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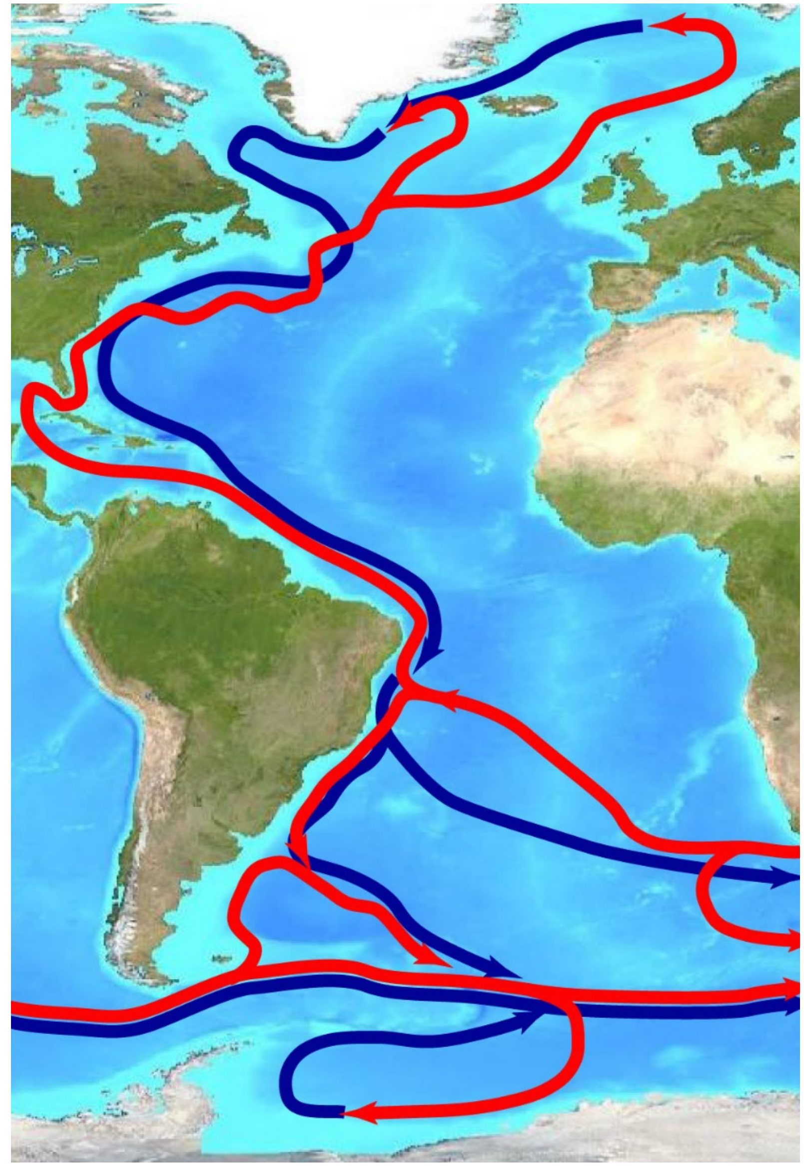
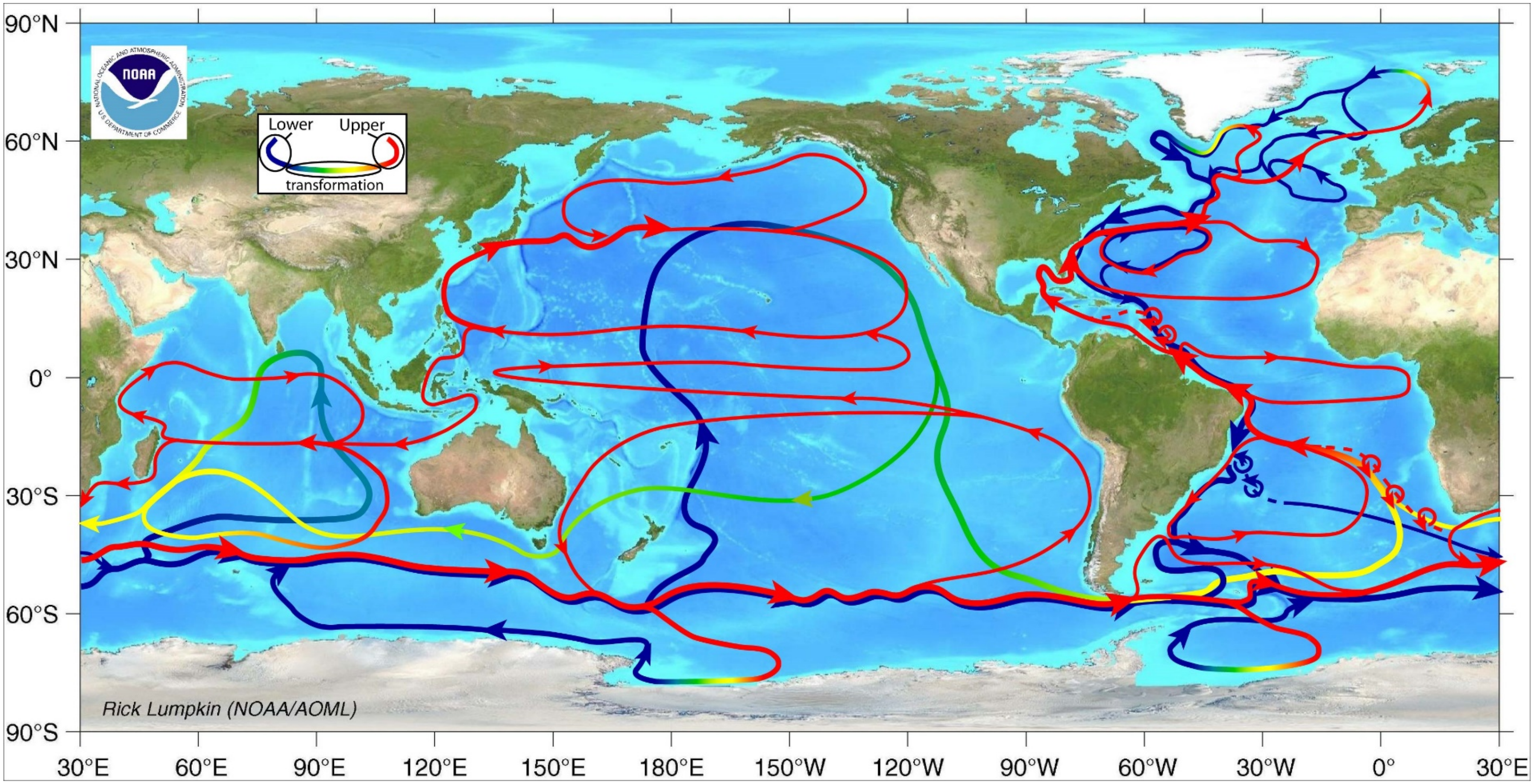
Observing the structure and variability of the Atlantic Meridional Overturning Circulation

Rick Lumpkin

NOAA's Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

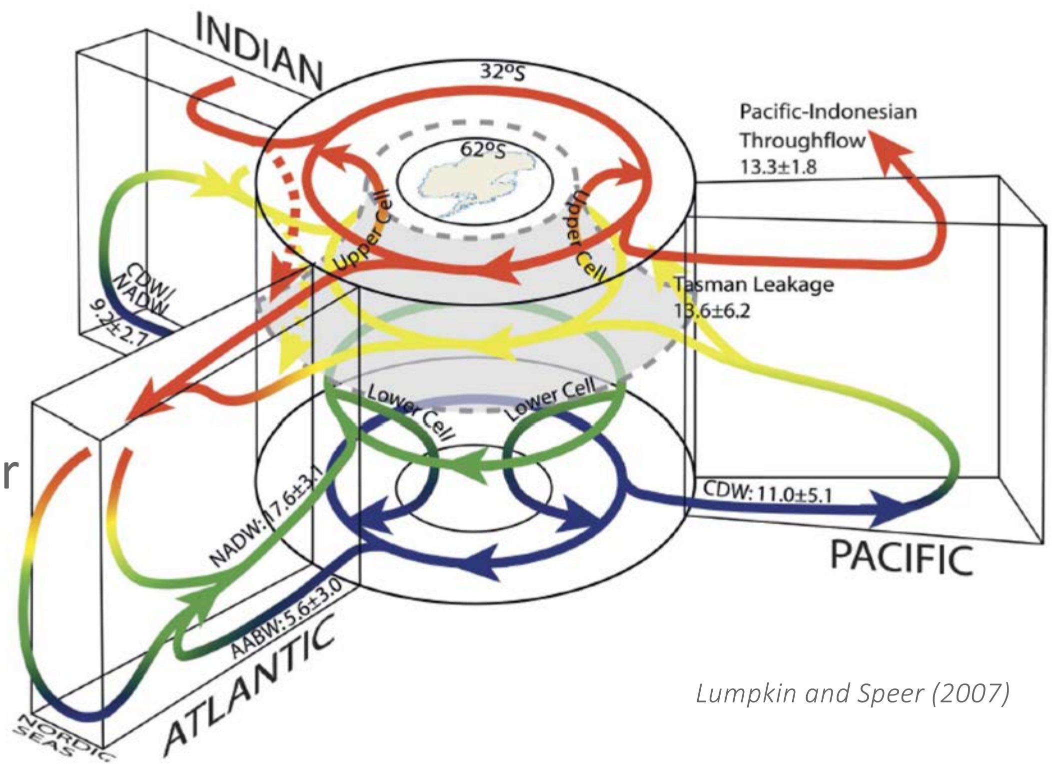


What is the Meridional Overturning Circulation (MOC)?



Why do we need to observe the Meridional Overturning Circulation (MOC)?

- MOC carries large amounts of water, heat, salt, carbon, nutrients and other substances around the globe
- Atlantic MOC (AMOC) is responsible for ~2/3 of the oceanic northward heat transport
- AMOC impacts global and regional climate, sea level, extreme weather events, ecosystems, and fisheries



Lumpkin and Speer (2007)

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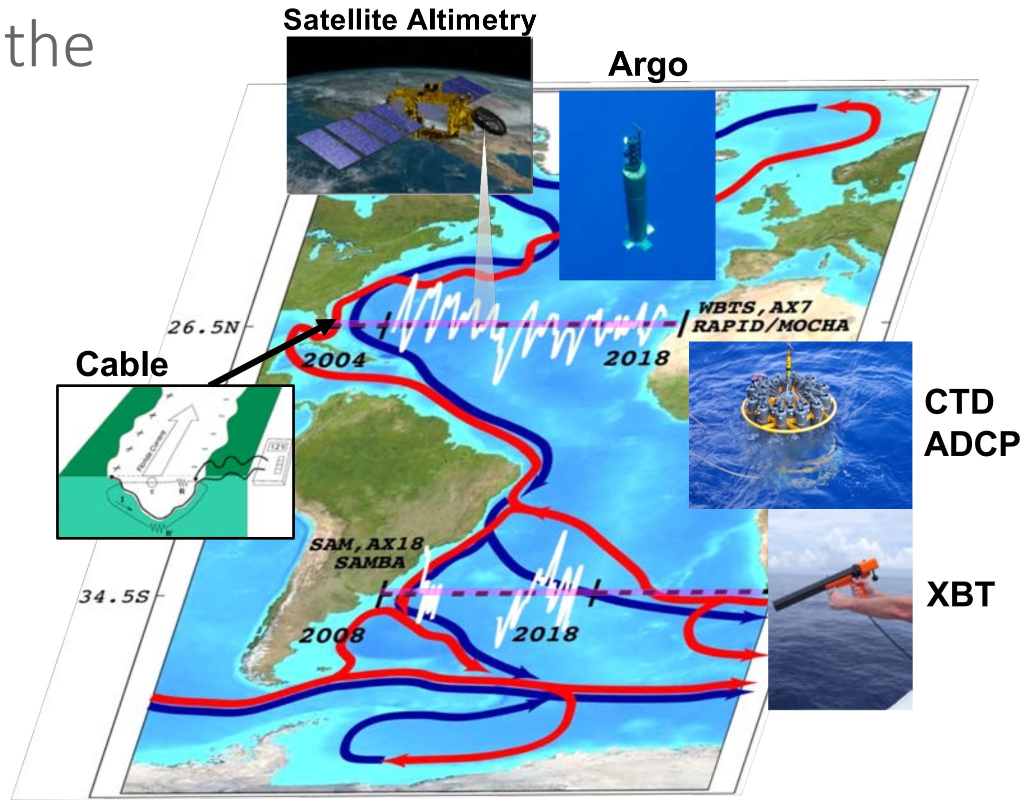
AOML is monitoring AMOC in both the North and South Atlantic

- Continuous measurements of the Florida Current transport with a submarine cable supplemented with hydrographic surveys since 1982;

- Multi-year in situ observations (XBT and Argo) and the advent of satellite altimetry made it possible to combine satellite and in situ observations to derive the AMOC and Meridional Heat Transport estimates at different latitudes.



- 1982 — Florida Current Transport with submarine cable
- 1992 — Satellite Altimetry
- 1995 — AX7
- 2002 — AX18
- 2004 — Argo

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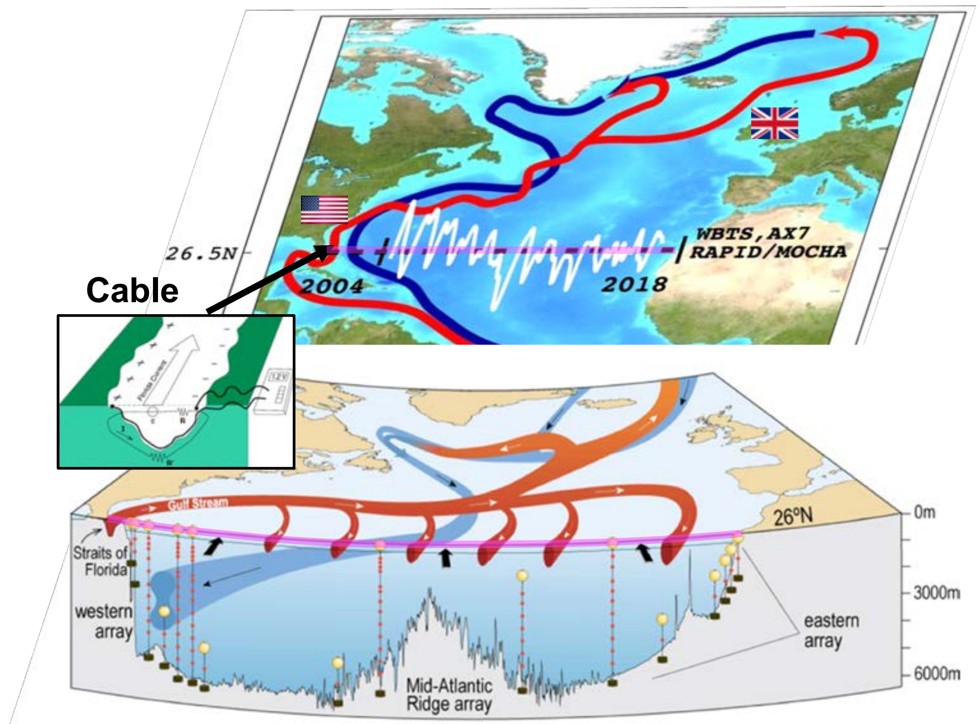
AOML is monitoring AMOC in both the North and South Atlantic

- North Atlantic: RAPID-MOCHA-WBTS moored array at 26.5°N since 2004
  - **Why this latitude:** Leverages already existing measurements of the Florida Current; targets latitude of maximum northward oceanic heat transport in the Atlantic Ocean
  - **Observing platforms:** cable, tall moorings, Pressure Inverted Echo Sounders (PIES), Argo, hydrography
  - **Partners:** RSMAS-Univ. Miami and National Oceanographic Centre (UK)



https://mocha.rsmas.miami.edu/methods/index.html

- 1982 — Florida Current Transport with submarine cable
- 1992 — Satellite Altimetry
- 1995 — AX7
- 2002 — AX18
- 2004 — Argo, RAPID-MOCHA-WBTS

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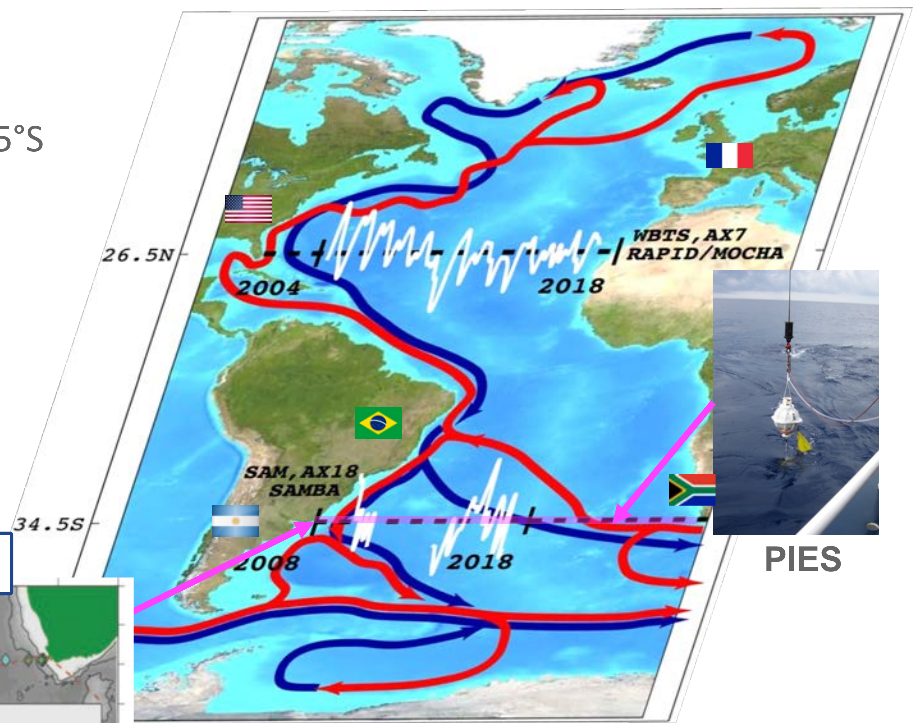
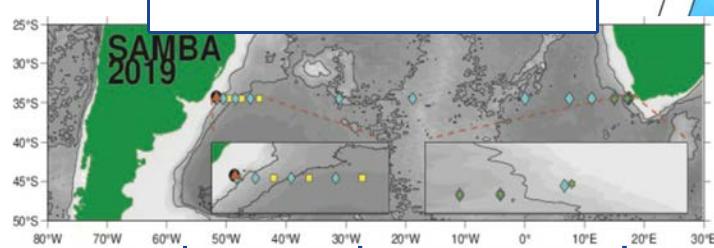
AOML is monitoring AMOC in both the North and South Atlantic

- South Atlantic: MOC Basin-wide moored Array (SAMBA) at 34.5°S since 2009
  - **Why the South Atlantic:** Convenient to monitor inter-ocean exchanges; freshwater flux into the South Atlantic may control the AMOC stability; South Atlantic is the only basin with equatorward heat transport
  - **Observing platforms:** PIES, tall moorings
  - **Partners:** France, South Africa, Argentine, Brazil





1982 — Florida Current Transport with submarine cable

1992

1995

2002

2004 — Argo, RAPID-MOCHA-WBTS

2009 — SAMBA

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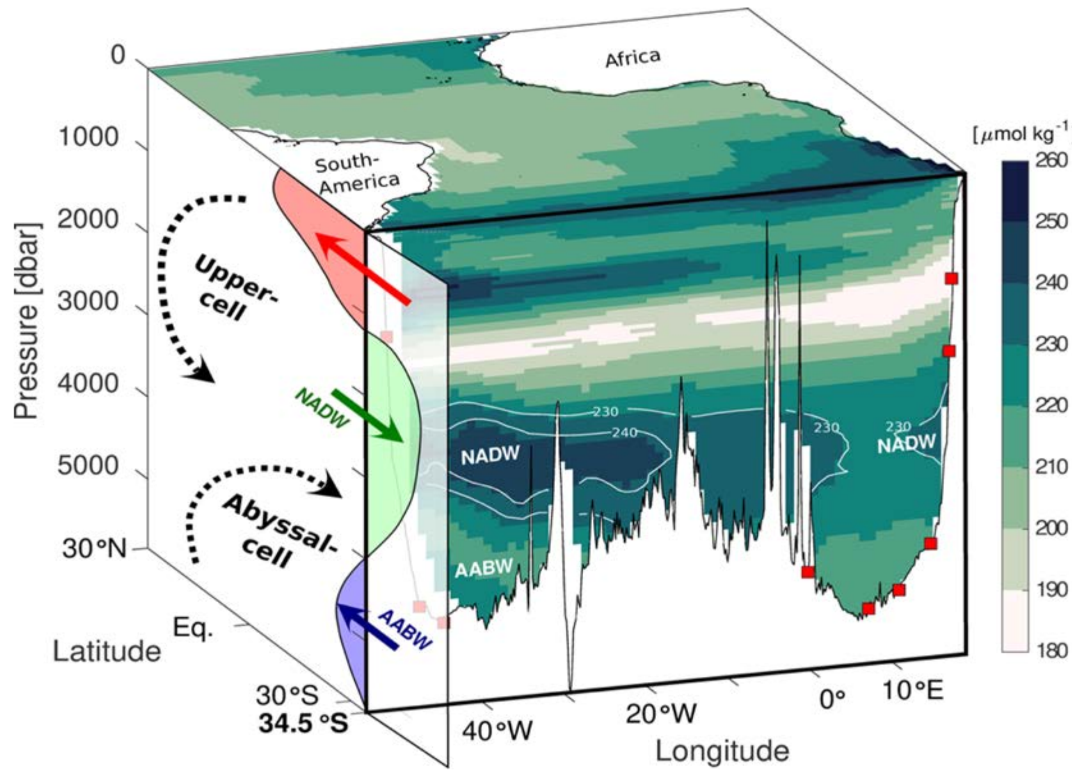
Major findings & implications

- **AMOC abyssal cell is highly energetic**
  - Highly energetic AMOC in both cells (s = 15.5 Sv, 6.2 Sv). Variations in the abyssal-cell appear to be largely independent of the overlying upper-cell variability
  - No meaningful trends are observed in either cell
  - Longer time series will be necessary to study seasonal-interannual variability and to detect long-term trends to identify any climate-related trends
- **Deepest, coldest parts of the ocean are getting warmer**
  - All sites along the SAMBA array exhibited a deep sea warming trend of 0.02 to 0.04 degrees Celsius per decade between 2009 and 2019
  - A significant warming trend in the deep sea where temperature fluctuations are typically measured in thousandths of a degree
  - This increase is consistent with warming trends in the shallow ocean associated with anthropogenic climate change

SAMBA: SAMoc Basinwide Array (34.5°S)



Kersalé et al. (2020)

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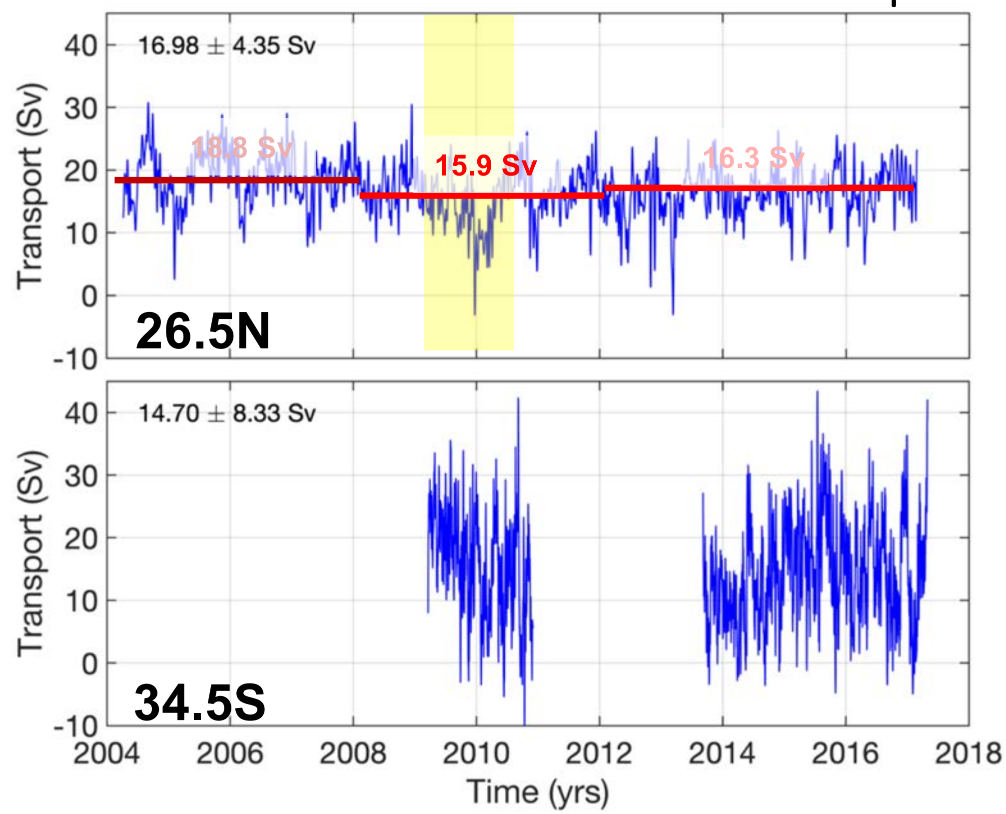
Major findings & implications

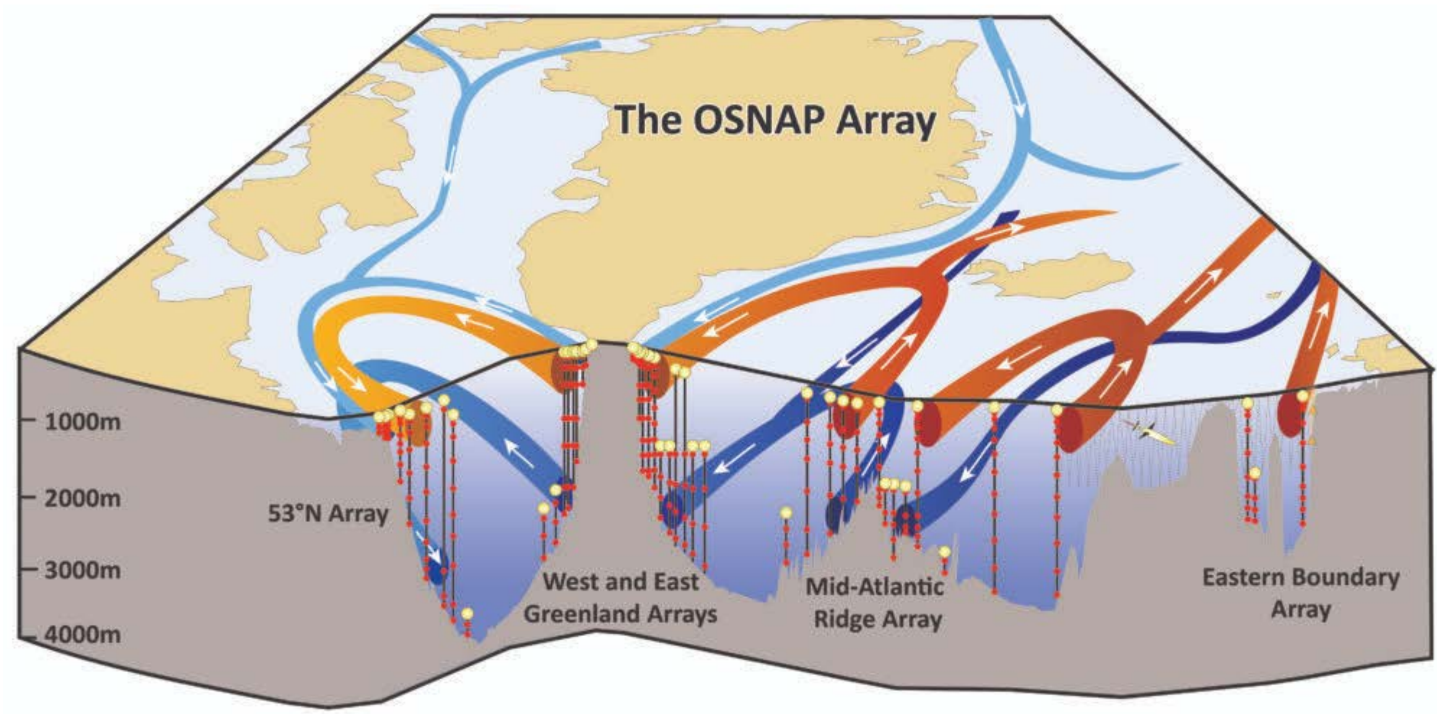
- **AMOC is highly variable**
  - Time scales from a few days to interannual
  - Lack of coherency between North and South Atlantic MOC
  - 30% reduction in 2009/10 at 26.5N exceeded the range of interannual variability found in climate models
  - Continuous monitoring is necessary to avoid aliasing high-frequency variability, and to identify any climate-related trends
- **The North Atlantic Ocean is in a state of reduced overturning since 2008**
  - Between 2004-2008 and 2008-2012, the AMOC **reduced by 2.9 Sv** (significant at the 95% level)
  - This is consistent with concurrent changes in other key climate parameters, such as heat content, SSH, SST, and air-sea latent heat flux

AMOC northward transport



Frajka-Williams et al. (2019), Meinen et al. (2018), Smeed et al. (2018)

Labrador Sea Convection & AMOC (OSNAP)



https://www2.whoi.edu/site/bower-lab/osnap-overturning-in-the-subpolar-north-atlantic

- OSNAP (Lozier et al., 2019):
  - Overturning in the Subpolar North Atlantic Program
  - Launched in August 2014
  - First complete data recovery in April 2016 (21 months record)
  - Second recovery in May 2018 (46 months)
  - OSNAP West
  - OSNAP East

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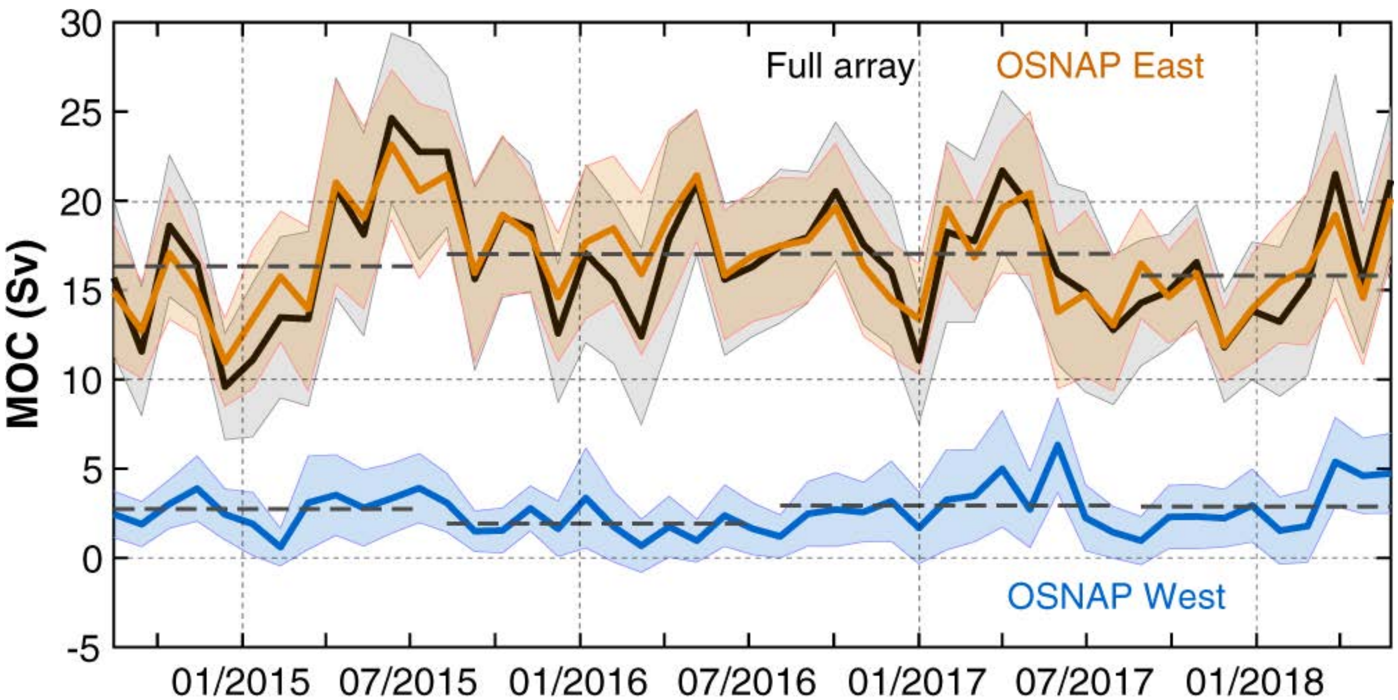
Labrador Sea Convection & AMOC (OSNAP)



Li et al. (2021, Ncomm)

- OSNAP West vs East
  - OSNAP East contributes 15.6 ± 0.8 Sv to the AMOC
  - OSNAP West contributes only 2.1 ± 0.3 Sv
  - OSNAP East contributes ~7 times greater than the West
  - Similar results found in the latest update (Li et al., 2021)

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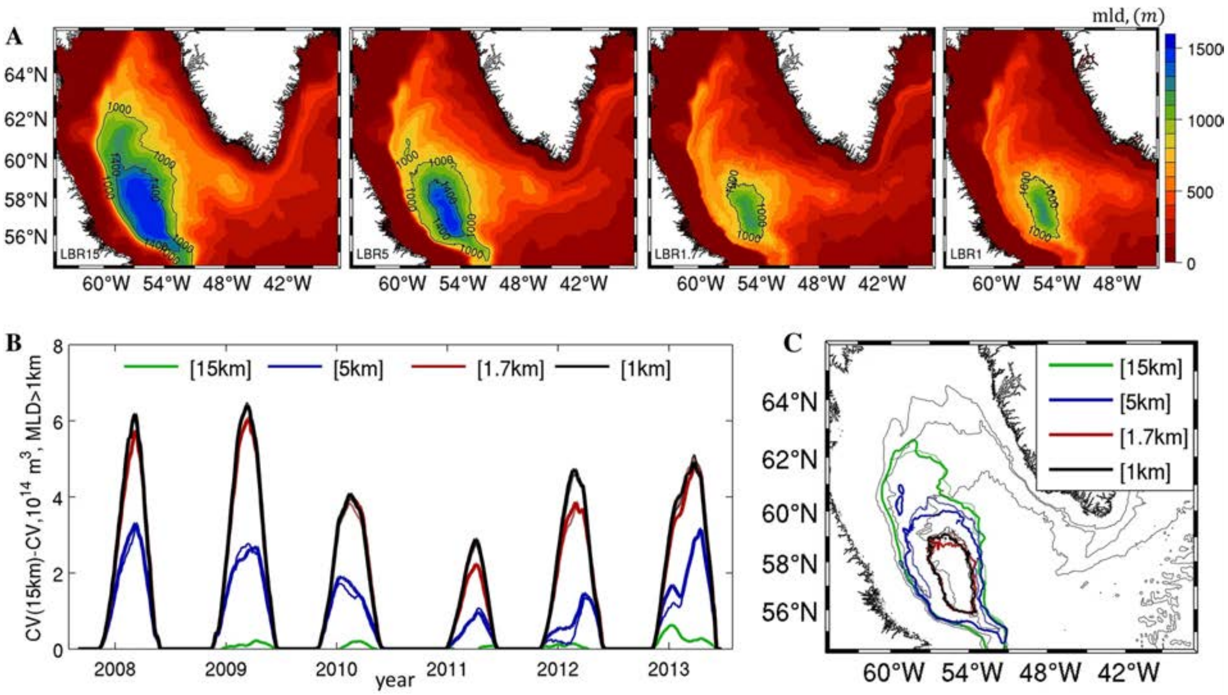
Labrador Sea Convection & AMOC (Models)



Tagklis et al. (2020)

- Tagklis et al. (2020):
  - Carried out four sets of high-resolution ocean model experiments
  - Current high-resolution ocean models (1/12°: ~ 5km) significantly overestimate Labrador Sea convection
  - **At least ~ 2km resolution is required (~1/24°**) to properly simulate Labrador Sea convection
  - Is there a global ocean model run at 1/24° resolution?

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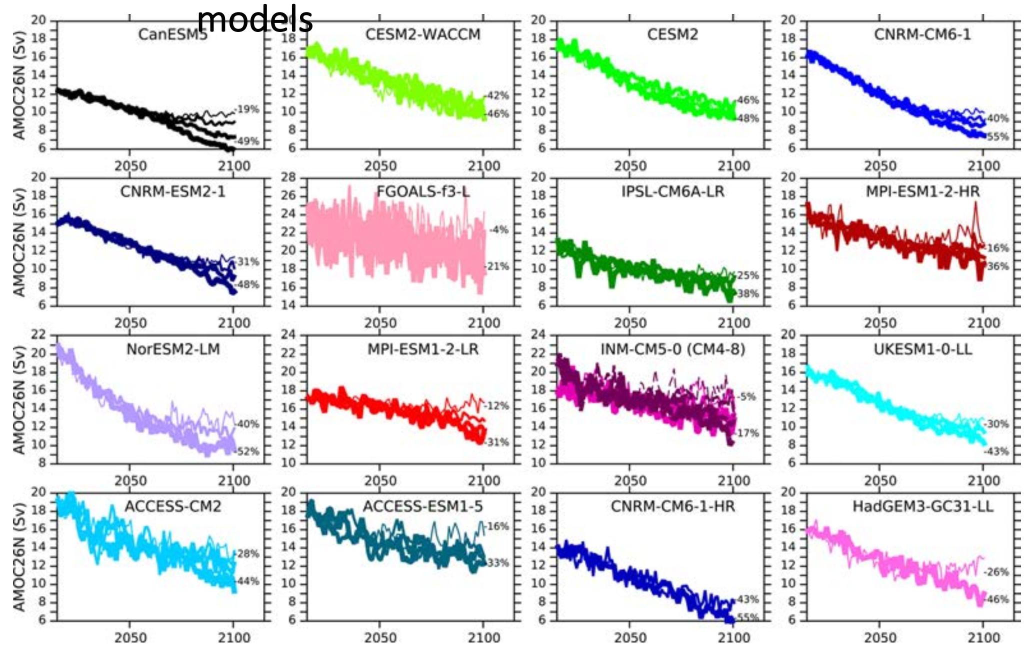
Projected slowdown of the AMOC during the 21st Century

- **Projected slowdown of the AMOC**
  - Climate models predict the AMOC will slow in response to increasing greenhouse gases
  - Increased rainfall and melting of the Greenland Ice Sheet add fresh water to the surface ocean, reducing the salinity
  - Both the surface warming and freshening increase the surface stratification, inhibiting the sinking and thus weakening the flow of the AMOC
- **Coupled Model Intercomparison Project Phase 6 (CMIP6)**
  - Multi-model simulations under different anthropogenic forcing scenarios by 2100 under low-end (SSP1-2.6), medium-end (SSP2-4.5), and high-end (SSP3-7.0; SSP5-8.5) forcing scenarios
  - The projected AMOC decline by the end of the 21st century shows weak dependence on the scenarios
  - The overall consusus suggests AMOC decline of 34-45% by 2100

Time series of AMOC at 26°N for 17 CMIP6 models



Weijer et al. (2020)

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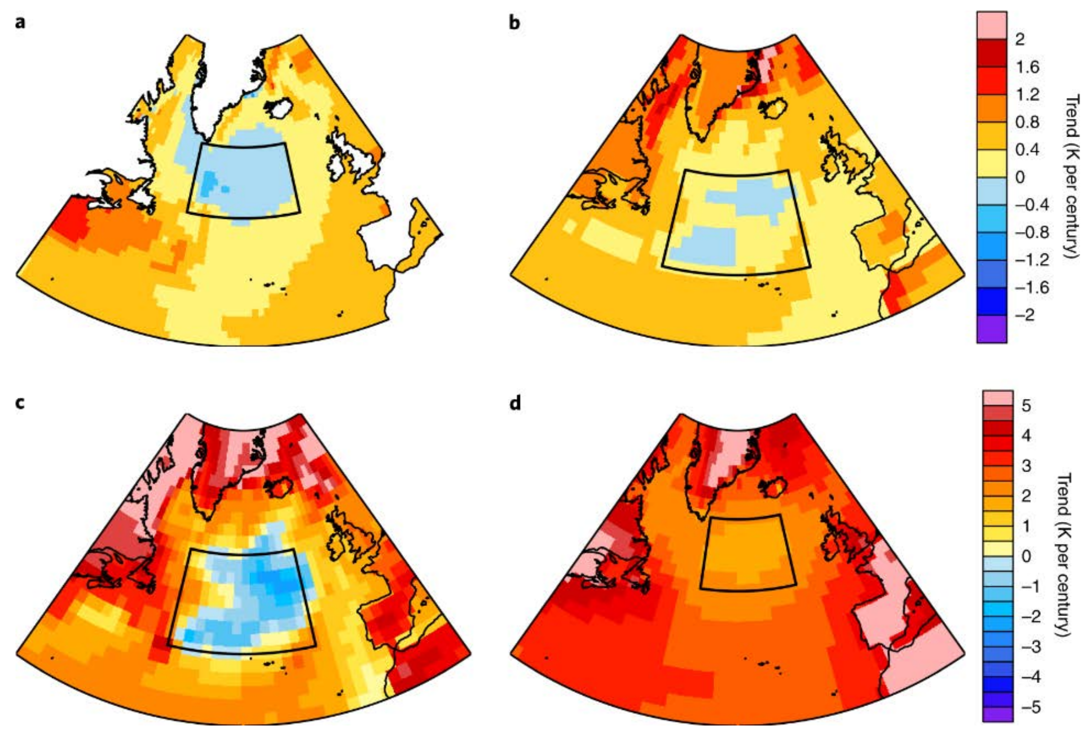
North Atlantic warming hole

- **Cooling of the North Atlantic Ocean**
  - The projected slowing down of the AMOC reduces the northward transport of oceanic heat
  - The slower AMOC is associated with a cooling in the North Atlantic Ocean
  - This cooling is expected to partly offset the greenhouse-induced warming in surface air temperature (SAT) over the North Atlantic
  - A larger reduction in the AMOC is associated with greater cooling in the North Atlantic
- **North Atlantic warming hole**
  - The North Atlantic warm hole is a robust feature in observations over the past 130 years
  - This North Atlantic warm hole is a robust feature in climate model projection for the 21st century

Surface temperature trends in the North Atlantic



Keil et al. (2020)

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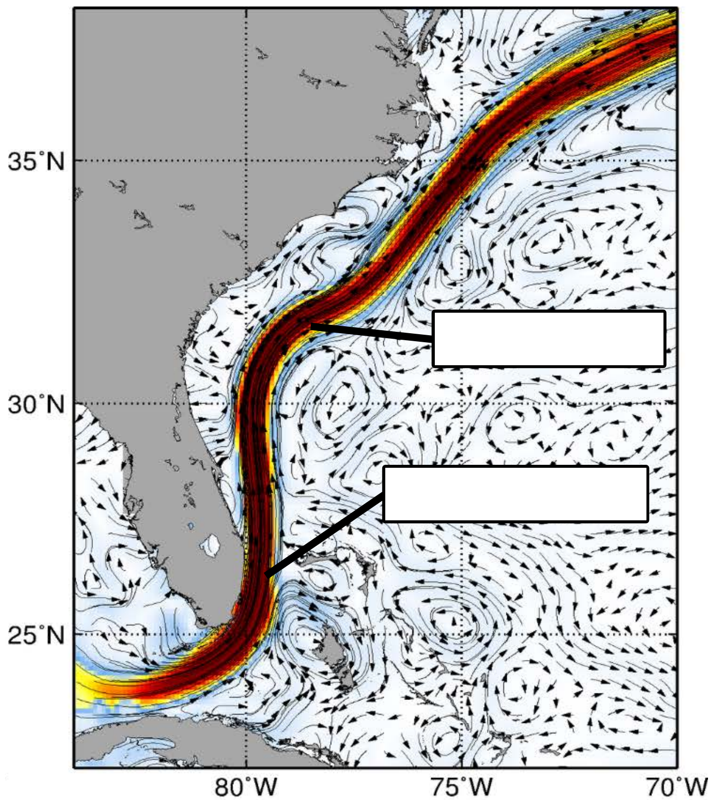
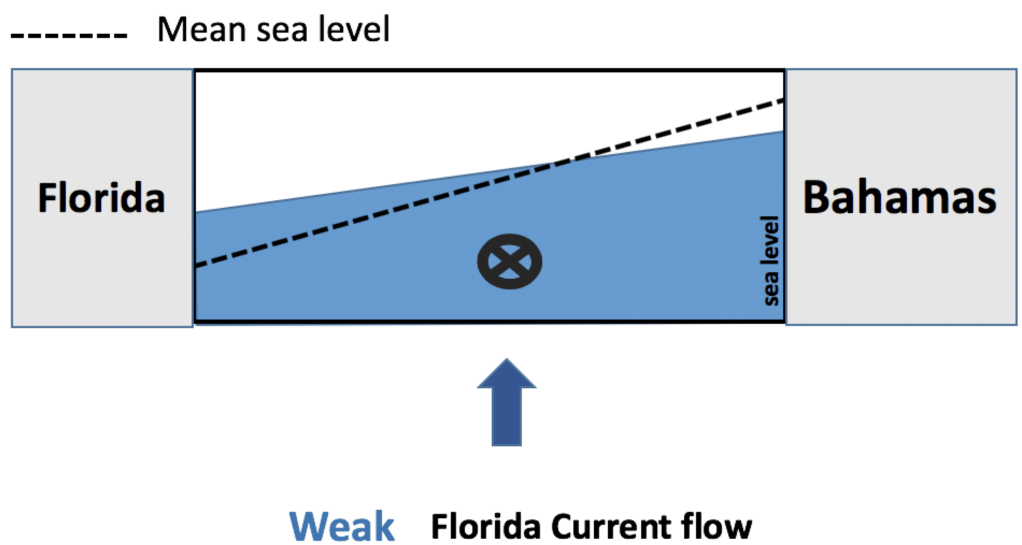
Accelerated sea-level rise along the US east coasts





- A weak Florida Current can increase sea-level in Miami by **up to 20 cm** (*Domingues et al., 2016*)
- A 30% slowdown of the AMOC can **cause an 8 -10 cm** increase in sea level rise by 2100 (*Little et al., 2019*)

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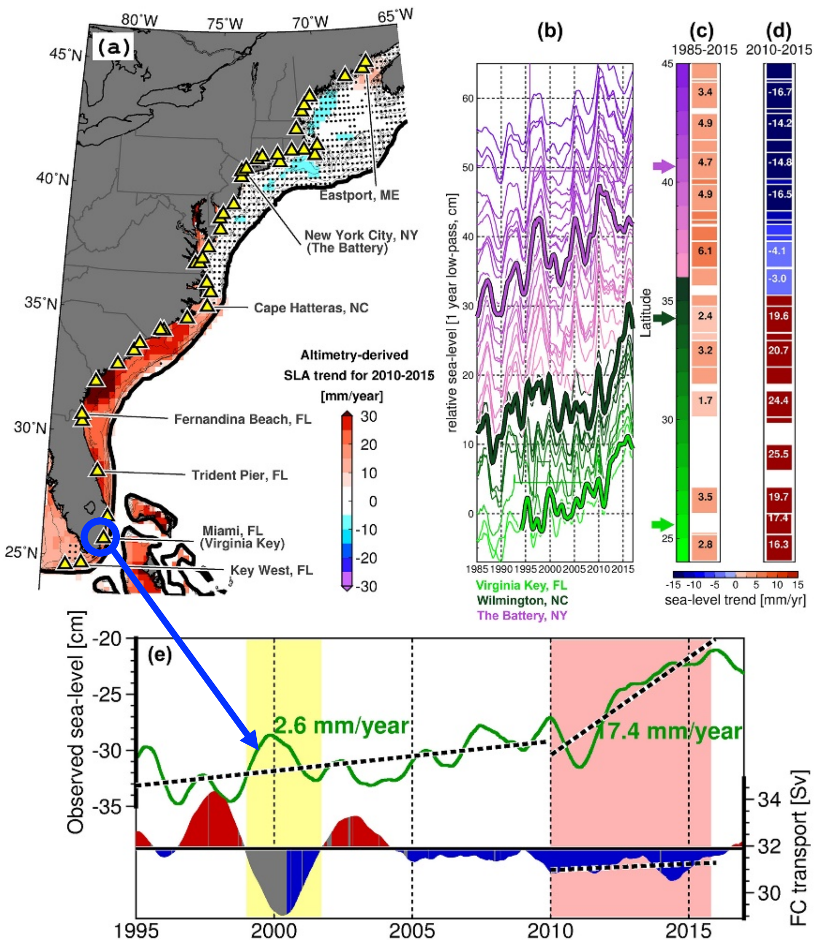
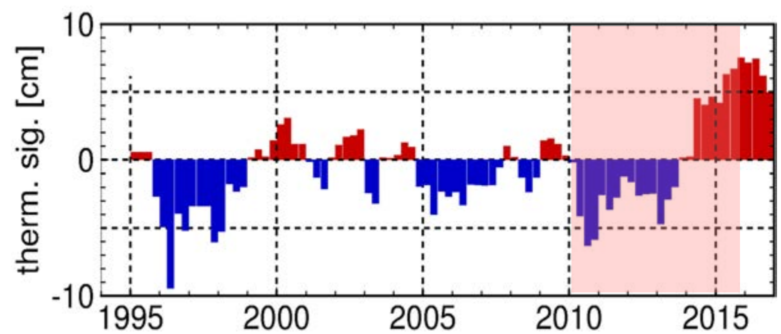
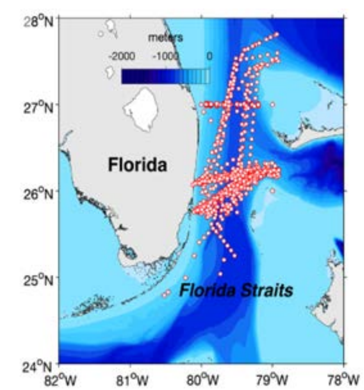
Sea level changes from tide gauges and altimetry (Domingues et al., 2018)



- Strong oscillations in the Florida Current transport played an important role in sea level variations in Miami in 1997-2005.
- In other periods, the Florida Current volume transport is not the major contributor to the interannual variability of sea level along the east coast of Florida
- The dynamic sea level rise south of Cape Hatteras in 2010-2015 (~10 cm) was mostly accounted for by an unprecedented warming of the Florida Current (Domingues et al., 2018)

ΔT is calculated using 541 CTD and 1925 XBT profiles in the Florida Straits





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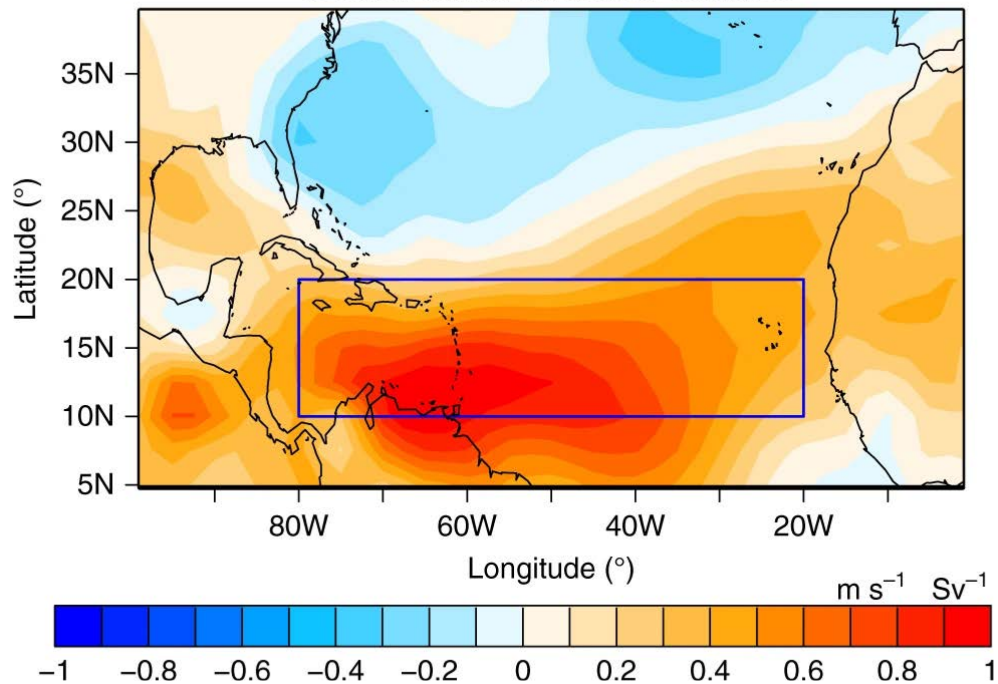
Suppression of Atlantic hurricane activity

- **North Atlantic SST and Atlantic hurricane activity**
  - Atlantic hurricane activity is influenced by SST anomalies in the Pacific & Atlantic Oceans
  - Warm North Atlantic → Increase hurricanes
  - Warm Pacific → Suppress hurricanes
- **Differential inter-ocean warming**
  - A slowing AMOC suppresses warming of the North Atlantic
  - Pacific warms faster than the North Atlantic
  - This increases the vertical wind shear over the main development region, and thus decreases overall Atlantic hurricane activity in the 21st century

Observed trend regression of inverted vertical wind shear on the AMOC



Yang et al. (2017)

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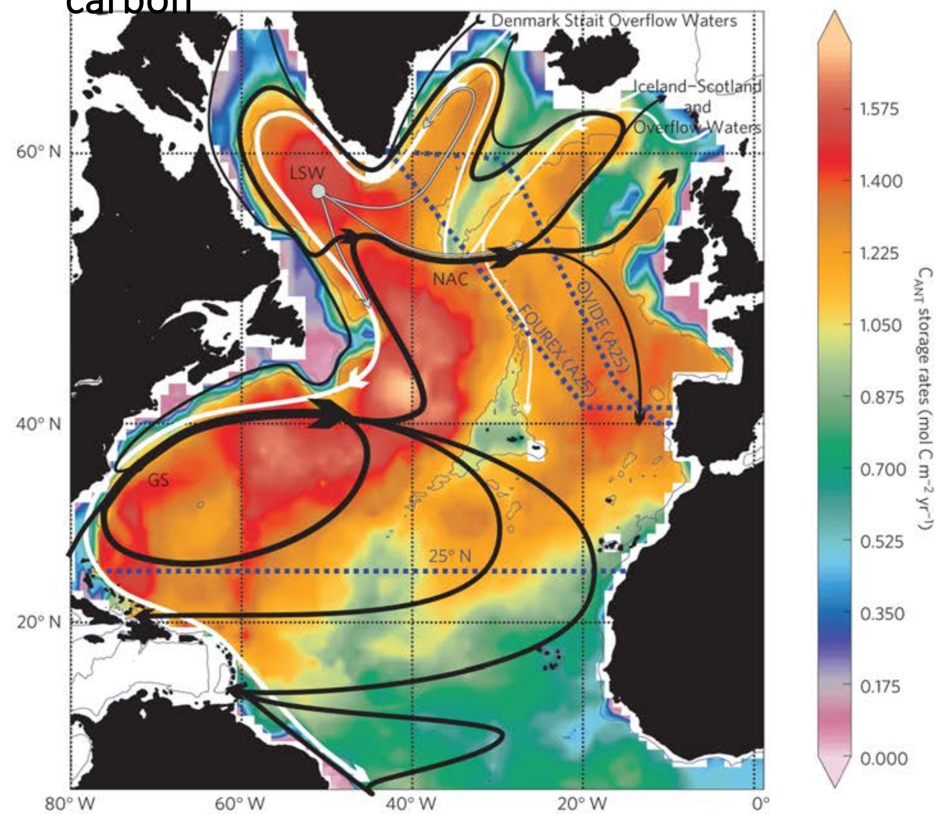
Reduced oceanic uptake of atmospheric CO_2

- **The North Atlantic accounts for about one-third of global oceanic uptake of atmospheric CO_2**
  - The North Atlantic represents only 13% of the global ocean area
  - However, it accounts for about one-third of global oceanic uptake of atmospheric CO_2
  - This is due to the AMOC and associated deep water formation
- **Reduced oceanic uptake (sequestration) of atmospheric CO_2**
  - A future slowing AMOC and associated deep water formation will limit the ocean's role of atmospheric CO_2 sequestrations.

Storage rate of anthropogenic carbon



Perez et al. (2013)

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Decline of marine ecosystems in the North Atlantic Ocean

- **AMOC supports upwelling of nutrient-rich deep water to the surface ocean**
  - AMOC and the associated deep winter mixed layers allow replenishment of surface nutrient levels from the deep ocean
  - Shoaling of the winter mixed layers as a consequence of the AMOC reduction and the associated development of a strong halocline decreases nutrient supply to the photic zone, leading to rapid plankton demise (Schmittner, 2005)

Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation

Andreas Schmittner

College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Admin. Bldg, Corvallis, Oregon 97331, USA

Reorganizations of the Atlantic meridional overturning circulation were associated with large and abrupt climatic changes in the North Atlantic region during the last glacial period[1–4]. Projections with climate models suggest that similar reorganizations may also occur in response to anthropogenic global warming[5–7]. Here I use ensemble simulations with a coupled climate–ecosytem model of intermediate complexity to investigate the possible consequences of such disturbances to the marine ecosystem. In the simulations, a disruption of the Atlantic meridional overturning circulation leads to a collapse of the North Atlantic plankton stocks to less than half of their initial biomass, owing to rapid shoaling of winter mixed layers and their associated separation from the deep ocean nutrient reservoir. Globally integrated export production declines by more than 20 per cent owing to reduced upwelling of nutrient-rich deep water and gradual depletion of upper ocean nutrient concentrations. These model results are consistent with the available high-resolution palaeorecord, and suggest that global ocean productivity is sensitive to changes in the Atlantic meridional overturning circulation.

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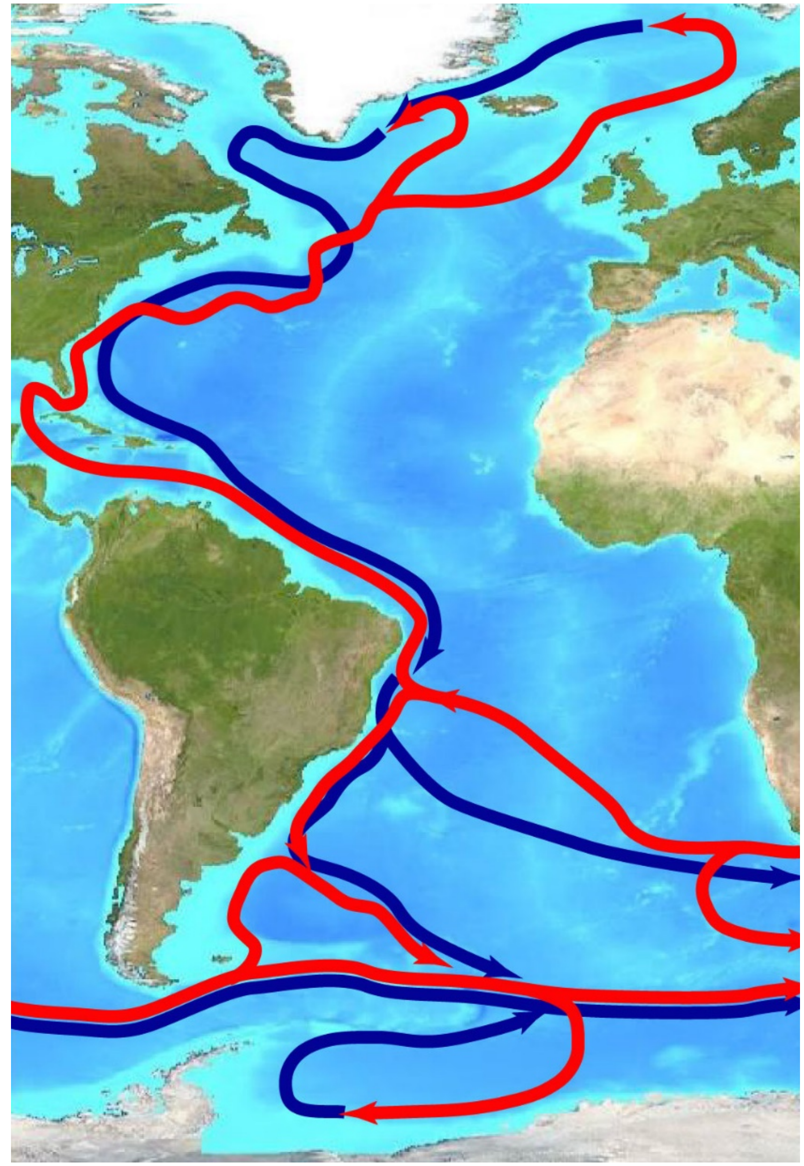
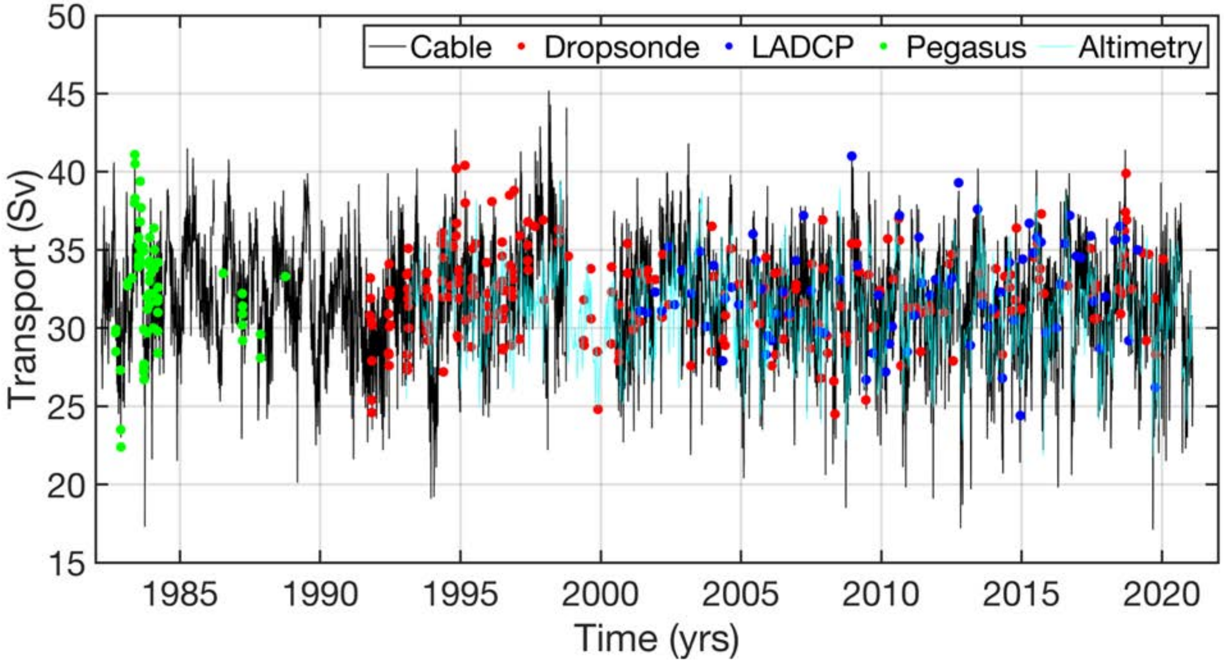


Extra slides

3. Estimates of Florida Current volume transport



FC transport estimate	Trend (Sv decade [1])
Cable (1982-2021)	−0.3 ± 0.2
Altimetry (1993-2021)	−0.2 ± 0.2
Cal/Val cruises (1982-2021)	0.1 ± 0.3

Mean transport:

- from cable = 31.8 ± 3.4 Sv
- from cruises = 32.3 ± 3.1 Sv
- from altimetry = 31.1 ± 2.8 Sv

Florida Current volume transport has been stable over time → no significant slowdown and associated coastal sea level rise