The impact of wintertime sea-ice retreat on convection in the Nordic Seas

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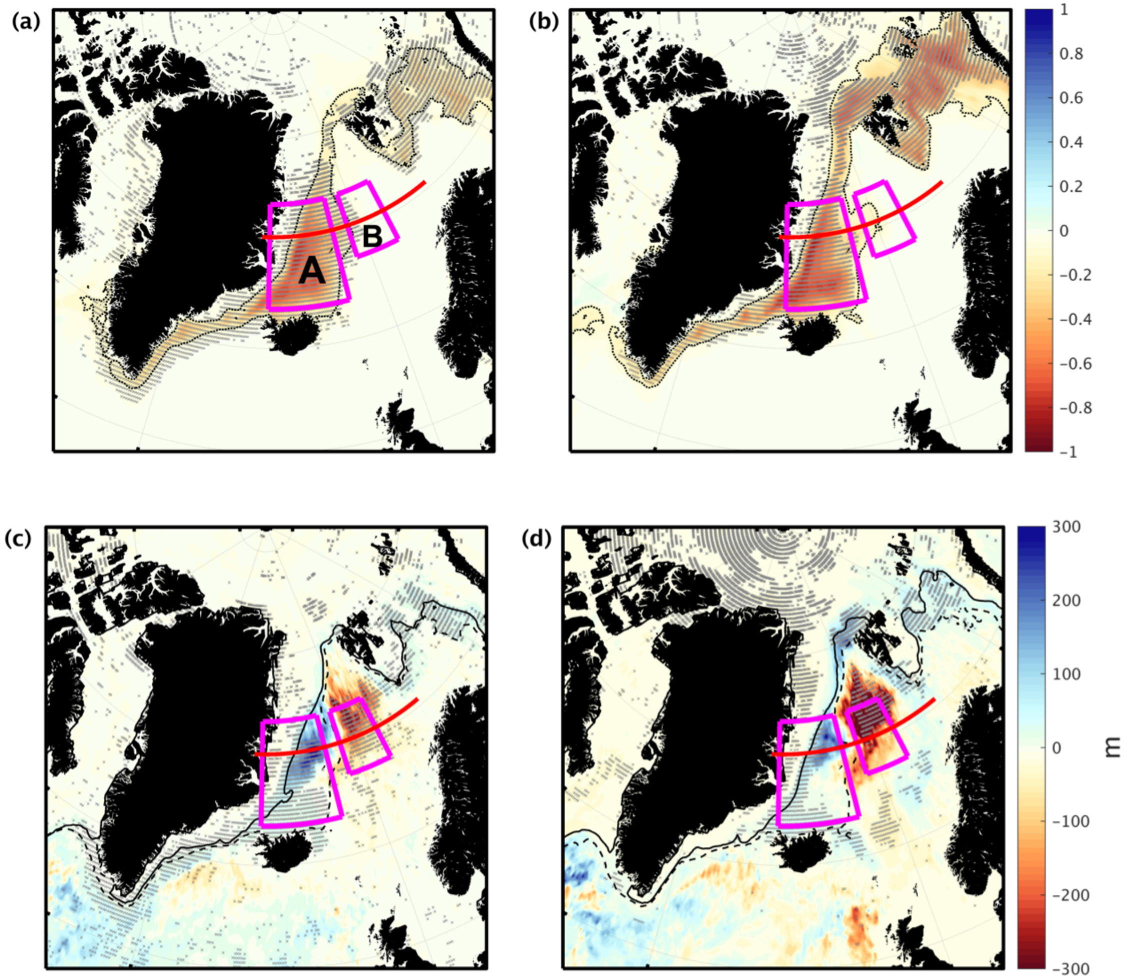


Figure 1 | The change map in sea ice concentration (SIC; top) and the MLD (bottom) between sea ice low and high sea ice conditions (low minus high) in the CTRL (left) and GW (right) scenarios. Dotted contours depict a SIC change of 0.1, dashed and solid contours are the SIC of 0.15 in high and low years, respectively. The boxes and latitudinal section at 72.5 ^{o}N are shown. Significance of 95% is indicated in grey dots.

- Control runs (CTRL): the largest sea ice loss lies to the west of Greenland and in the Iceland Seas. The **mixed layer depth (MLD) deepens** in the BOX-A, with an especially notable anomaly in the Greenland Sea. However it becomes **shallower** further away from the sea ice edge (BOX-B).

- Global Warming scenario (GW): the retreat of sea ice occurs almost everywhere. The **MLD deepens** in most of **BOX-A**, and the **shoals** in the **BOX-B**. The shoaling is considerably strengthened compared with that seen in CTRL.

- Convective mixing in the Nordic Seas is largely induced by buoyancy loss (Moore et al., 2015), connecting the near-surface with deep ocean by ventilation (Lique et al., 2018). While sea ice cover acts as a barrier mitigating heat fluxes between atmosphere and ocean (Day et al. 2013). However, the dramatic loss of sea ice in recent decades is creating a new sea-ice-air environment where large swathes of ice-covered regions are now exposed to the atmosphere.

- Here we aim at investigating how sea ice retreat under global warming impacts **deep convection** in the Nordic Sea. We focus on the **marginal-ice-zone** where the air-sea temperature difference is large, promoting high heat flux events during periods of off-ice winds.

Methodology

Figure 2 | The time evolution of the area average sea ice concentration (SIC) for CTRL and GW in the (a, b) BOX-A and (c, d) BOX-B. (a, c) The thin coloured lines are individual ensemble members. The black line is the time mean of all ensemble members and the grey shading indicates +/- 1 standard deviation from that mean. (b, d) The thin coloured lines are individual ensemble members with the thick line depicting the median. The thick black line is the observed SIC evolution from HadSST. The vertical grey blocks indicate the periods used for normal (1970-1981) and reduced (2008-2019) sea ice years.

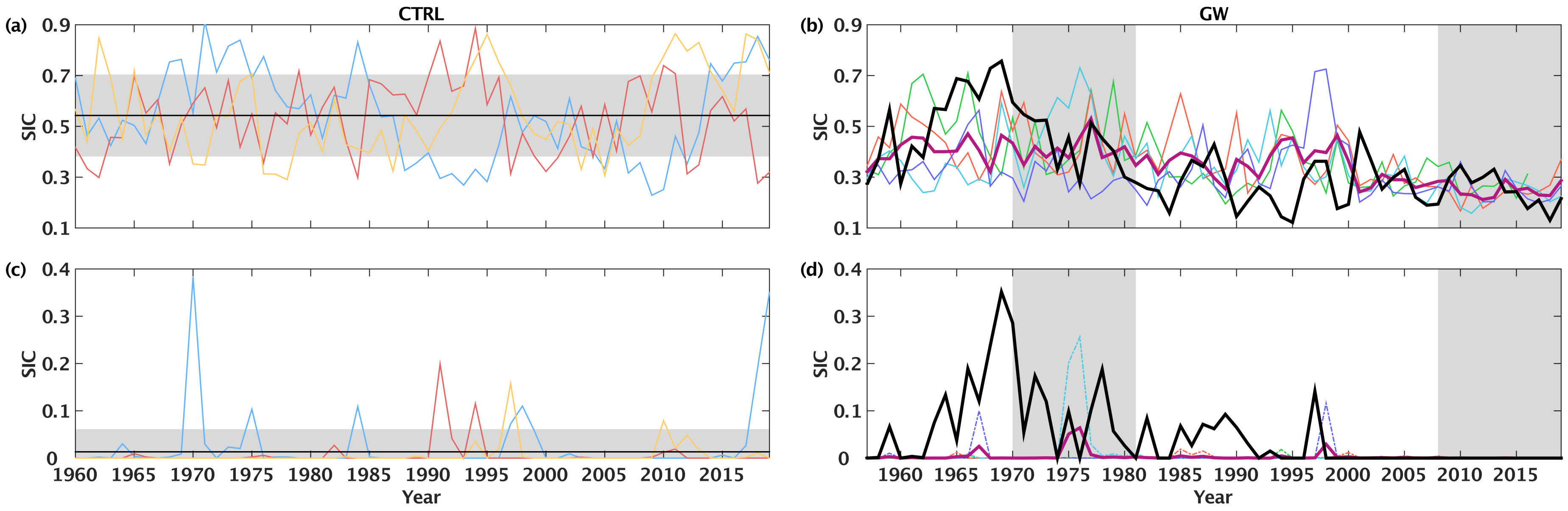
- Three 65-year control runs (labelled CTRL) where there is no anthropogenic forcing.

- Four transient integrations (labelled GW) were run from 1957-2019 with greenhouse emissions following the CIMP5 RCP Historical scenario from 1957 to 2005 and the CIMP5 RCP4.5 scenario afterwards (Shaffrey et al., 2017).

- For CTRL, sea ice high/low composites are defined by averaging those years that deviate more than 1-standard deviation from the long term mean.

- For the GW,
  1970-1981: normal sea ice decade
  2008-2019: reduced sea ice decade

HiGEM Model and Experimental Analysis



In this study we used the High-Resolution Global Environmental Model (HiGEM), which is a fully coupled atmosphere-ice-ocean climate model with high resolutions in both atmosphere and ocean. Spatial resolutions are shown as bellows:

Atmosphere component:
- Horizontal: 5/6 degree in latitude and 5/4 degree in longitude
- Vertical: 38 unevenly spaced levels

Ocean component:
- Horizontal: 1/3 degree in latitude and longitude
- Vertical: 40 unevenly spaced levels

Ice component:
- Horizontal: 1/3 degree in latitude and longitude
- Zero-layer thermodynamics and five category ice thickness distribution

Results

Changes of surface variables in response to sea ice retreat

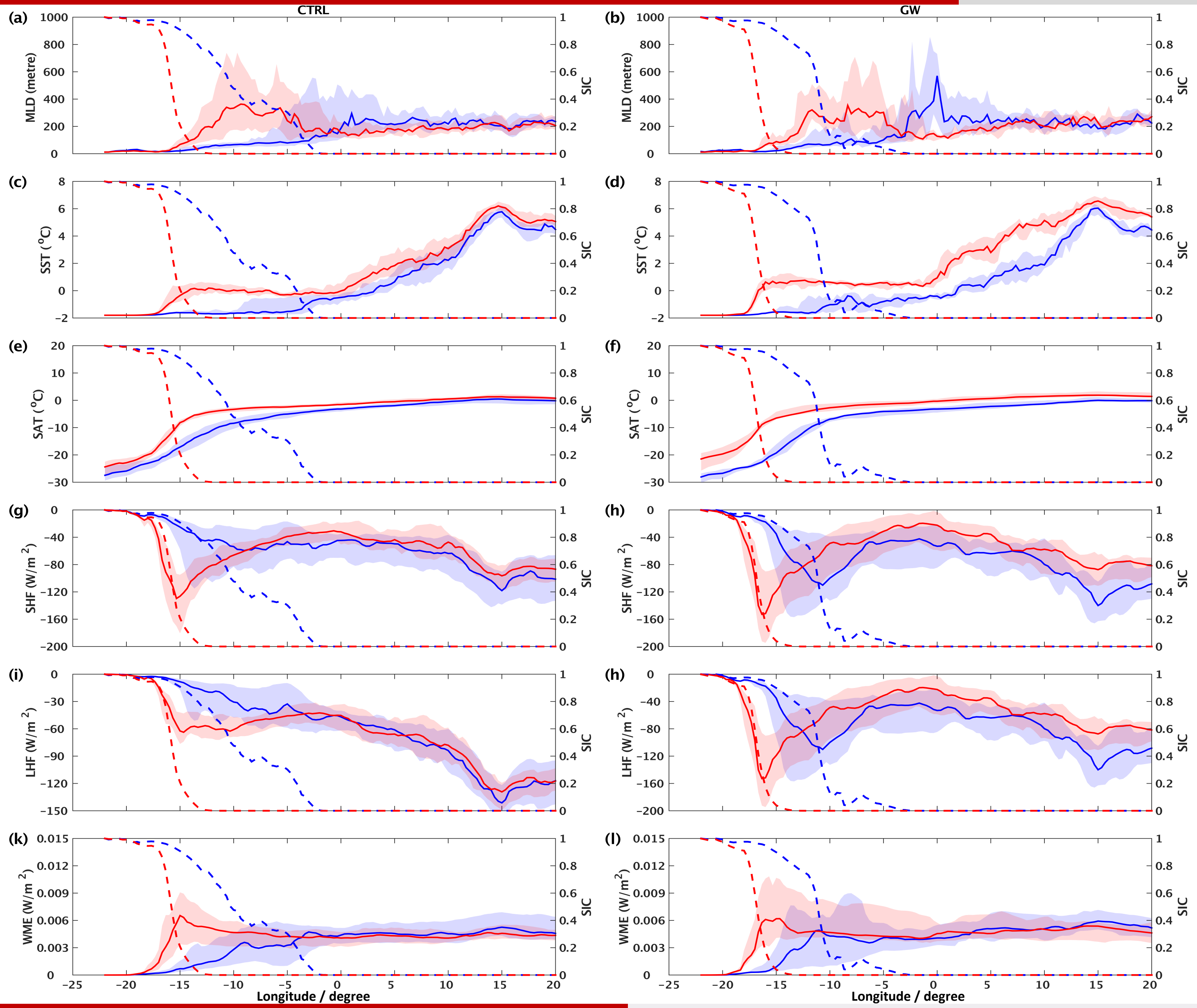


Figure 3 | The sections at 72.5 °N of median (a, b) MLD, (c,d) sea surface temperature (SST), (e,f) surface air temperature (SAT), (g, h) sensible heat fulx (SHF), (i, j) latent heat flux (LHF), and (k, l) wind mixing energy (WME) in sea ice high (blue) and low (red) conditions for the CTRL (left column) and GW (right column) scenarios (solid lines). Dotted lines in each panel are the SIC, the shadings are between 25% and 75% quantiles.

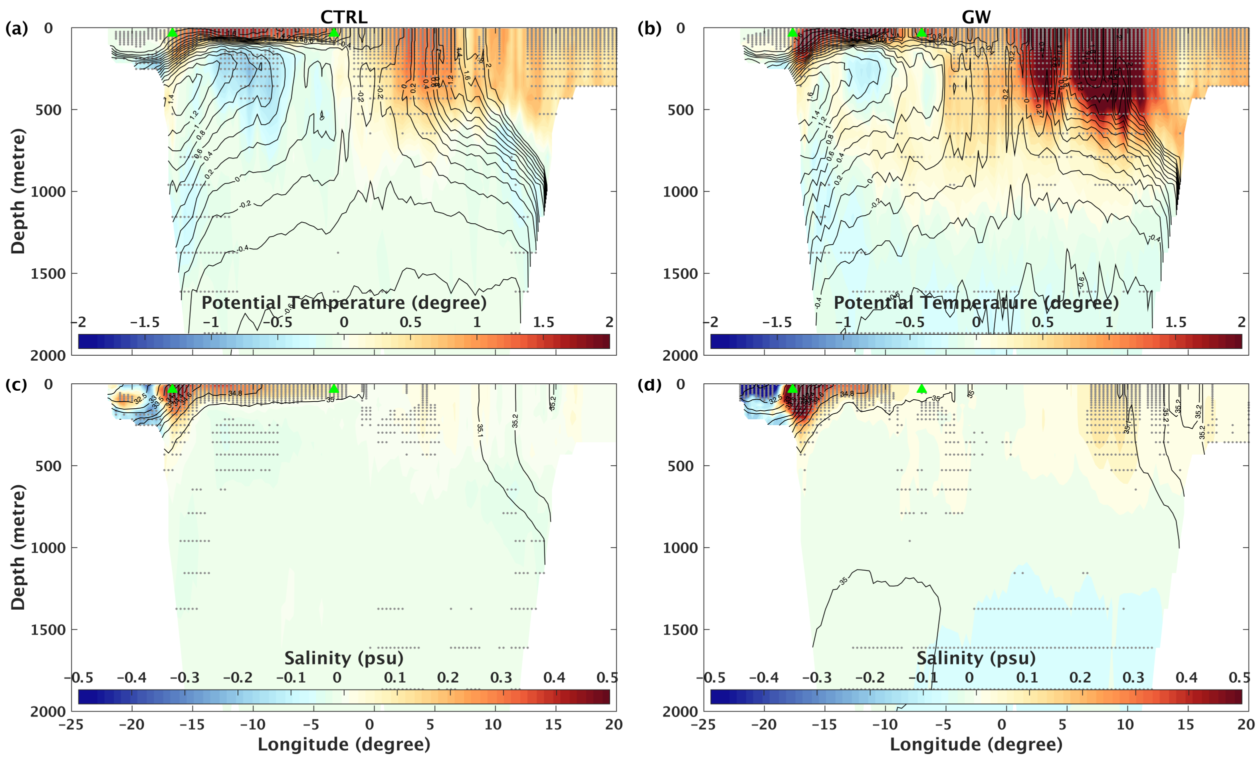
In the CTRL:

- In the sea ice retreating region, the mixed layer has a pronounced thickening by about 250m in response to sea ice retreats.
- Buoyancy losses by turbulent heat fluxes are greatly increased in the sea ice retreating region.
- There is also an increase in wind mixing energy as a greater proportion of the ocean is in direct contact with the atmosphere.

In the GW:

- In the sea ice retreating region, the MLD deepens by about 300m. Away from this region, there is a shoaling of the MLD by about 200 m, which has implications for convection in centre of the gyre.
- The biggest ocean warming occurs in open ocean, increasing by 2.5-3 °C. Here the atmosphere increases by the same extent.
- Away from the region of sea ice retreat, sensible heat flux and wind mixing energy remain largely unchanged, which should result in no significant changes in MLD.

Changes of ocean stratification in response to sea ice retreat



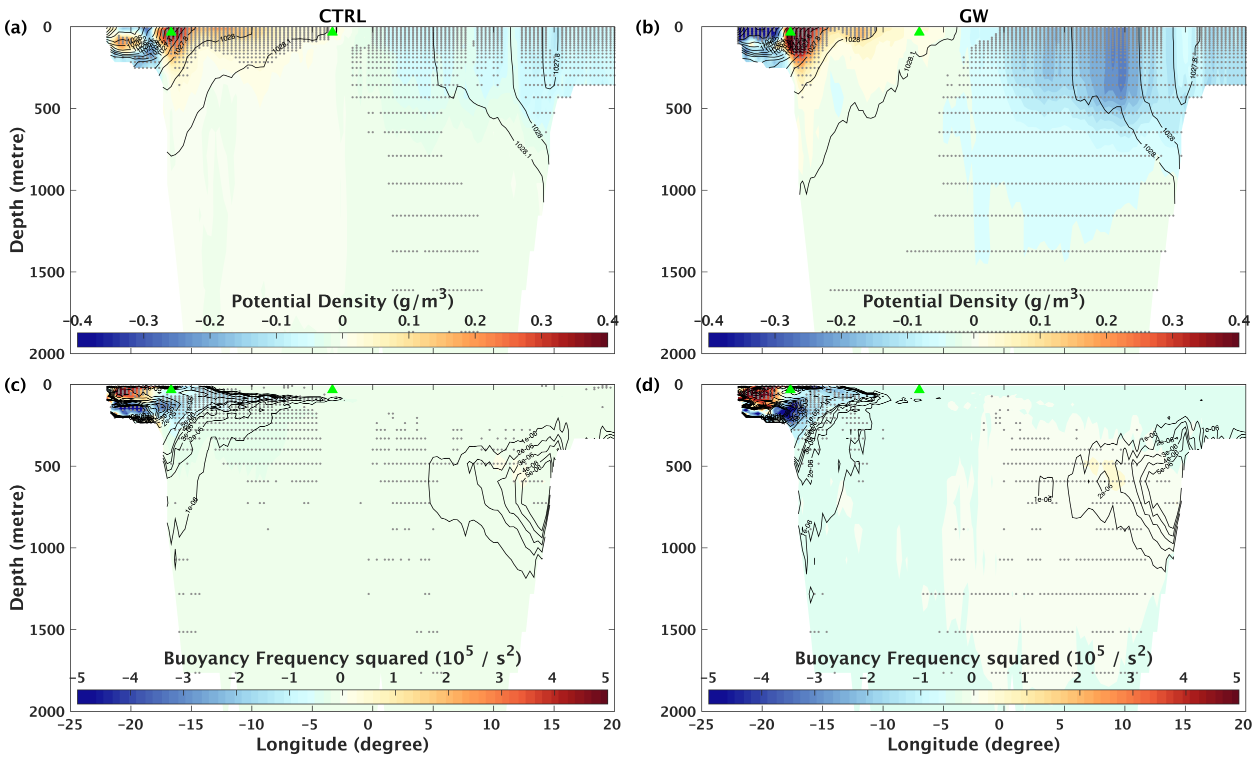


Figure 4 | The change in (a, b) temperature and (c, d) salinity, between sea ice low and high conditions for the CTRL (left column) and GW (right column), contours are background field in sea ice high condition, significance of 95% is indicated in grey dots. The green triangles at the surface indicate the region of sea ice retreat.

Figure 5 | The change in (a, b) density and (c, d) buoyancy frequency squared between sea ice low and high conditions for the CTRL (left column) and GW (right column), other indications are the same as the Figure 4.

In the CTRL:

- A warming and salinification is taking place in the upper ocean of the region of reduced sea ice.
- Density anomalies are consistent with salinity anomalies in the region of sea ice retreat, and consistent with temperature anomalies away from that region.
- Stratification becomes weaker in the region of sea ice retreat, which is beneficial to deeper convection.

In the GW:

- The upper ocean in the region of sea ice retreat becomes significantly warmer and more saline. Another large warming away from the ice edge extends down to approximately 1000 m.
- In the region of sea ice retreat, the ocean changes are similar to those in the CTRL, density anomalies are dominated by salinity anomalies.
- In the ocean interior, water density becomes significantly lighter, resulting in a more stratified layer in the upper ocean that constrains vertical mixing and inhibits deep convection.

Conclusions

- The wintertime sea-ice retreat leads to remarkable changes in convection at the sea ice edge resulting from the changes in ocean surface heat exchange and wind stress forcing.

- The ocean response to sea-ice differences is qualitatively similar for the CTRL and GW experiments, but intensified for GW.

- Close to the ice edge, the sea ice retreat allows enhanced mechanical wind mixing and a greater loss of buoyancy from the ocean. In addition, brine rejection from enhanced sea ice production contributes to weaker stratification that promotes deep convections.

- Outside the sea ice edge the ocean warms intensifying the stratification in the upper ocean which discourages convection. Climate warming enhances this effect.

References

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