERES product

— Missions with CERES instruments

TOA flux anomalies plot adapted from Norman
Loeb's 2021 CERES-Libera [science team presentation](#)

Recent acceleration in global ocean heat accumulation by mode and intermediate waters

Li et al., Nature Comm.
(2023)



135 Years of Temperature Change

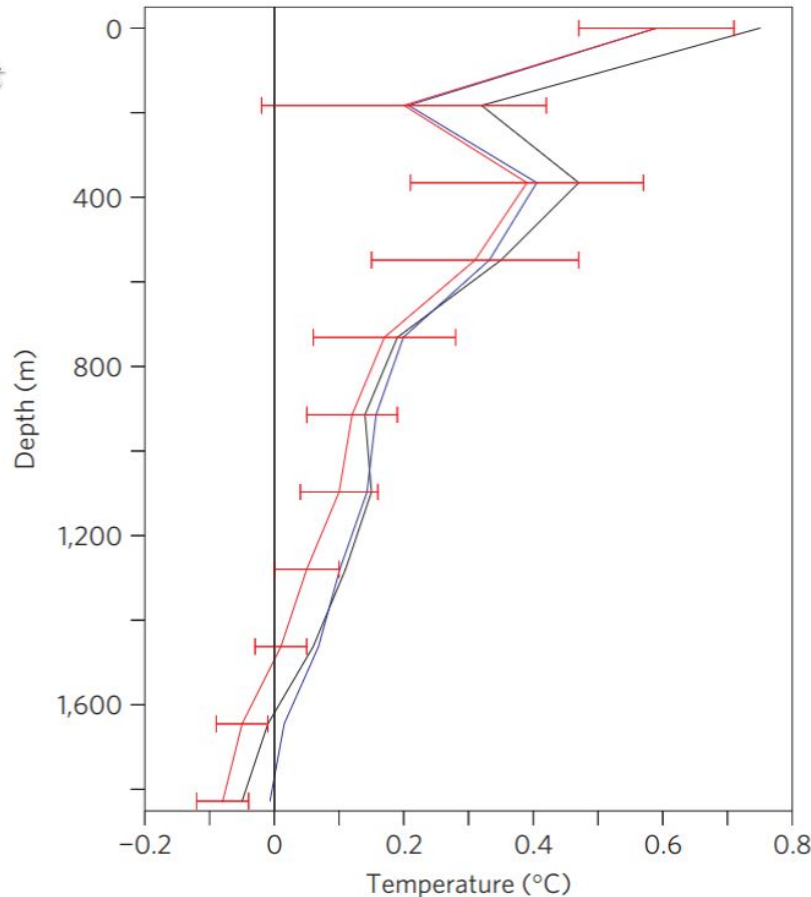
Argo (2010) minus
HMS Challenger (1875) temperature

Global average difference

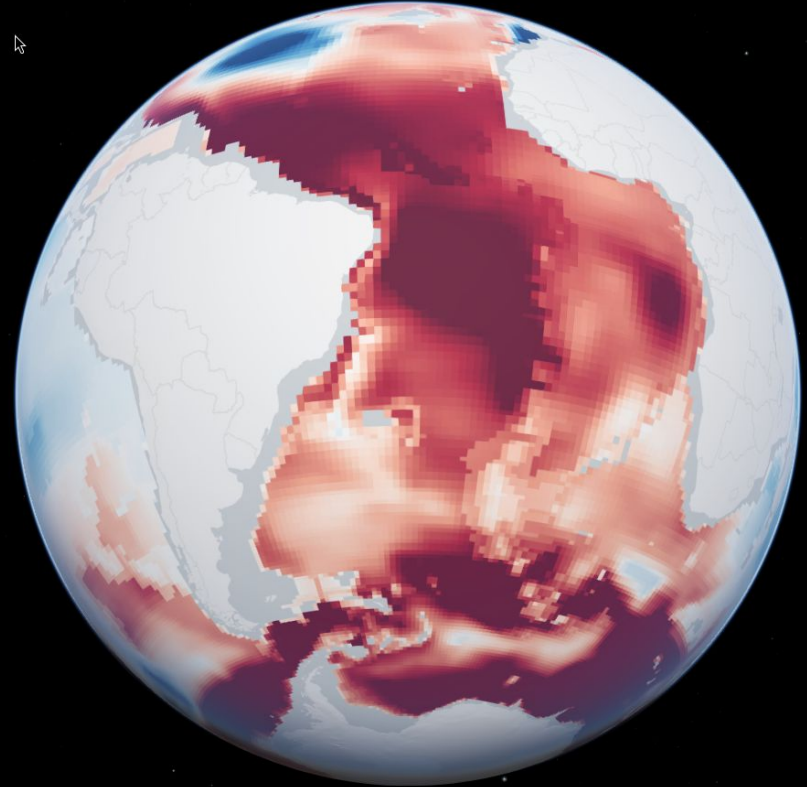
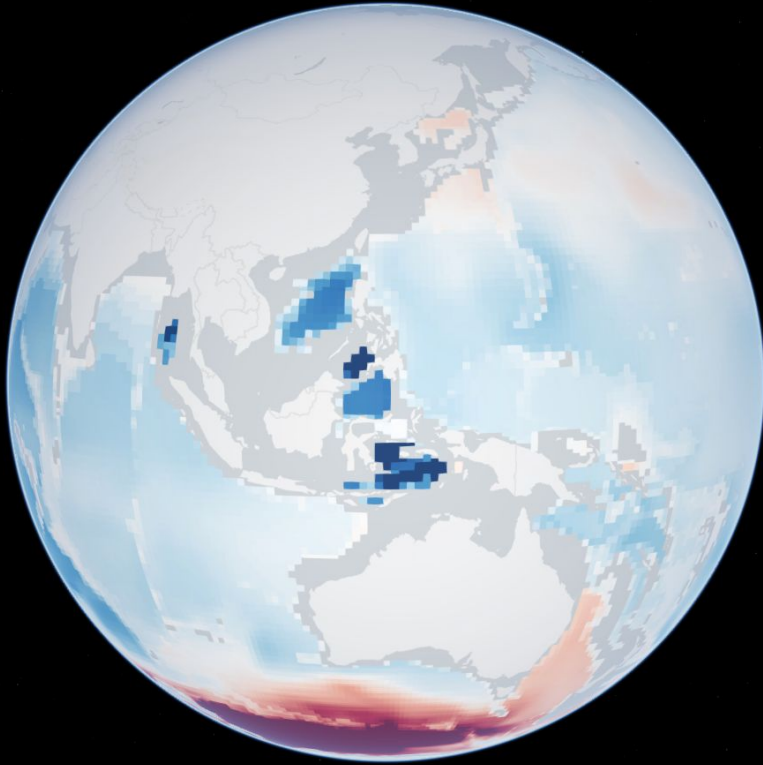
Can we detect ocean heat uptake below
the depth of Argo floats?

Could the ocean truly be losing heat at
those depths?

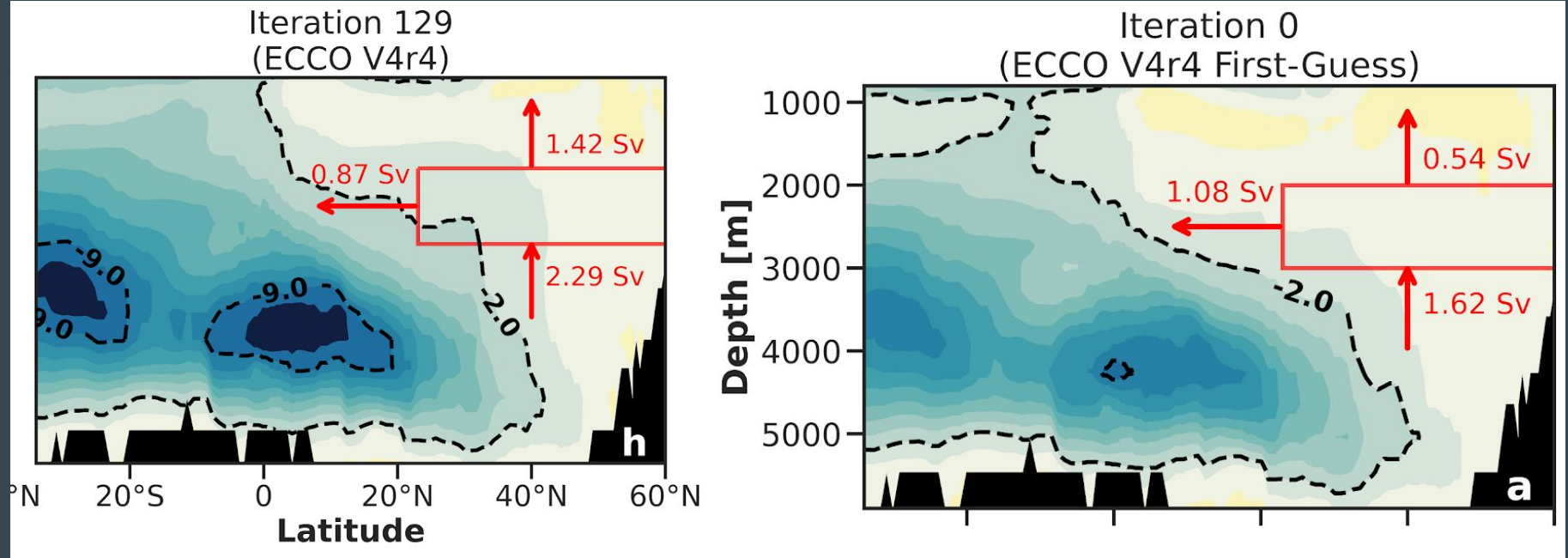
Roemmich et al. 2012



ECCO reconstructs Indo-Pacific cooling and Atlantic warming (2 - 4 km depth).



Mechanisms of mid-depth cooling in ECCO



Consequence of strengthened abyssal overturning circulation (L) relative to first guess (R)

Meza & Gebbie (2025), but also see Monkman & Jansen (2024) and Trossman et al. 2022

The state of large-scale ocean physics

Mesoscale interaction

New and continuing satellite missions are the only viable source of global observations that detect large-scale/mesoscale interactions.

AMOC

The combination of satellite altimetry, satellite vector winds, and ECCO give a convincing dynamical picture of AMOC variability out to several decades.

Earth's energy imbalance

Ocean heat uptake constrained by GRACE, altimetry, and Argo:

- Is consistent with top-of-atmosphere measurements
- Is now measured well enough to detect an acceleration

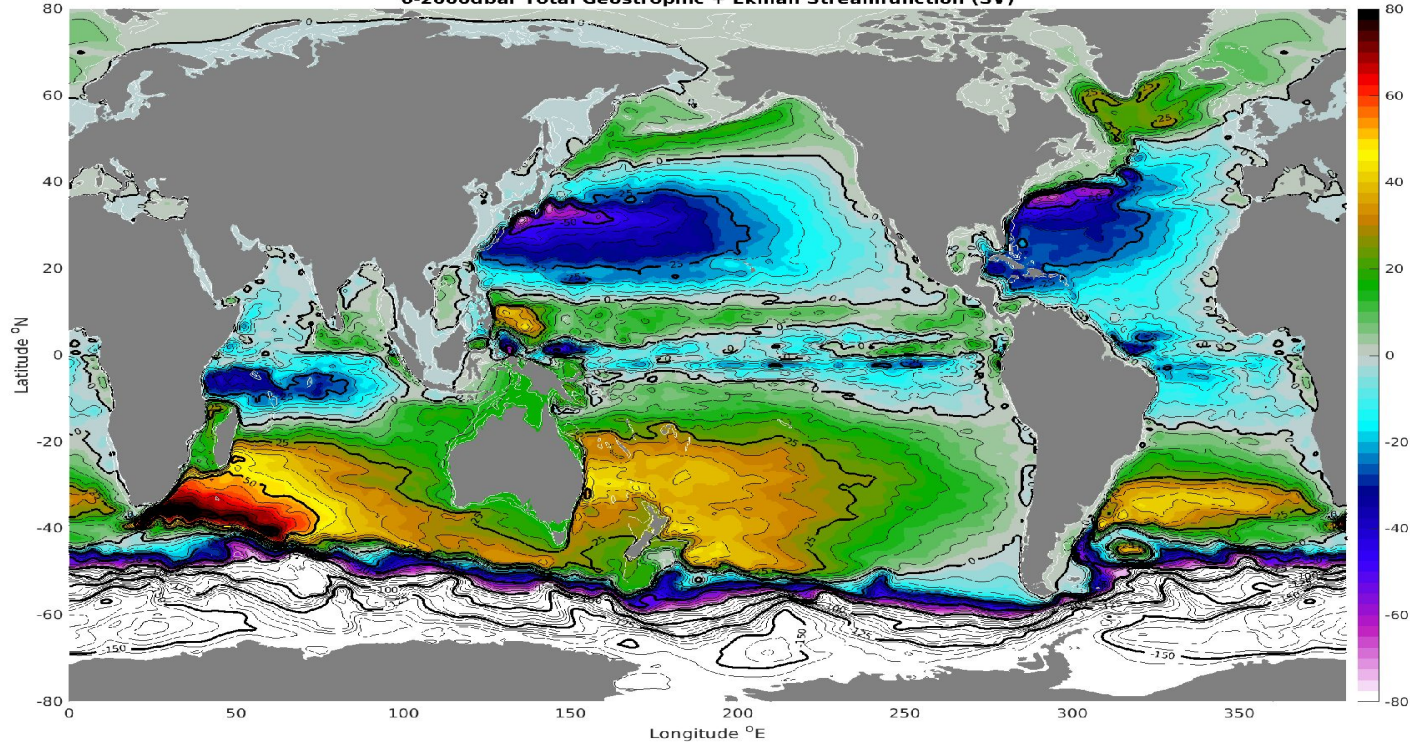
Takeaway:

Our spectacular view of the ocean is sometimes taken for granted, but would have been seen as a fantasy just a few decades ago.

Extra Slides

...

0-2000dbar Total Geostrophic + Ekman Streamfunction (SV)

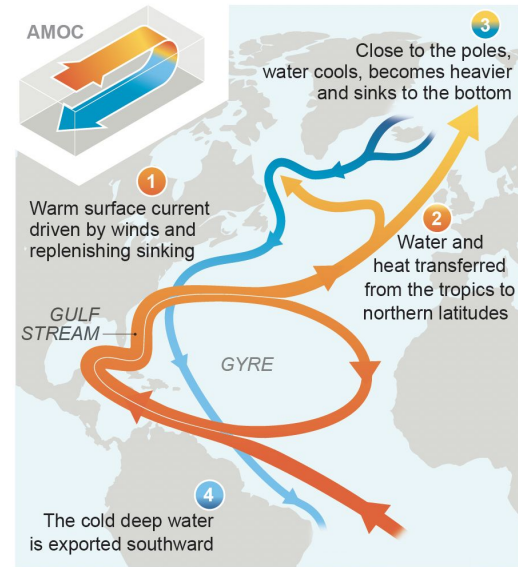


- Transports align with previous observations e.g. Indonesian Throughflow $\sim 15\text{Sv}$
- ACC jets coalesce through fracture zones
- WBC standing meanders and eddies resolved
- WBC recirculations
- Zapiola Gyre in the Argentine Basin
- Island tip jets

What is the Atlantic Meridional Overturning Circulation (AMOC)?

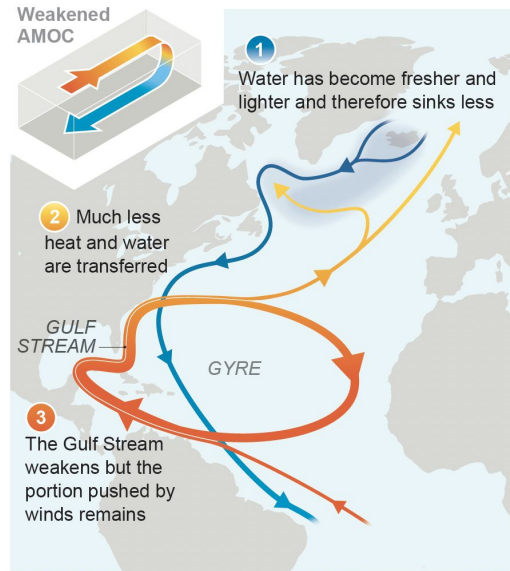
Today

The Gulf Stream is part of both the horizontal, subtropical gyre and the vertical, Atlantic Meridional Overturning Circulation (AMOC)



In a warmer world

Climate change weakens the AMOC, which slows the Gulf Stream down



Accumulating
(integrating) meridional
velocity V zonally

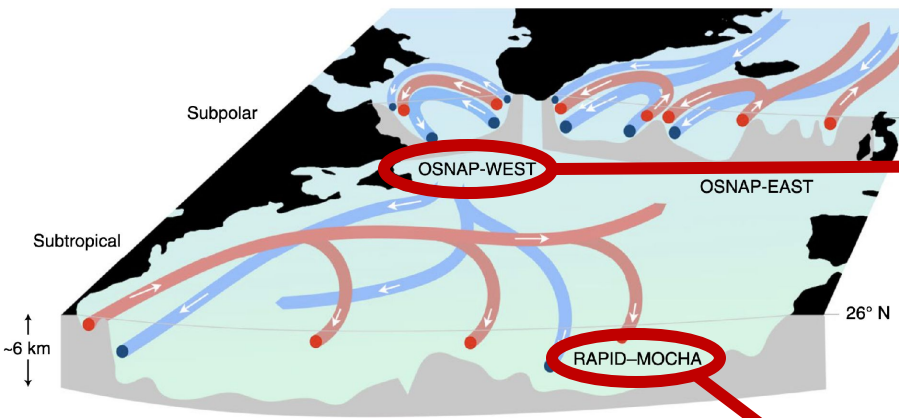
$$V_{cc}(z, \phi, t) = \sum_j V(\lambda_j, z, \phi, t)$$

ϕ : latitude
 λ : longitude
 z : depth

... and vertically to depth of max. transport:

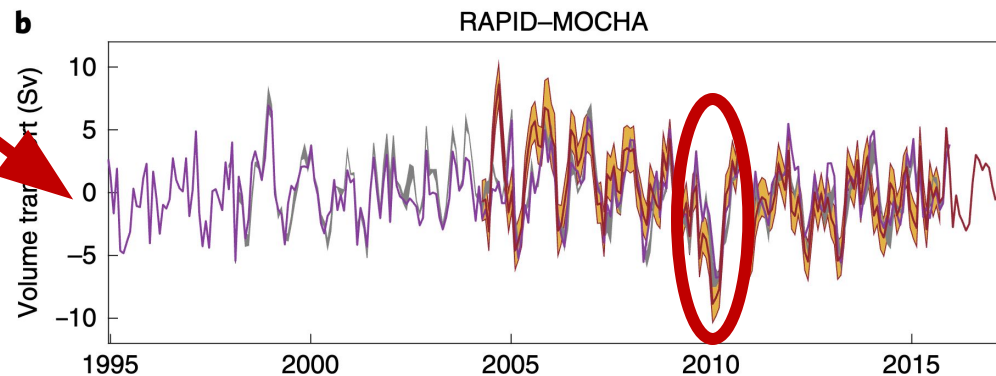
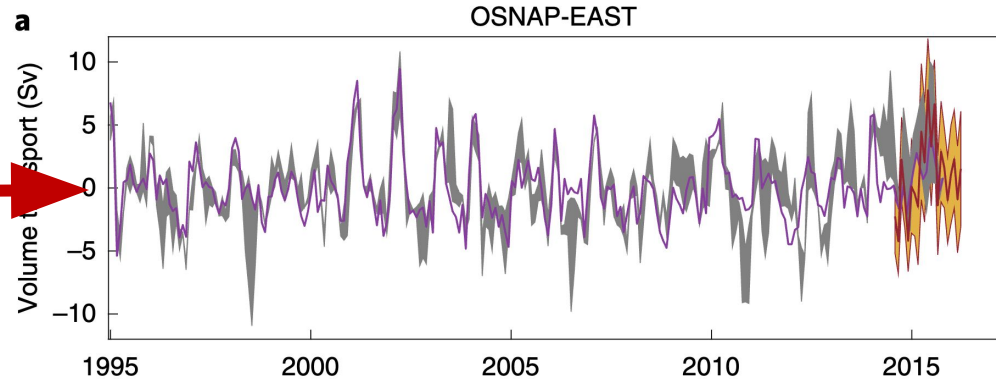
$$V_{MOC}[z_{max}(t), \phi, t] = \max_z \left[\int_{z(\phi, t)}^{\eta(\phi, t)} V_{cc}(z, \phi, t) dz \right]$$

Sources of subtropical and subpolar North Atlantic overturning variability



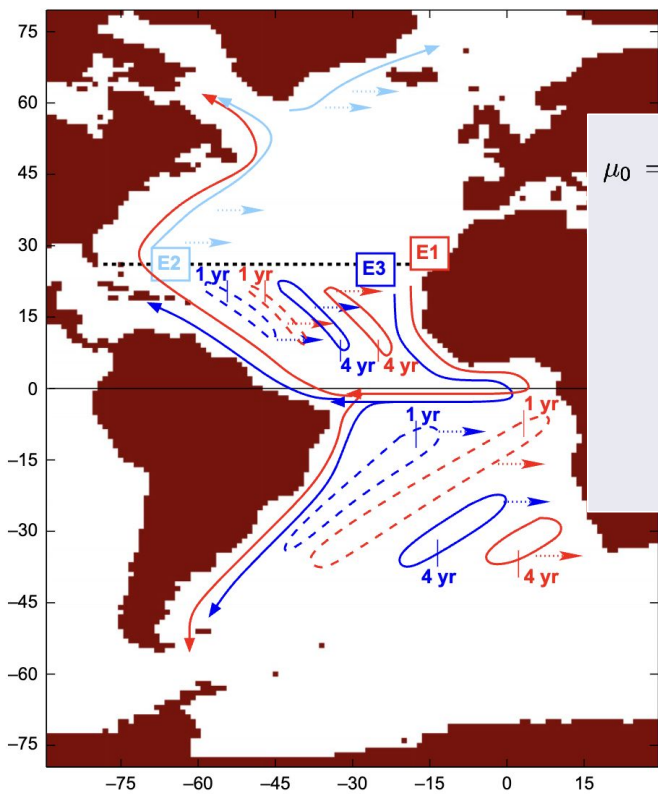
$$C_P(t) = \int_{t-\tau}^t \int \mathcal{P}(\mathbf{x}, t') \mathcal{G}_P(t; \mathbf{x}, t - t') d\mathbf{x} dt'$$

- Reconstruction of C_P through convolution of (lagged) sensitivity kernels $\mathcal{G}_P$ with surface perturbations
- reproduces observed AMOC weakening around 2010!



Dynamical attribution of AMOC variability through oceanic teleconnections

P. Heimbach et al. / Deep-Sea Research II 58 (2011) 1858–1879

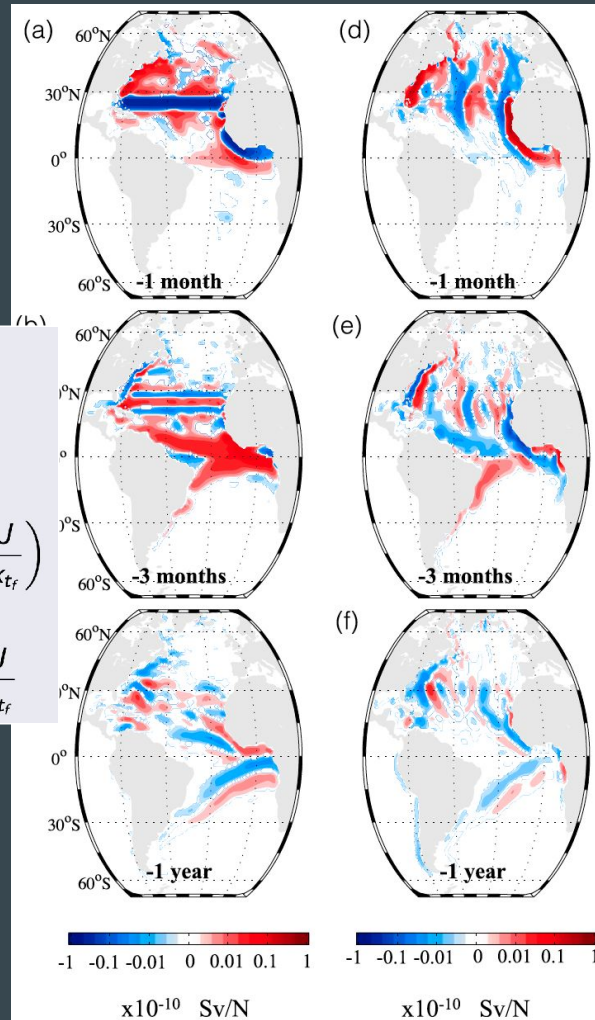


Heimbach et al, Deep Sea Res.

Sensitivity of AMOC @ 26N to atmospheric forcing back in time

$$\begin{aligned}\mu_0 &= \frac{\partial J}{\partial x_0} = \sum_{1 \leq t \leq t_f} \frac{\partial x_t}{\partial x_0} \left(\frac{\partial J}{\partial x_t} \right) \\ &= \frac{\partial x_1}{\partial x_0} \left(\frac{\partial J}{\partial x_1} \right) + \frac{\partial x_1}{\partial x_0} \frac{\partial x_2}{\partial x_1} \left(\frac{\partial J}{\partial x_2} \right) \\ &\quad + \dots + \frac{\partial x_1}{\partial x_0} \dots \frac{\partial x_{t_f}}{\partial x_{t_f-1}} \left(\frac{\partial J}{\partial x_{t_f}} \right) \\ &= \mathbf{L}^T \frac{\partial J}{\partial x_1} + \mathbf{L}^T \mathbf{L}^T \frac{\partial J}{\partial x_2} + \dots + \mathbf{L}^T \dots \mathbf{L}^T \frac{\partial J}{\partial x_{t_f}}\end{aligned}$$

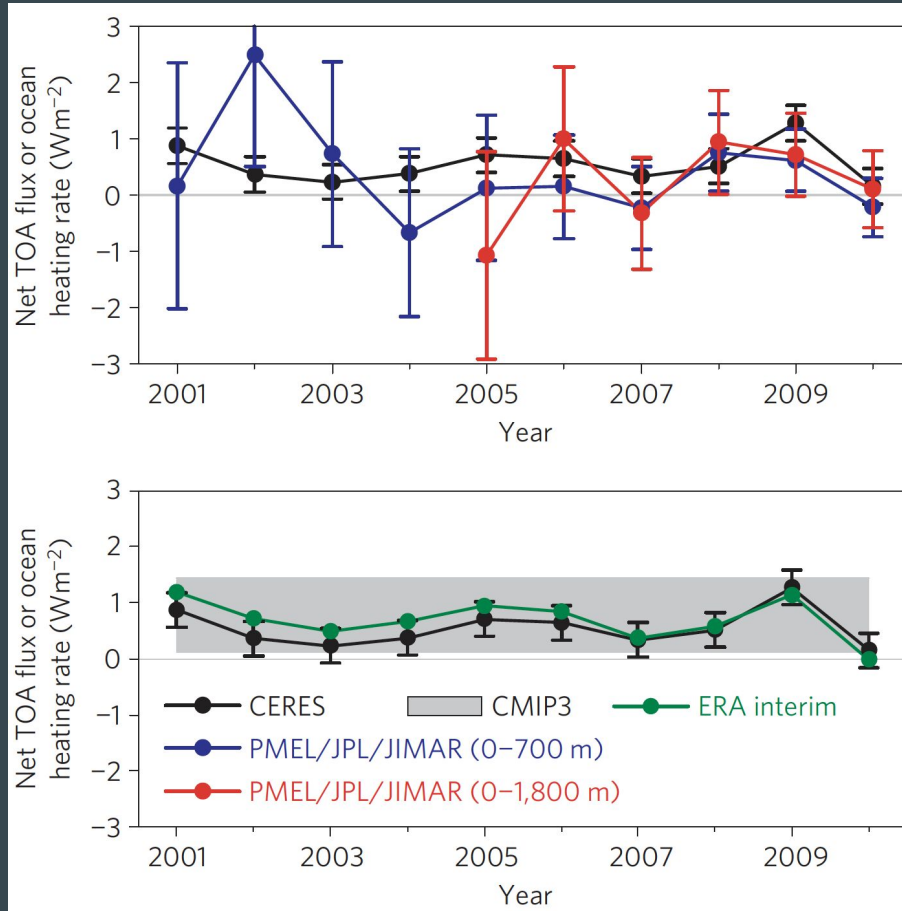
- backpropagated via the adjoint model
- reveals remote & back-in-time sources of variability
- mediated by adjoint Rossby



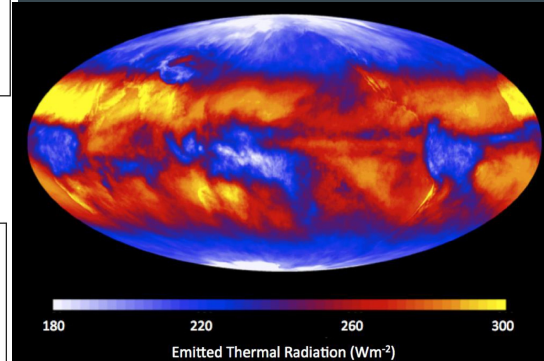
Pillar et al., J. Clim.

The Earth's net radiative imbalance – 2012 estimate

Loeb et al., Nature Geo. (2012)



Clouds and the Earth's
Radiant Energy System
(CERES)



CERES:

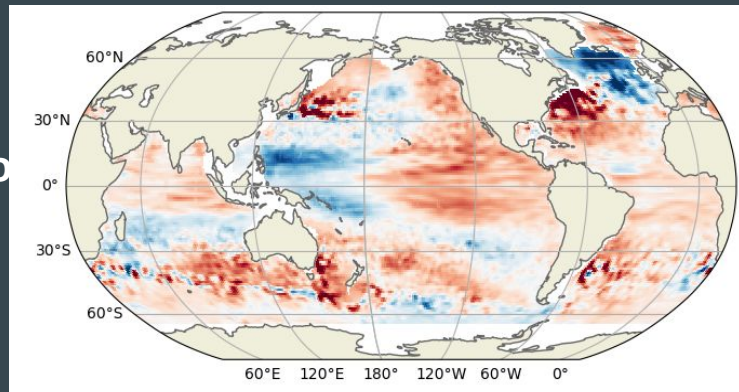
6 instruments on
4 satellites (TRMM,
Terra, Aqua, SNPP)

ECCO V4r6 heat and steric height trends are consistent with Argo [0–2000 m]

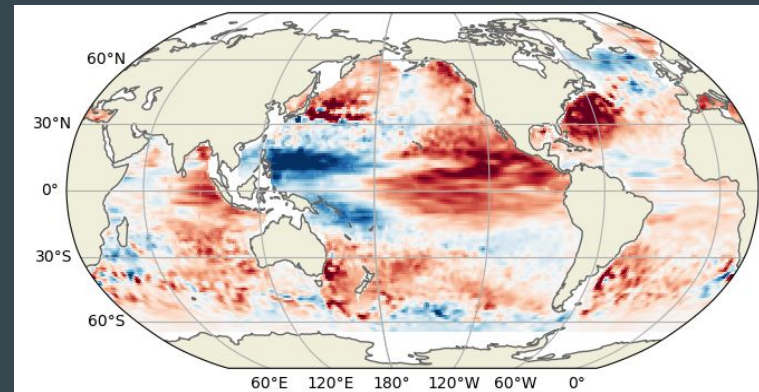
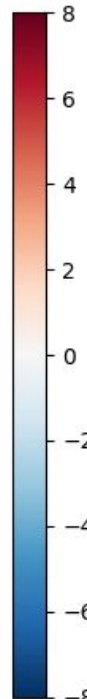
Ocean Heat Trend (Wm^{-2})

Steric height trend (mm yr^{-2})

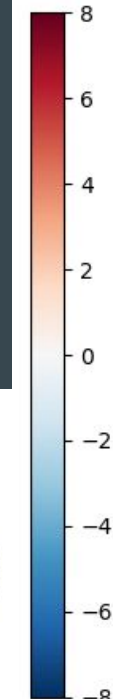
Argo



Wm^{-2}



mm yr^{-2}



ECCO

