# Quantifying the Contribution of Surface Buoyancy Forcing to Recent Subpolar AMOC Variability

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## 1. Introduction

In the Subpolar North Atlantic (SPNA) warm surface waters arriving via the Gulf Stream and North Atlantic Current undergo an intense loss of buoyancy, and are transformed to cold dense waters which subsequently sink and are exported southward at depth.

This process, known as surface buoyancy forcing, plays a key role in controlling variability in the Atlantic Meridional Overturning Circulation (AMOC) on interannual to multidecadal timescales.

Quantifying the contribution of surface buoyancy forcing to AMOC variability is essential for modelling how the AMOC will respond to predicted warming and freshening at high latitudes.

Here, we apply principles of water mass transformation to reconstruct the annual surface-forced overturning circulation (SFOC) in the Subpolar North Atlantic (48-65 °N, 5-60 °W) from 1980-2020. For comparison, we also reconstruct AMOC variability over the same period.

We further partition “SFOC Full” (5-60 °W) into a West component, “SFOC West” (43 60 °W), comprising the Labrador Sea, and an East component, “SFOC East” (5-43 °W), comprising the Irminger and Iceland basins, thus elucidating the dominant region of deep water formation in the Subpolar North Atlantic.

## 2. Data & Methods

In this study, we use monthly data sets from the GODAS ocean reanalysis, extracted for the Subpolar North Atlantic (48-65 °N, 5-60 °W) from January 1980 – December 2020.

### The Overturning Streamfunction (AMOC)

The overturning streamfunction in density coordinates, $\psi(\theta,\rho)$, defines the net northward transport of waters denser than ρ across latitude θ:

$$\psi(\theta,\rho) = \int_{\rho}^{\rho_{max}} \int_{\phi_w}^{\phi_e} \int_{0}^{H} h(z)\, v(\phi,\theta,z)\, \Lambda\left(\rho_{\phi,\theta,z},\rho\right)\, dz\, d\phi\, d\rho$$

We derive $\psi(\theta,\rho)$ using the meridional component of current velocity (v) from GODAS, zonally integrated in longitude ($\phi$) and depth ($z$). The annual maximum of $\psi(\theta,\rho)$ in a given year is used to estimate the annual strength of the AMOC.

### The Surface Forced Overturning Streamfunction (SFOC)

By applying principles of water mass transformation, the overturning streamfunction, $\psi(\theta,\rho)$, is equivalent to the diapycnal volume flux across density surfaces, G$(\theta,\rho)$:

$$G(\theta,\rho) = \boldsymbol{F(\theta,\rho)} - \partial D_{diff}(\theta,\rho)\, \partial\rho + C(\theta,\rho)$$

In the absence of mixing, the volume flux G(θ, ρ) equates to F(θ, ρ), the surface-forced water mass transformation rate across ρ and north of θ, thus defining the surface-forced overturning streamfunction, $\psi_{surf}(\theta,\rho)$:

$$\psi_{surf}(\theta,\rho) = F(\theta,\rho)$$

We derive $\psi_{surf}(\theta,\rho)$ from surface density flux fields, computed from GODAS variables of net surface heat flux ($Q_{net}$), salt flux ($F_s$), potential temperature (T), and salinity (S). The annual maximum of $\psi_{surf}(\theta,\rho)$ is used to estimate the annual strength of SFOC.

## 3. Time Series Analysis

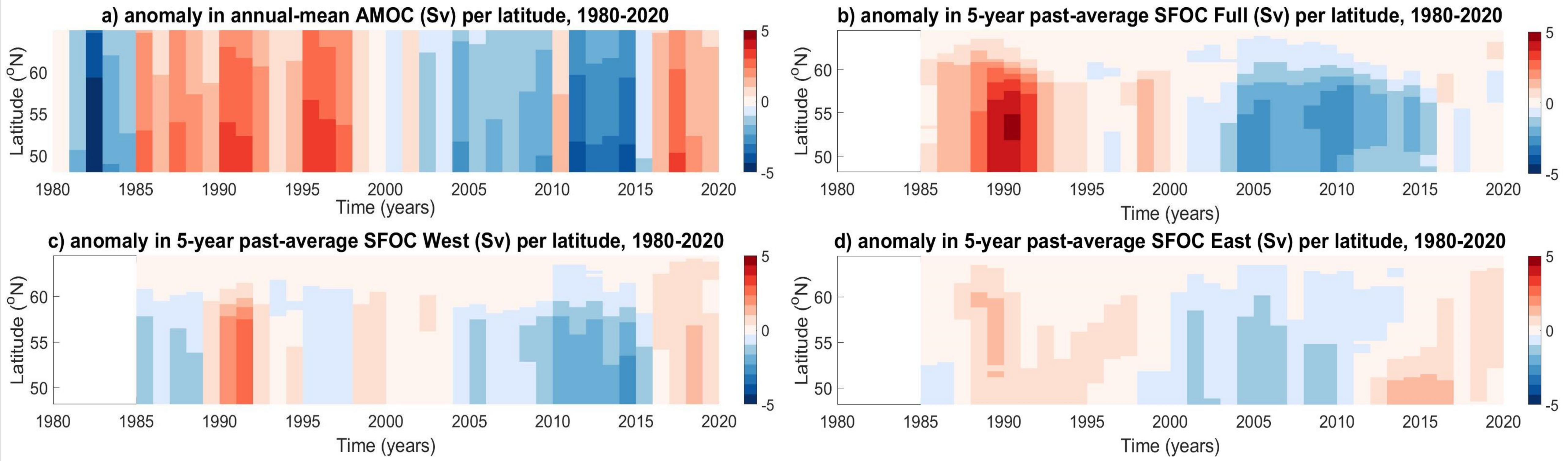


*Figure 1* – *Time series of overturning anomalies (Sv) per latitude from 1980-2020 for: a) annual maximum AMOC; b) 5-year past-average SFOC Full; c) 5-year past-average SFOC West; d) 5-year past-average SFOC East. 5-year past-averages are a moving average calculated each year from 1985-2020, from the mean maximum overturning of the preceding 5 years. Annual anomalies are calculated by subtracting the maximum overturning in a given year from the mean maximum overturning over 1980-2020. Positive anomalies are shown in red, negative anomalies are shown in blue.*
***Mean maximum overturning (± standard deviation): AMOC = 15.3 ± 2.4 Sv ; SFOC Full = 18.2 ± 3.5 Sv; SFOC West = 11.7 ± 3.3 Sv; SFOC East = 12.1 ± 1.8 Sv.***

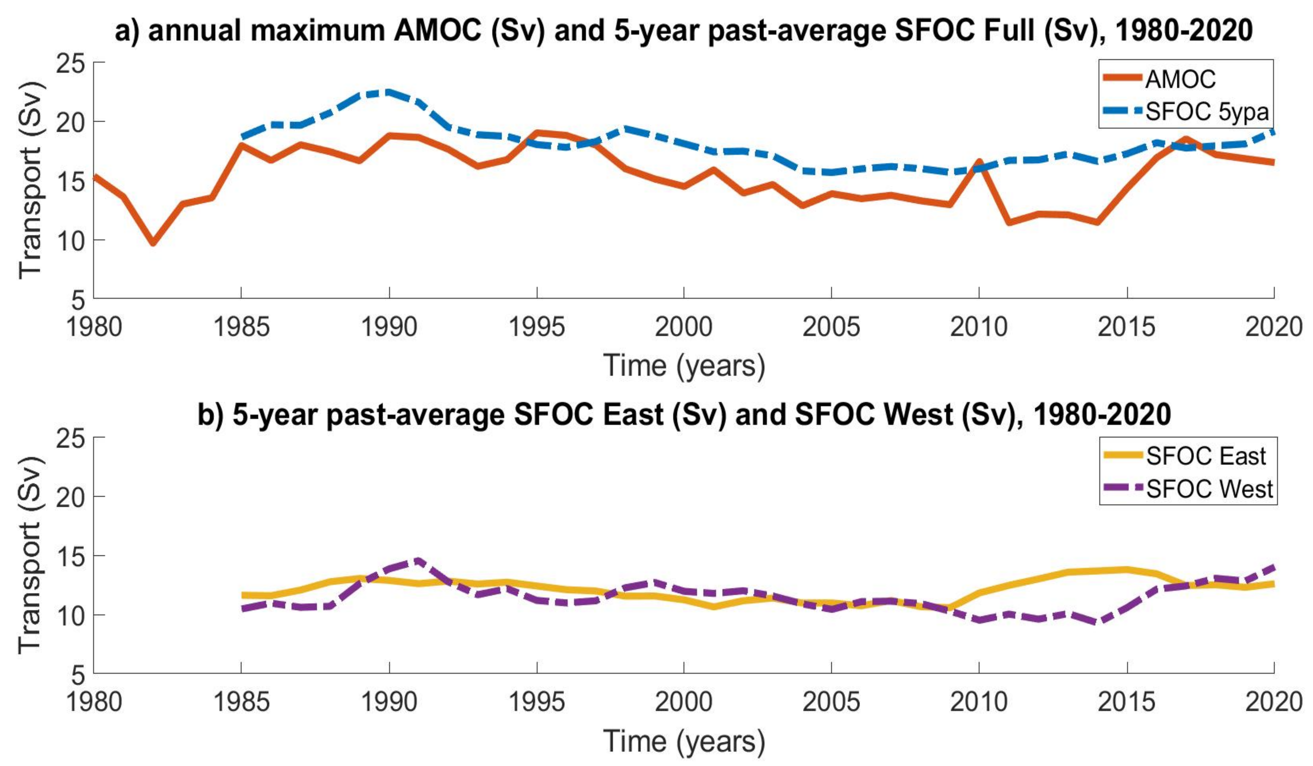


*Figure 2* – *Time series of overturning transport (Sv) from 1980-2020, for: a) annual maximum AMOC (red) and 5-year past-average SFOC Full (blue dashed); b) 5-year past-average SFOC East (gold) and SFOC West (purple dashed).*
***Correlations: AMOC and SFOC 5ypa, r= 0.66; SFOC Full and SFOC West, r= 0.76: SFOC Full and SFOC East, r= 0.37.***

## 4. Streamfunction Analysis

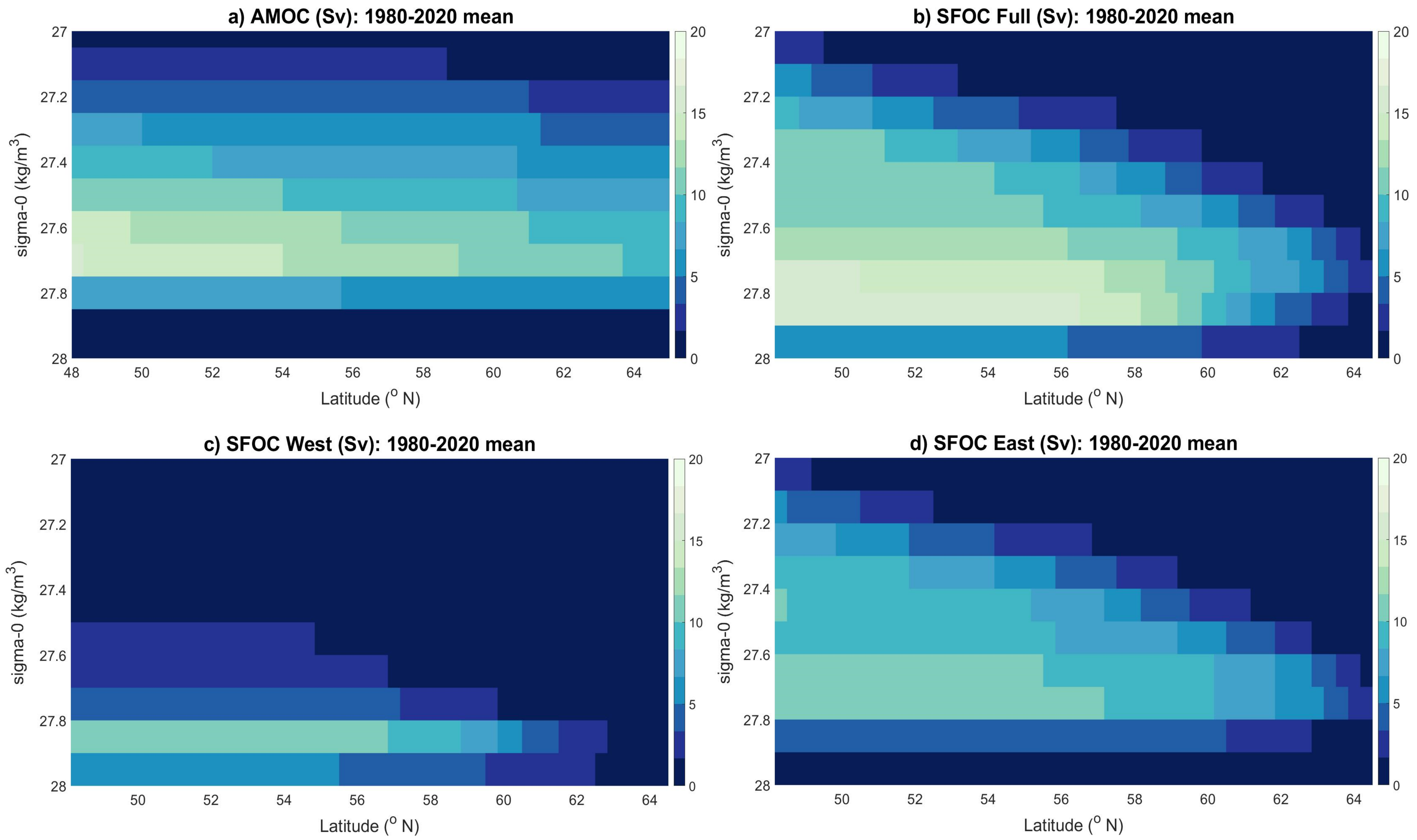


**Figure 3 –** *Time-mean overturning (Sv) in latitude-density space, averaged over 1980-2020, for a) AMOC; b) SFOC Full; c) SFOC West; d) SFOC East; Potential density ($\sigma_o$, where $\sigma_o$ = ρ - 1000), is binned in in 0.1 kg/m³ intervals from 27.0 – 28.0 kg/m³ (y-axis reversed). Maximum overturning shown by lighter colours, ranging from 0 Sv (dark blue) to 20 Sv (light green). Sense of overturning is defined clockwise.*
***Densities of maximum overturning: a) AMOC = 27.7 kg/m³; b) SFOC Full = 27.8 kg/m³ ; c) SFOC West = 27.8 kg/m³ ; d) SFOC East = 27.7 kg/m³ ).***

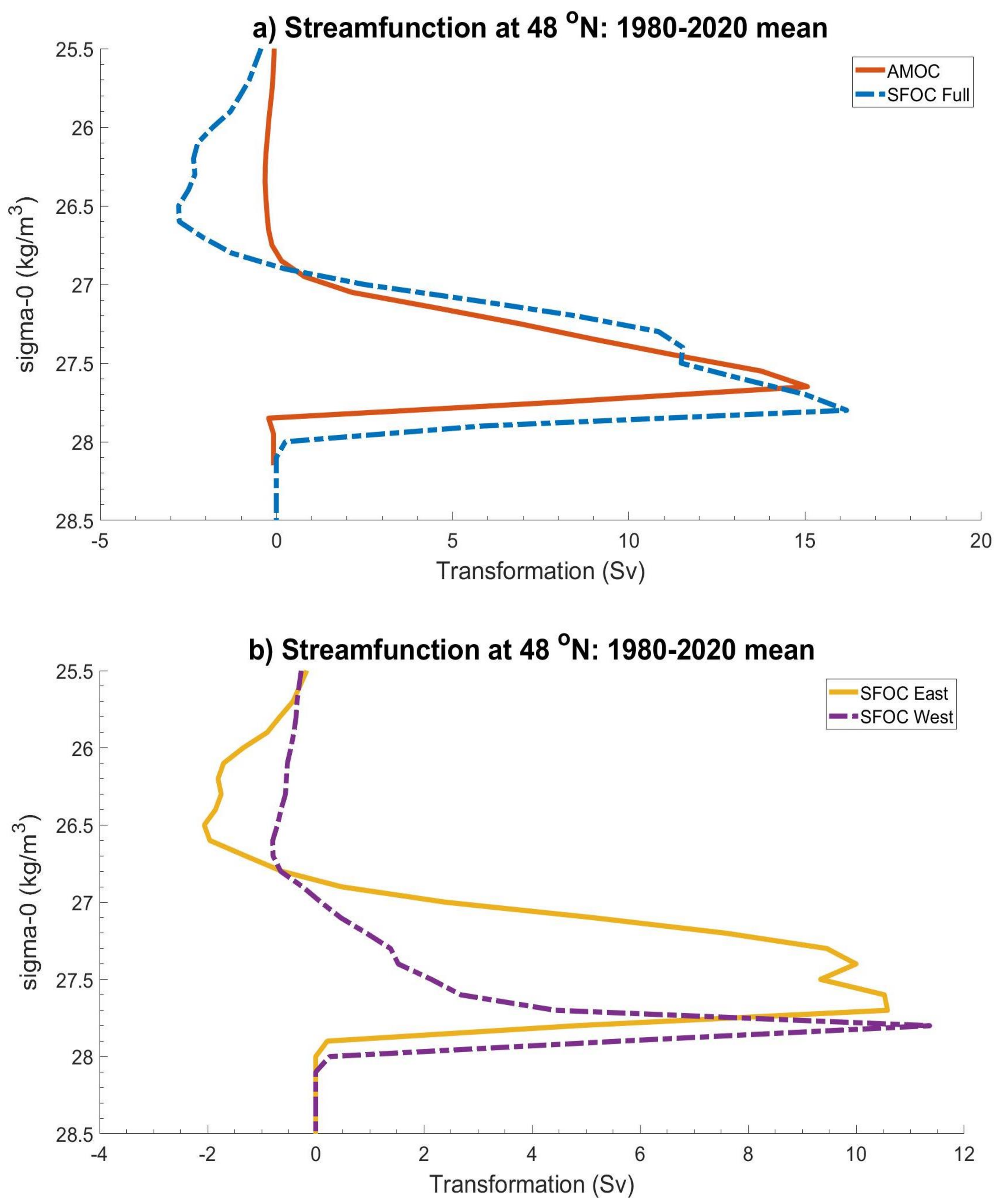


*Figure 4* – *Time-mean (1980-2020) overturning streamfunction at 48 °N for a) AMOC (red) and SFOC Full (blue dashed); b) SFOC East (Gold) and SFOC West (purple dashed).* ***Maximum overturning: AMOC = 15.1 Sv; SFOC Full = 16.2 Sv; SFOC West = 11.4 Sv; SFOC East = 10.6 Sv***

## 5. Conclusions

Reconstruction of the annual-mean surface-forced overturning circulation (SFOC) over 1980-2020 provides a close match with the corresponding AMOC in the SPNA.

The interannual and decadal variability in AMOC and SFOC is best reproduced when a 5-year past-averaging window is applied to SFOC.

Plotted in latitude-density space, maximum surface-forced overturning is identified at densities above 27.7 kg/m³, associated with Labrador Sea Water (LSW).

Separating the contributions to SFOC from the east and west regions of the subpolar gyre reveals SFOC variability is dominated by changing water mass transformation in the Labrador Sea.

These results suggest that the eastern dominance in subpolar AMOC variability observed over winters 2014/15 and 2015/16 may have been transient.

## 6. References & Acknowledgements

**GODAS Data:** This analysis was possible due to the public availability of the NCEP Global Ocean Data Assimilation System (GODAS) data provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov.

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