North Atlantic water mass transformation contributions to AMOC in eddy-parameterized and eddy-permitting simulations

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Motivation

The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the global climate system. Surface water mass transformation in the subpolar North Atlantic facilitates the deep convection that contributes to the deep southern flowing branch of AMOC. Surface transformation is thus a valuable diagnostic for interpreting observations of overturning circulation and evaluating model AMOC performance.

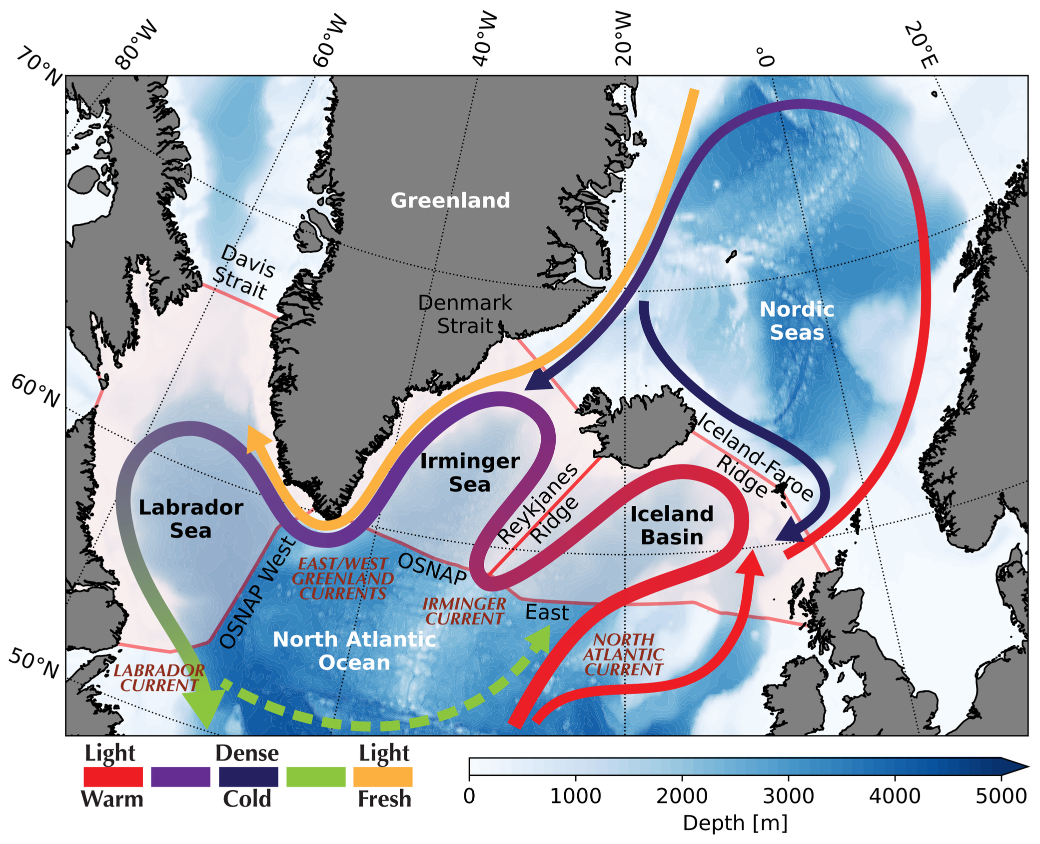

Figure 1 Map of the subpolar North Atlantic showing bathymetry, water mass analysis regions and subpolar gyre circulation. Regions are bounded equatorward by the Overturning in the North Atlantic Program (OSNAP) observing lines (Lozier et al., 2019).

Research question

How does surface water mass transformation contribute to overturning circulation in the subpolar gyre in eddy-parameterized vs. eddy-permitting ocean models?

Method

Water mass transformation is determined from surface net heat (H_{net}) and freshwater (F_{net}) fluxes based on the Walin (1982) framework. Temperature and salinity transformation are defined by Evans et al. (2014).

Density transformation

$$Tr(\rho) = -\underbrace{\frac{1}{\Delta\rho}}_{\text{Bin size}} \iint_A \left[\underbrace{\frac{\alpha H_{net}}{C_p}}_{\text{Heat flux component}} + \underbrace{\beta S F_{net}}_{\text{Freshwater flux component}}\right] \times \underbrace{\Pi\left[\rho, \rho'(x,y)\right]}_{\text{Binning function}} \, dA$$

Temperature transformation

$$Tr(T) = \frac{1}{\Delta T}\iint_A \frac{H_{net}}{\rho' C_p} \times \Pi\left[T, T'(x,y)\right] \, dA$$

Salinity transformation

$$Tr(S) = -\frac{1}{\Delta S}\iint_A S' F_{net} \times \Pi\left[S, S'(x,y)\right] \, dA$$

Simulations

Model for Prediction Across Scales (MPAS)

- Ocean and sea ice components (MPAS-Ocean, MPAS-Seaice)
- Unstructured hexagonal mesh, allows regional refinement of horizontal resolution
- Part of the DOE Energy Exascale Earth System Model (E3SM) (Golaz et al., 2022)

Configurations

- Low Resolution (LR), 30-60 km, Gent-McWilliams mesoscale eddy parameterization
- High Resolution (HR), 6-18 km, mesoscale eddy permitting/resolving

Forcing

- Coordinated Ocean-ice Reference Experiments II (CORE-II) protocol
  - Reanalysis + observations, 1948-2009 record

Simulation biases (years 50-60)

AMOC mean state and time series at 26.5 N

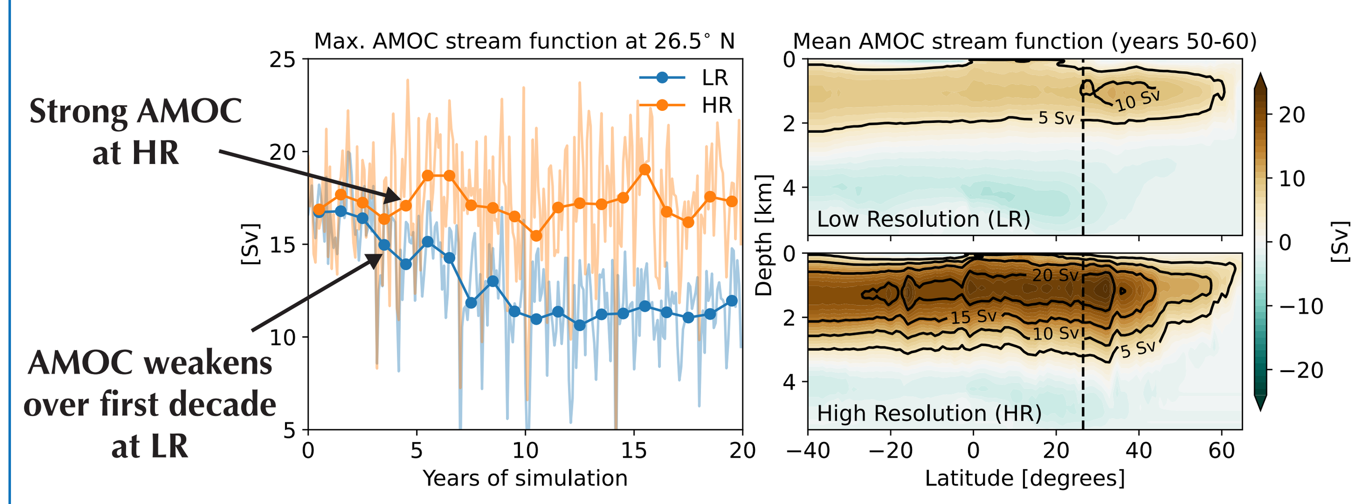

Figure 2 AMOC stream function time series at 26.5 degrees N and time mean.

Surface tracers and mixed layer depth in the subpolar gyre

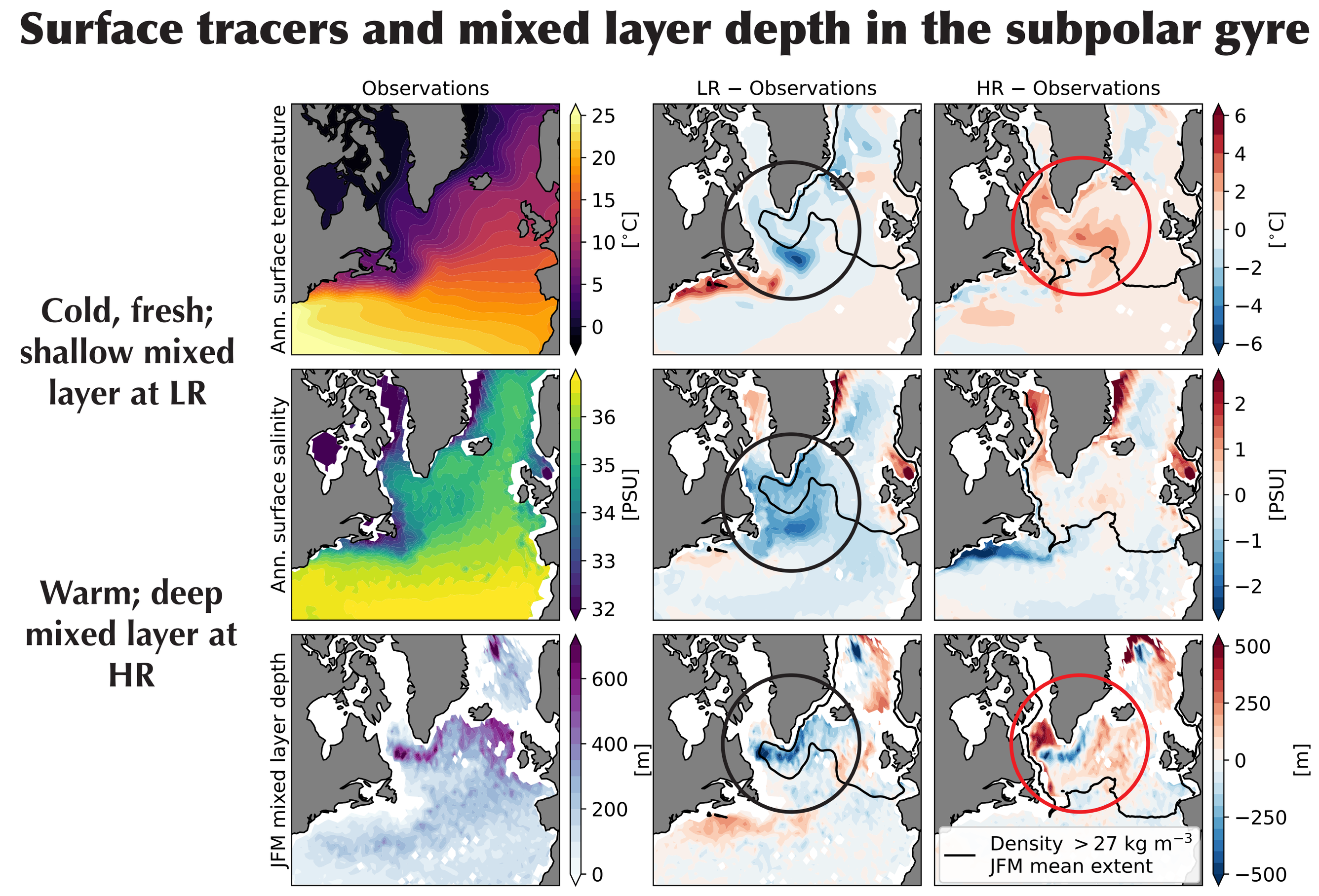

Figure 3 Annual surface temperature and salinity and Jan-Mar mixed layer depth biases relative to observations. Temperature is from the merged Hadley Center-NOAA/OI data set (Hurrell et al., 2008). Salinity is from the NASA Aquarius satellite (Fore et al. 2016). Mixed layer depth is from an ARGO float climatology (Holte et al., 2017).

Early simulation biases (years 0-10)

Subpolar gyre circulation

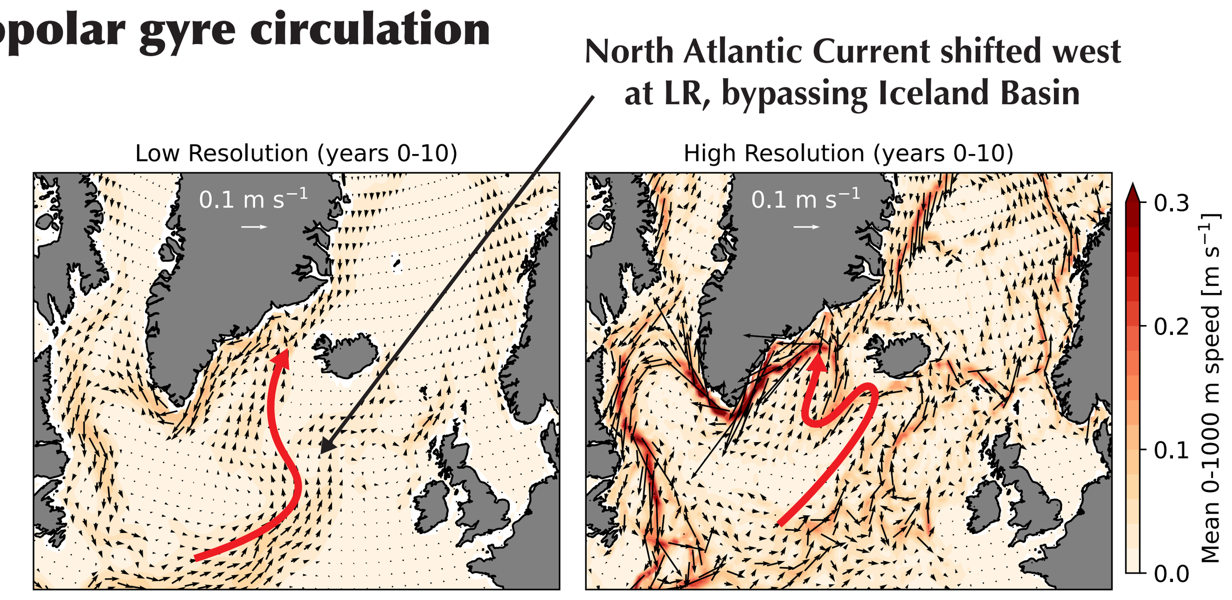

Figure 4 Surface to 1000 m averaged velocity fields.

Transport and density through the OSNAP line

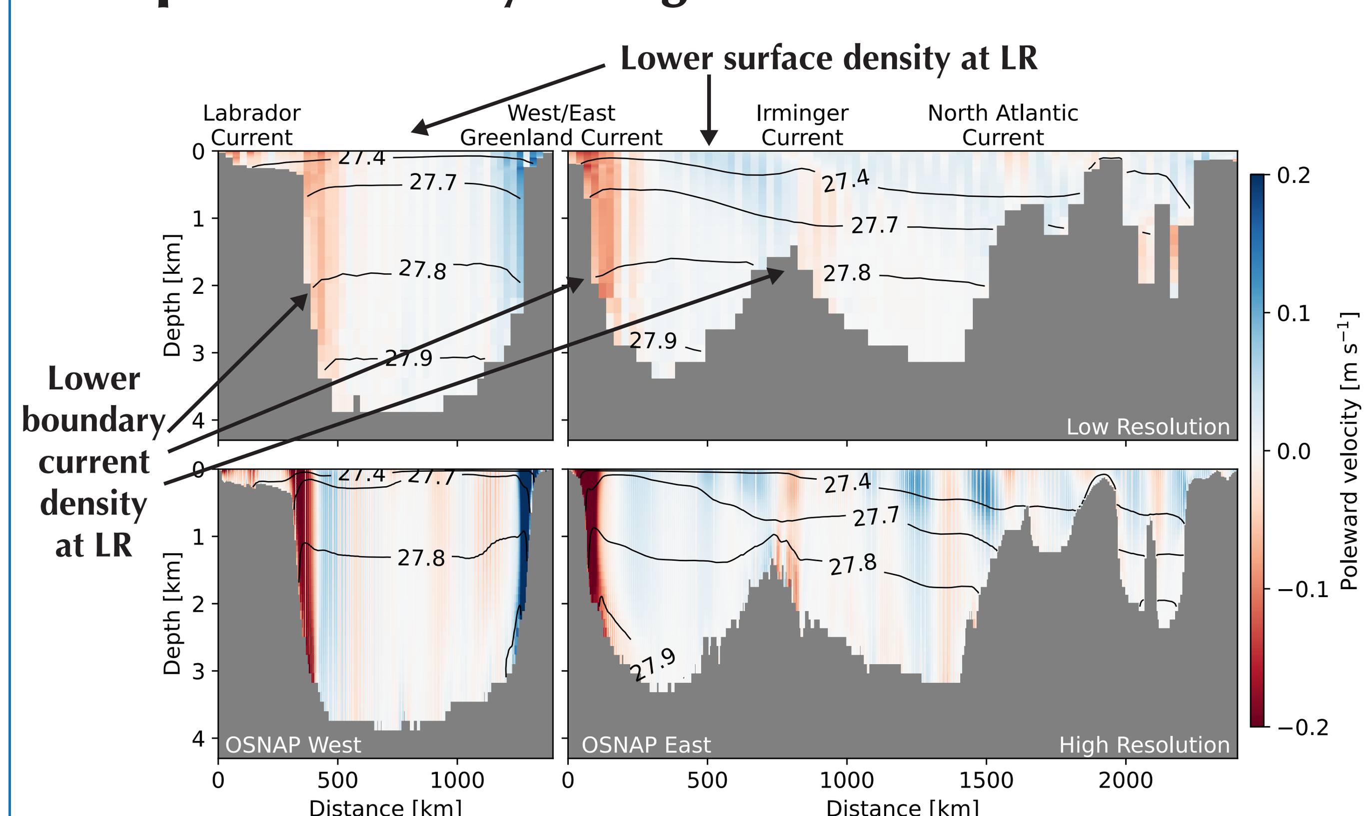

Figure 5 Poleward velocity (blue/red) and potential density (black contours) at the OSNAP line (see Fig. 1).

Water mass analysis

Surface transformation maps (HR minus LR)

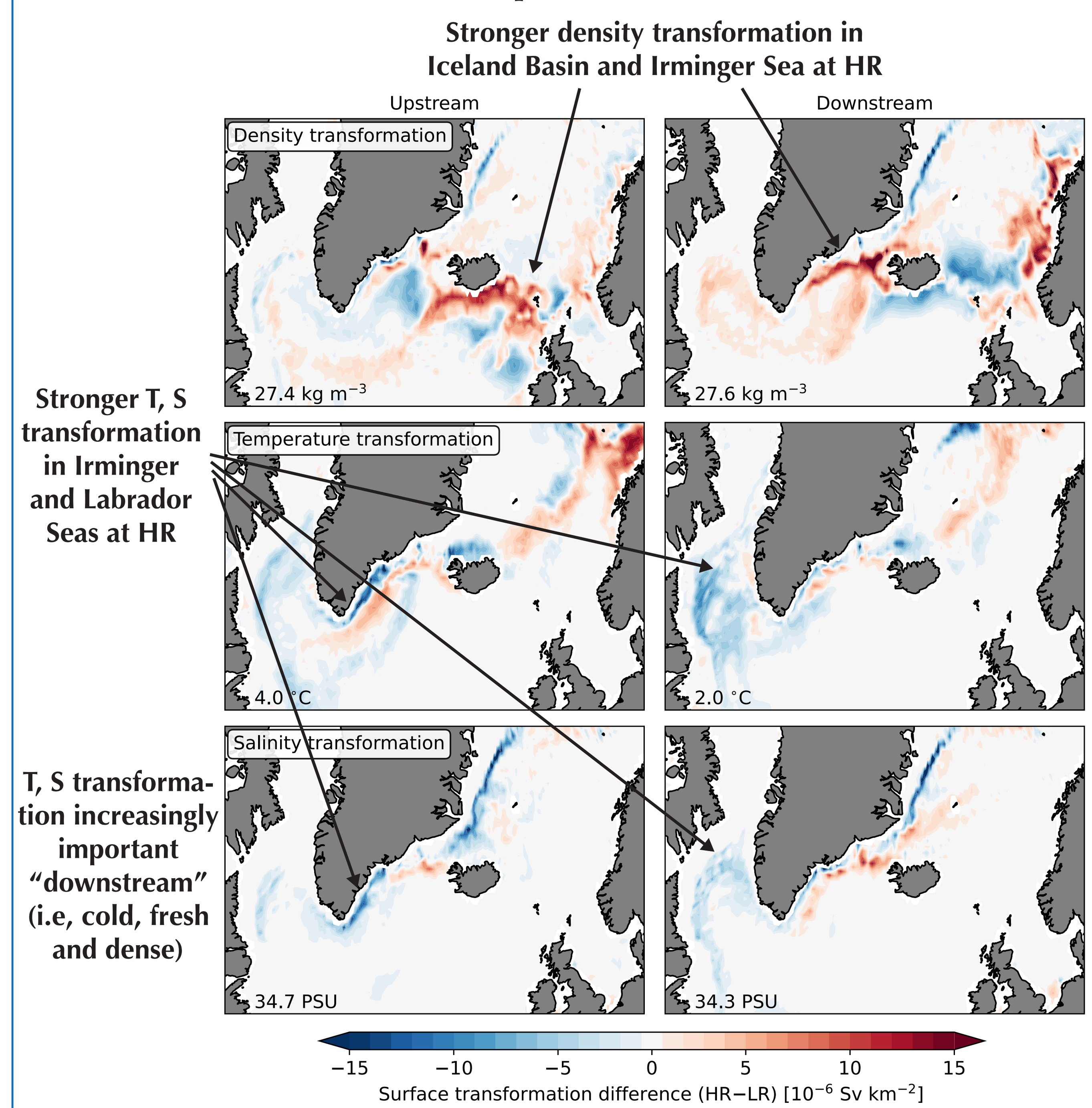

Figure 6 Surface transformation maps obtained as the integrand of the transformation equation at selected density, temperature (T) or salinity (S) bins. "Upstream" bins are light, warm and salty. "Downstream" bins are dense, cold and fresh.

Surface transformation and net import/export by region

- Temperature and salinity transformation plotted together as vectors in T-S space
- Net transport into (out of) each region binned by T, S and contoured in blue (red)

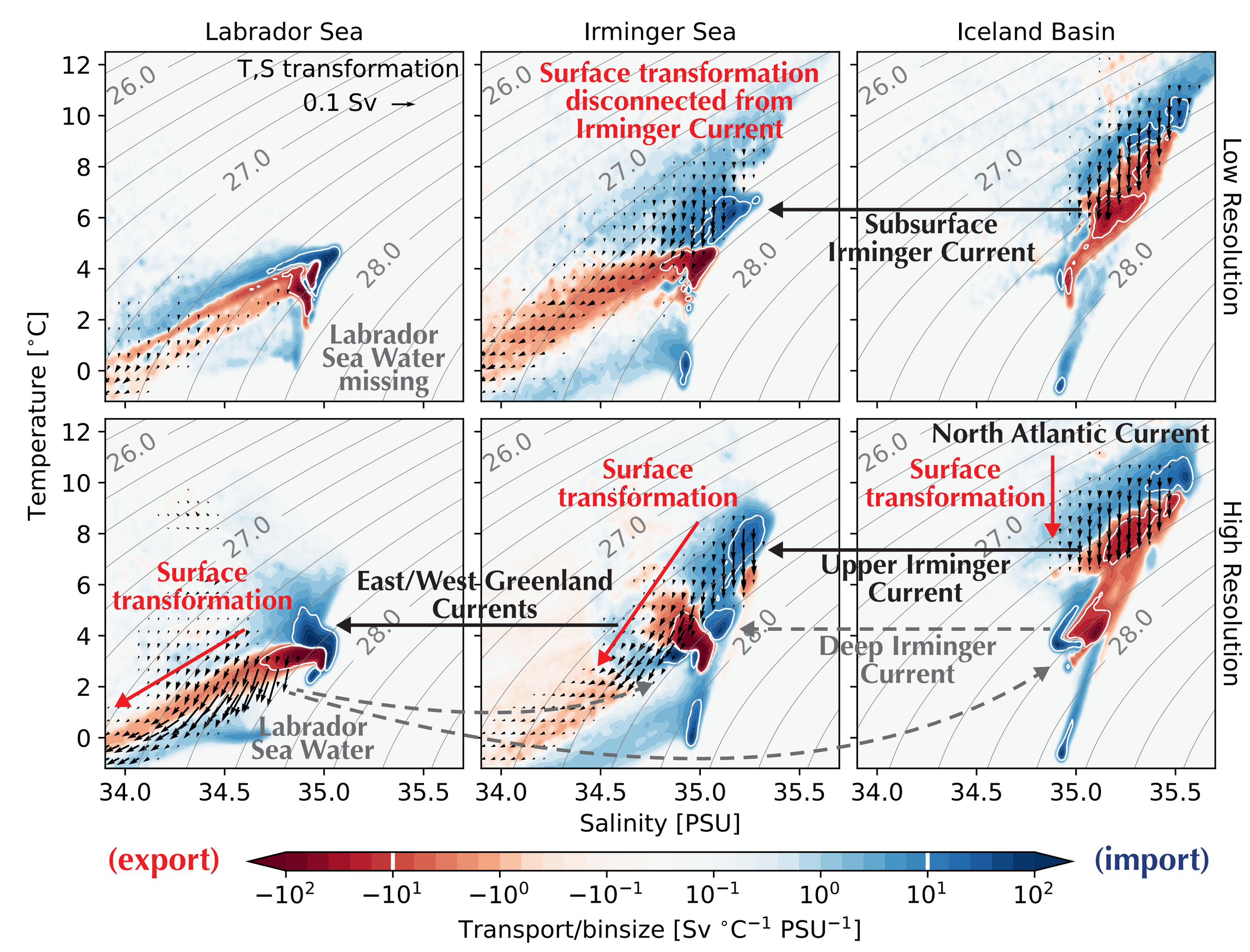

Figure 7 Surface T-S transformation (arrows) and net import (blue) and export (red) transports by region. Potential density contours are shown in gray.

Key points

1. Water mass analysis in temperature-salinity space can reveal important circulation features related to AMOC.
2. Water mass transformation continuously cools and freshens the subpolar gyre between the Iceland Basin and Labrador Sea.
3. The absence of this pathway (e.g., at LR) may interrupt the subpolar gyre overturning, preventing deep AMOC-related water masses from forming

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