The importance of the Gulf Stream—North Atlantic current transition zone to decadal AMOC variability

Martha W. Buckley (AER/COLA) and John Marshall (MIT)

Introduction

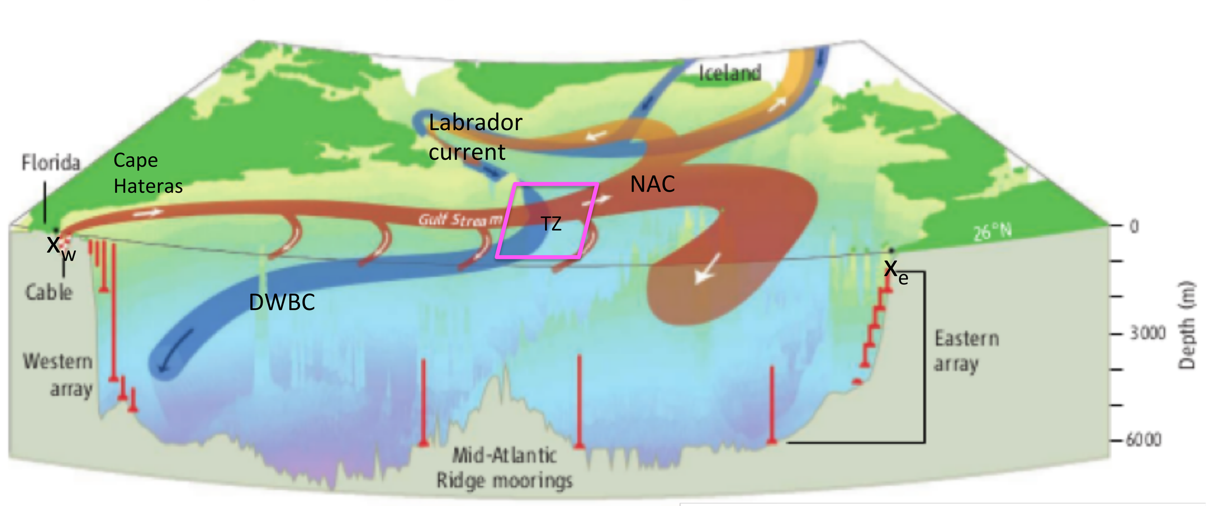
Currently there is no accepted mechanism of decadal AMOC variability, and little theory upon which the community agrees. However, there are several robust features of decadal AMOC variability, which can be used to inform mechanisms.

Robust features of decadal AMOC variability

- Buoyancy anomalies on the western boundary are key (Bryden et al., 2009; Longworth et al., 2011; Cabanes et al., 2009; Buckley et al., 2012; Tulloch and Marshall, 2012).
- A pacemaker region is located in the subpolar gyre/ on the subtropical-subpolar gyre boundary (Danabasoglu, 2008; Zhang, 2008; Biastoch et al., 2008; Tziperman et al., 2008; Hawkins and Sutton, 2009; Zanna et al., 2011; Buckley et al., 2012).
- Meridionally coherent AMOC variability is communicated southward from this pacemaker region (Kawase, 1987; Marotzke and Klinger, 2000; Johnson and Marshall, 2002a,b; Deshayes and Frankignoul, 2005; Zhang, 2010).

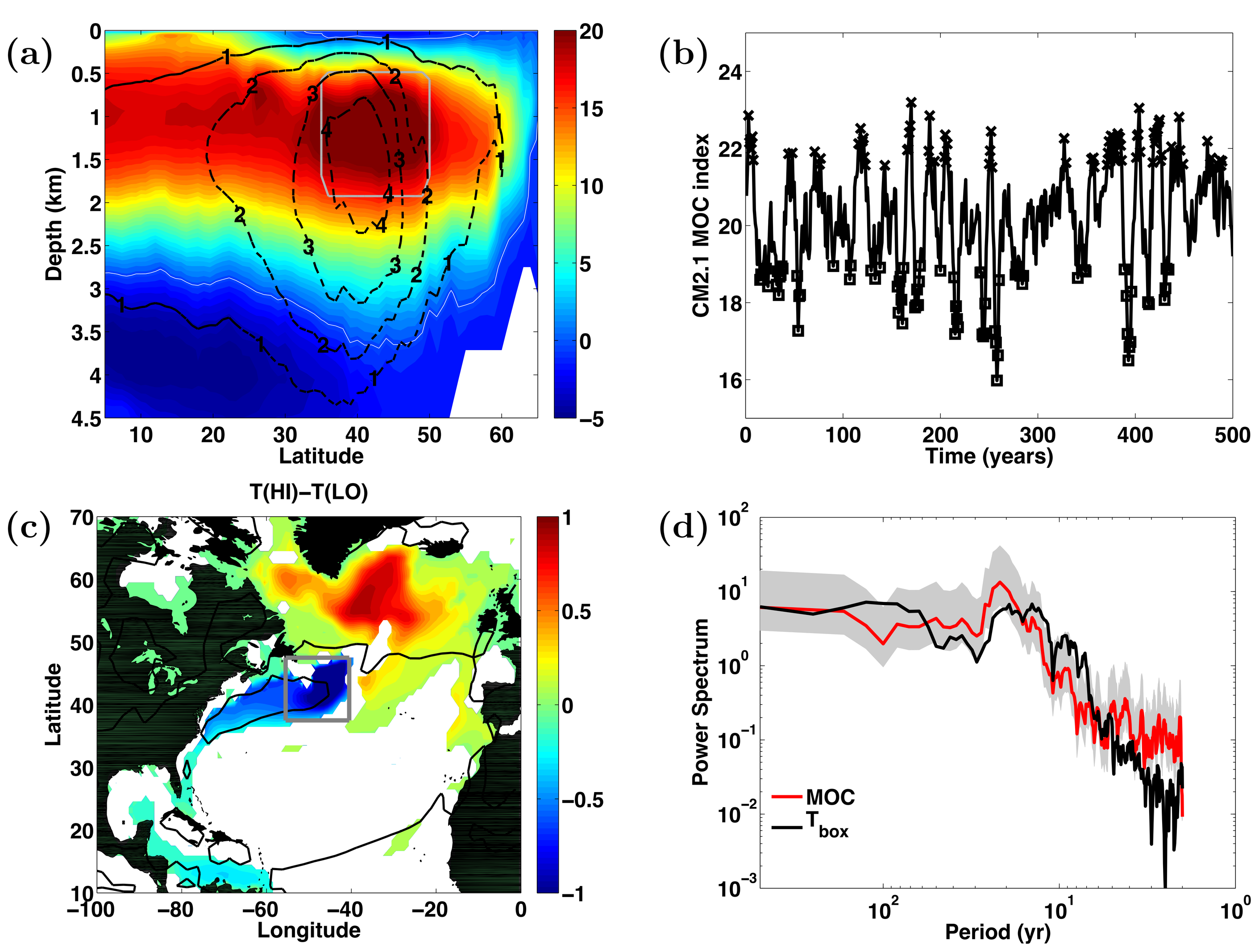
Importance of the Gulf Stream—North Atlantic current transition Zone (TZ)

Here we argue that the western margin of the subtropical—subpolar gyre boundary, the Gulf Stream—North Atlantic current transition zone (TZ), is a key region influencing decadal AMOC variability.



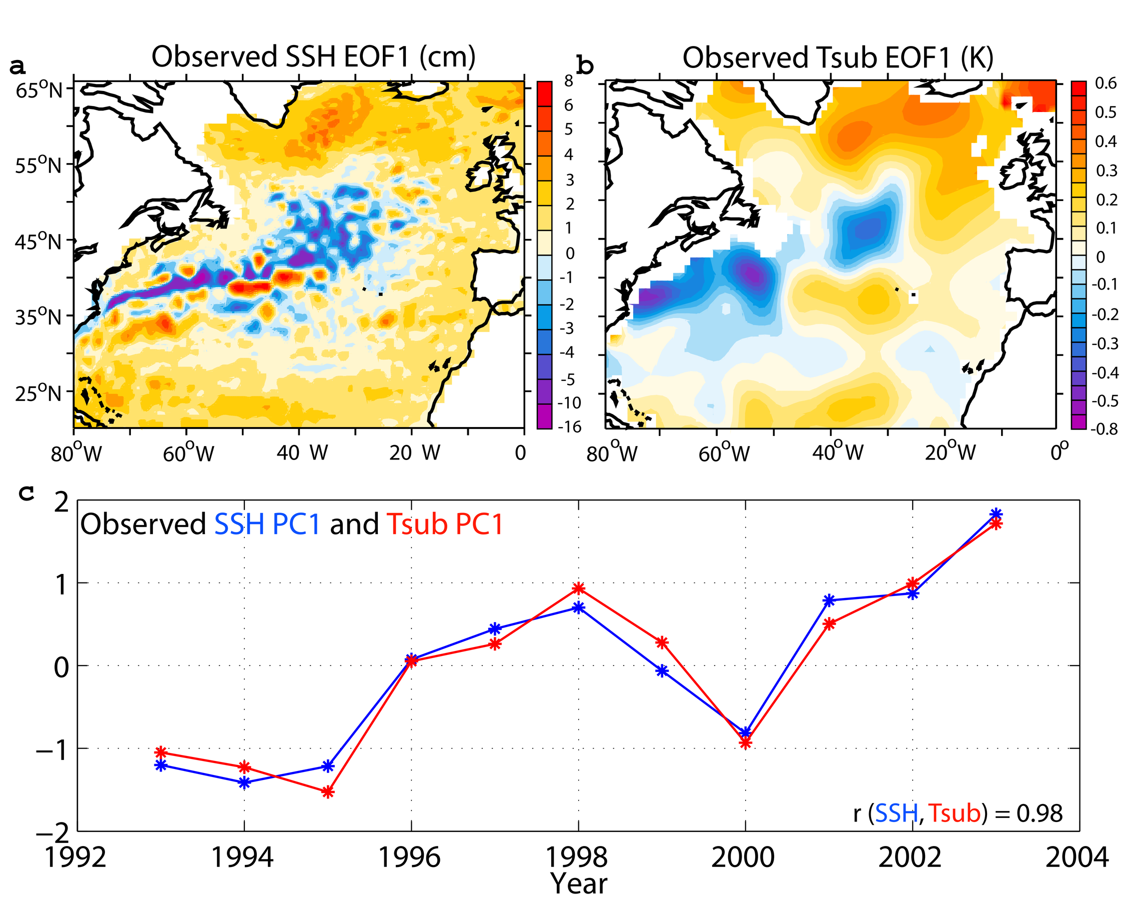
Variations in upper-ocean buoyancy (top km) in the TZ are key to understanding low-frequency variations in the AMOC, which are dominated by the thermal wind component.

Schematic of the North Atlantic, modified from Church (2007). The magenta box highlights the Gulf Stream—North Atlantic current transition zone (TZ).



Note large T anomalies in the TZ associated with meridionally coherent AMOC variability.

(a) Eulerian-mean AMOC (Sv, colors) in CM2.1 and AMOC anomaly (Sv, black contours) formed by (HI)-(LO) composites described in (b). (b) time series of the AMOC index, defined as the average AMOC from 35—50°N and from 500—1800 m depth, as indicated by the white box in (a). Years marked by x's (squares) denote years that are more than one standard deviation above (below) the time mean. These are used to construct (HI)-(LO) composite maps, shown in (a and c). (c) Composite (HI) -(LO) map of temperature averaged over the top 1 km. White shading indicates regions that are not significant at the 95% confidence level. Grey box shows the TZ region. (d) (red) Normalized power spectra of the AMOC index and (black) temperature (K) averaged over the top 1 km in the TZ [grey box shown in (c)]. The gray shading is a 95% confidence interval. Modified from Tulloch and Marshall (2012).



Note large SST and T_{sub} anomalies in the TZ region.

Variability of observed annual mean anomalies of sea surface height (SSH) and temperature averaged over the top 400m (Tsub). (a) Observed SSH EOF1 (cm, 30%) and (b) observed Tsub EOF1 (K, 33.4%) for 1993-2003. (c) Observed SSH PC1 (blue) and Tsub PC1 (red) during 1993-2003 (normalized). From Zhang (2008).

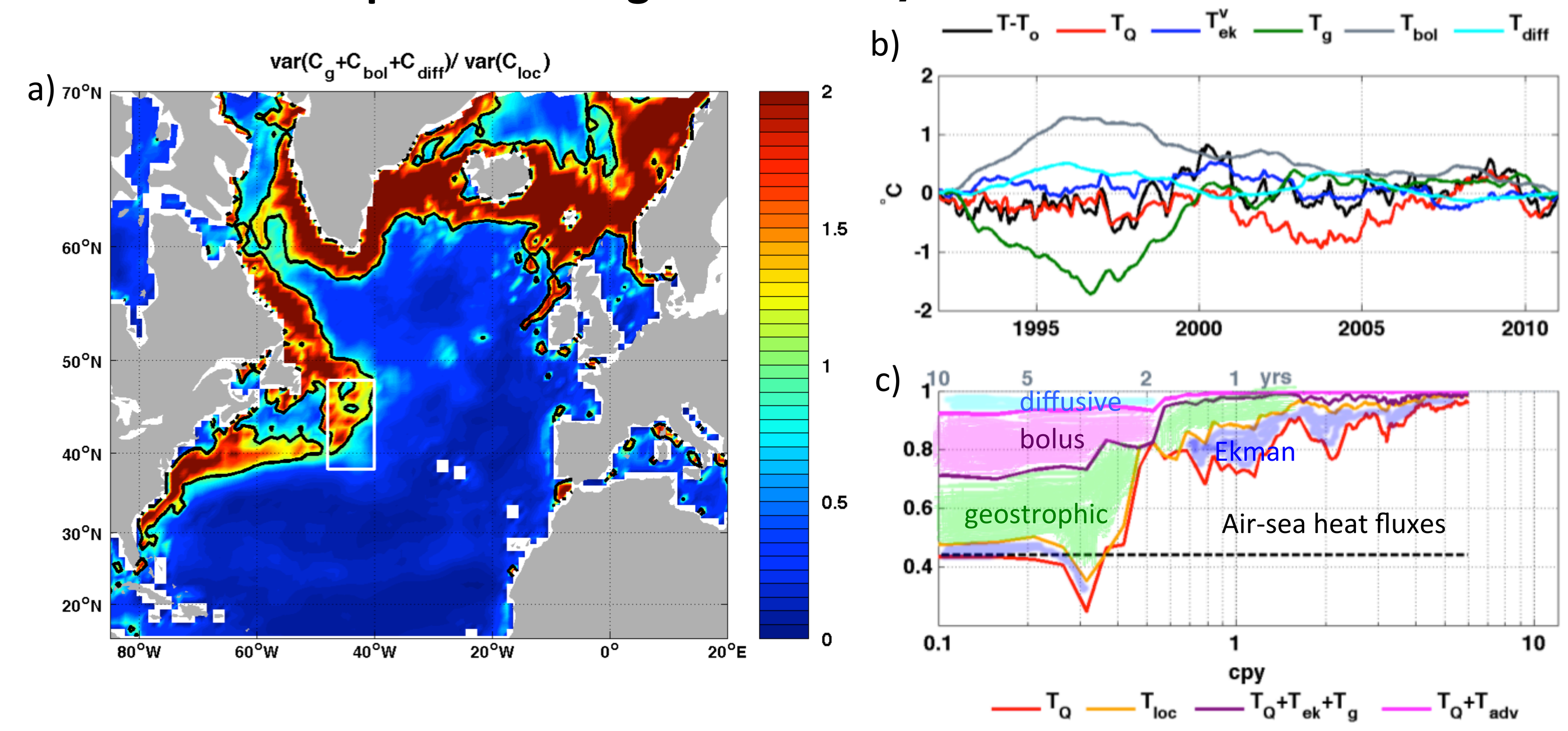
Mechanisms for creating buoyancy anomalies in the TZ

A myriad of processes may be important in creating buoyancy anomalies in the TZ, including:

- local atmospheric forcing (Frankignoul and Hasselmann, 1977; Cayan, 1992a, 1992b; Seager et al., 2000)
- westward propagating baroclinic Rossby waves (te Raa et al., 2004; Hirschi et al.,2007; Frankcombe et al., 2010; Zanna et al., 2011, 2012; Buckley et al., 2012)
- gyre wobbles (Frankignoul et al., 1997; Marshall et al., 2001) and changes in the Gulf Stream path (Frankignoul et al. 2001; Joyce and Zhang, 2010)
- anomalies advected/propagated from high latitudes (Curry et al., 1998; Pena Molino et al., 2011; Sebille et al., 2011).

The complex ocean dynamics in this region may explain why the AMOC and its variability are so sensitive to changes in model formulation, including resolution, overflow parameterizations, etc. (Danabasoglu et al., 2012).

Role of atmospheric forcing vs. ocean dynamics



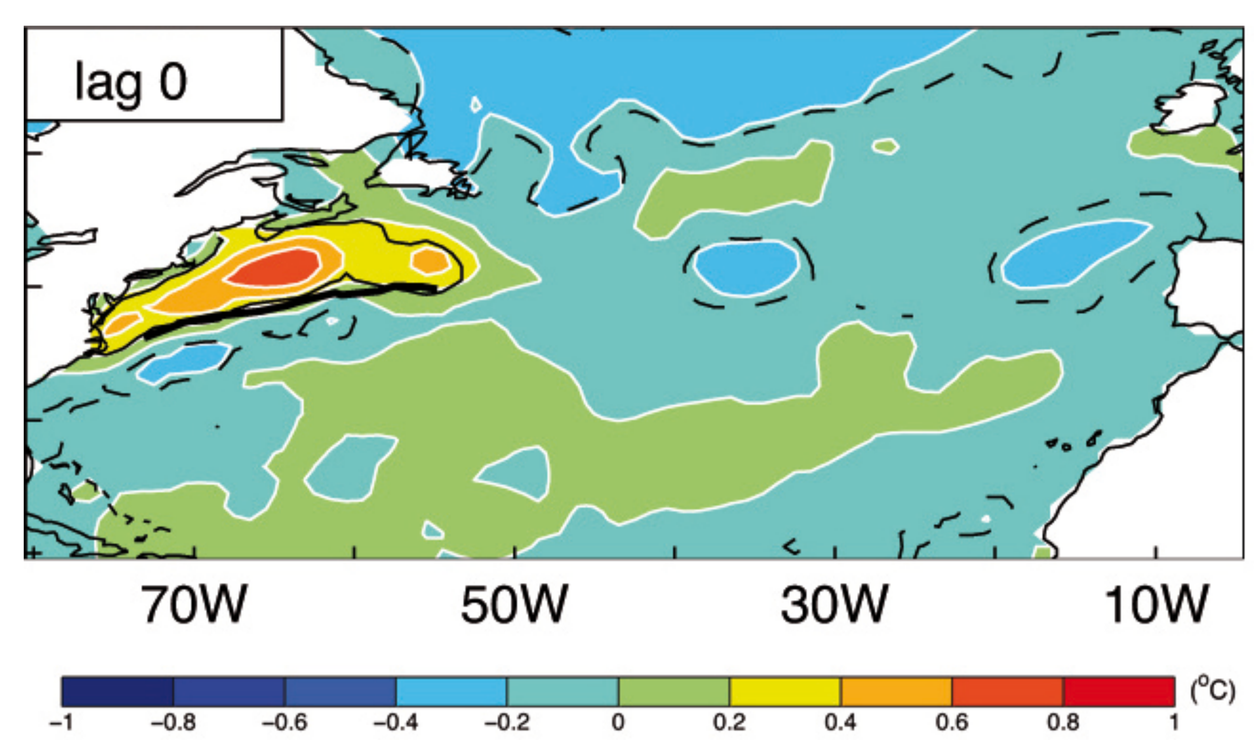
Note importance of geostrophic (T_g) and bolus (T_{bol}) convergences and anticorrelation between T_g and T_{bol}.

Contributions to upper ocean heat content (H) as a function of timescale.

A heat budget analysis over the maximum climatological MLD (integral denoted as H), a measure of the heat contained in the ``active'' ocean layers, using the ECCO v4 state estimate. (a) Map shows the ratio of the variance of convergences due to ocean dynamics ($C_g+C_{bol}+C_{diff}$) to convergences due to local forcing (C_{loc}). The ratio is small over the gyre interiors, but large over boundary currents and the TZ region. (b-c) The temporally integrated heat budget over the TZ (white box in panel a). (b) Time series of temperature ($T-T_o$), air-sea heat fluxes (T_Q), convergence due to Ekman mass transport variability (T_{ek}^v), geostrophic convergences (T_g), bolus convergences (T_{bol}), and diffusive convergences (T_{diff}). The advective convergence (T_{adv}) is separated into the linear advective convergence (T_{lin}) and T_{bol} and $T_{ek}+T_g \approx T_{lin}$. (c) Magnitude of the coherence between $T-T_o$ and various sums of terms in the T budget. Modified from Buckley et al. (2014).

Geostrophic currents (eddy and mean) dominate temperature variability on interannual timescales. Local air-sea heat flux and Ekman mass transport variability dominate on intraannual timescales.

Changes in the Gulf Stream path



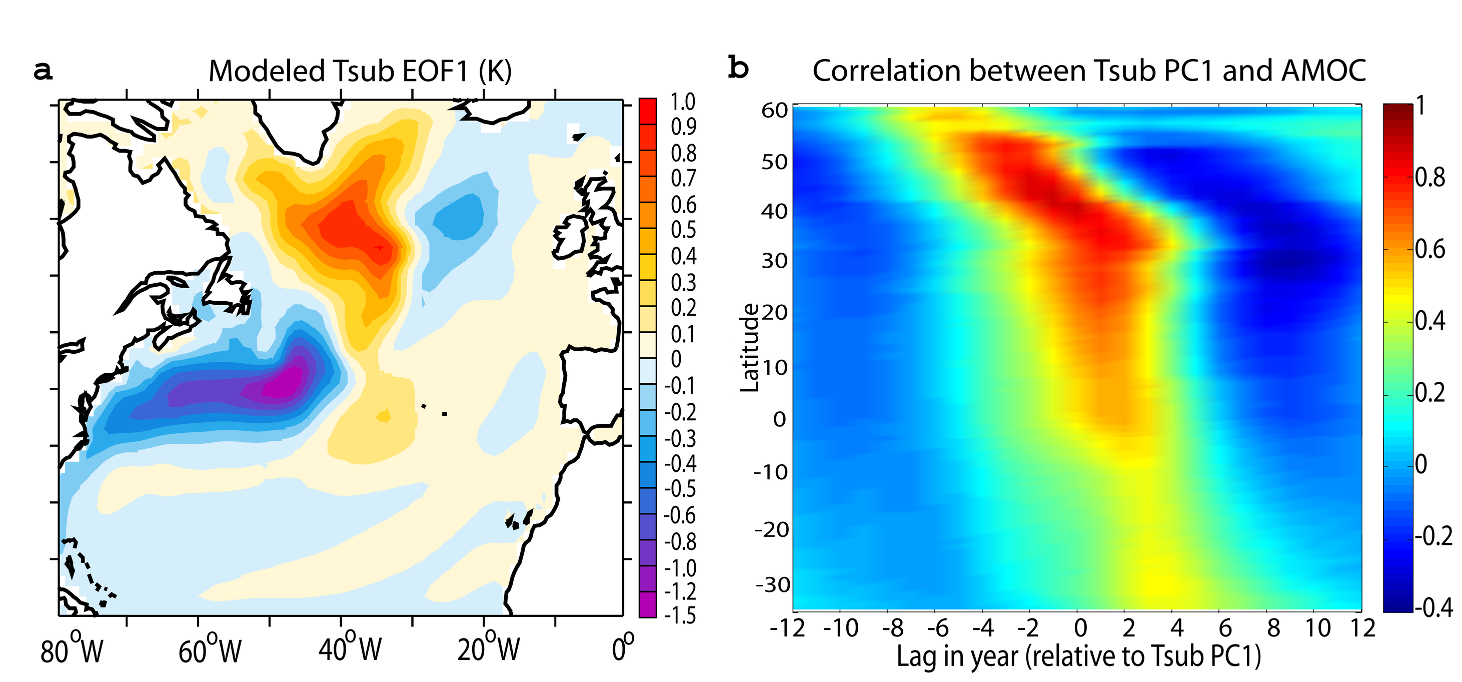
Note substantial SST anomalies in the TZ region.

Regression between SST anomalies and the first principal component time series of the Gulf Stream path derived from the TOPEX/Poseidon altimeter (1992--1998). The dashed-dotted line indicates the 5% level for no correlation. Positive (negative) contours are in black (white) and dots indicate zero. Modified from Frankignoul et al. (2001).

Meridional communication of buoyancy anomalies from the TZ

For meridionally coherent AMOC variability, buoyancy anomalies must be communicated southward from the TZ via:

- Advection (Curry et al., 1999; Koltermann, 1999; Pena Molino, 2011; Marotzke and Klinger, 2000; ; Zhang, 2010; Buckley et al., 2012)
- Kelvin waves (Kawase, 1987; Johnson and Marshall, 2002a,b; Deshayes and Frankignoul, 2005; Zhang, 2010)



(a) First EOF of temperature over the top 400 m (Tsub) (K, 24.8% of variance) from GFDL CM2.1 1000-year control integration. From Zhang (2008). (b) Correlation between Tsub PC1 and AMOC strength variations at all latitudes. The AMOC strength at each latitude is defined as the maximum of the annual mean zonal integrated Atlantic overturning streamfunction in density space. From Zhang (2010).