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

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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**

**Figure 1**

![Diagram showing isopycnals in the Atlantic and Indo-Pacific regions.](image-url)

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
- Adiabatic flow
- Cell that spans warm and cold temperatures
- Adiabatic upwelling in Southern Ocean

**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

The Atlantic transports heat northward in both hemispheres.

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

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

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Figure 3.
(a) Meridional ocean heat transports (OHT, positive northward) in PW (10^15 W) for the global ocean (black), the Indo-Pacific (green), and the Atlantic (blue) from NCEP atmospheric reanalysis [Trenberth and Caron, 2001].
(b) Atlantic OHT from NCEP atmospheric reanalysis (blue) [Trenberth and Caron, 2001] is compared to several direct estimates: Ganachaud and Wunsch [2003] (black diamonds), Talley [2003] (grey circles), Lumpkin and Speer [2007] (yellow stars), the RAPID-MOCHA array at 26.5°N [Johns et al., 2011], Hobbs and Willis [2012] (orange diamond), and Garzoli et al. [2013] (magenta cross). The vertical bars indicate the uncertainty range for the direct estimates. Also compared are the Atlantic OHT in CM2.1 (green solid) and CCSM4 (green dashed) preindustrial control simulations (modified from Msadek et al. [2013]) and the GFDL ECDA (1960–2010, solid purple) [Chang et al., 2012] and ECCOv4 (1992–2012, dashed purple) [Forget and Ponte, 2015; Forget et al., 2015] ocean state estimates.
(c) Observed hemispheric asymmetry of temperature in the atmosphere and ocean (in °C) computed from the NCEP reanalysis and the World Ocean Atlas. The asymmetric component of a temperature field \( T_{\text{as}} \) is defined as \( T_{\text{as}} = (T - T_{\text{south}}) / 2 \) where \( T_{\text{south}} \) is the latitude [from Marshall et al., 2014a].

(3) Reviews of observations of the AMOC [Srokosz et al., 2012], with particular observations and inferences from a decade of AMOC observations at 26.5°N [Srokosz and Bryden, 2015]; (4) A critical discussion of the linkages between deep convection and the AMOC [Lozier, 2012]; (5) Reviews of the surface and deep pathways of the AMOC [Lozier, 2010]; (6) A review on the importance of the South Atlantic to the AMOC [Garzoli and Matano, 2011]; (7) A brief review of the relationship between the AMOC and sea level, in particular sea level fluctuations on the east coast of the United States [Srokosz and Bryden, 2015]; and (8) Reviews on connections between the AMOC and climate on paleoclimate timescales [Broecker, 2007] and abrupt climate change [Clark et al., 2002; Alley, 2007].

Despite the interest and scrutiny of AMOC by the community, progress in understanding decadal climate variability and its connection to the AMOC has been hampered by a paucity of observations, the formidable challenge of representing key processes in models, and our somewhat limited knowledge of underlying mechanisms. Controlling mechanisms are a function of timescale. On short (intra-annual to interannual) timescales, AMOC variability is primarily the response to local wind forcing. On longer (decadal) timescales, AMOC variability involves a complex interplay between wind-driven and thermohaline processes. A coordinating theme running through this review is the critical role played by buoyancy anomalies in the region east of the Grand Banks, where the separated Gulf Stream, the North Atlantic Current, and Labrador Currents interact at the western confluence of the subtropical and subpolar gyres. We shall call this region (marked by a box in Figures 1 and 4) the “transition zone” and use simple dynamical considerations to argue that it is central to our understanding of decadal and multidecadal AMOC variability.
Ocean heat transport & overturning in temperature coordinates

• 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 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).

\[
\frac{\partial}{\partial t} \left[ \int_{-h}^{h} \mathbf{v} \cdot \mathbf{u} \right] = - \int_{-h}^{h} \frac{\partial}{\partial y} \left( \rho \mathbf{v} \cdot \mathbf{u} \right) \cdot \mathbf{v} \, dz + \int_{-h}^{h} \rho \mathbf{v} \cdot \mathbf{g} \, dz + \int_{-h}^{h} \mathbf{v} \cdot 
\]

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

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

The MD contour spectra (Fig. 4b) reveal that in the subpolar gyre, the buoyancy-driven AMOC exhibits variance across time scales, from interannual to multidecadal. In the subtropical gyre, little variance occurs on any time scale, but the variability that does occur is primarily at decadal or multidecadal time scales, as indicated by the standardized contour spectra (Fig. 4d). This suggests the potential presence of interhemispheric buoyancy-forced AMOC variability on low-frequency time scales. These results show that even though buoyancy drives AMOC variations in the subpolar gyre on interannual to multidecadal time scales, primarily low frequencies penetrate into the subtropical gyre (Johnson and Marshall 2002a,b, 2004; Böning et al. 2006; Zou et al. 2019).

In the FC, AMOC variability in the subtropics is dominated by high variance wind-driven variability (Figs. 4a,c). At 26°N, the MD shows less variance than the FC at time scales of 2–10 years (Figs. 5c,d), consistent with subtropical AMOC variability being primarily wind-driven as seen in the Ocnflux experiments and...
Buoyancy plays a strong role in variability of horizontal 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).
Are subpolar SST variations related to the AMOC?
On what timescales?
Decadal variations in Subpolar North Atlantic SST

SST differences

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

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

Advective heat transport convergence dominates OHC tendency. (see also Robson et al., 2016; Foukal et al., 2018; Yeager, 2020)

- 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

3 year running mean anomalies of:

b) Heat transport across 50°N

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 50°N.

- Note: Extreme events (e.g., 2015 cold blob) are connected to strong atmospheric forcing and less predictable (e.g., Maroon et al., 2021; Josey et al., 2018; Yeager et al., 2016).
Predictability of subpolar North Atlantic apparent in observations

- 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)