The role of the AMOC in ocean heat transport and implications for subpolar North Atlantic SST variations

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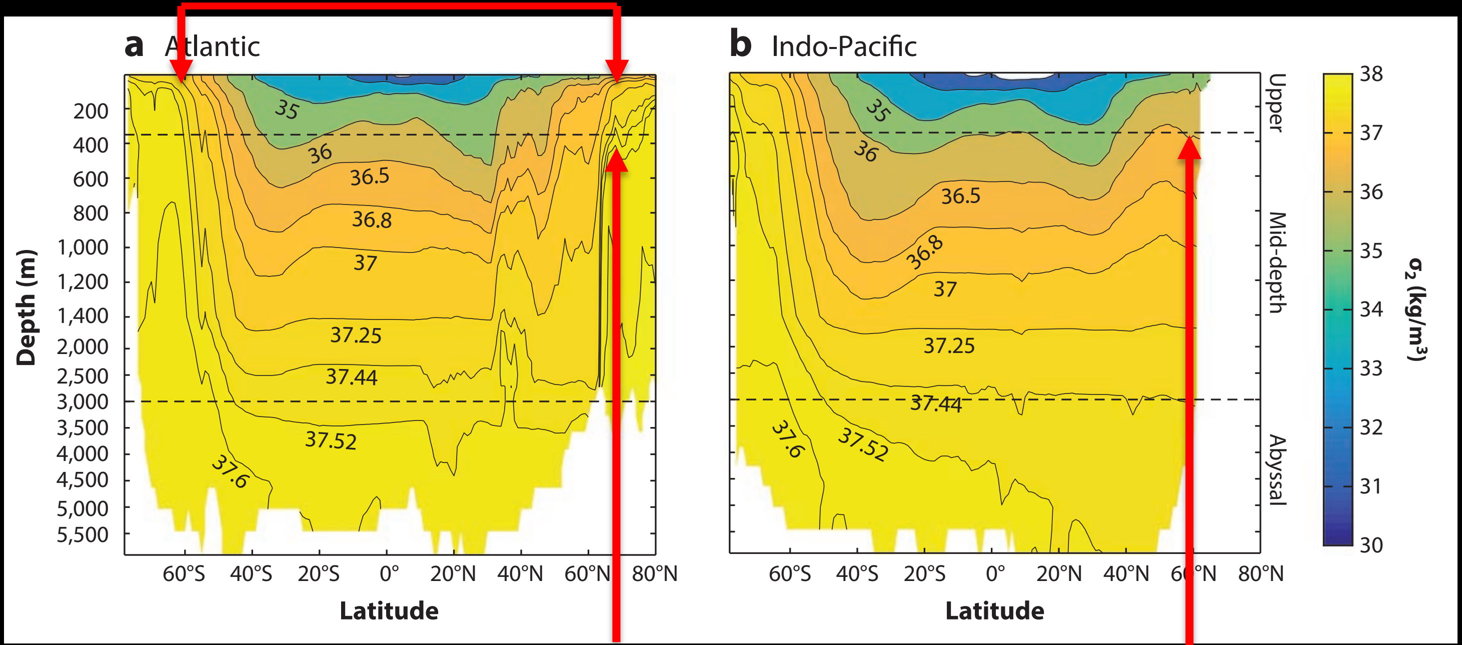
Paper of relevance to Task Team 2: Jackson et al. (2021): The evolution of the North Atlantic Meridional Overturning Circulation since 1980. *Nature Reviews Earth & Environment*.

Why is there a deep overturning in the Atlantic

- Sea surface salinity is higher in the North Atlantic than the North Pacific (Ferreira et al., 2008).
- Cooling creates very dense waters in North Atlantic.
- Shared isopycnals between North Atlantic and Southern Ocean allows dense waters to upwell adiabatically, driven by winds over the Southern Ocean (e.g., Marshall and Speer, 2012).

Shared isopycnals



From Cessi (2019)

Steeply sloping isopycnals

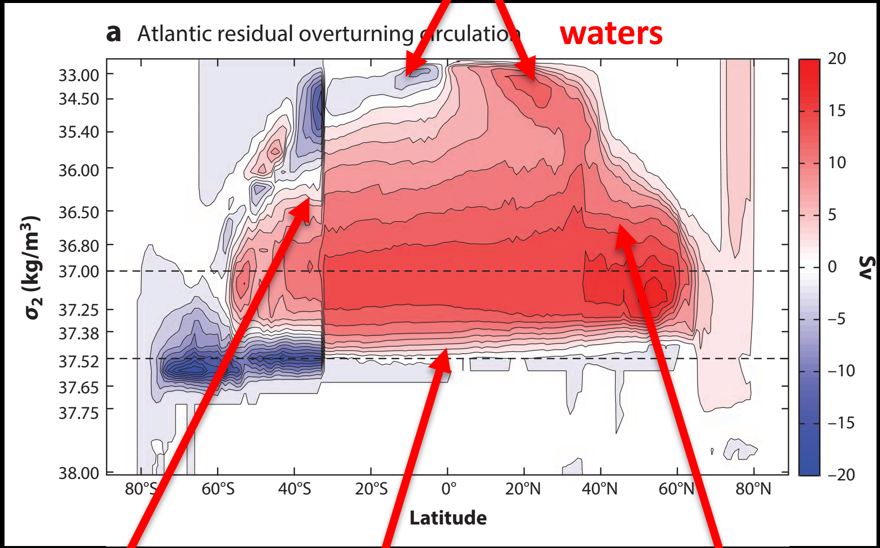
Isopycnal slopes more shallow

Overturning circulation in the Atlantic and Indo-Pacific

Atlantic

Shallow wind-driven cells

Subtropical mode waters



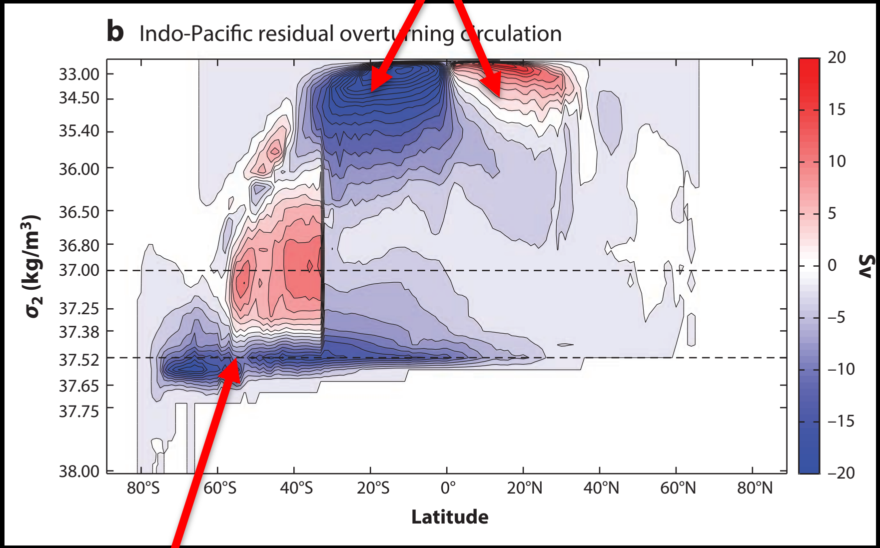
Adiabatic upwelling in Southern Ocean

Adiabatic flow

Cell that spans warm and cold temperatures

Indo-Pacific

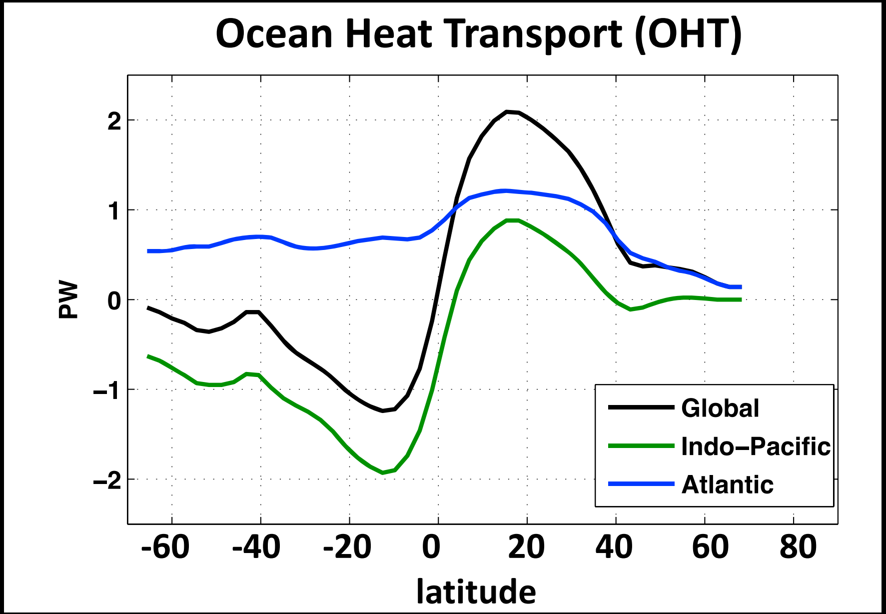
Shallow wind-driven cells



Abyssal cell related to Antarctic Bottom Water Formation (will not discuss this today)

From Cessi (2019), velocities are from ECCO v4 (Forget et al.,2015)

The AMOC and ocean heat transport

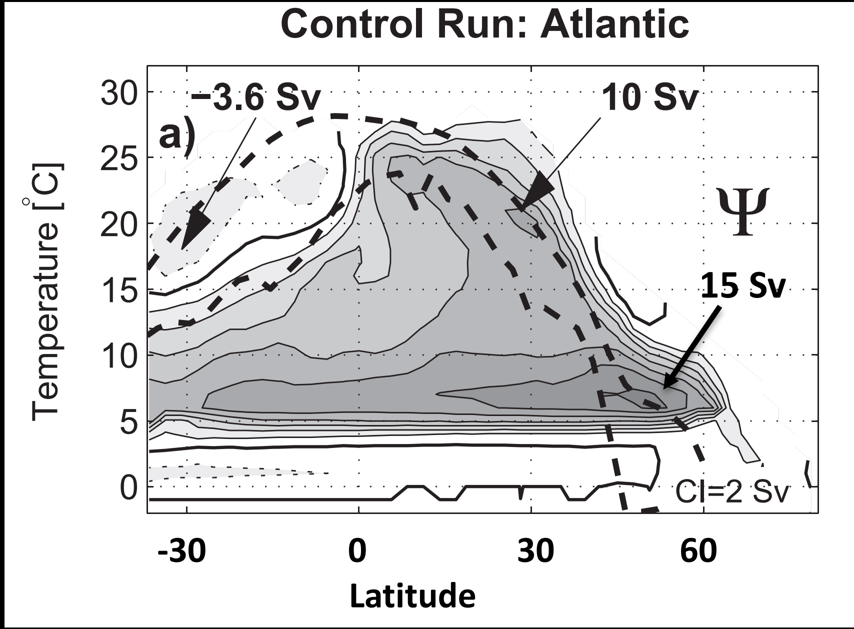


From Buckley & Marshall (2016)
Data reproduced from Trenberth & Caron (2001)

The Atlantic transports heat northward in both hemispheres.

How much of the Atlantic ocean heat transport is related to the deep overturing?

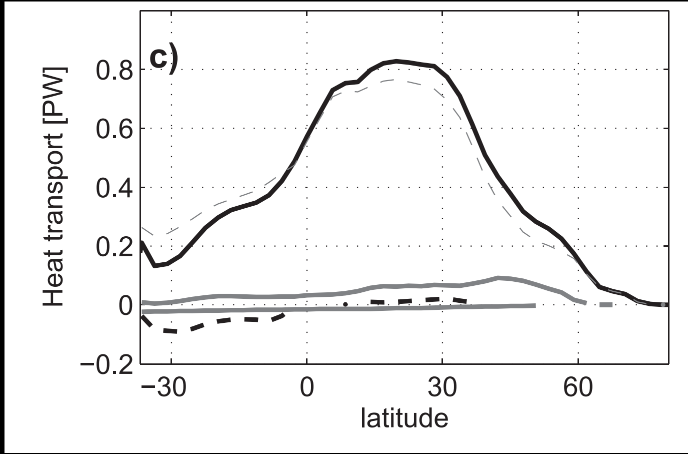
Ocean heat transport & overturning in temperature coordinates



$$\mathcal{H} = \rho_o C_p \int_{\theta_{bottom}}^{\theta_{top}} \Psi \, d\theta$$

$$\mathcal{H} \approx \rho_o C_p \, \Psi \, \Delta\theta$$

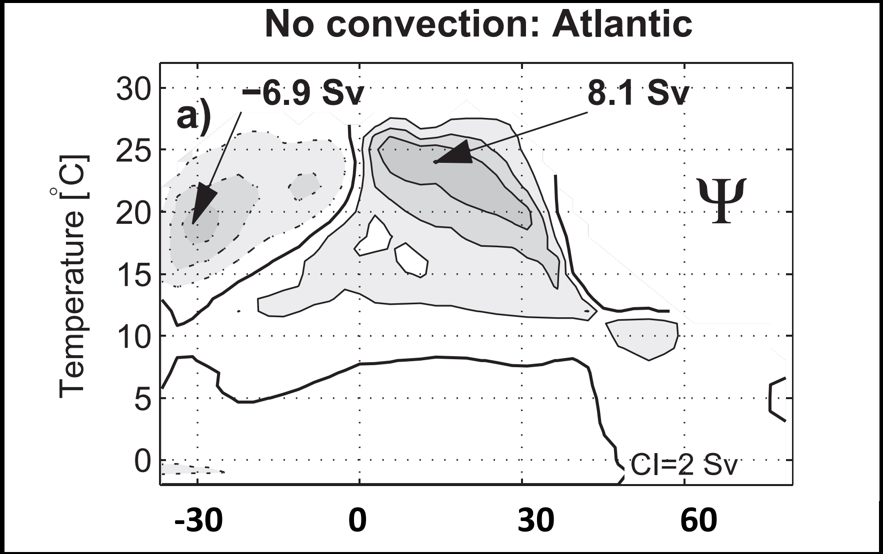
$$\Psi \approx 15 \text{ Sv}, \ \Delta\theta \approx 15\,^{\circ}\text{C} \rightarrow \mathcal{H} \approx 0.9 \, PW$$

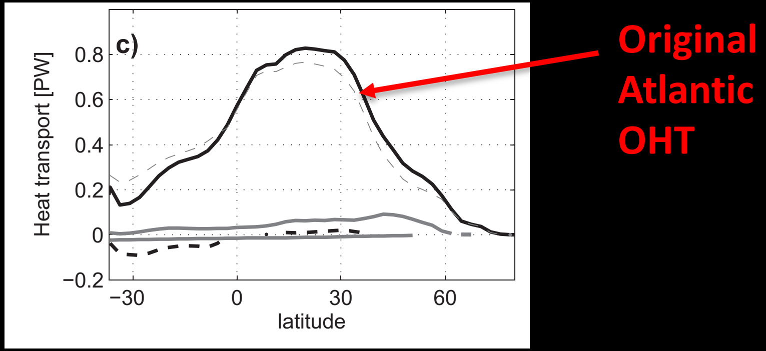


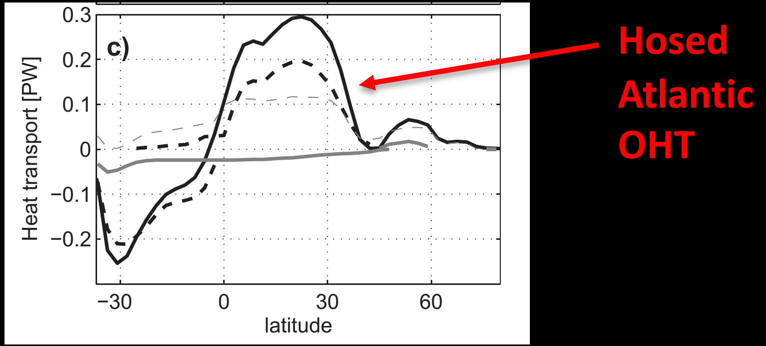
- **Overturning circulation spans warm and cold temperature classes.**
- **Atlantic ocean heat transport (OHT) cannot be uniquely ascribed to a surface or deep circulation.**

Figures from Ferrari and Ferreira (2011)

How much does the AMOC contribute to OHT?







Water hosing experiment to shut off convection in the North Atlantic.

- Circulation spanning both warm and cold temperature classes disappears.

Figures from Ferrari and Ferreira (2011)

- Peak Atlantic OHT decreases from 0.8 PW to 0.3 PW
- About 60% of peak OHT in the Atlantic OHT is due to shallow-to-deep circulation.

The role of the deep circulation in the mean Atlantic OHT

- Atlantic ocean heat transport (OHT) cannot be uniquely ascribed to a thermocline or deep circulation.
- Model experiment: suggests 60% of the peak Atlantic Ocean heat transport can be ascribed to a circulation that extends from thermocline to mid-depth.
- Note: Talley et al (2003) used a careful watermass decomposition to estimate role of NADW in Atlantic Ocean heat transport from observations.
    - She also found 60% of Atlantic OHT peak is due to NADW transport.
- The mean AMOC is sensitive to winds over the Southern Ocean, which drive upwelling and are needed to sustain the circulation (e.g., Abernathy et al., 2011).

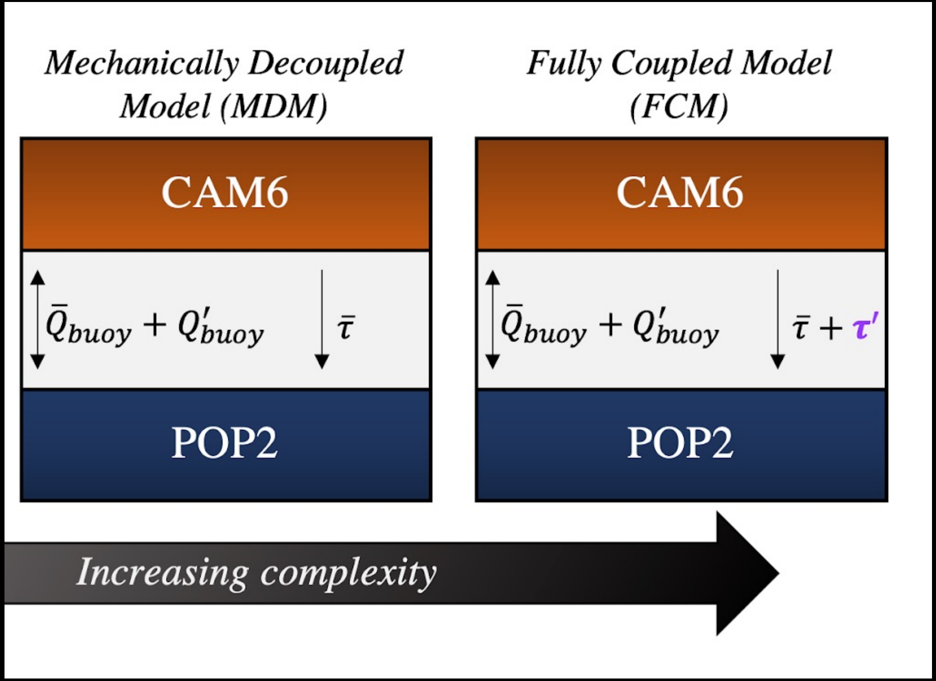
Variations of the AMOC and ocean heat transport

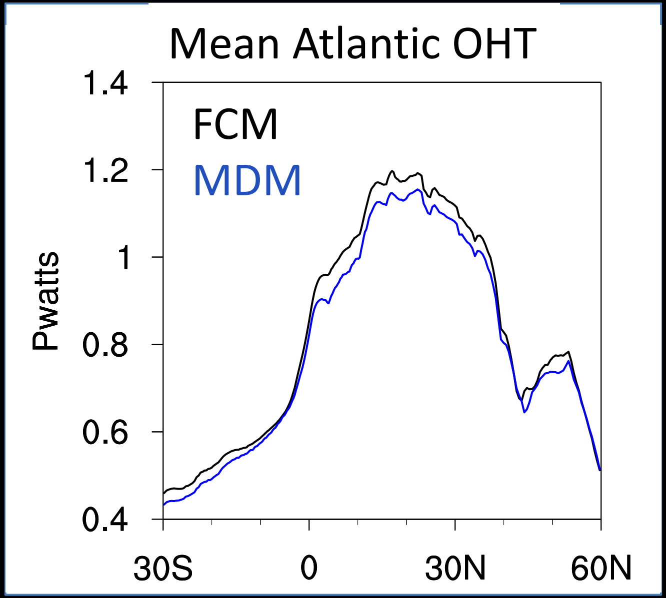
- In the mean, mechanical forcing is clearly needed to sustain the AMOC.
- However, perhaps temporal variations of the AMOC due to wind forcing and buoyancy forcing are distinct and can be considered separately.
- Modeling studies suggest that large-scale, low-frequency variations of the AMOC are primarily related to buoyancy forcing over the subpolar North Atlantic.
    - Yeager and Danabasoglu (2014) show heat fluxes applied only over the Labrador Sea explain most of decadal variability of the AMOC in ocean-ice hindcast version of CESM1.
    - In a series of papers, T. Delworth and colleagues show that AMOC variability is response of ocean to heat flux variations associated with the North Atlantic Oscillation (Delworth and Zeng, 2016; Delworth et al., 2016; Delworth et al., 2017).

Separating the effects of time variable wind and buoyancy forcing

Separate the effects of time variable wind and buoyancy forcing in a coupled model framework (CESM2)

- Momentum (wind stress) forcing applied to ocean is set to be mean climatology.
- This is referred to as the mechanically decoupled model (MDM).

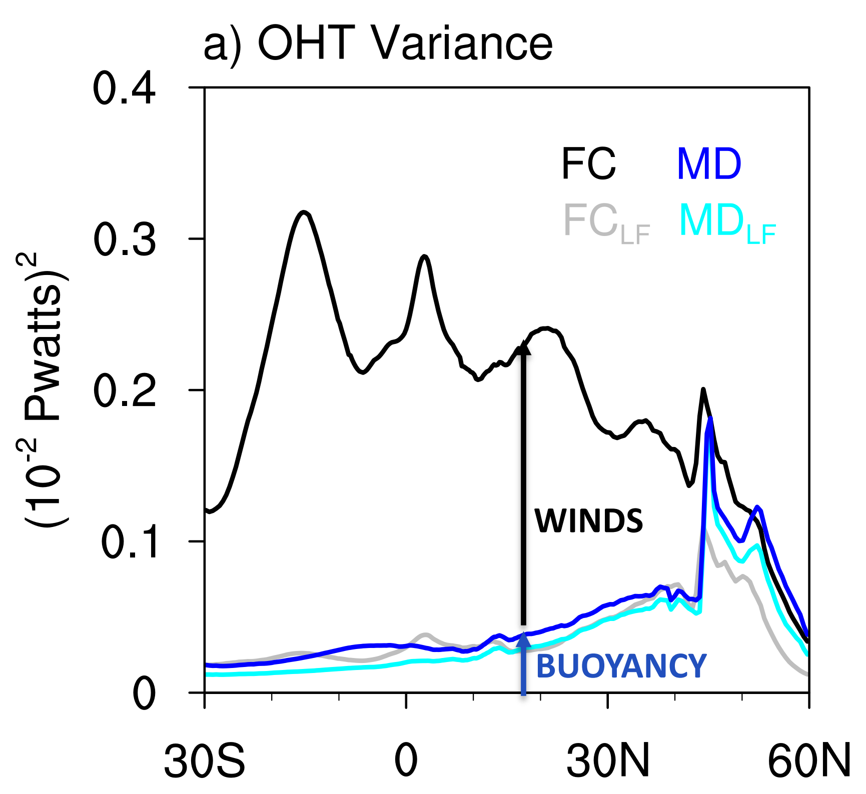




Sarah Larson (NC State) ; Larson et al (2018, 2020)

Mean Atlantic OHT is quite similar in FCM and MDM.

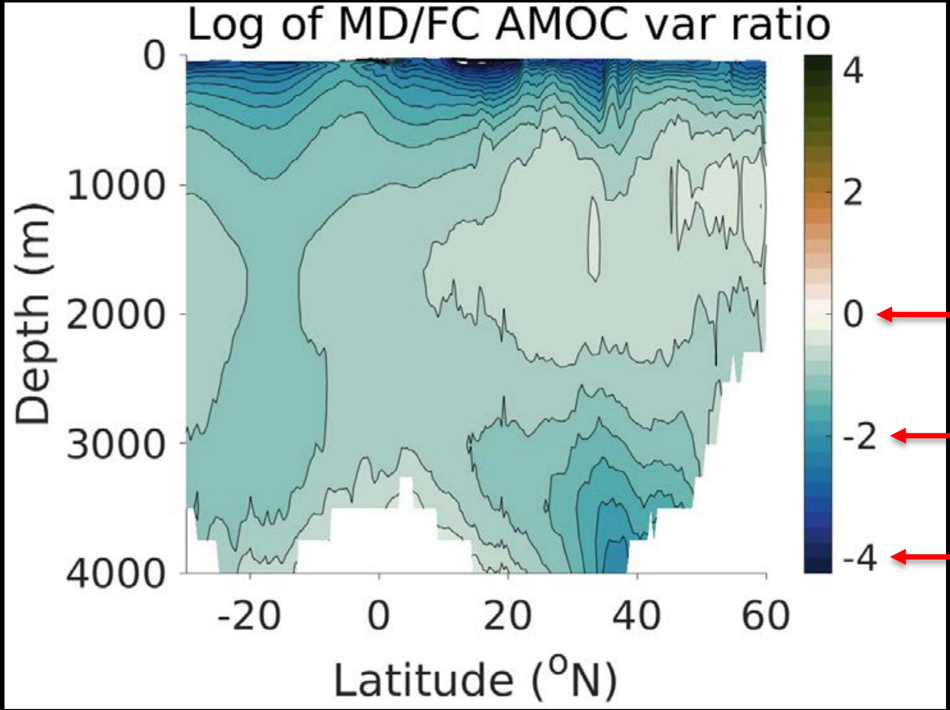
Ocean heat transport variations: a strong role for wind forcing



- In the tropics and subtropics, most of the variance in Atlantic ocean heat transport is related to wind-driven variations, even at low frequencies.
- Buoyancy forcing plays a role in ocean heat transport variations in the subpolar North Atlantic (40°-60°N).

Larson et al (2020)

Role of winds and buoyancy in AMOC variability



$$\ln\left(\frac{\sigma^2(\psi_{MDM})}{\sigma^2(\psi_{FCM})}\right)$$

LOG SCALE:

FCM and MDM same variance

FCM has 7x more variance

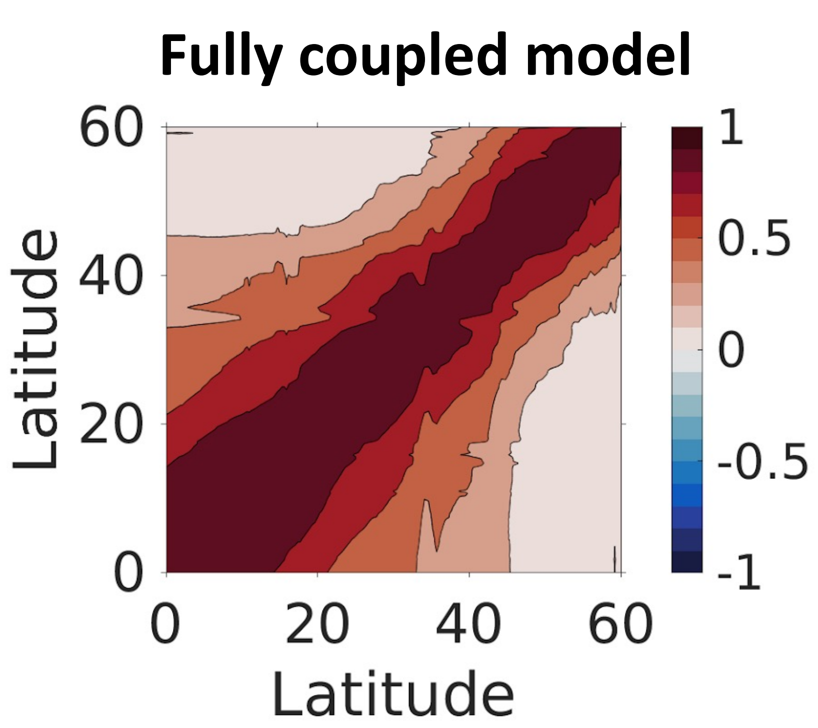
FCM has 55x more variance

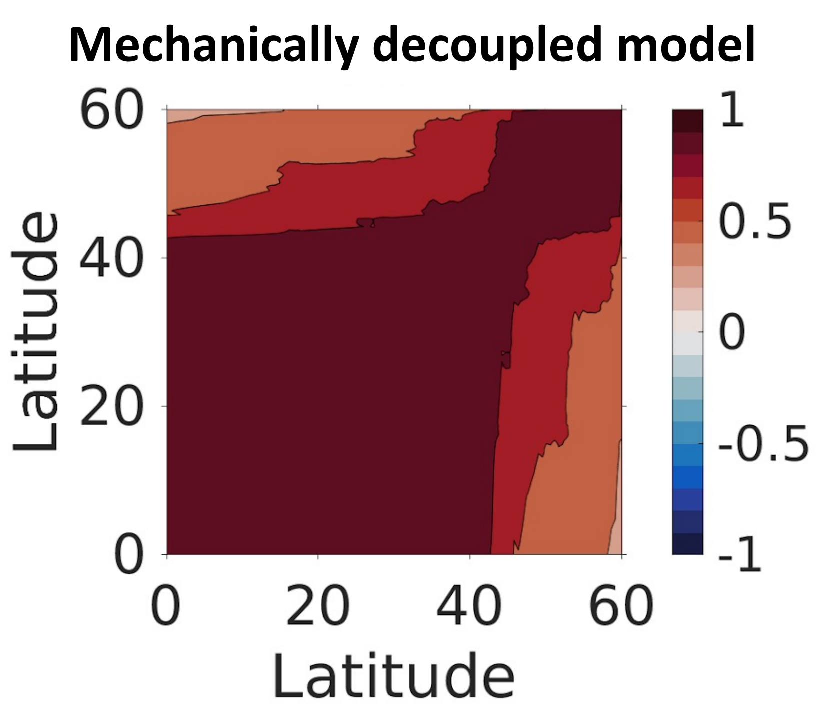
From Larson et al. (2020), updated to CESM2 by Kay McMonigal [to do: update to density coordinate].

Wind variability increases AMOC variance everywhere, particularly

- near the surface
- in tropics/subtropics.

Winds disrupt meridional correlation of the AMOC



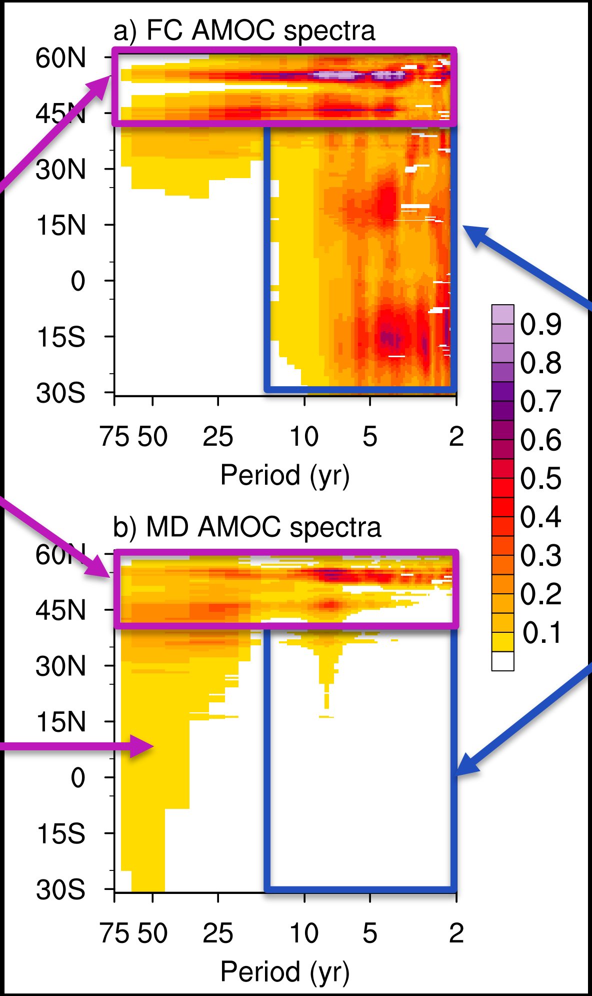


Kay McMonigal (personal communication)

Similar results from ocean-only experiments: Boning et al. (2006) and Biastoch et al (2008)

[To do: analysis for Atlantic OHT or AMOC strength in density coordinates.]

AMOC variability: regional and timescale dependence



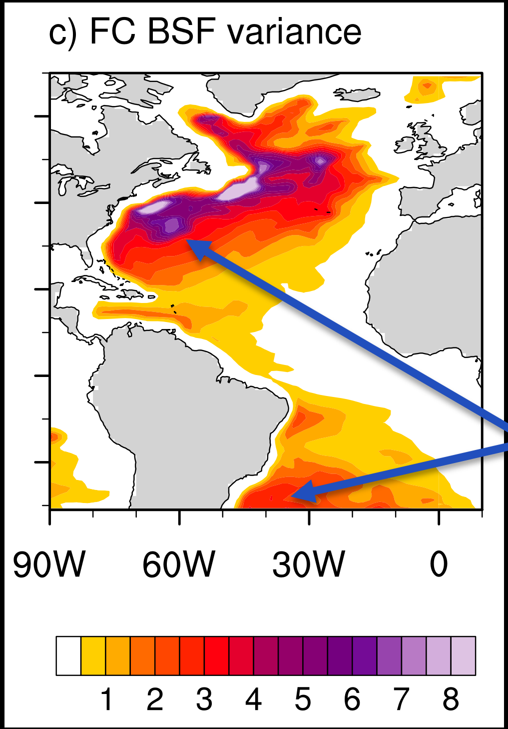
Both wind and buoyancy forcing play a role in the subpolar North Atlantic.

Only low-frequency buoyancy forced AMOC anomalies are communicated southward to subtropics/Tropics.

Wind forcing dominates AMOC variability in the tropics and subtropics.

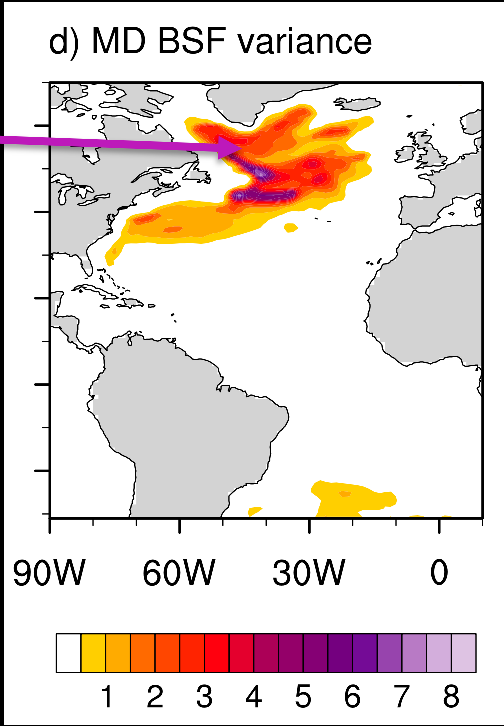
Larson et al (2020)

Buoyancy plays a strong role in variability of horizonal circulation



Buoyancy forcing plays a significant role in variations in the barotropic streamfunction in the subpolar North Atlantic.

Wind forcing dominates variability in barotropic streamfunction in subtropics and Tropics.



One cannot assume horizontal circulation is wind forced.

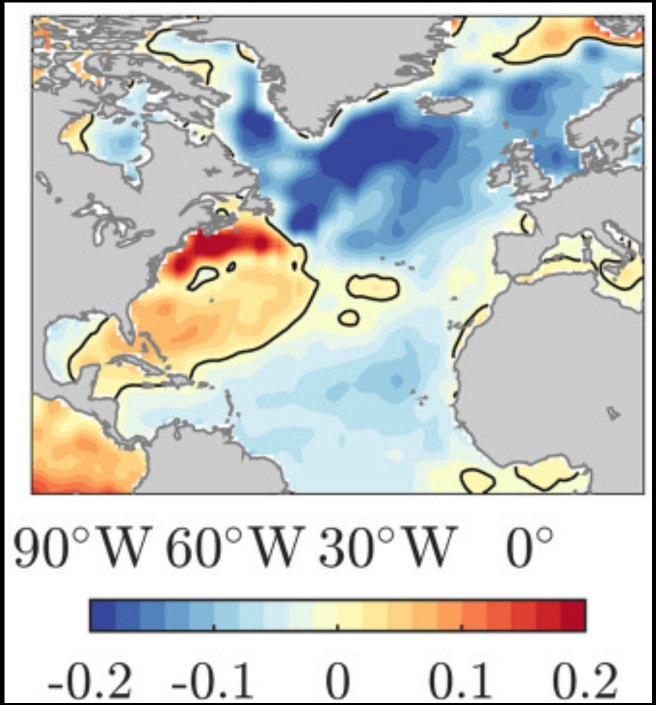
Horizontal gyre and overturning circulation are coupled by bottom pressure torques (Yeager, 2015).

Larson et al (2020)

Are subpolar SST variations related to the AMOC?
On what timescales?

Decadal variations in Subpolar North Atlantic SST

SST differences
[2005-2015] minus [1994-2004]

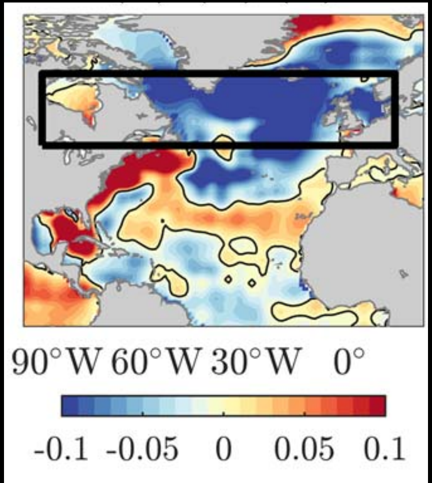


Piecuch et al., (2017)
SST from NOAA-OI-SSTv2

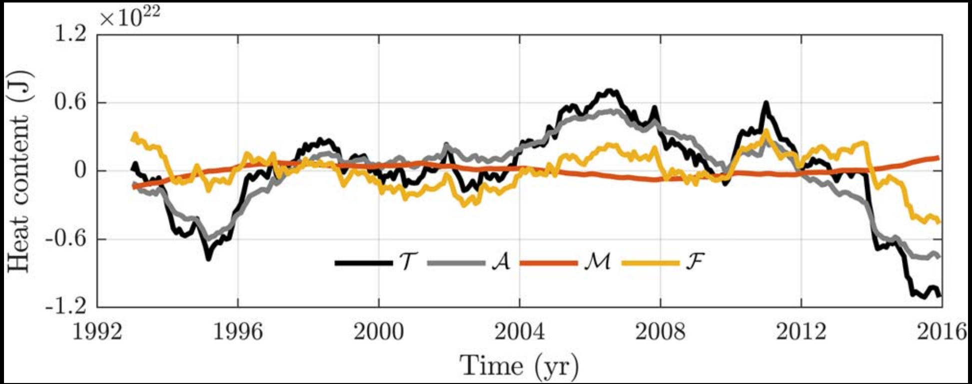
[See also Robson et al., 2016; Foukal et al., 2018; Jackson et al., 2022]

Decadal variations in subpolar SST: a role for the ocean circulation

OHC differences
[2005-2015] minus [1994-2004]



Heat budget in subpolar North Atlantic



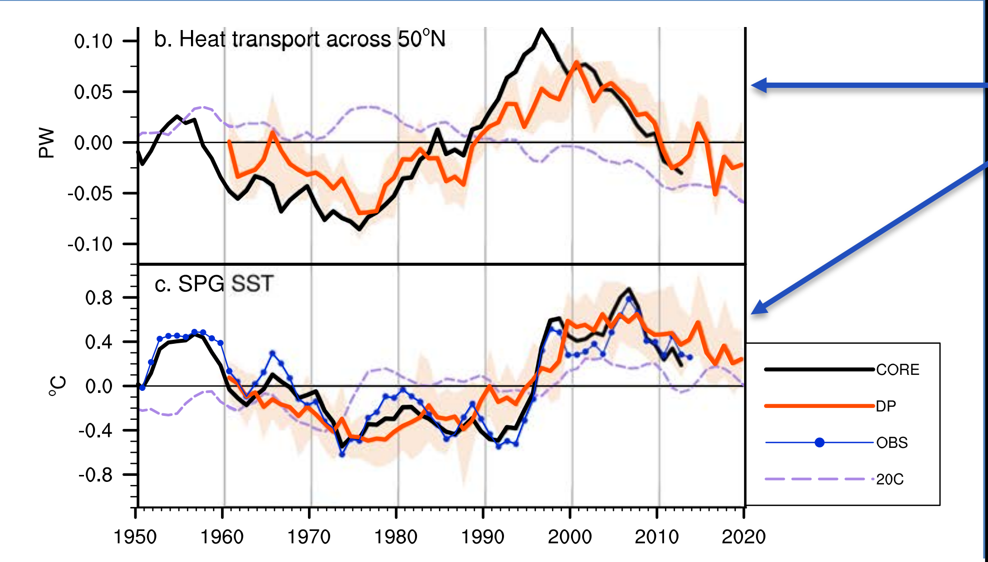
Advective heat transport convergence dominates OHC tendency.

(see also Robson et al., 2016; Foukal et al., 2018; Yeager, 2020)

Confident that ocean heat transport played a role, but difficult to diagnose origin of OHT variations.

- Claim related to AMOC variations (Robson et al., 2016)
- Claim related to variations in horizontal gyre circulation (Piecuch et al., 2017)
- Claim related to overlying winds (Piecuch et al., 2017, Hakkinen & Rhines, 2009; Hakkinen et al., 2011)

Subpolar North Atlantic SST variations are predictable



Yeager et al (2015)

3 year running mean anomalies of:

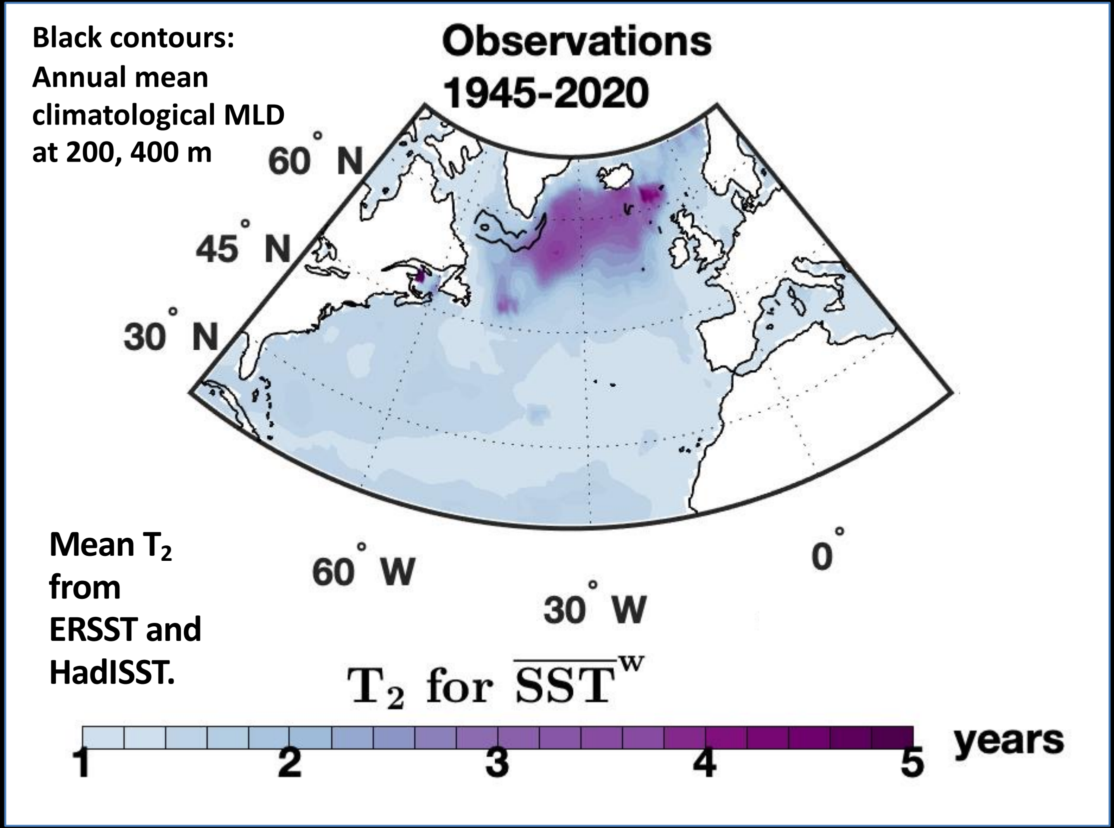
b) Heat transport across 50ºN

c) Subpolar gyre SST (SPG SST)

- Black curves: reanalysis forced ocean-ice model (CORE).
- Blue curves: observational estimates
- Red curves: the CESM decadal prediction averaged over the 5–7 year forecast period.
- Purple dashed curves: ensemble mean of the six-member uninitialized CESM 20C simulations.

- **SST anomalies in subpolar North Atlantic predictable on interannual to decadal timescales**
- **Connected to Atlantic ocean heat transport variations at 50ºN.**
- **Note: Extreme events (e.g., 2015 cold blob) are connected to strong atmospheric forcing and less predicable** (e.g., . Maroon et al., 2021; Josey et al., 2018; Yeager et al., 2016).

Predictability of subpolar North Atlantic apparent in observations



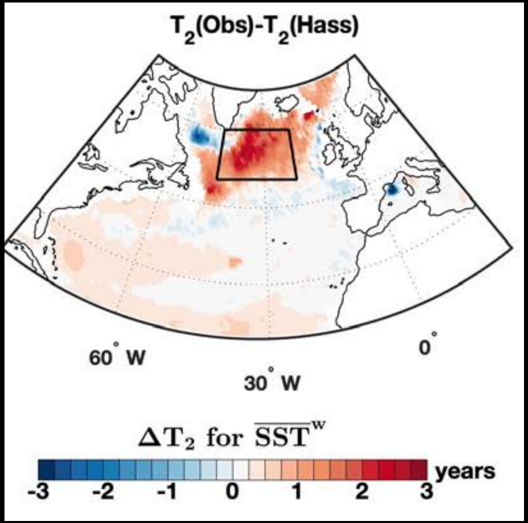
Modified from Buckley et al (2019)

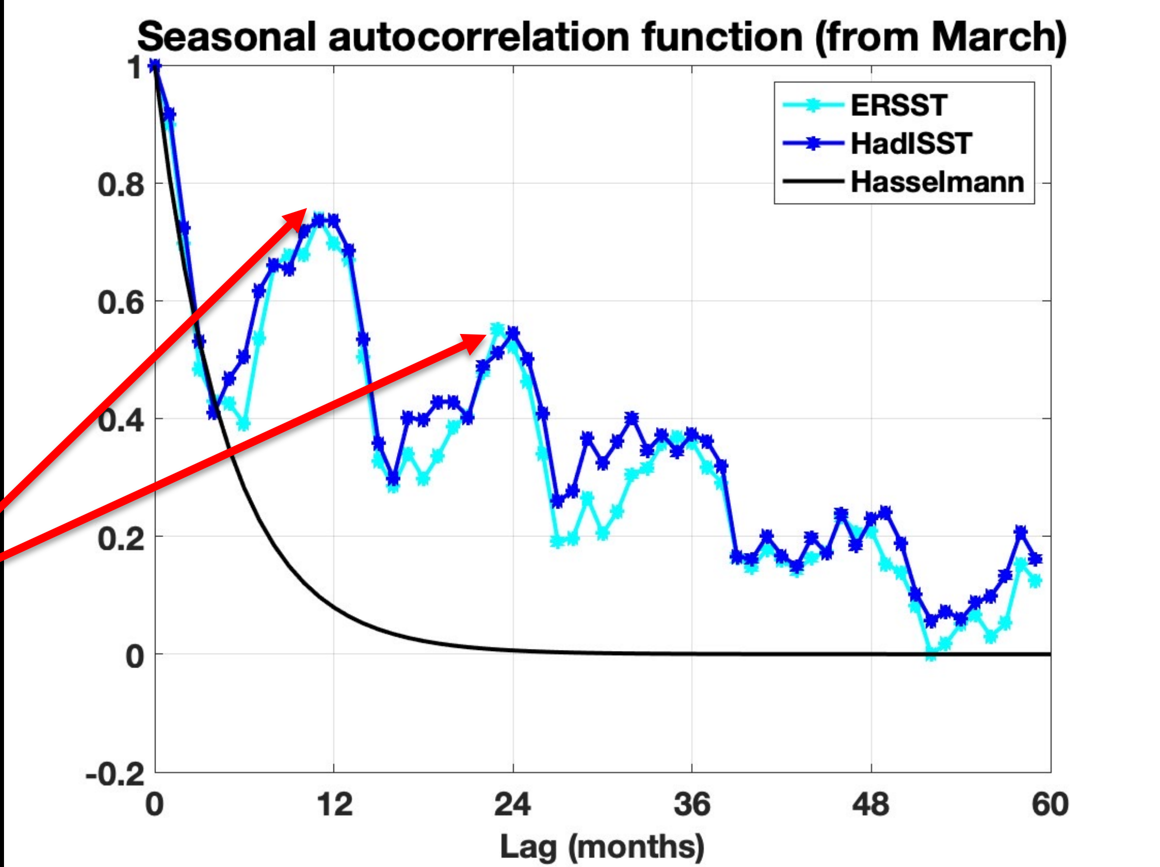
- **Predictability timescale (T_2) for wintertime SST.**
- **T_2 is longest in the central subpolar North Atlantic (Buckley et al., 2019).**
- **T_2 is low in the Labrador Sea despite deep MLDs.**

See Laurie Trenary's poster for

- A comparison of predictability between observations and models
- Insight into ocean dynamical processes leading to predictability.

Predictability in central subpolar gyre: role of reemergence





Seasonal ACF suggests reemergence of wintertime SST anomalies in the central subpolar North Atlantic.

Summary

- The overturning circulation in the Atlantic is responsible for the Atlantic transporting heat northward in both hemispheres.
  - About 60% of the peak Atlantic Ocean heat transport is related to a circulation that spans the warm thermocline waters and cold mid-depth waters.
- Determining the role that the deep overturning plays in ocean heat transport and Atlantic SST variations is challenging.
  - often uses unjustified assumptions (e.g,. Heat transport related to zonal mean circulation is due to the AMOC).
  - Or requires model experiments (e.g., water hosing)
- A more tractable problem may be to determine the roles of
  - 1D mixed layer processes: mixed layer depth variations & entrainment (see Li et al., 2020; Deser et al., 2003; deCoetlogon & Frankignoul, 2003; Glenn Lui's poster)
  - Ekman heat transports (see Buckley et al., 2014, 2015; Larson et al., 2018)
  - geostrophic ocean dynamics (see Buckley et al., 2014, 2015)
  - Various forcings (wind, buoyancy, see Larson et al., 2018, 2020)