Exploring the impact of the rise of Greenland-Scotland Ridge on ocean circulation and climate

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Abstract

Changes in the geometry of ocean basins have been influential in driving climate change throughout Earth's history. Here we focus on the appearance of the Greenland-Scotland Ridge (GSR) and try to understand its impact on the ocean state, including global circulation, heat transport, T and S properties and ventilation timescales, which will be useful for interpreting paleoproxies. To this end, we use a coupled atmosphere-ocean-sea ice model with idealized geometry and consider two geometrical configurations. The reference configuration (noridge) comprises two wide strips of land set 90° apart extending from the North Pole to 40°S, separating the Northern Hemisphere ocean into a small and a large basin. In the ridge configuration a zonally symmetric oceanic ridge, that extends across the Atlantic-like basin at 60°N, mimicking the GSR, is added. In addition, we consider two climatic limits of noridge: a warm case where the northern high latitudes are seasonally ice-free and a cold case where a perennial sea ice cover is present. In both cases of noridge deep-water formation occurs at the North Pole in the Atlantic-like basin. When the ridge is introduced, the flow of warm Atlantic water to the high latitudes is hampered and the ocean heat transport across 70°N decreases by ~60% which causes cooling and freshening north of the ridge. Downwelling shifts south of the ridge, thereby altering the structure of the upper overturning cell dramatically. Despite these changes, the Northern Hemisphere surface climate response is surprisingly small for the warm climate case. This is because the subpolar gyre circulation continues to transport warm water across the ridge, keeping the northern North Atlantic relatively warm and ice-free. In the colder climate case, however, the presence of sea ice provides a strong non-linear feedback, which amplifies the cooling induced by the ridge, and causes sea ice to expand. Our results highlight the possible disconnect between changes in the localization of deep-water formation, the structure of the AMOC and the properties of water masses and changes in Northern Hemisphere climate. Implications for the interpretation of paleoproxy records from the North Atlantic region will be discussed.

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Motivation

- Changes in land-sea configuration throughout Earth's history have had a profound effect on ocean circulation and climate. Reorganizations of continents and appearance of oceanic ridge alter the geometry of ocean basins and influences how the ocean circulation re-distributes heat around the globe.
- This work focuses on the **Greenland-Scotland Ridge (GSR)** and explore its role in shaping the *ocean circulation*, *heat transport* and *high latitude climate*. In particular, we seek to understand how the appearance of the GSR affects deep water formation and the Atlantic Meridional Overturning Circulation (AMOC).

Methods

MITgcm aquaplanet

Model configuration

- Coupled **ocean-atmosphere-sea ice** model with idealized topography
- Configured on cubed sphere grid at 2.8° resolution *(CS32)*
- 3,000 m deep and flat-bottomed **ocean** with 30 levels; Intermediate complexity **atmosphere** with 5 levels (*SPEEDY*); 2.5 layer thermodynamic **sea-ice** model (*THSICE*). No sea ice dynamics

Experimental design

A **ridge** with a sill depth of 500 m is introduced between 61°-65°N in the small basin mimicking the GSR. The model is integrated forward for 200 years.

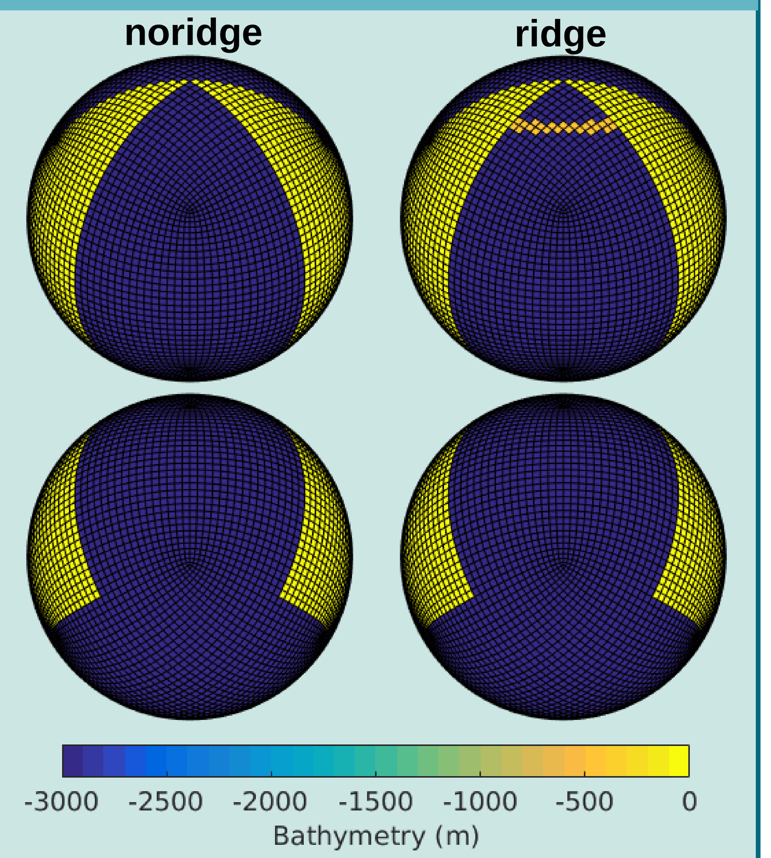
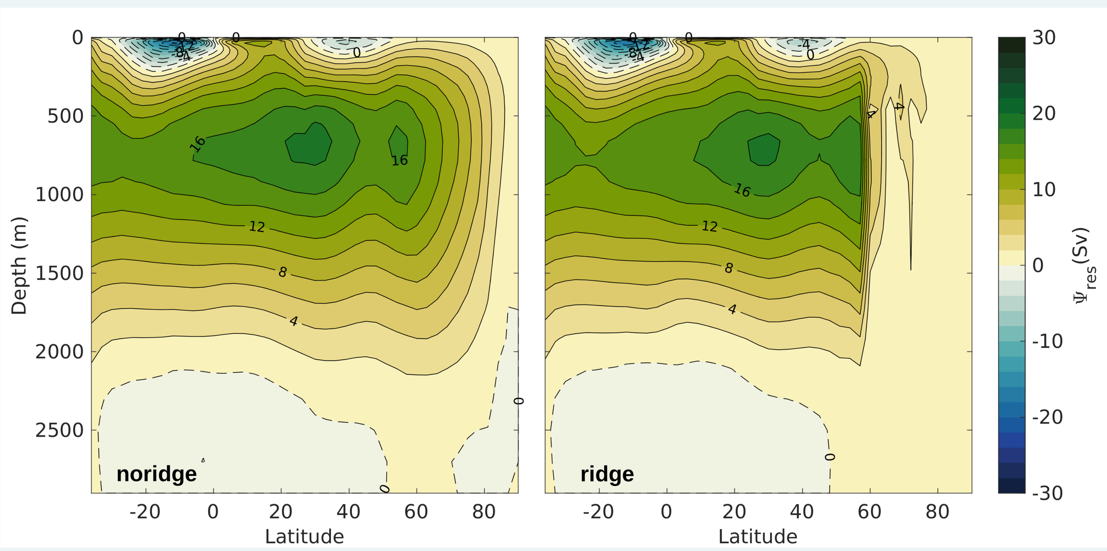
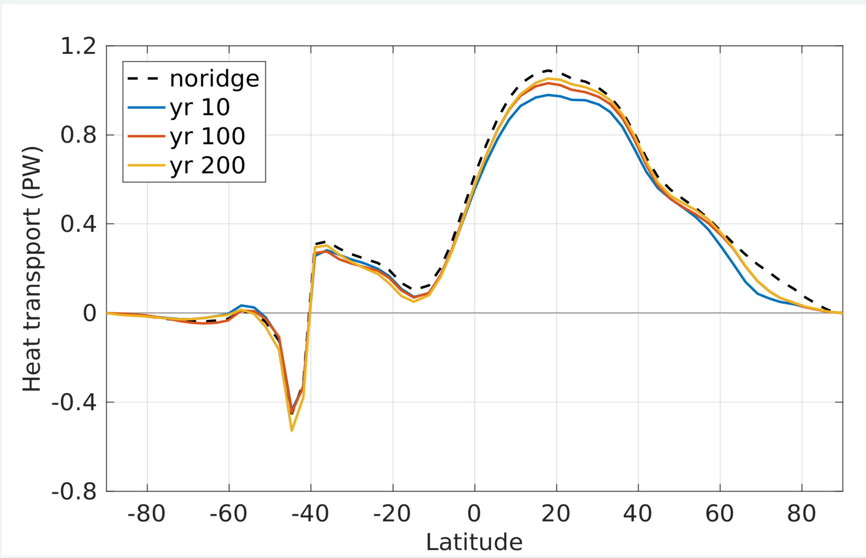


Figure 1 – Land-ocean configurations of the MITgcm Aquaplanet used in this study.

Results

Small basin MOC and heat transport

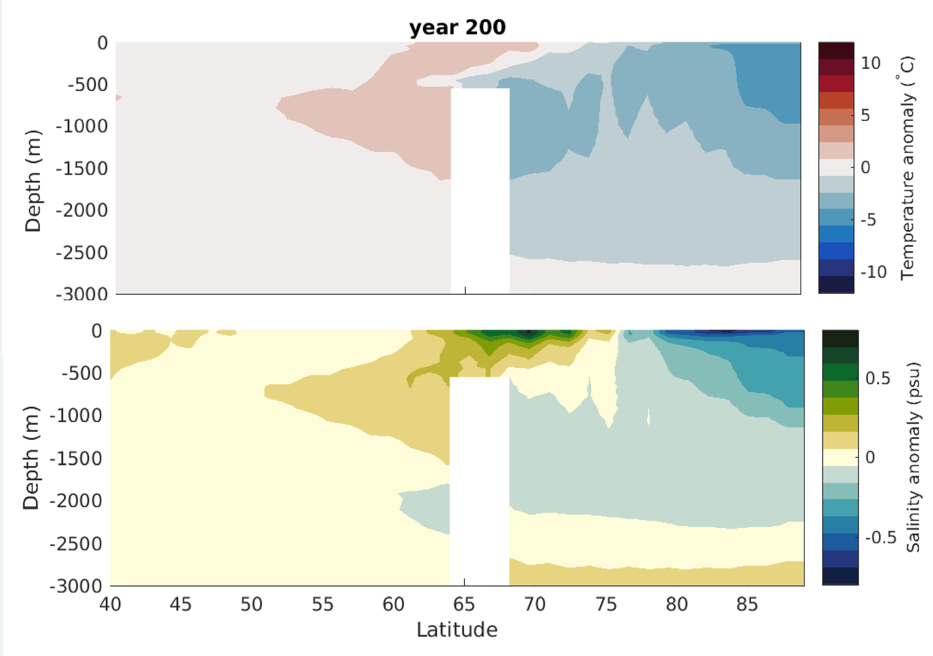




- Unrestricted northward flow of subpolar waters in *noridge* keeps northern high latitudes warm and ice-free
- The ridge partly blocs inflow of North Atlantic water and mid-to-high latitude OHT decreases by 0.2 PW (~36%)
- Downwelling shifts southwards with large structural changes in AMOC, but maximum strength is unchanged

Figure 2 – Small basin overturning streamfunction (Sv) for *noridge* (left) and *ridge* (right) and zonal mean ocean heat transport (PW) for years 10, 100 and 200 after the ridge is introduced. Dashed black lines corresponds to *noridge*.

Hydrographic changes in the small basin



Temperature and salinity anomalies

- *Cooling and freshening* north of the ridge, but *warmer and saltier* conditions south of ridge
- High latitudes become less ventilated

Figure 3 – Zonal mean anomalies of potential temperature (°C) and salinity (psu) in the small basin. Anomalies are relative to a 50-year average at the end of *noridge*.

Density changes

- Strong meridional density gradient develops across the ridge
- Dense water is formed north of the ridge
- Pressure gradient sets up zonal jet along the ridge

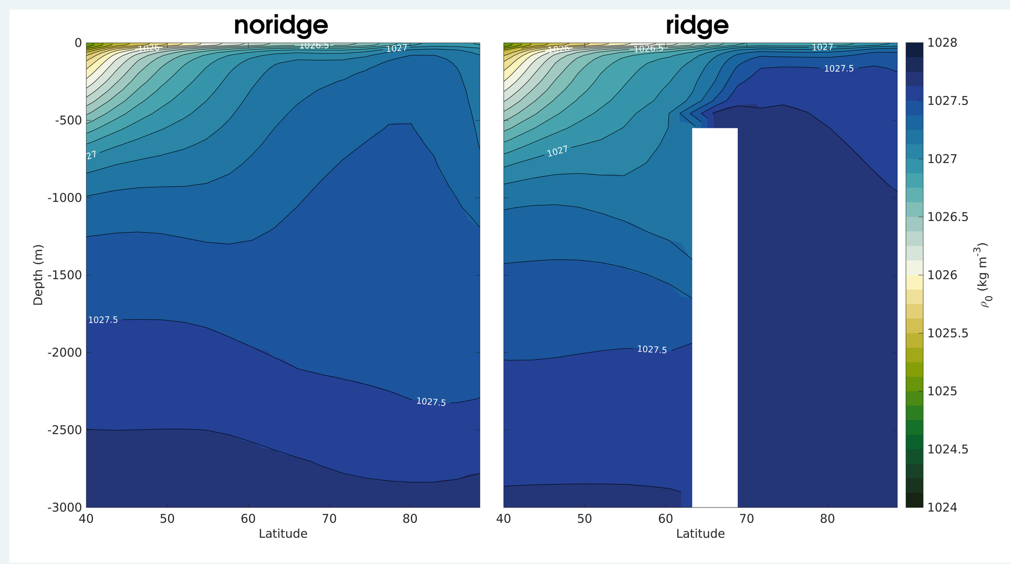
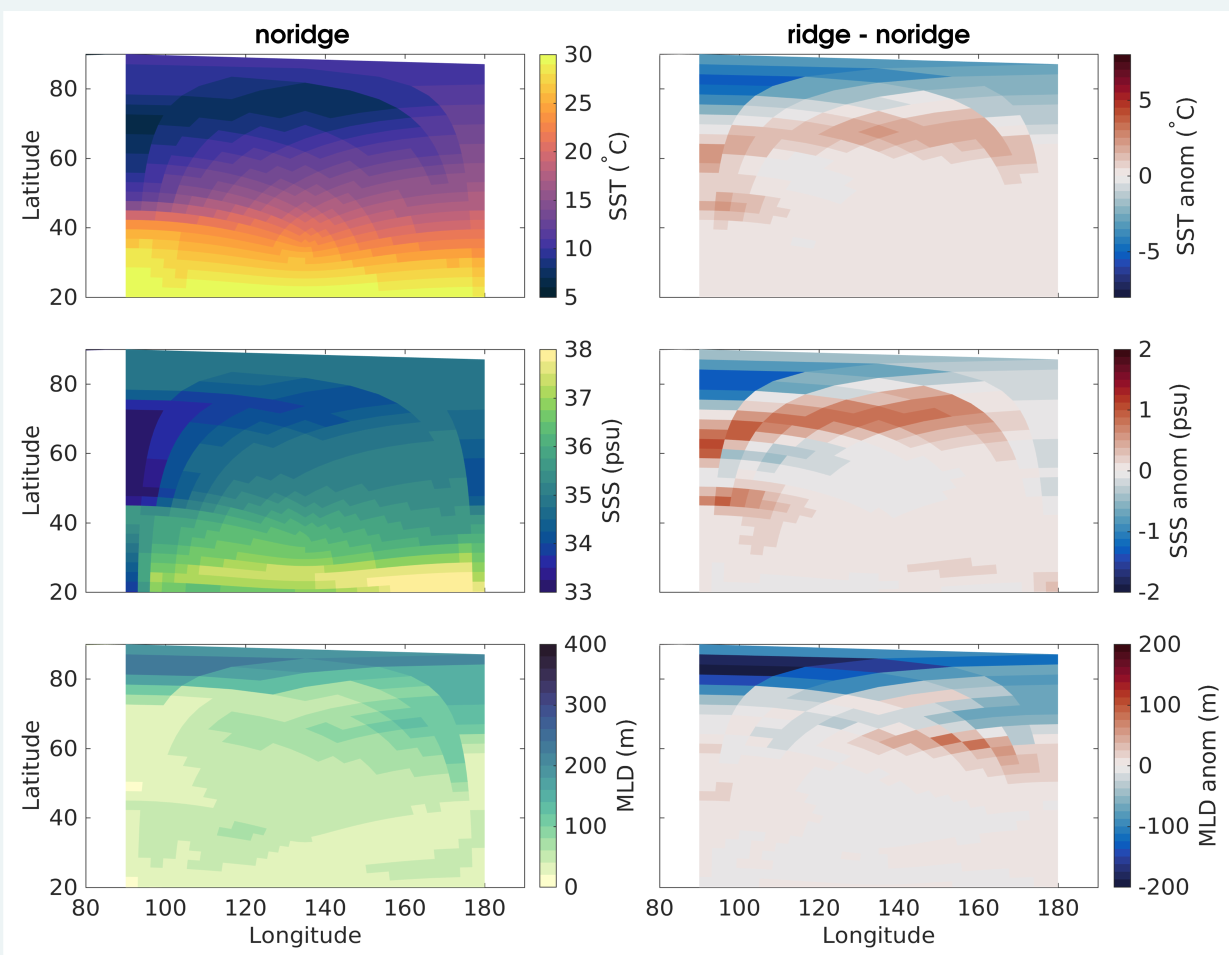


Figure 4 – Zonal mean potential density in the small basin for *noridge* (left) and *ridge* (right).

Surface climate response



SST / SSS / MLD

- Surface cooling and freshening at northern boundary
- ML shoals at northern boundary in *ridge*

Figure 5 – Left panel shows SST (°C; top), SSS (psu; middle) and mixed layer depth (m; bottom) in the small basin for *noridge*. Right panel shows anomalies for *ridge* relative to *noridge*.

Surface buoyancy fluxes

- Heat fluxes dominates surface buoyancy loss at subpolar and polar latitudes
- Reduced ocean heat loss at high northern latitudes weakens buoyancy loss in *ridge*

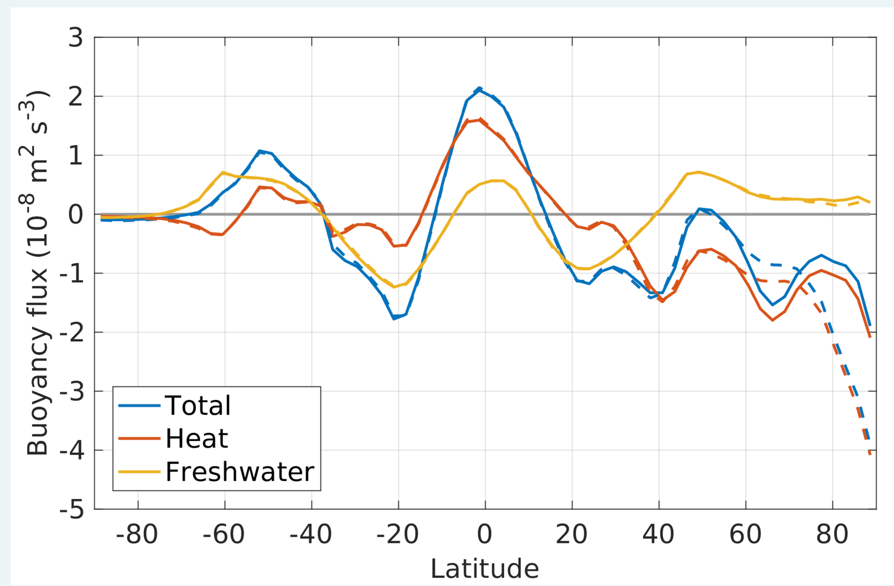


Figure 6 – Zonal mean surface buoyancy flux ($m^2\ s^{-3}$) in the small basin for *noridge* (dashed) and *ridge* (solid)

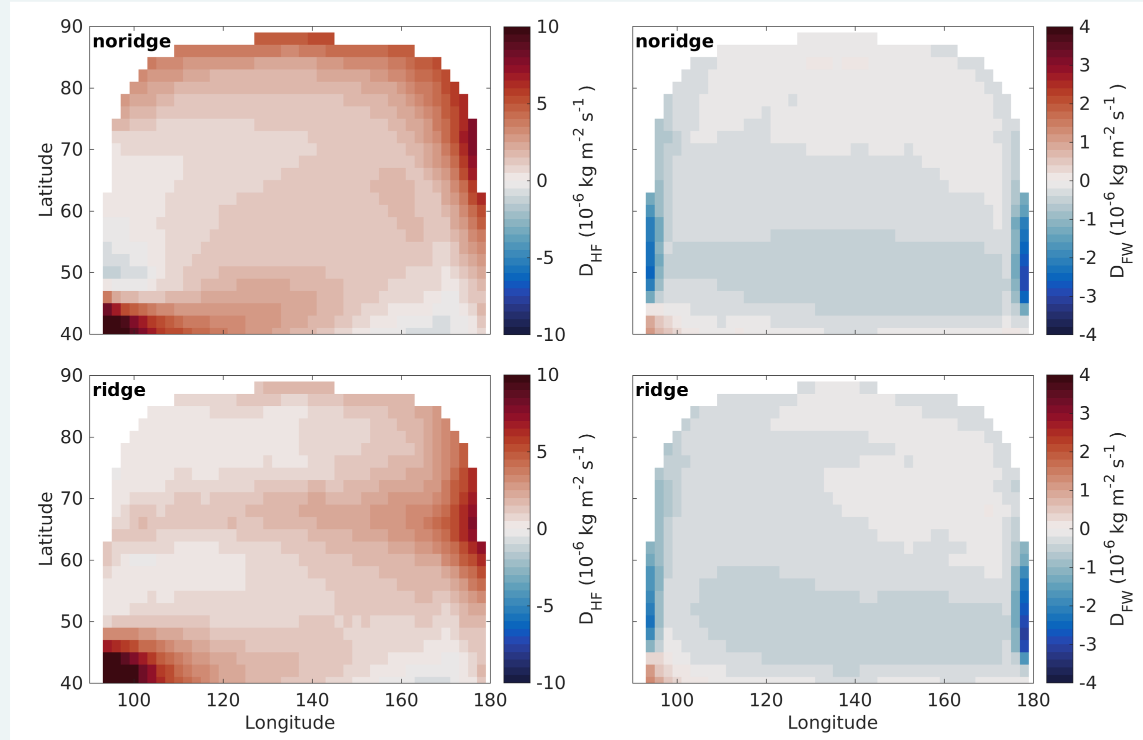
Localization of deep water formation

Water mass transformation by surface density fluxes [Walin (1982); Speer and Tziperman (1992)]

The transformation of surface waters to lighter or heavier density classes by buoyancy fluxes between outcropping isopycnals ρ and ρ+δρ, is equivalent to a diapycnal volume flux *F(ρ)* across the outcropping isopycnal:

$$F(\rho) = \frac{1}{\Delta T \Delta \rho} \int_{year} dt \iint_{area} dA \delta(\rho - \rho') D(x,y,t)$$

Surface density flux: $$D = D_{HF} + D_{FW} = -\frac{\alpha Q_{HF}}{c_p} + \beta S Q_{FW}$$



Density fluxes

Figure 7 – Mean thermal (D_{HF}; left) and haline (D_{FW}; right) contribution to the surface density flux (10^{-6} kg m^{-2} s^{-1}) over a period of 10 years for noridge (top) and ridge (bottom). Positive values indicate densification.

Water mass transformation

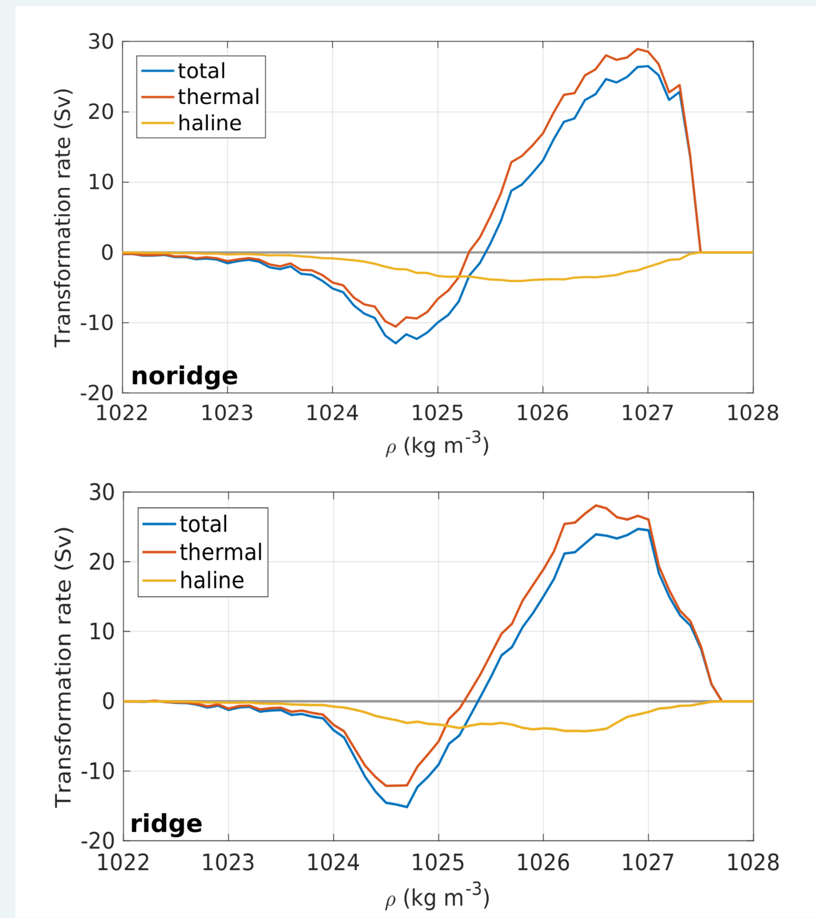


Figure 8 – Surface forced water mass transformation *F(ρ)* in Sverdrups (10^6 m^3 s^{-1}) for *noridge* (top) and *ridge* (bottom) over 10 years. *F(ρ)* is estimated from the spatial integral of the surface density flux *D* over the North Atlantic spanning the density range ρ = 1022-1028 kg m^{-3} with a density bin width of $\Delta\rho$=0.1. The total (blue) is decomposed into its thermal (red) and haline (yellow) contribution. Negative values imply a transformation of surface water to lower density classes, positive values indicate transformation to greater densities.

Conclusion

- Introducing the GSR restricts northward flow of subpolar waters by the upper overturning branch and OHT across 70°N decreases by 36%
- Convection shifts southward altering the structure of the AMOC, but the maximum does not change
- Arctic Basin cools and freshens while it gets warmer and saltier south of the ridge. Dense waters forms north of the ridge resulting in a large meridional density gradient between the Arctic Basin and North Atlantic
- Relatively modest surface climate response (SST/SSS/sea ice), but major changes in circulation suggests a potential disconnect between big AMOC changes and changes in Northern Hemisphere surface climate