On the Long-term Mean AMOC across the Arctic-Atlantic Gateways and the Subpolar North Atlantic

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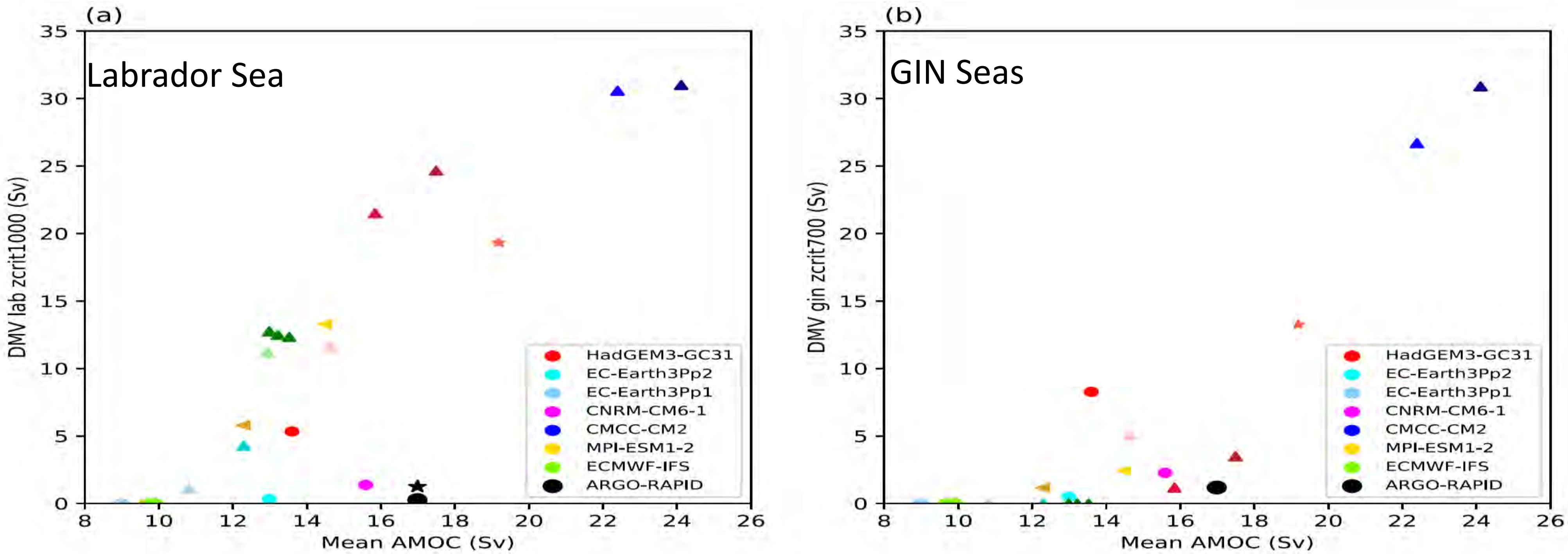
Introduction – Large Model Spread/Uncertainties in AMOC Mean State and Future Projections

- CMIP6 models exhibit large spread and uncertainties in the mean state AMOC strength and projections of future AMOC changes (Weijer et al. 2020), causing large uncertainties for projected future regional climate changes (Bellomo et al. 2021)

- In general, models with larger mean-state AMOC tend to have larger future AMOC decline (Gregory et al. 2005; Winton et al. 2014; Weijer et al. 2020; Bellomo et al. 2021)

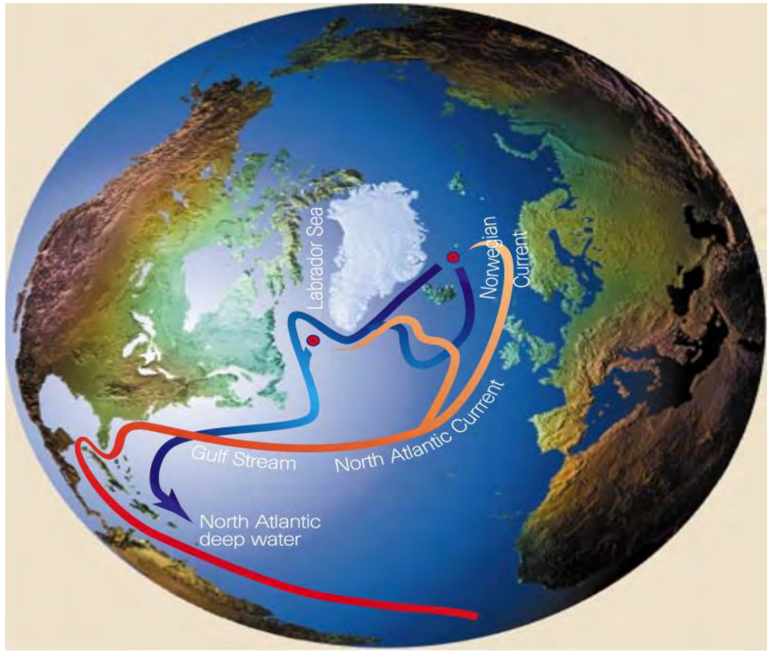


Roberts et al. 2020, JAMES

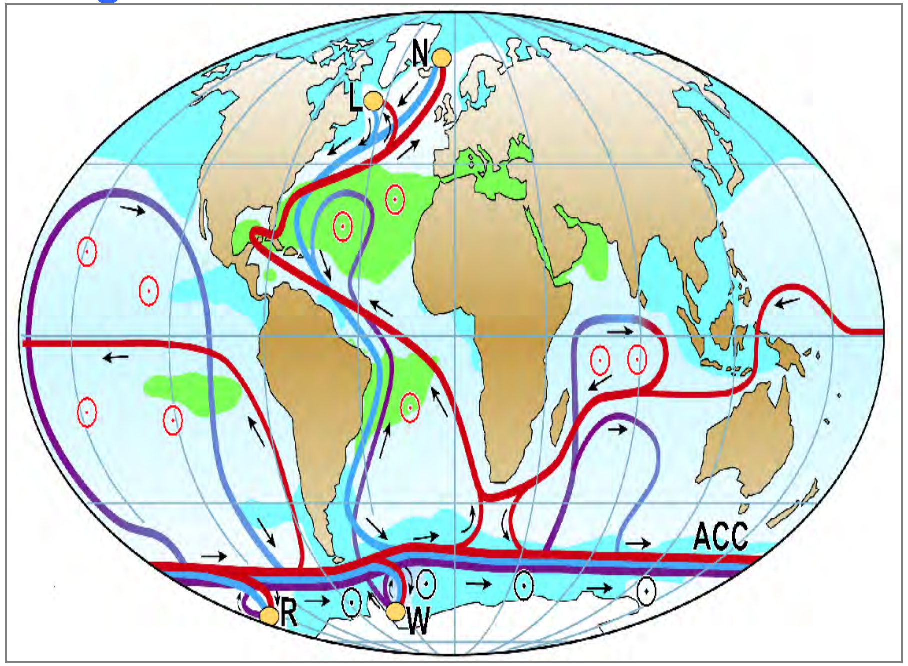
- The mean state AMOC strength from CMIP6 HighResMIP historical simulations also has a large spread and is sensitive to modeled mean state deep mixed volume in the Labrador Sea and GIN Seas deep convection regions

Introduction – Challenging Issues

AMOC Schematic Diagrams



Rahmstorf, 1999, Nature

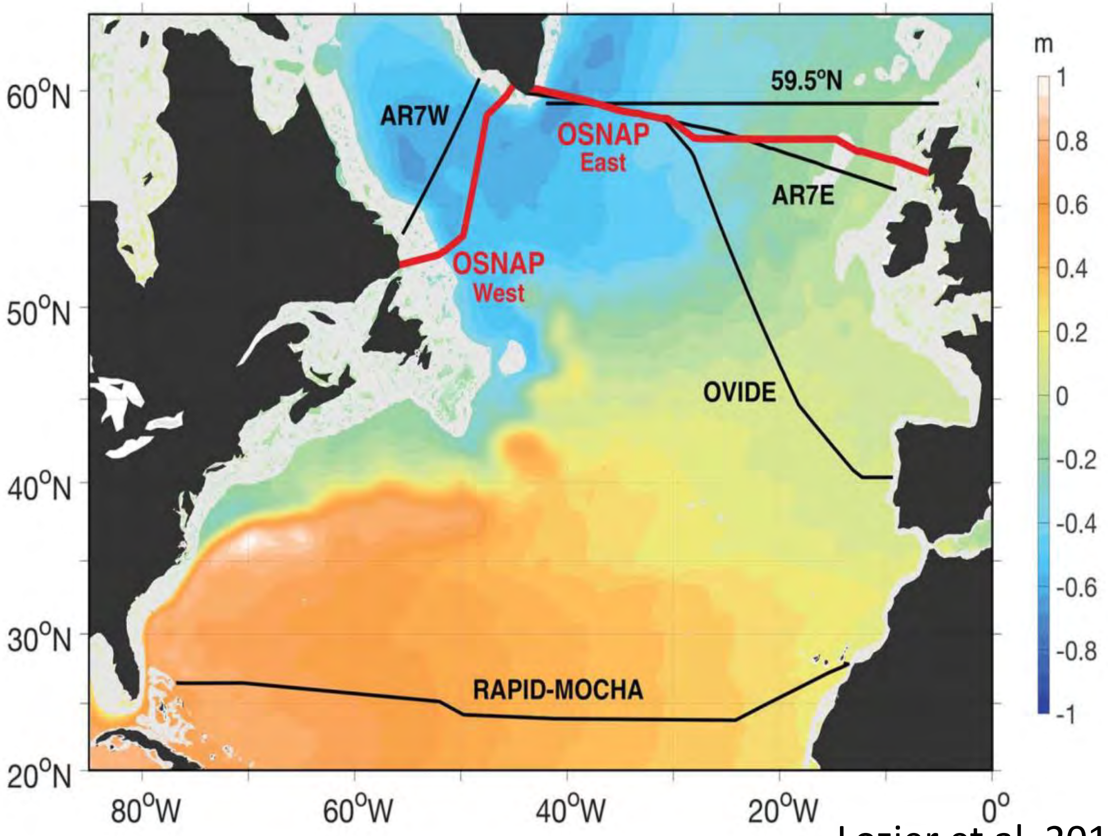


Kuklbrodt et al. 2007, Reviews of Geophysics

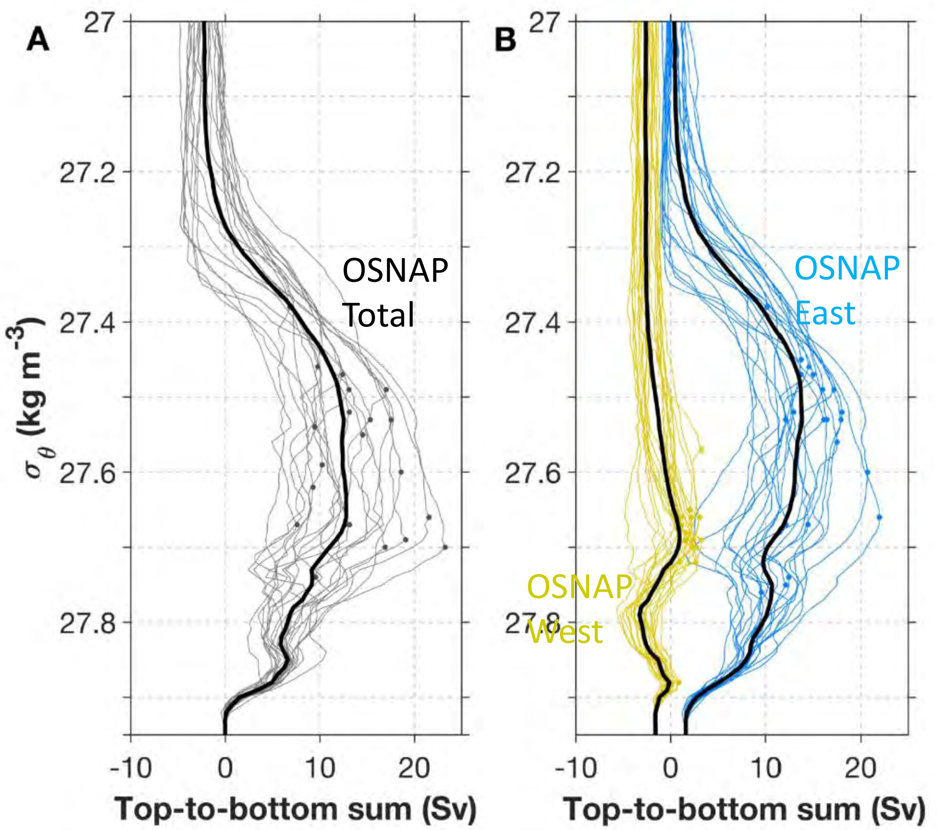
- It's often viewed that the Greenland Sea is the northern terminus of the AMOC and the Greenland Sea deep convection provides the densest source water to the AMOC (Lumpkin & Speer, 2003; Olsson et al. 2005; Brodeau & Koenigk, 2016; Heuzé, 2017; Brakstad et al. 2019), although this view has been questioned by earlier observational analyses (Rudels, 1995; Mauritzen, 1996; Eldevik et al. 2009)

- There is no established long-term mean state of directly observed AMOC over the past several decades to determine the source water of the mean AMOC and whether model simulated AMOC mean state and changes are reliable

Introduction – Discrepancy between Observed and Modeled AMOC across OSNAP West



Lozier et al. 2019, Science



AMOC in density space

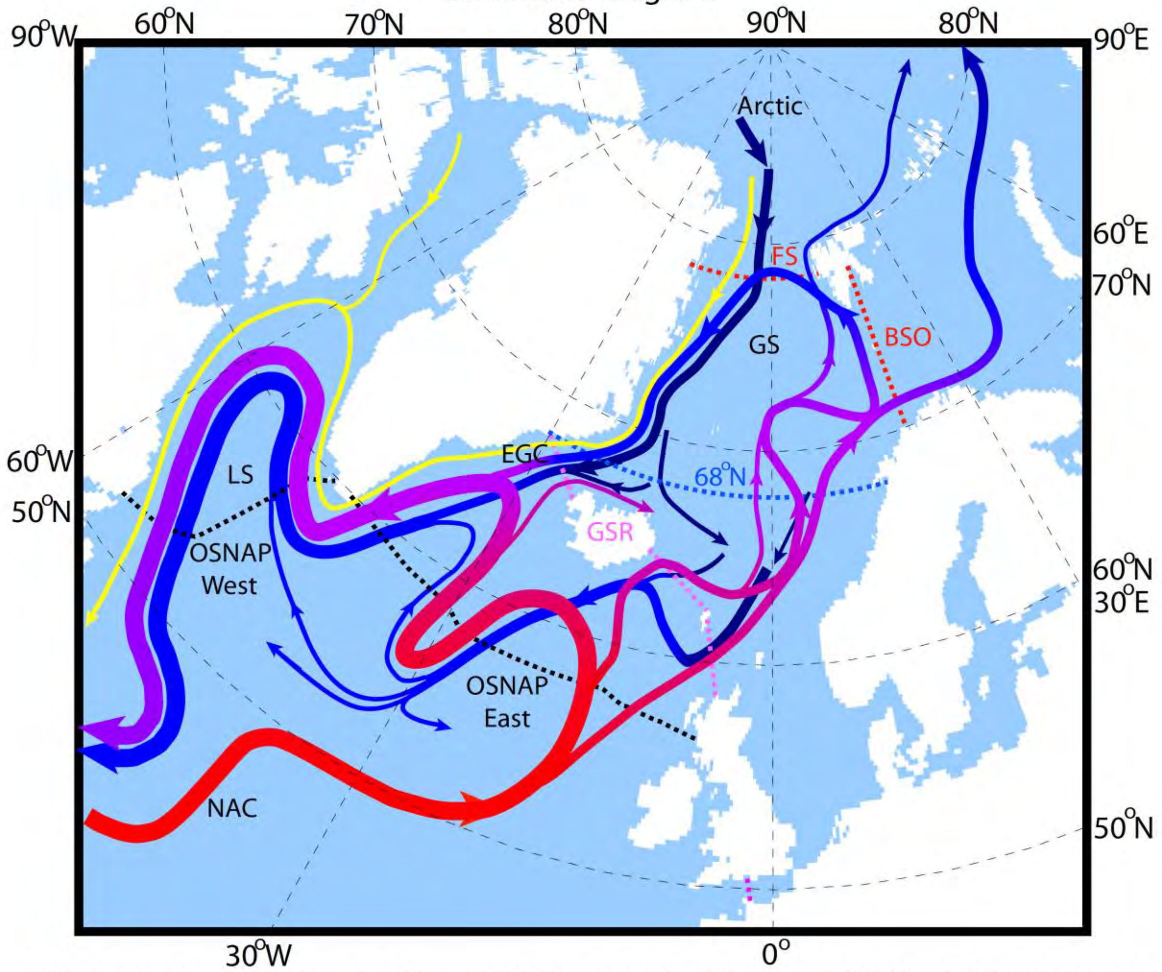
- Many climate models simulate a strong contribution of Labrador Sea deep convection to the AMOC, but this has also been challenged by observational analyses (Dengler et al. 2006; Pickart and Spall, 2007; Sarafanov et al. 2012; Holte and Straneo, 2017; Rossby et al. 2017; Chafik & Rossby, 2019; Lozier et al. 2019; Zou et al. 2020; Li et al. 2021)

- For example, recent observations from the OSNAP team during a period of strong Labrador Sea deep convection (Lozier et al. 2019) showed that the AMOC across the OSNAP section is dominated by the eastern component, and the western component across the Labrador Sea is very small. It's unclear whether the recent observation represents a long-term feature

Long-term Mean AMOC Estimated by Robust Diagnostic Calculations (RDC)

RDC are conducted using an eddy-permitting coupled model (GFDL CM2.5) constrained by observed hydrographic climatology to provide a holistic picture of the long-term mean AMOC across Arctic-Atlantic gateways and the subpolar North Atlantic over the past several decades

Schematic Diagram

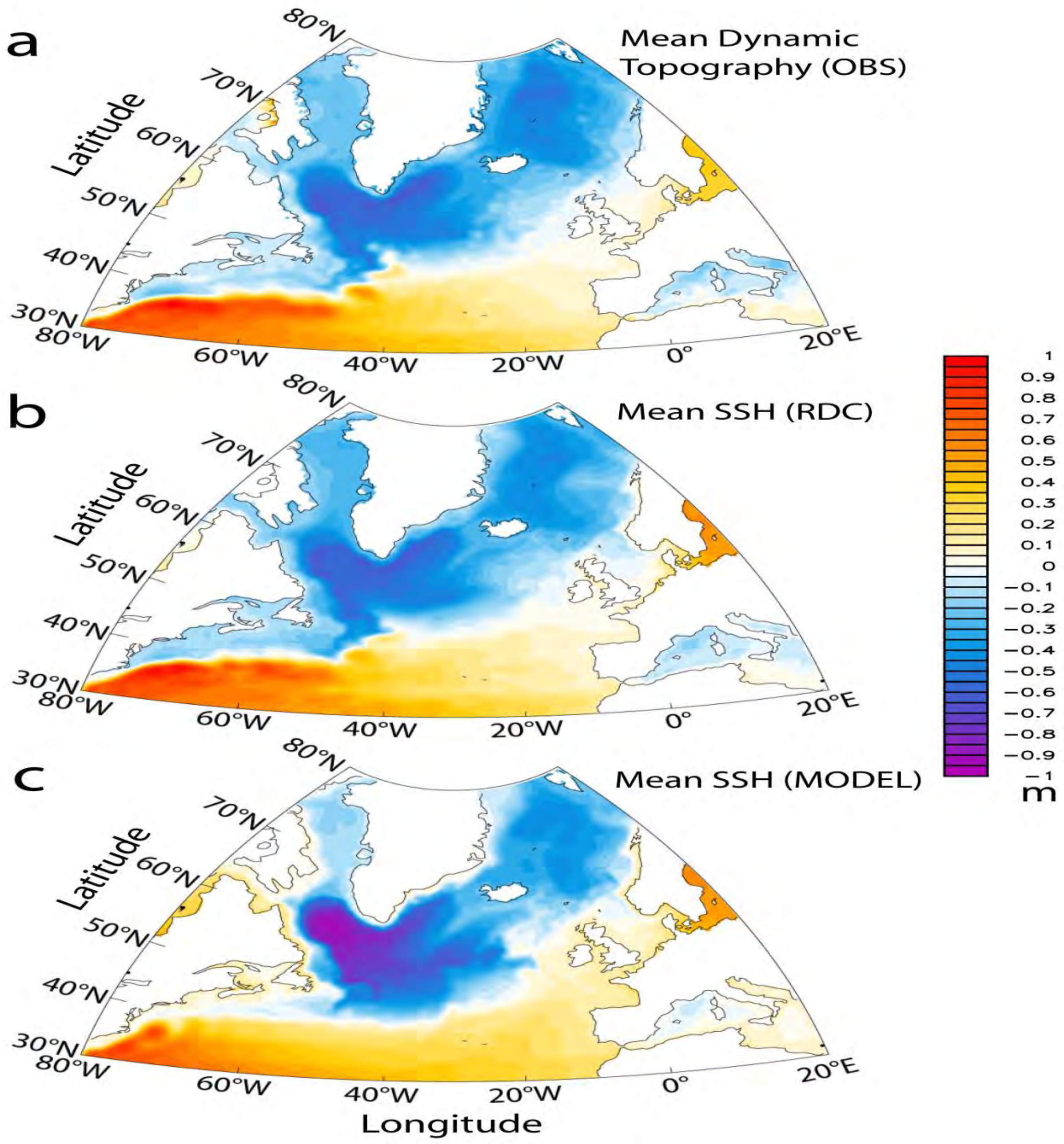


LS: Labrador Sea GS: Greenland Sea EGC: East Greenland Current NAC: North Atlantic Current
GSR: Greenland-Scotland Ridge FS: Fram Strait BSO: Barents Sea Opening

- The RDC method was originally proposed by Sarmiento and Bryan (1982), in which modeled temperature and salinity are restored back to observed hydrographic fields to produce dynamically consistent velocity fields
- The RDC approach can provide more insight on ocean dynamics (such as the mechanism of the Gulf Stream separation and its linkage with the AMOC (e.g. Zhang and Vallis, 2007)

Zhang and Thomas, 2021
https://www.nature.com/articles/s43247-021-00182-y

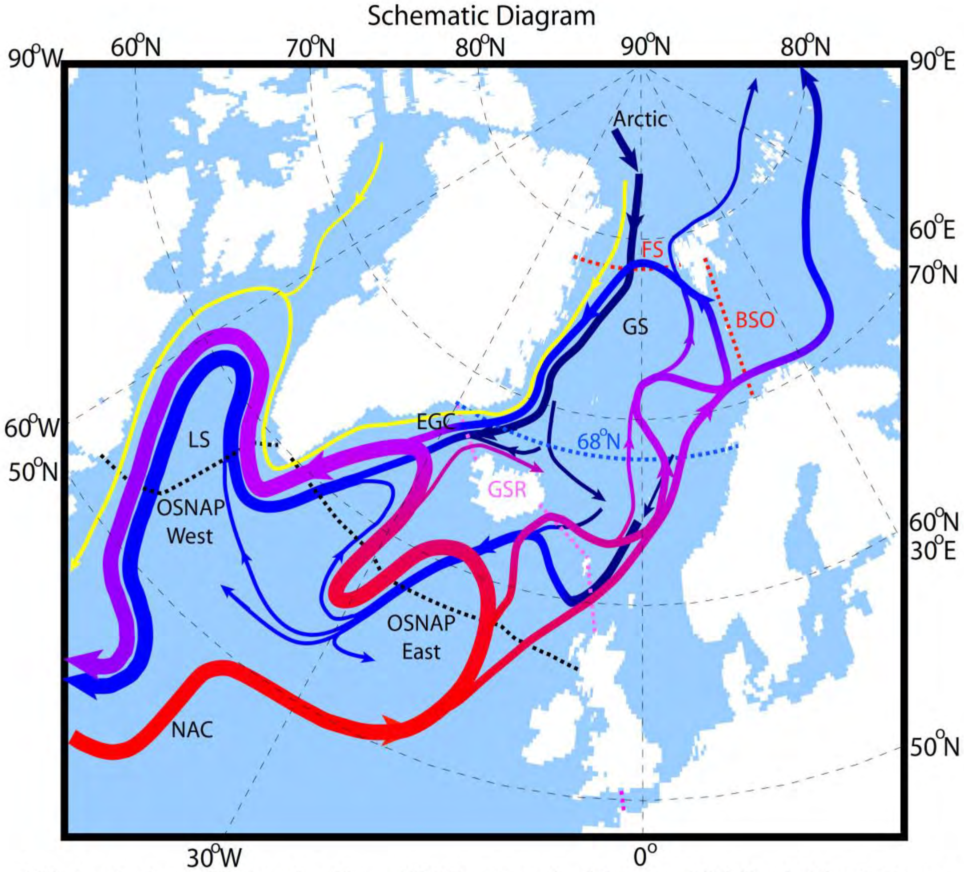
Long-term Mean Sea Surface Height



- The long-term mean SSH in RDC compares well with the independent satellite-observed mean dynamic topography, with a realistic Gulf Stream separation and a realistic North Atlantic Current (NAC) pathway moving into the northwest corner

- The control simulation exhibits typical deficiencies in the Gulf Stream separation and the NAC pathway (which shifts too far east and misses the northwest corner) as found in many models

Long-term Mean AMOC across the Arctic-Atlantic Gateways



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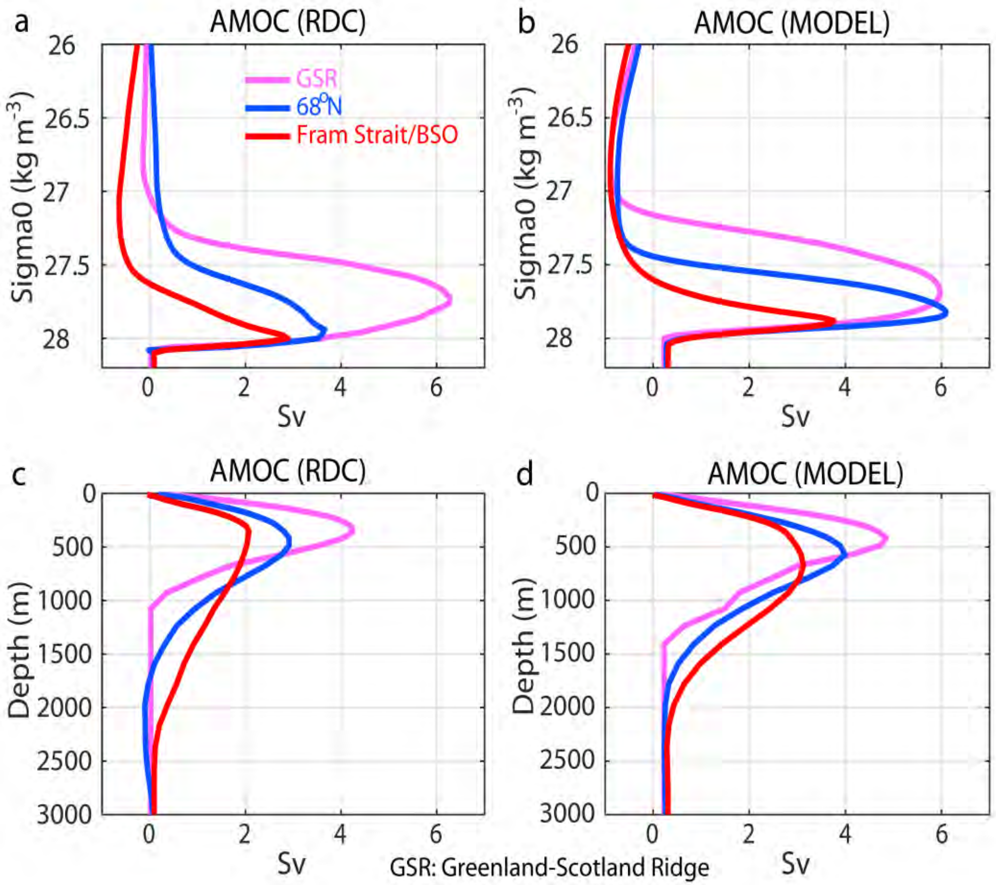
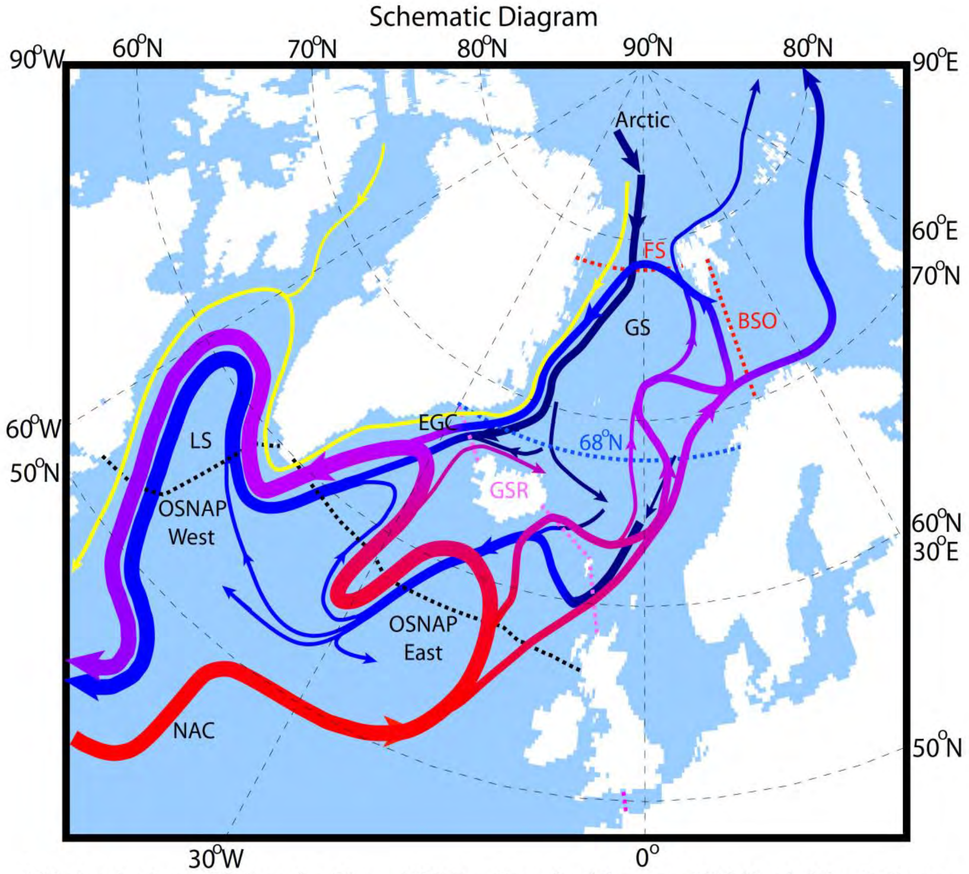


GSR: Greenland-Scotland Ridge

BSO: Barents Sea Opening

- The relatively denser part (σ_0>28.0 kg/m^3) of the mean GSR overflow is dominated by the deep branch of the mean AMOC across the FS/BSO (i.e. the Arctic outflow), indicating the densification along the Atlantic inflow entering the Arctic and transformed Arctic dense outflow, are important AMOC processes
- In the RDC, the region including the Greenland Sea (between 68^{o}N and the FS/BSO) contributes negligibly to the southward downstream mean AMOC transport, despite the presence of strong Greenland Sea deep convection
- The less denser part (27.8 kg/m^3<σ_0<28.0 kg/m^3) of the mean GSR overflow is supplied from the region south of 68^{o}N, where there is no deep convection

Long-term Mean AMOC across the Arctic-Atlantic Gateways



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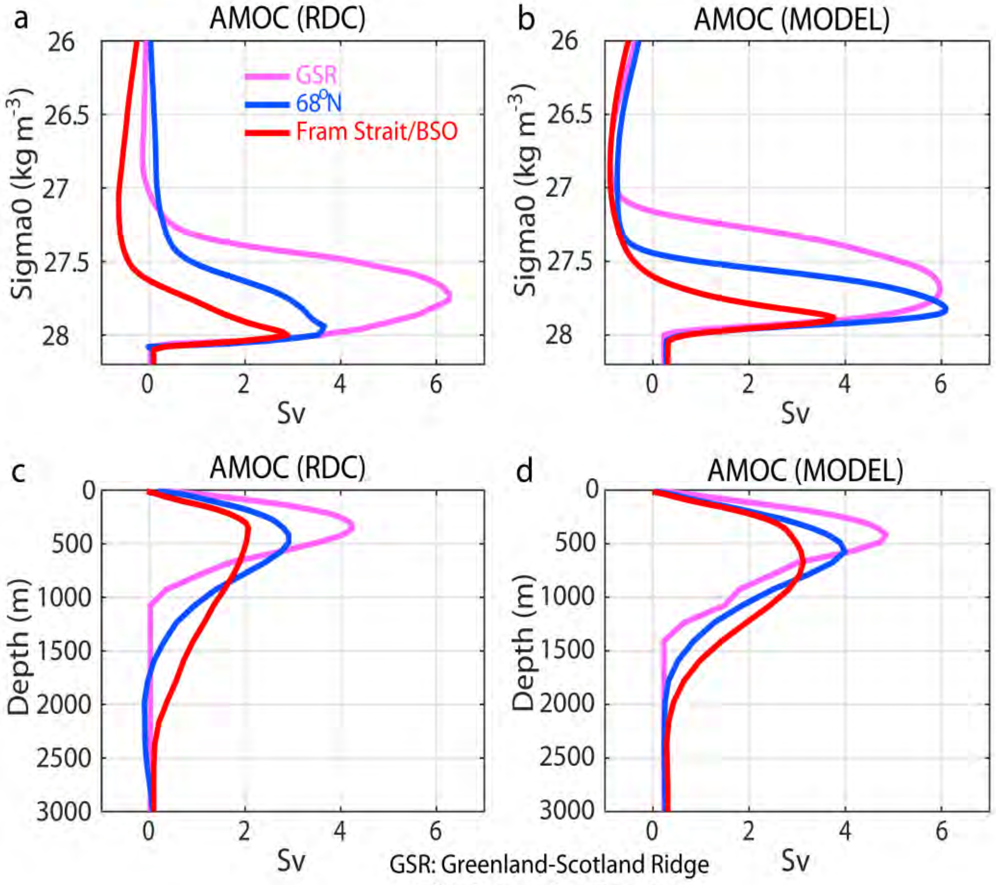

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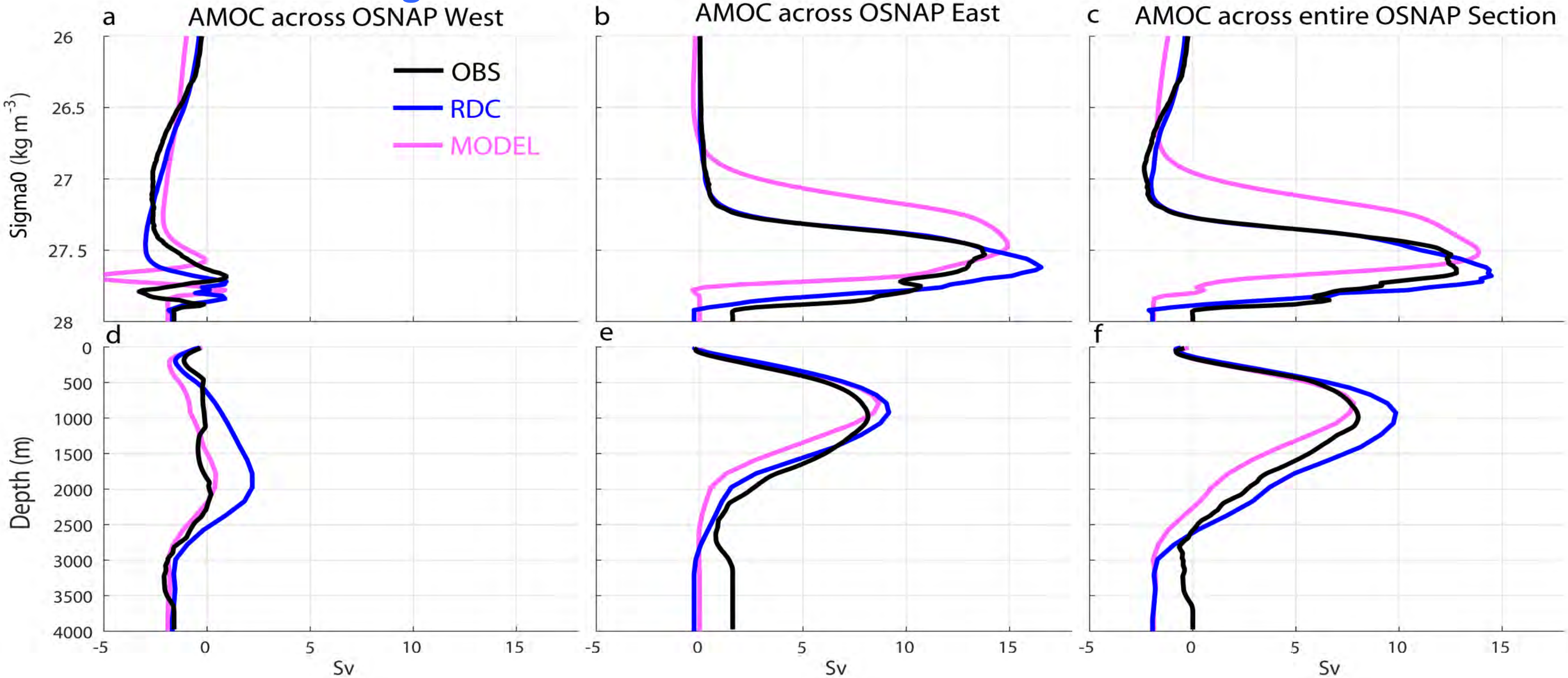
- In the control simulation, the deep AMOC branch across the FS/BSO also provides the densest source water to the AMOC, but the AMOC across Arctic-Atlantic gateways shifts to lower densities, which is related to the model's deficiency in simulating the Arctic densification processes

- In the control simulation, the region including the Greenland Sea has a biased larger contribution to the density-space AMOC across 68°N due to model biases, despite the lack of modeled Greenland Sea deep convection

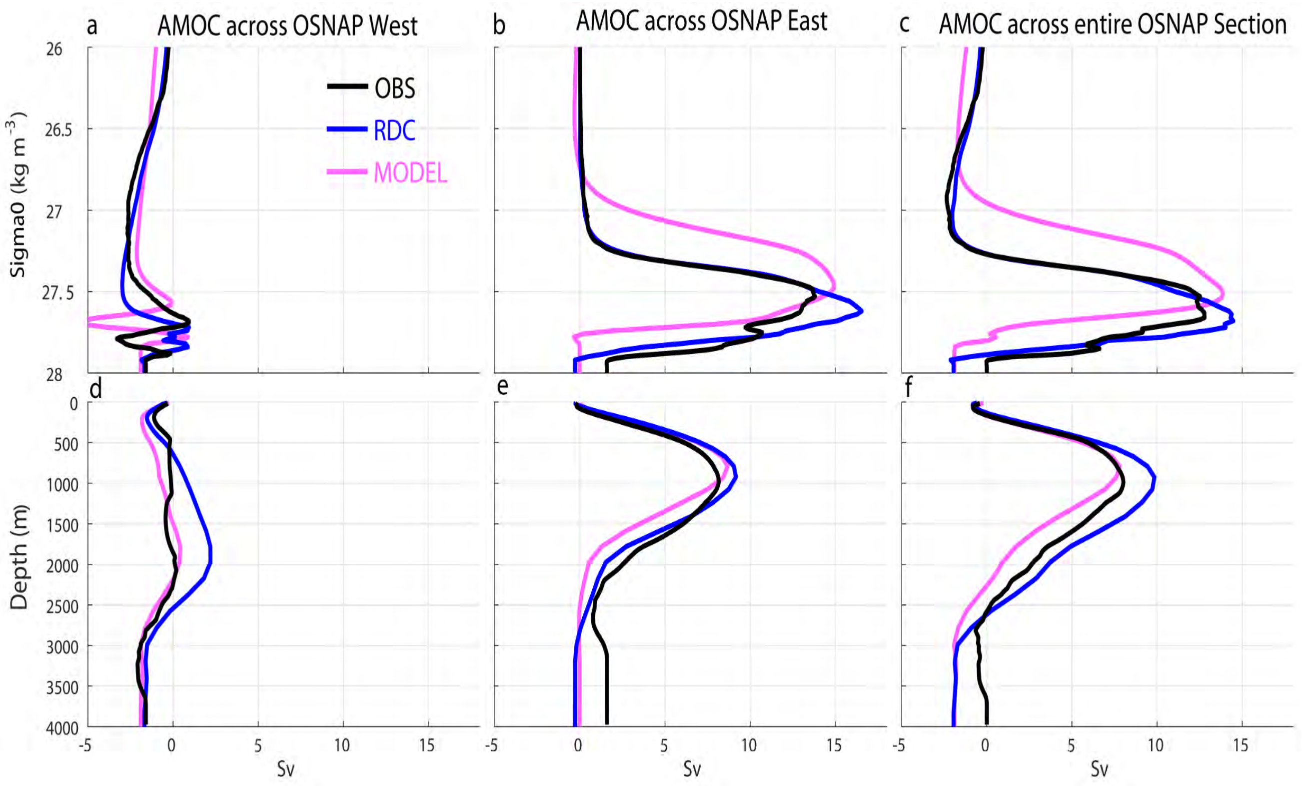
Long-term Mean AMOC across the OSNAP Section

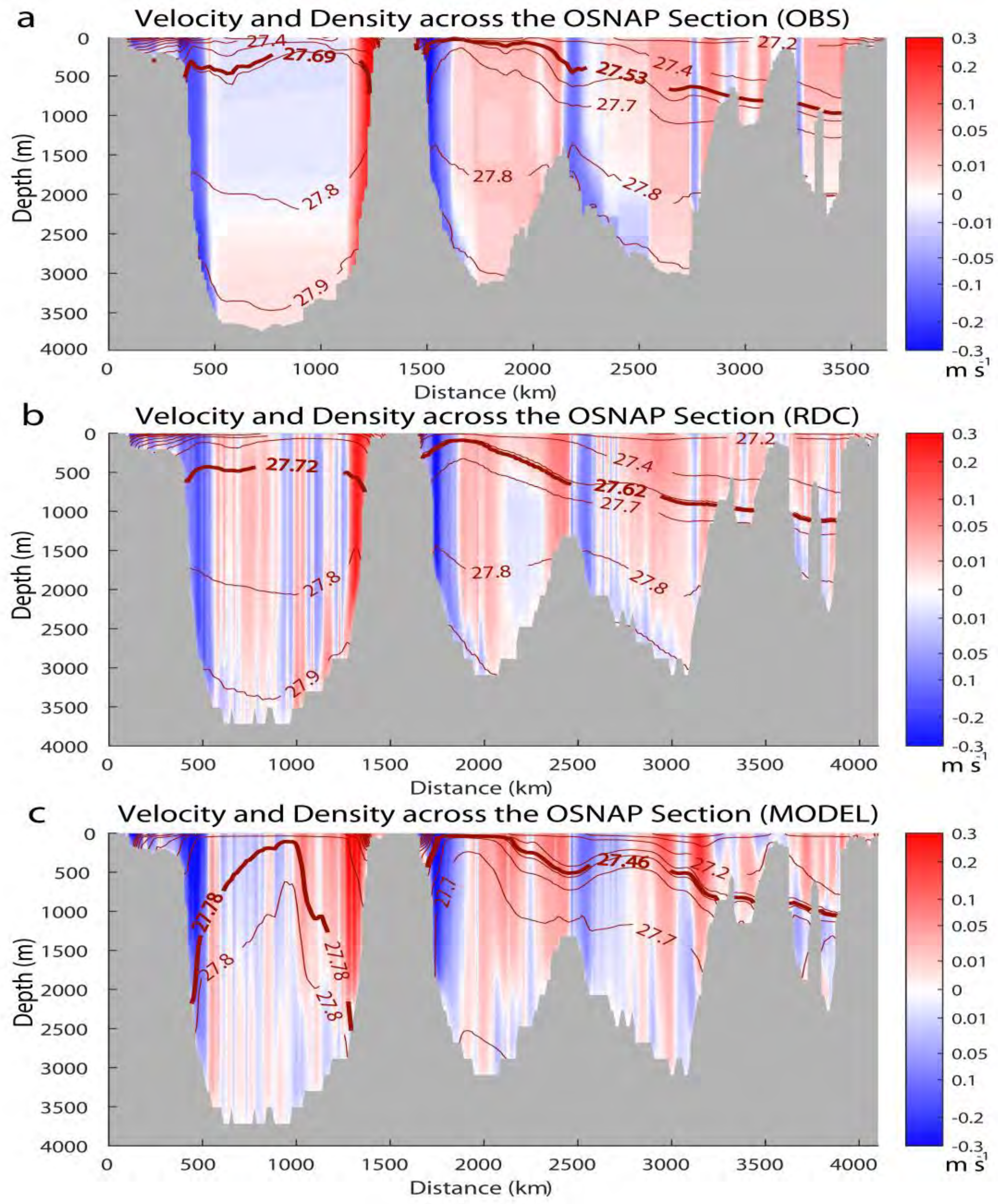


- The RDC-estimated mean AMOC across the OSNAP is also dominated by the East not the West component in both density/depth space, suggesting a minimal role of Labrador Sea deep convection in the long-term mean AMOC and the recent OSNAP observation is not just a short-term phenomenon

- The control simulation shows similar results, but the simulated AMOC across OSNAP East/OSNAP is shallower and shifts to lower densities due to model biases

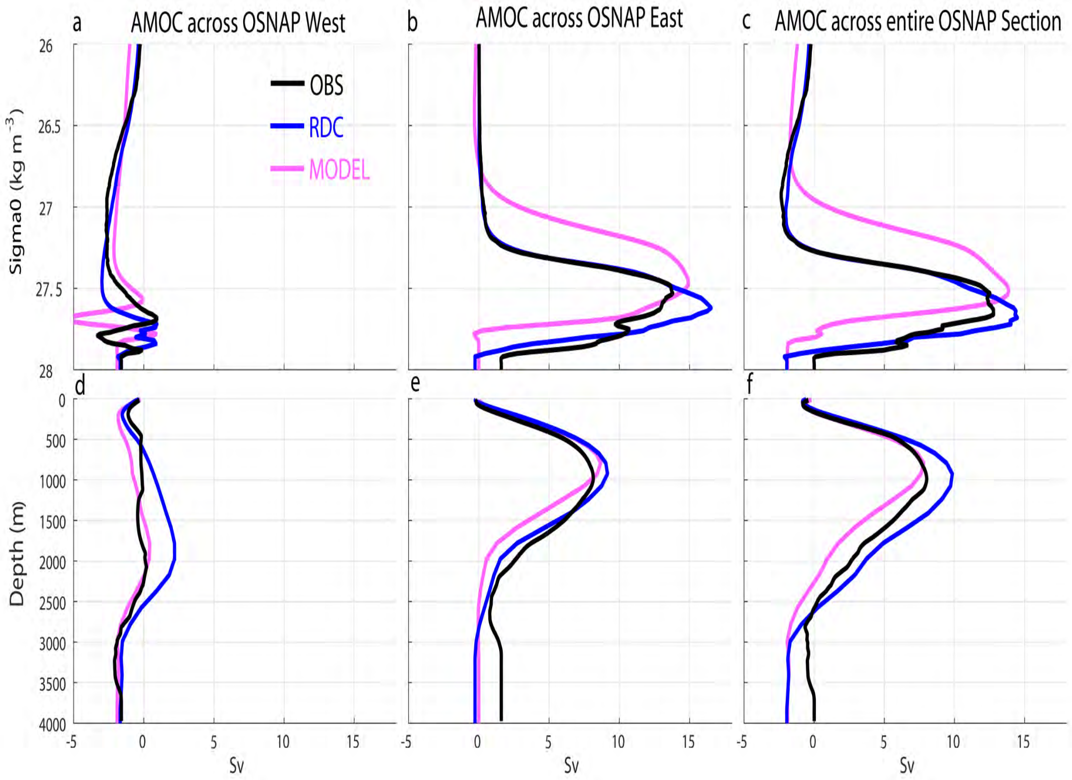
Long-term Mean AMOC across the OSNAP Section

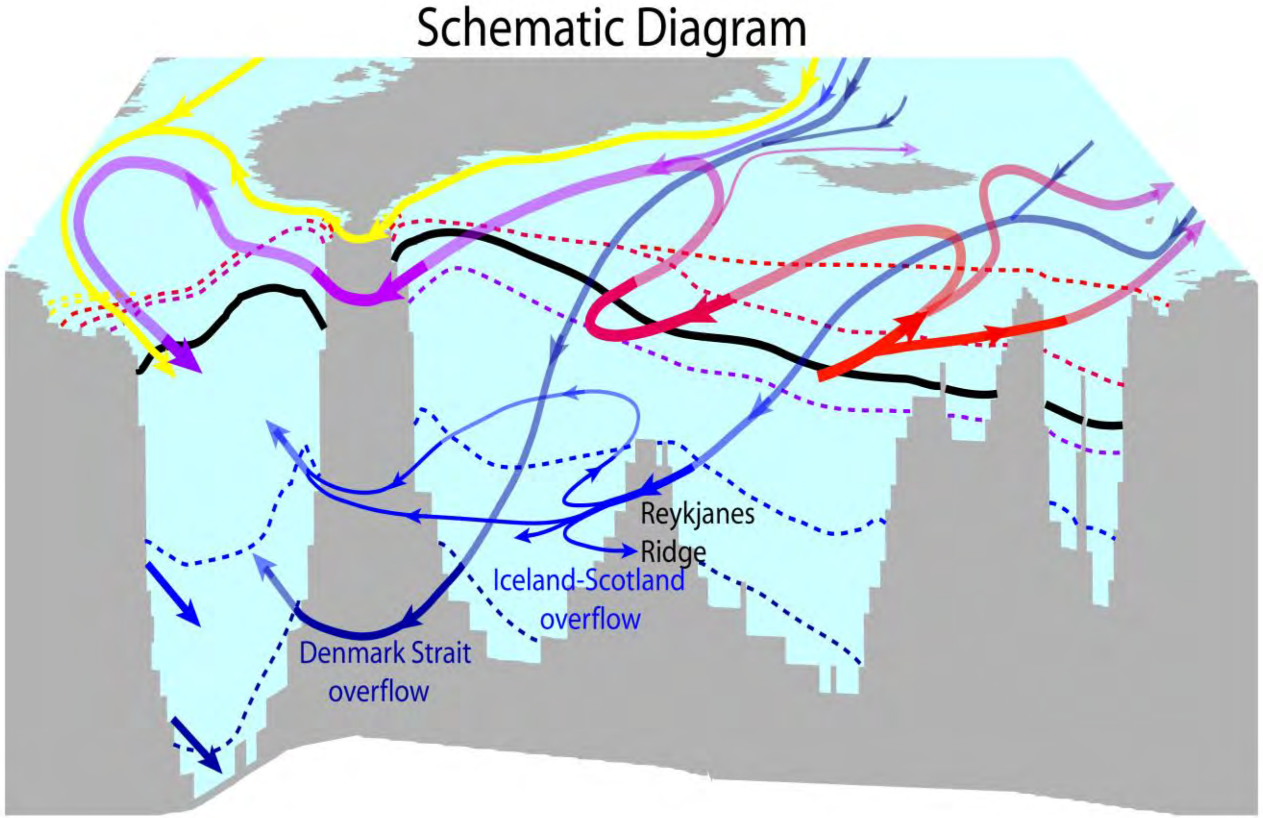




- Across OSNAP East, the density contrast is much larger than that across OSNAP West, sustaining a much larger depth space AMOC than that across OSNAP West through the thermal wind relationship

- The control simulation has unrealistically strong Labrador Sea deep convection, but simulates a similar small density contrast between boundary inflow and outflow, and thus a similar small AMOC across OSNAP West



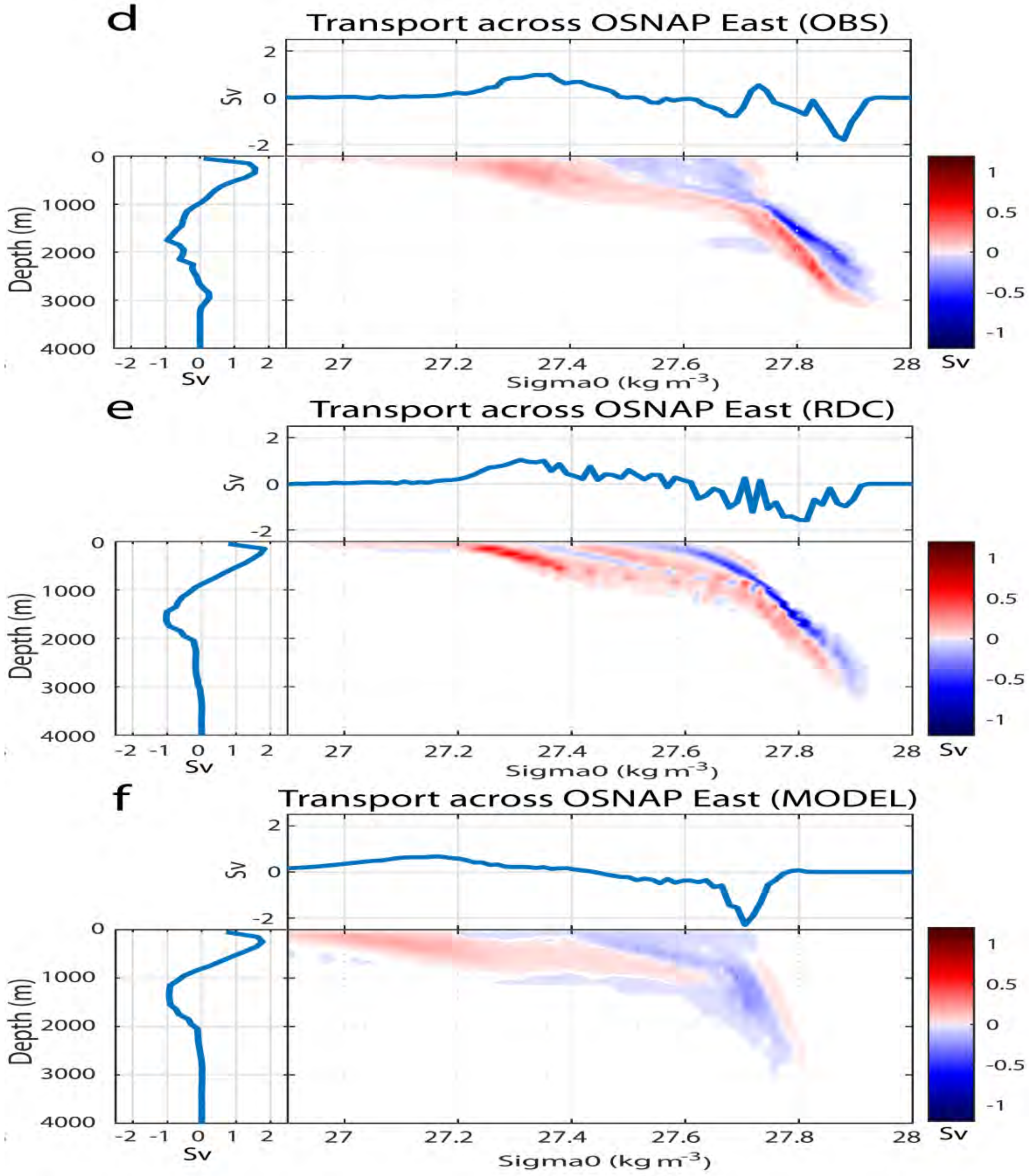


- Across OSNAP East, the lighter (denser) branch of the northeastern subpolar gyre moves northward in the interior/eastern side (southward near the western boundary) above (below) the sloping isopycnal at which the maximum AMOC occurs, resulting in a much larger maximum AMOC in density-space than that in depth-space

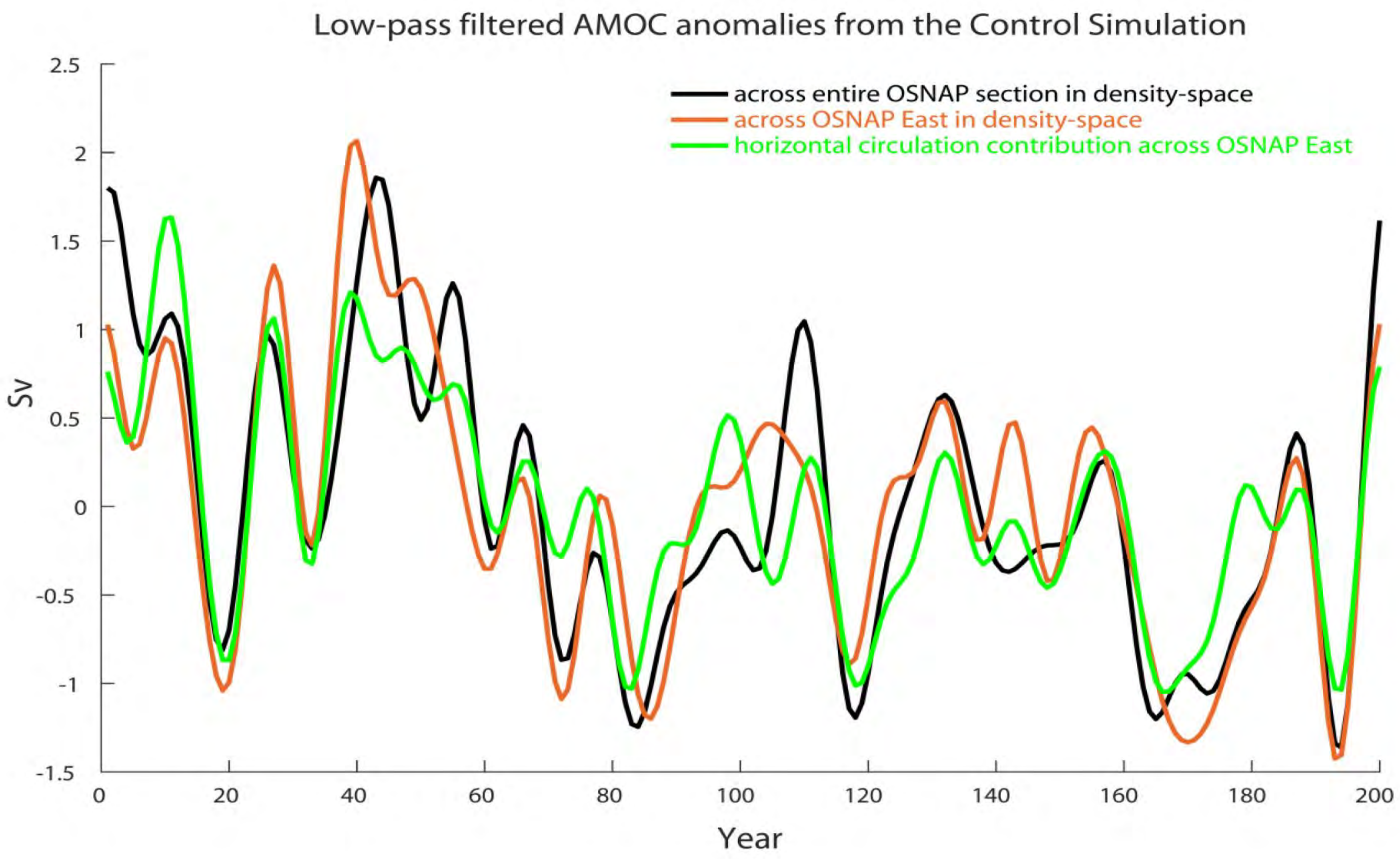
- Horizontal gyre across sloping isopycnals contributes substantially to the long-term mean density-space AMOC across OSNAP East, providing an additional important mechanism for why the AMOC is much larger in the east than that in the west in density-space

- The much larger density contrast across OSNAP East sustains a much larger maximum density-space AMOC through both thermal wind and horizontal gyre contributions

σ-z Diagram across OSNAP East

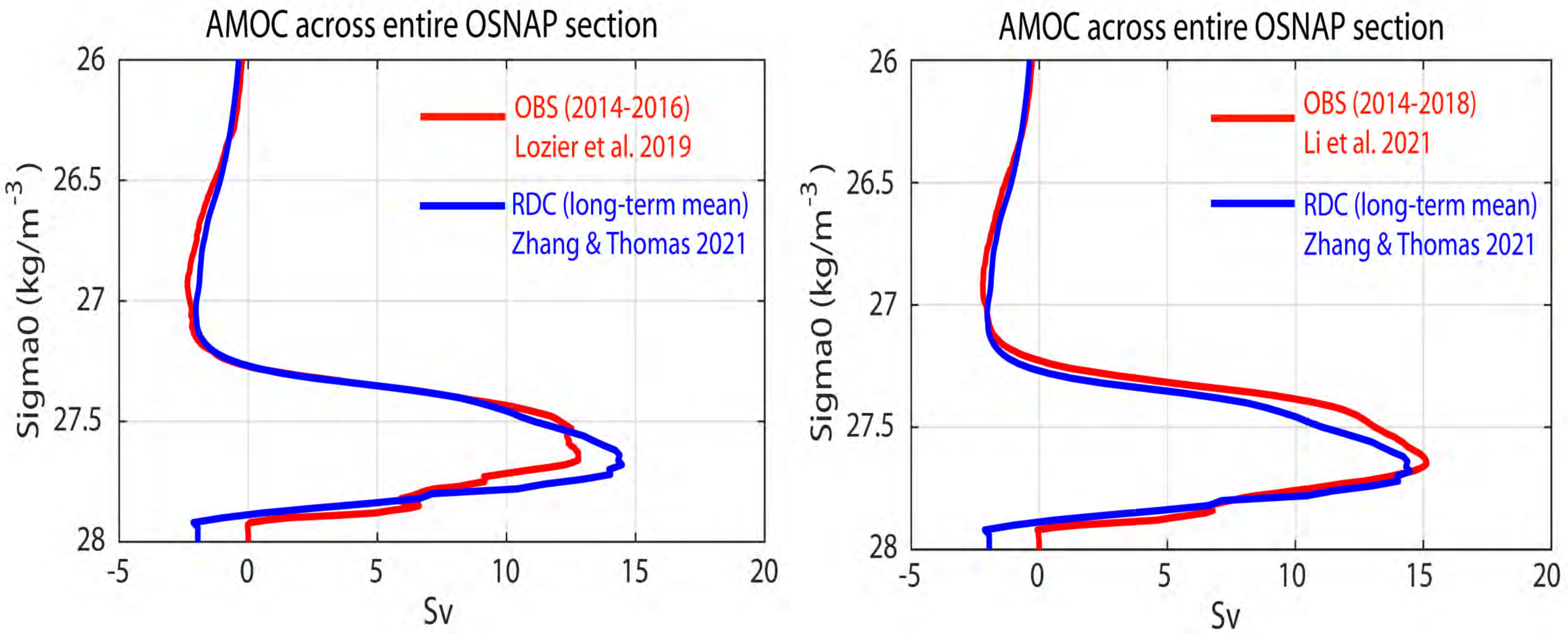


- A σ-z diagram is designed to illustrate the horizontal gyre contributions to density-space AMOC
- The color shading represents integrated volume transport over each density bin and depth bin across a section
- Across OSNAP East, the positive inflow and negative outflow of the horizontal gyre are partially canceled along depth levels but not along density levels due to their different densities
- The σ-z diagrams for observations and RDC are very similar. The modeled horizontal gyre contribution to the density-space AMOC shifts to lower densities



In the control simulation, the low-frequency anomalies of the maximum density-space AMOC across the OSNAP section are highly correlated with the component across OSNAP East and its horizontal gyre contribution

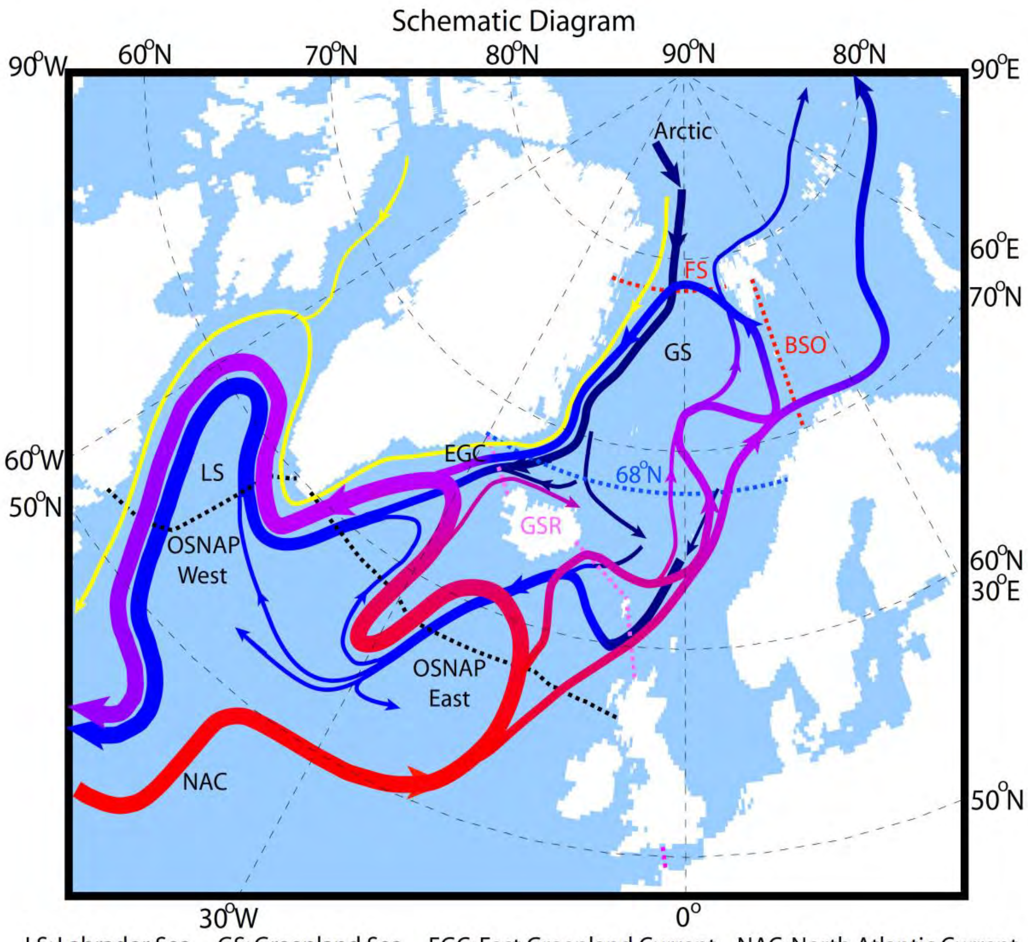
Observed Subpolar AMOC Strength over the Recent Period vs. RDC-Estimated Long-Term Mean



Across the OSNAP section, the recently observed AMOC strength over the period 2014-2018 is similar to the RDC-estimated long-term mean AMOC strength over the past several decades

The RDC results suggest that in contrast to the traditional view:

Summary and Discussion



- The deep AMOC branch across the Fram Strait and Barents Sea Opening (i.e. the Arctic outflow) provides the densest source water to the mean AMOC
- The Arctic Ocean, not the Greenland Sea, is the northern terminus of the mean AMOC
- Open-ocean deep convection in either the Greenland or the Labrador Seas contributes minimally to the mean AMOC strength
- Horizontal gyre across sloping isopycnals contributes substantially to the mean northeastern subpolar AMOC
- Climate models need to simulate realistic boundary currents and boundary density contrast to avoid overprojections of the role of open-ocean deep convection in future AMOC changes
- Climate models need to have a better representation of the Arctic shelf dense water formation, which affects the Arctic halocline and the density of the Arctic outflow