# Coupling between the Arctic and the Atlantic Meridional Overturning Circulation: A Review

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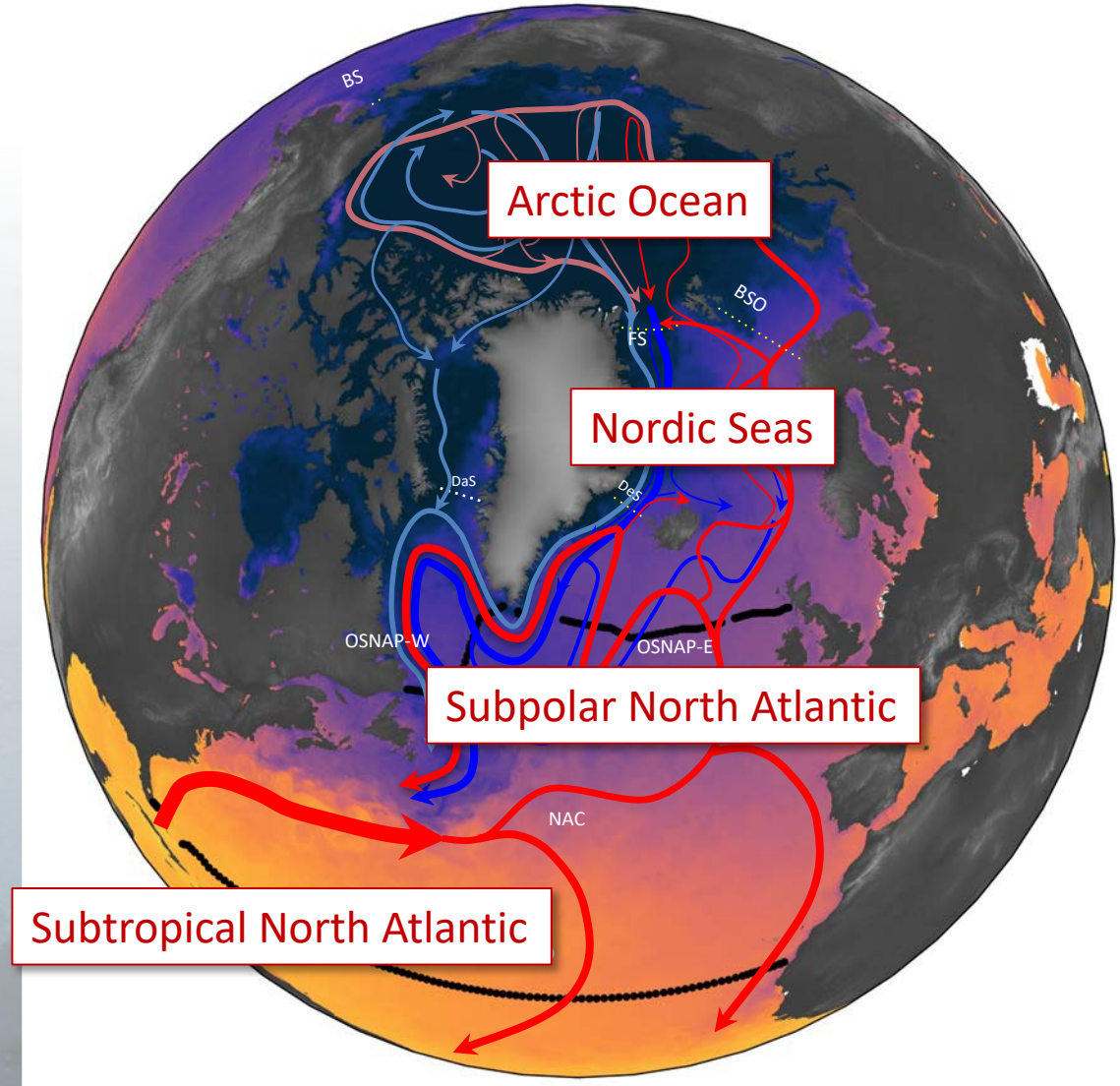
# Background

- Special issue of *Oceanography* on ***The New Arctic Ocean***
  - Several papers have already been published
  - https://tos.org/oceanography/issue/volume-35-issue-2
- This paper
  - Review recent advances in our understanding of interactions between the Arctic and the AMOC
- General audience
  - So not comprehensive

# LINKING THE AMOC AND THE ARCTIC

# Linking the AMOC and the Arctic

## What are the main exchange pathways between the Arctic and North Atlantic?




Definition: Arctic =

- Nordic Seas + Arctic Ocean
- Arctic Mediterranean

# Linking the AMOC and the Arctic

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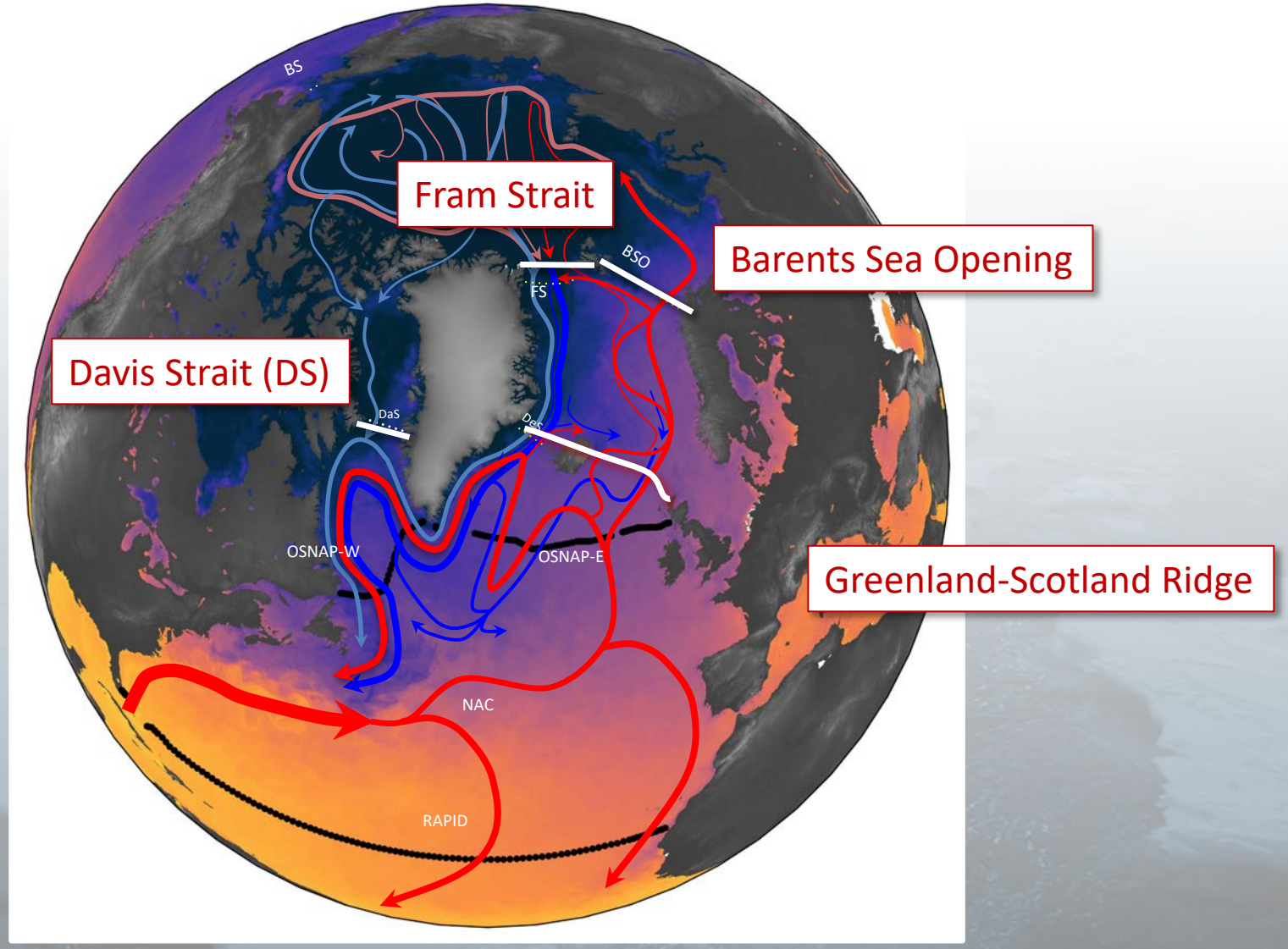

# Linking the AMOC and the Arctic

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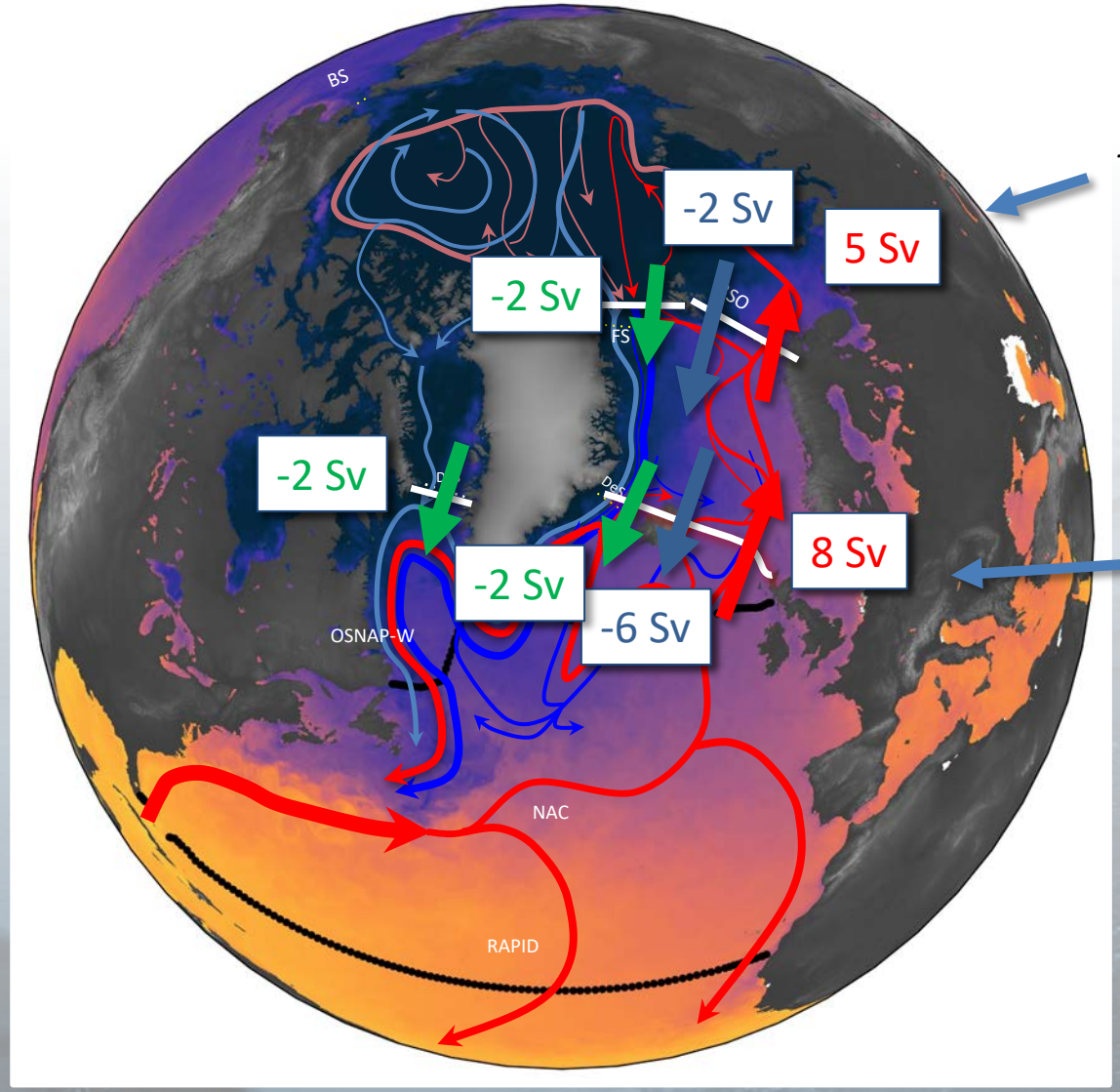
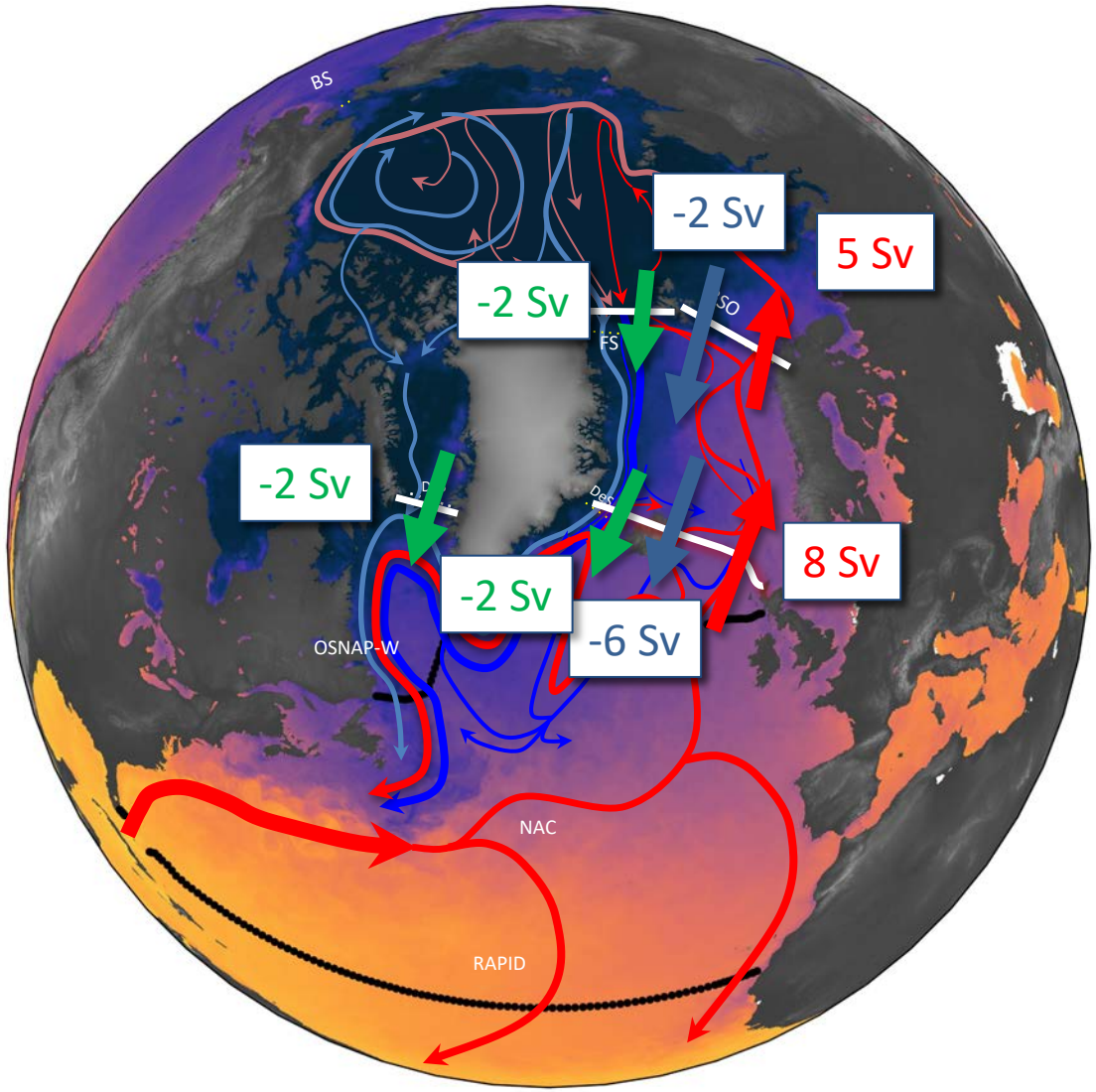



*Tsubouchi et al. (2018)*

*Østerhus et al. (2019)*

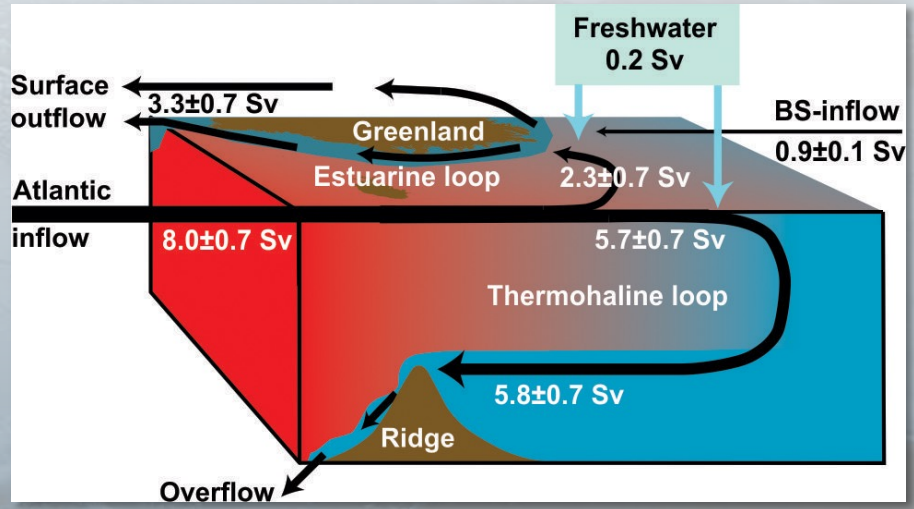
# Linking the AMOC and the Arctic

## What does this tell us about overturning cells?




- Double-estuarine model of the Arctic
  - Thermohaline cell: Atlantic Water to Overflow Water
  - Estuarine cell: Atlantic Water to Polar Water
- Thermohaline cell: 6 Sv
  - 2 Sv in Arctic Ocean
  - 4 Sv in Nordic Seas
- Estuarine cell: 3 Sv
  - In Arctic Ocean

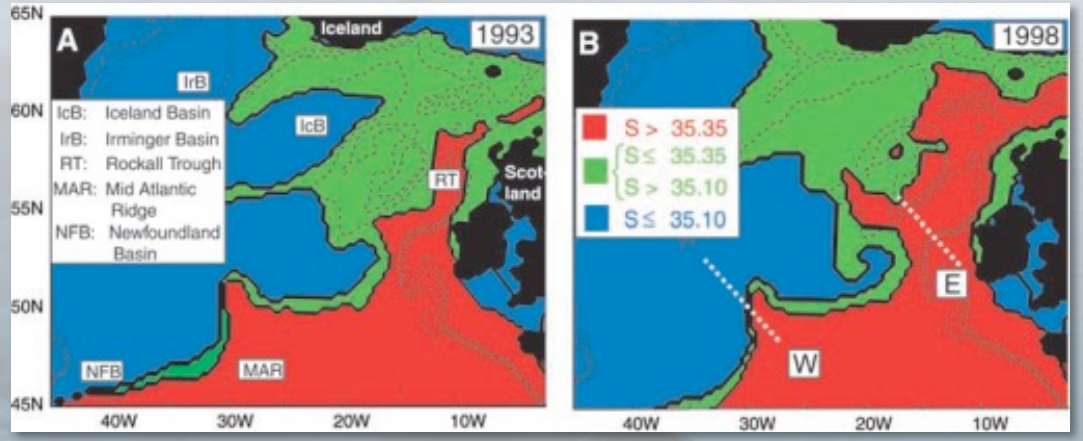
*Østerhus et al. (2019)*



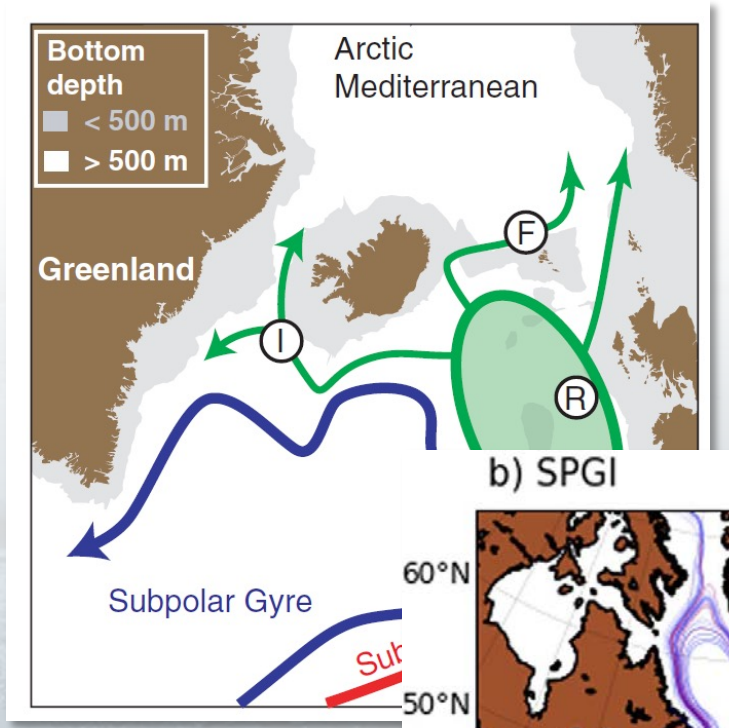
# Linking the AMOC and the Arctic

## How much inflow into Nordic Seas is of subtropical origins?

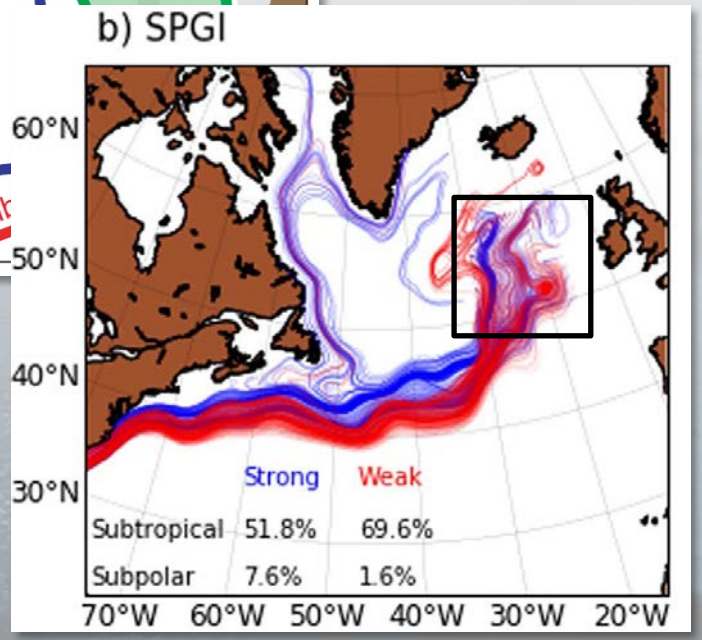
- Subpolar gyre modulates salinity of Eastern North Atlantic (ENA)
  - Strong gyre: fresh ENA
  - Weak gyre: salty ENA
- Between 50% and 70% is of subtropical origin




*Strong gyre* *Weak gyre*




*Hátún et al. (2005)*

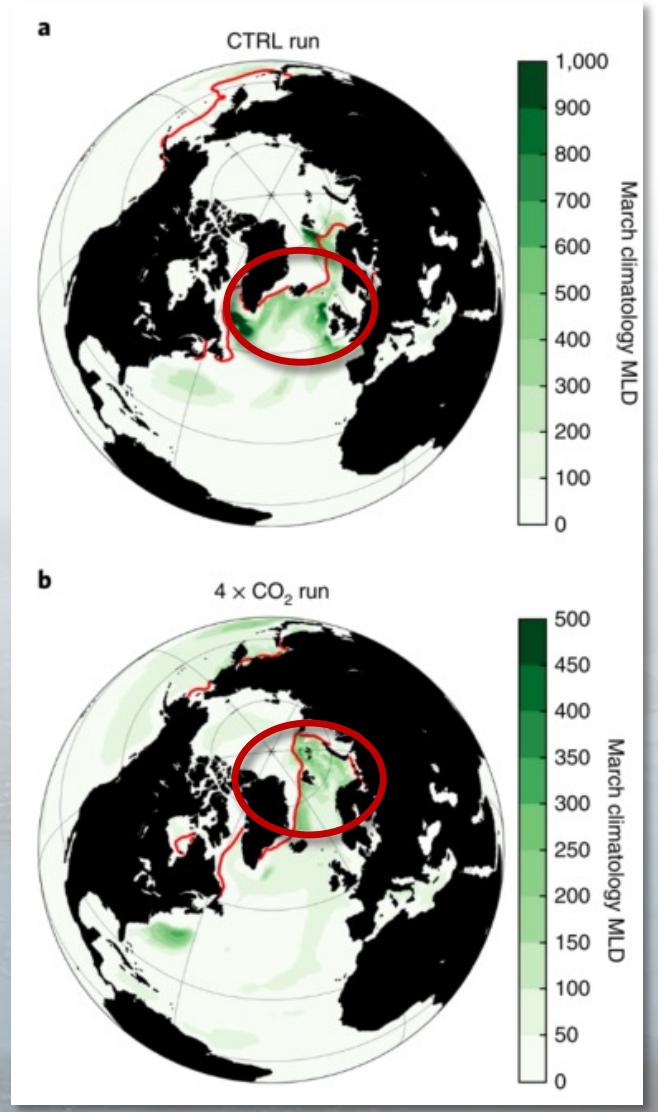



*Koul et al. (2020)*

# Linking the AMOC and the Arctic

## How will connection change in warming climate?

- AMOC projected to reach further into the Arctic
  - Northward shift of deep convection
    - E.g., Bitz et al. (2006), Lique & Thomas (2018)
- This implies a *stronger link* between the Arctic and the AMOC in the future
  - Despite weakening of the AMOC




*Lique & Thomas (2018)*

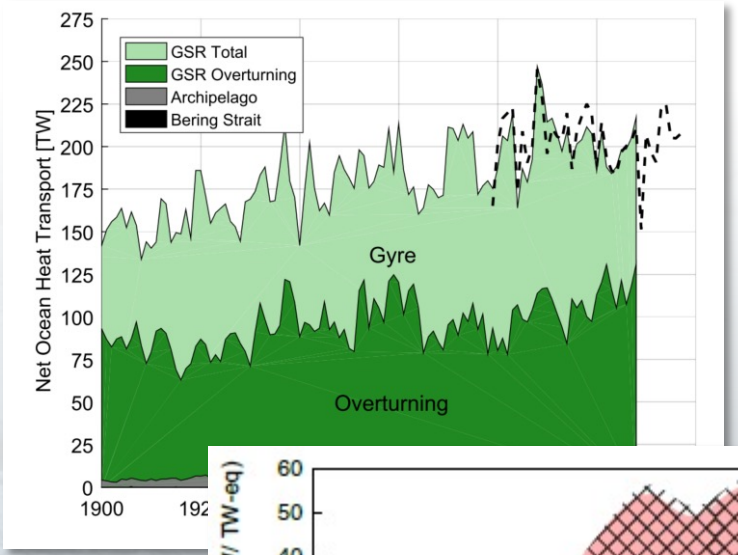
# AMOC IMPACTS ON ARCTIC

# Impact of AMOC on Arctic

**How important is the overturning circulation for the Arctic heat budget?**

- Overturning critical element of Arctic heat budget
  - More than 50% of heat import across GSR is due to overturning
- Heat transport is increasing
  - Despite weakening AMOC at 26N since early 2000s
  - Discontinuity between AMOC and OHT into the Arctic

OHT across Greenland-Scotland Ridge

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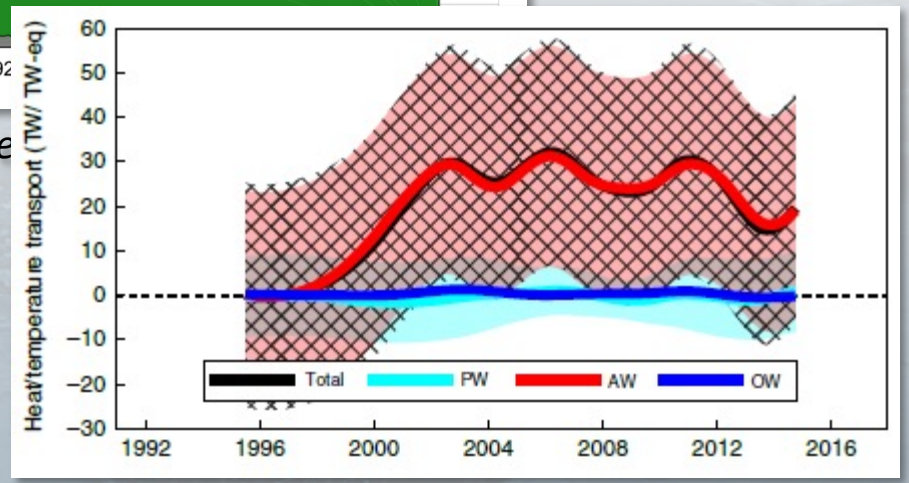
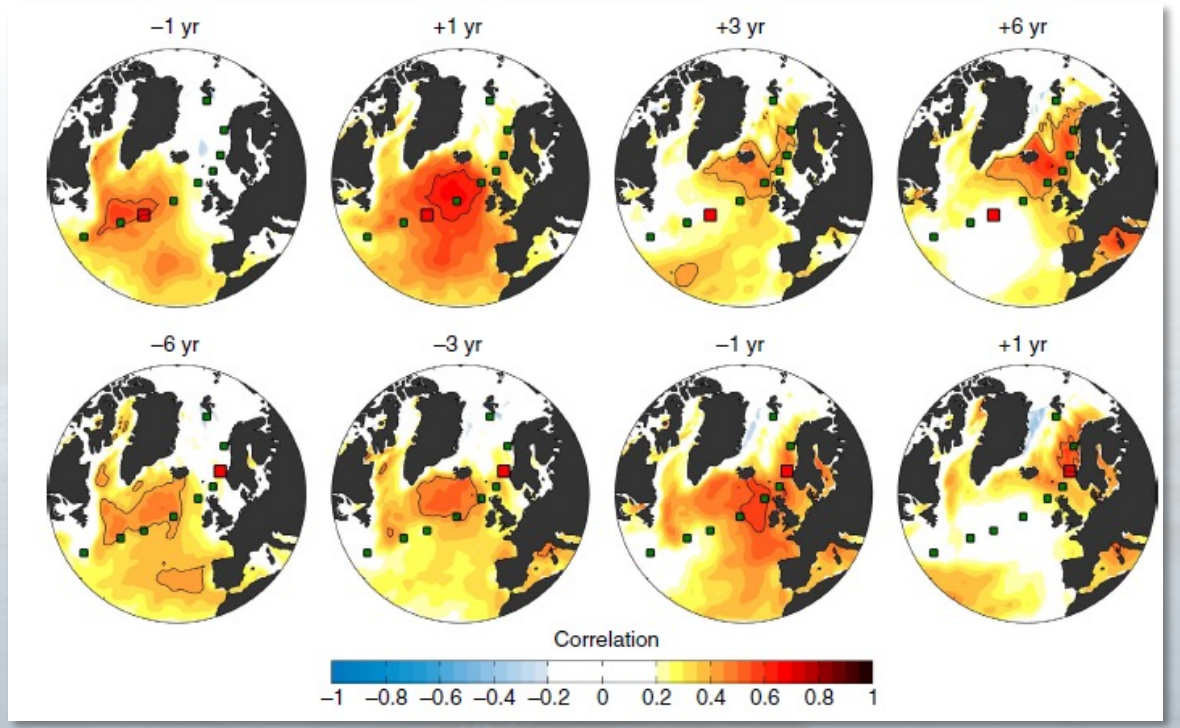



*Tsubouchi et al. (2021)*

# Impact of AMOC on Arctic

**To what extent does AMOC variability affect heat transport into the Arctic?**

- Heat content anomalies can be followed from subpolar North Atlantic into Nordic Seas
  - Predictability of Arctic sea ice
    - E.g., Yeager et al. (2015), Årthun et al. (2017)



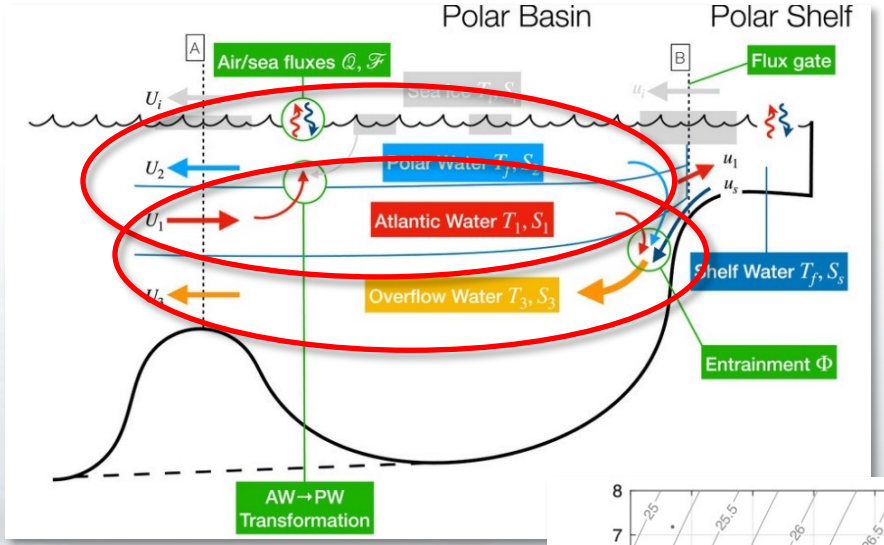

*Årthun et al. (2017)*

# ARCTIC IMPACTS ON THE AMOC

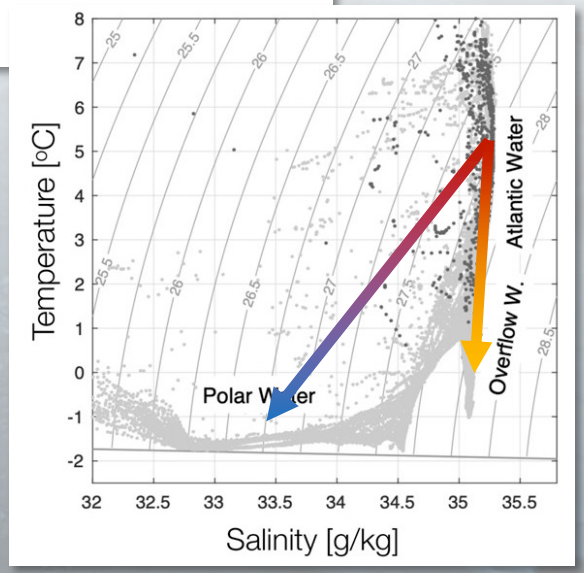
# Arctic Impacts on the AMOC

## Water Mass Transformations

- Double-estuarine model
  - Atlantic Water gets cooled and freshened: Polar Water
  - Atlantic Water gets mixed with Shelf Water: Overflow Water
- Thermal cell is robust
- Estuarine cell is vulnerable to *heat crisis*
  - Warming Atlantic Water
  - Increase meteoric freshwater flux
- 'Atlantification' may be a *precursor*



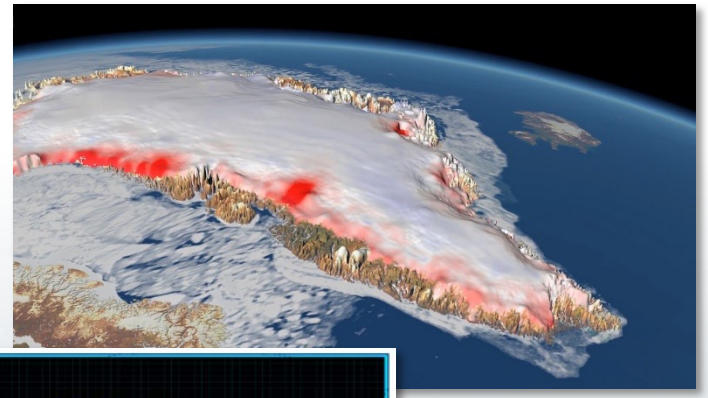

*Haine (2021)*



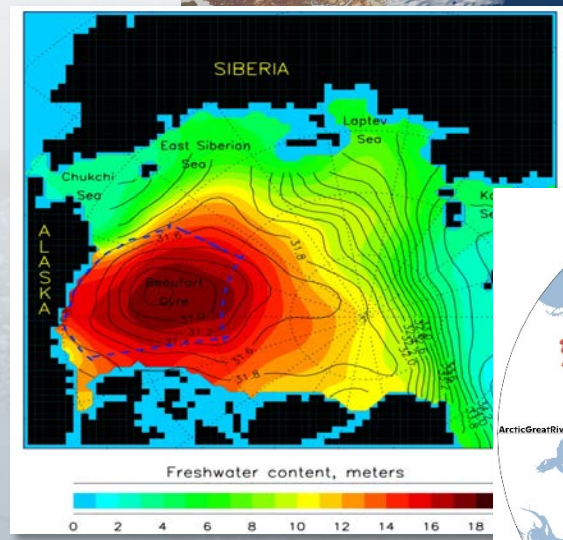
# Arctic Impacts on the AMOC

## Freshwater inputs

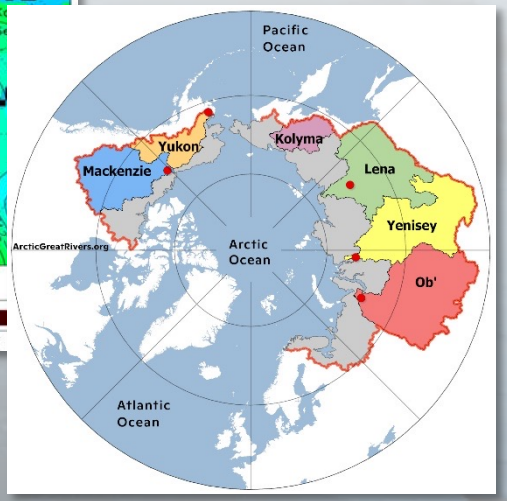
- AMOC is thought to be sensitive to freshwater input
  - Freshwater capping inhibits deep convection
    - E.g., Gelderloos et al. (2012)
- Many sources and reservoirs in the Arctic freshwater system:
  - Greenland Ice Sheet
  - Arctic rivers
  - Pacific inflow
  - Precipitation
  - Beaufort Gyre
  - Sea ice
- Many changes due to anthropogenic forcing
  - Jahn & Laiho (2020); Haine (2020)



*ESA*




*Proshutinsky et al. (2012)*

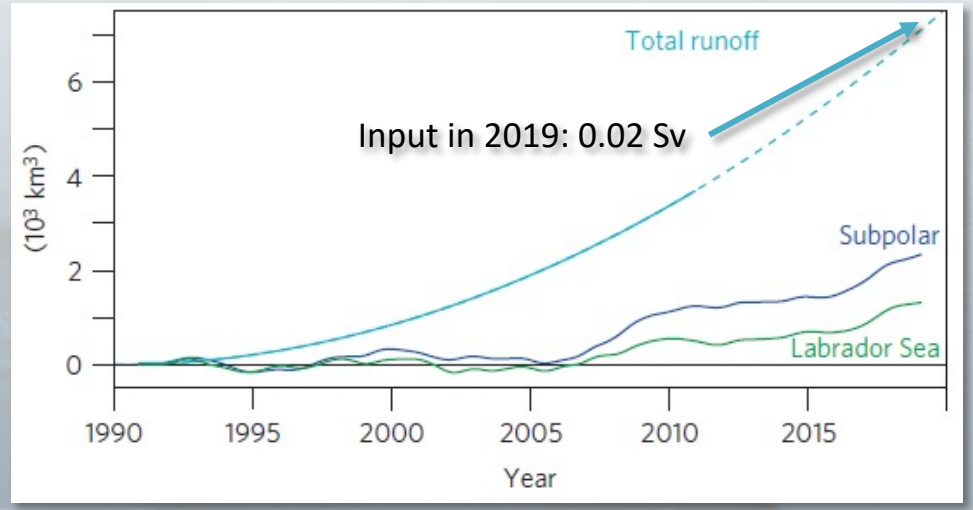



*Arctic GRO*

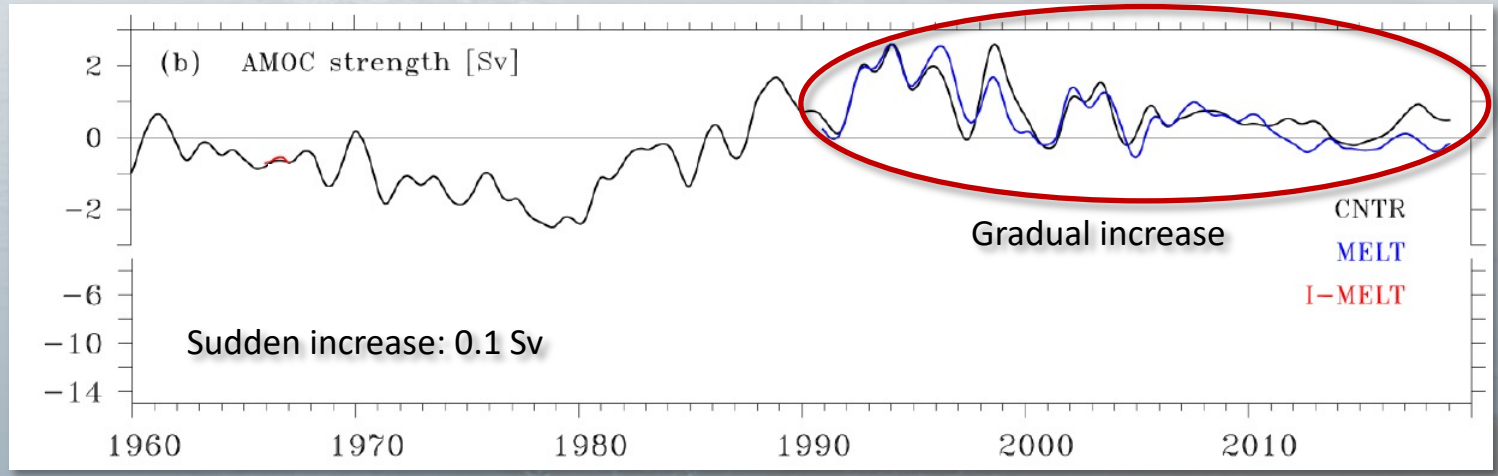
# Impact of Arctic on AMOC

## Impact of Greenland Ice Sheet melt?

- Böning et al. (2016): Greenland freshwater input in eddy-resolving ocean model
  - 'Realistic' gradual increase of 0.5 mSv/yr
  - *"freshwater anomaly has not yet had a significant impact on the Atlantic meridional overturning circulation"*



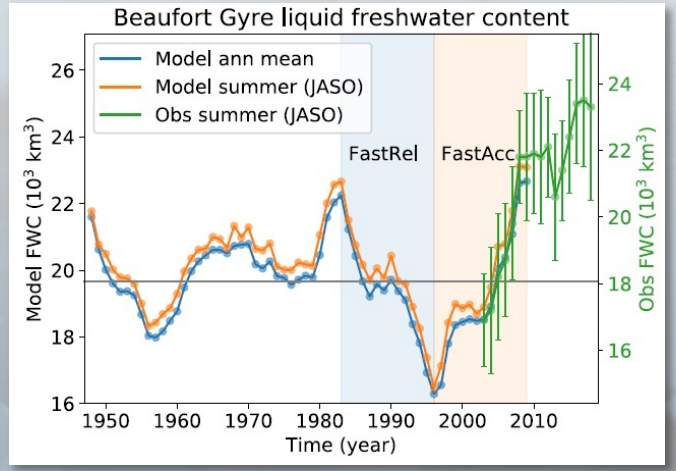

*Böning et al. (2016)*

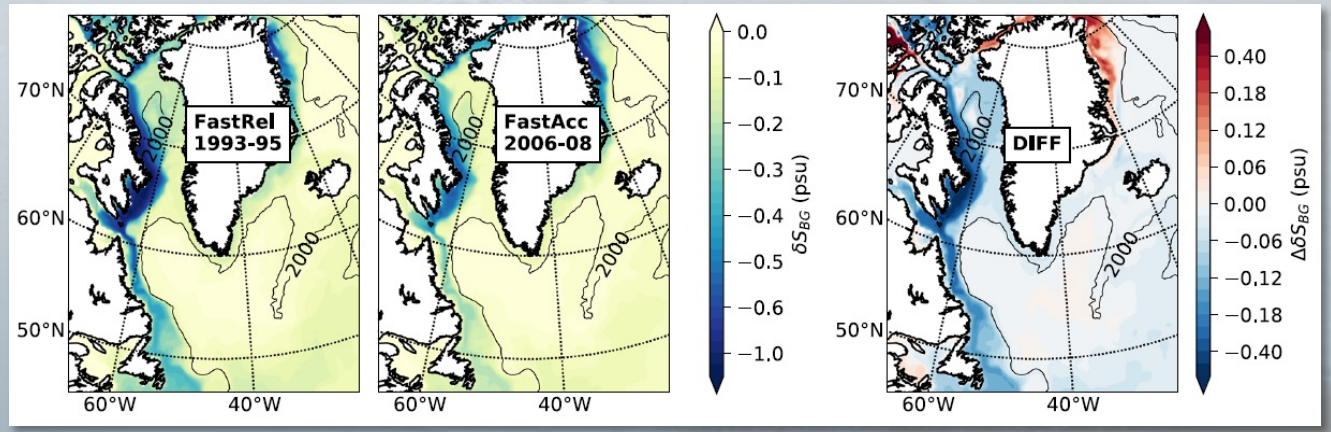


# Impact of Arctic on AMOC

## Impact of Beaufort Gyre variability?

- Zhang et al. (2021): Beaufort Gyre freshwater release in eddy-permitting ocean model
  - ‘Color’ BG waters during historical periods of:
    - Rapid freshwater release (1983–1995)
    - Rapid freshwater accumulation (1996–2008)
  - The Labrador Sea is freshened by 0.2-0.4 psu



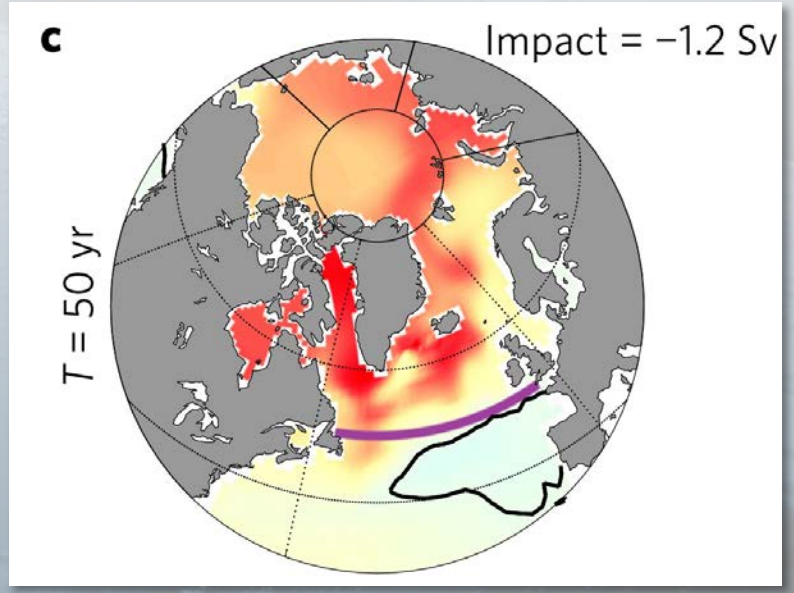




*Zhang et al. (2021)*

# Impact of Arctic on AMOC

## Impact of sea ice loss?

- Sévellec et al. (2017): Adjoint sensitivity study determines optimal heat and freshwater flux perturbations
  - On multi-decadal time scales, AMOC is most sensitive to buoyancy flux anomalies in the Arctic
  - Sea ice loss weakens AMOC, as Arctic Ocean absorbs more heat
    - Mediated by freshwater anomalies from changes in sea ice cycling (Liu et al. 2019)




*Sévellec et al. (2017)*

# Summary

- AMOC only partially responsible for OHT transport into Arctic
  - Important role for regional winds, gyre dynamics
- Many ways in which Arctic can impact AMOC
  - Water mass transformations
  - Many sources and reservoirs of freshwater
- The link between Arctic and AMOC is projected to strengthen
  - Despite weakening AMOC
  - Concerning given the large changes in Arctic freshwater budget

# EXTRAS

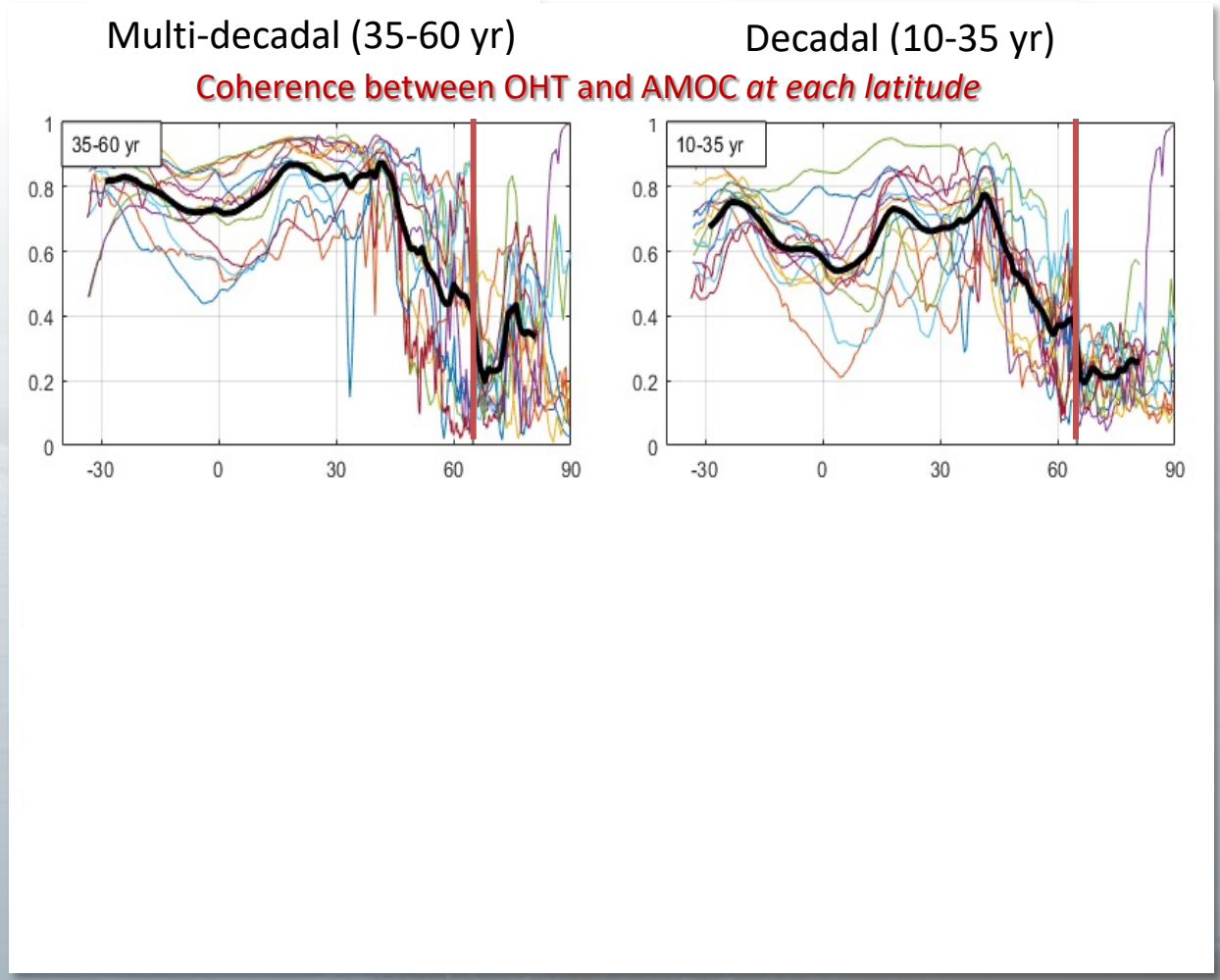
# Challenges

- Climate models continue to have significant biases in the Arctic and AMOC
  - Multi-model means often okay, but considerable model spread
- Most models do not resolve the fine-scale processes that are important for AMOC, the Arctic, and their interactions
  - Narrow boundary currents
  - Mesoscale eddies
  - Cross-shelf exchanges
  - Deep convection
  - Complex bathymetry
- Limited monitoring of critical gateway transports
  - No closed budgets
- Arctic, AMOC, and climate communities are not as well integrated as they should
  - Integration of modeling and observational communities has improved with US AMOC Science Team, FAMOS

# Impact of AMOC on Arctic

**To what extent does AMOC variability affect heat transport into the Arctic?**

- Analysis of CMIP6 models:
  - OHT strongly related to AMOC  south of 60°N
  - OHT at 65°N weakly related to AMOC at lower latitudes

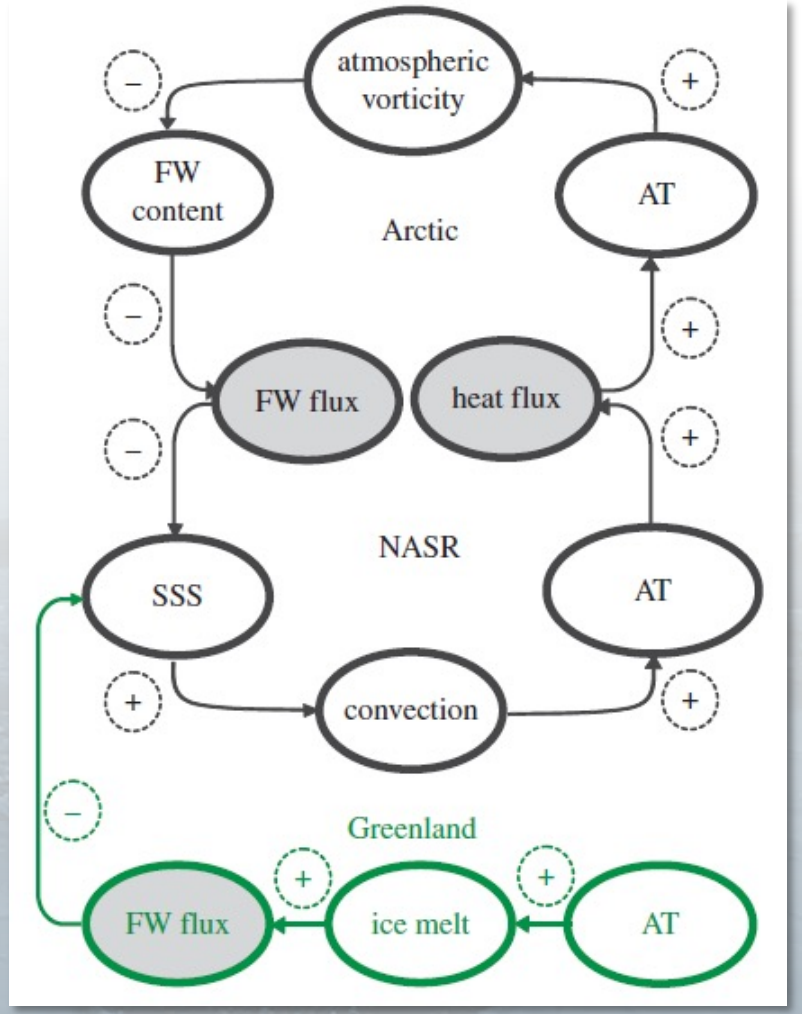



*Weijer et al. (in prep.)*

# Two-way Interactions Between Arctic and AMOC

## Coupled interactions

- Proshutinsky et al. (2015)
  - Explain decadal variability of alternating circulation patterns in the Arctic
  - Interaction between Arctic and subpolar North Atlantic
    - The Arctic regulates the North Atlantic via freshwater flux
    - The North Atlantic influences the Arctic via atmospheric heat flux
  - Greenland freshwater input might have interrupted feedback loop
- Also
  - Escudier et al. (2013)
  - Jungclaus et al. (2005)

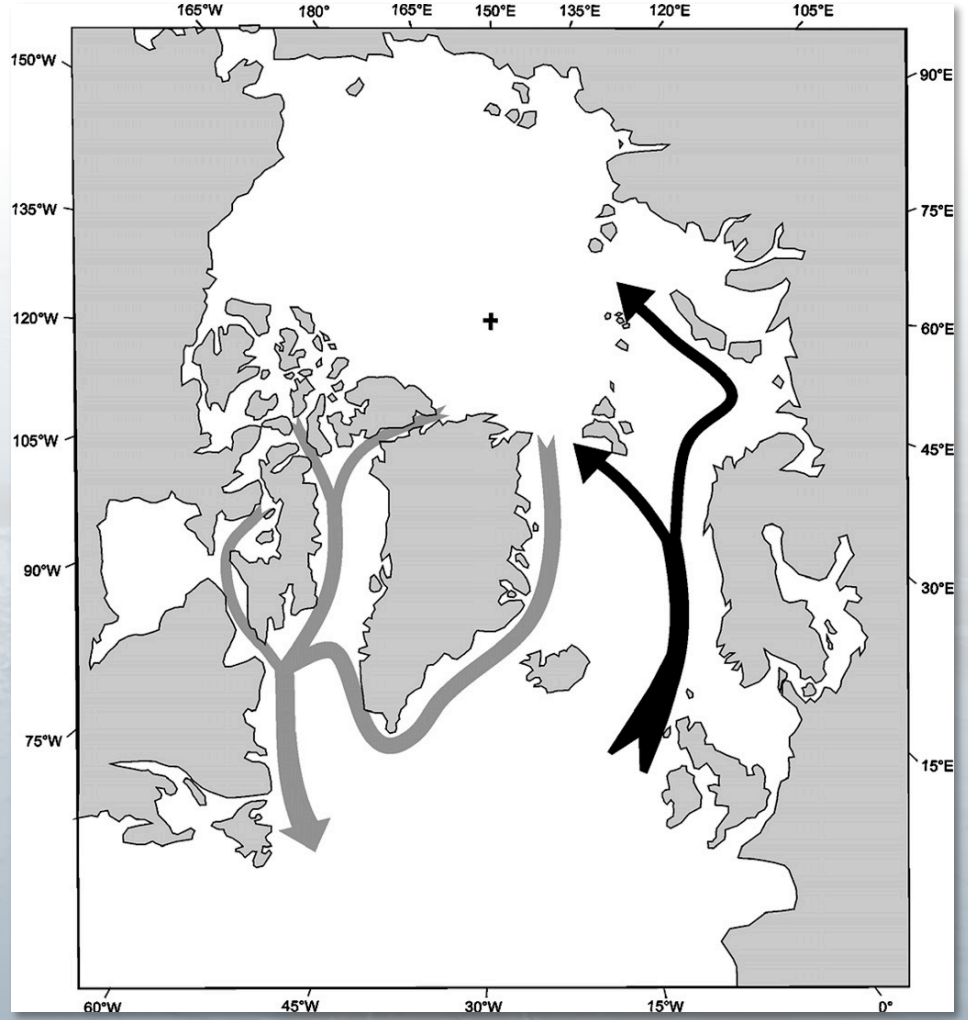



*Proshutinsky et al. (2015)*

# Two-way Interactions Between Arctic and AMOC

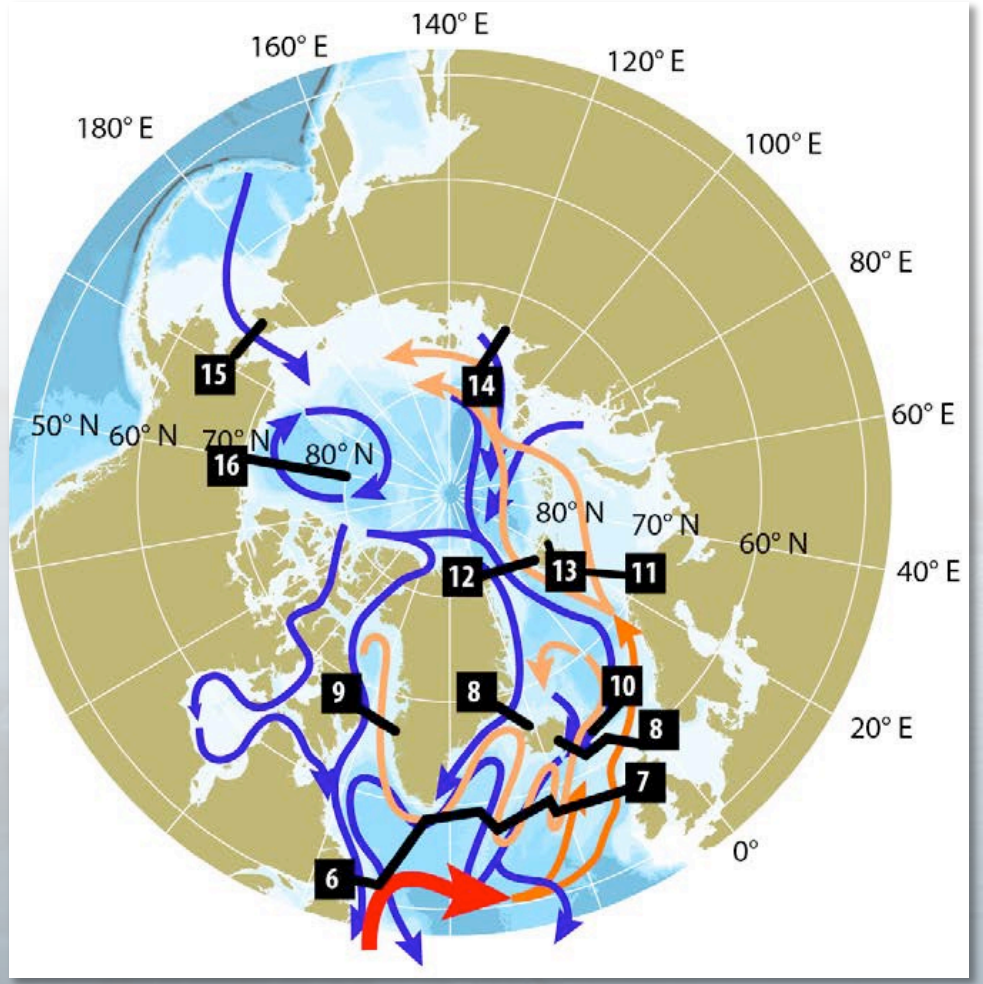
**Is northward inflow and southward outflow related?**

- Sundby & Drinkwater (2007):
  - GSAs may not reflect ‘salinity’ anomalies but ‘transport’ anomalies
  - Transport anomalies on the eastern and western side are anticorrelated
    - Fresh anomalies in the west (GSA’s) correspond to salty anomalies in the east (enhanced inflow of Atlantic Water)
  - May be driven by NAO




*Sundby & Drinkwater (2007)*

# Monitoring Arrays




*Berx et al. (2022)*

(6) The Overturning in the Subpolar North Atlantic Program (OSNAP) West array.
(7) OSNAP East array.
(8) the Greenland-Scotland Ridge (GSR) arrays.
(9) Davis Strait array.
(10) Svinoy mooring array.
(11) Barents Sea Opening array.
(12) Fram Strait array.
(13) Long-term variability and trends in the Atlantic Water inflow region (ATWAIN) array.
(14) Nansen and Amundsen Basin Observing System (NABOS).
(15) Bering Strait array.
(16) Beaufort Gyre Observing System (BGOS).

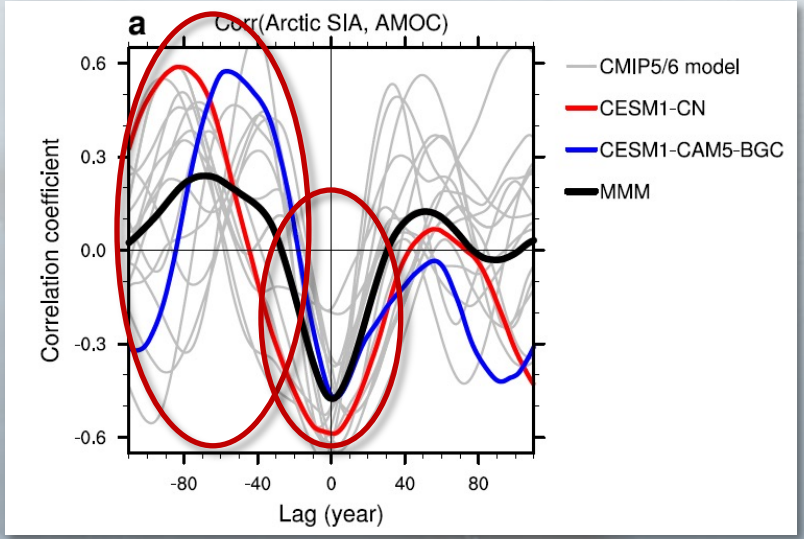
# TWO-WAY INTERACTIONS BETWEEN ARCTIC AND AMOC

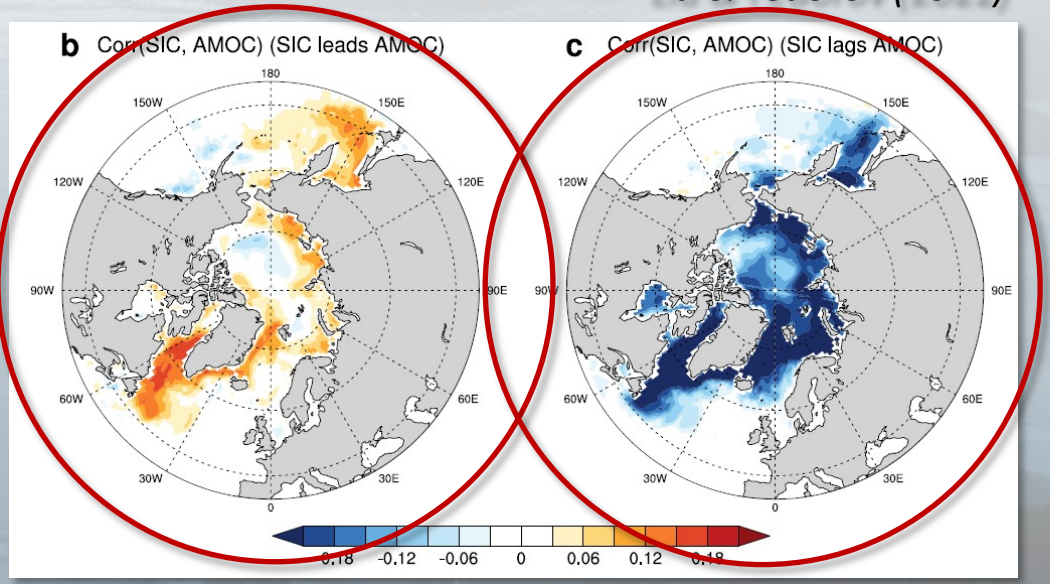
# Two-way Interactions Between Arctic and AMOC

**Is there evidence for two-way interactions between sea ice and AMOC?**

- Liu & Fedorov (2022): explore two-way interactions in CMIP models
  - AMOC anti-correlated with sea ice area
    - AMOC leads by 1 year
  - Sea ice area correlated with AMOC
    - Sea ice leads by 80 years

*Liu & Fedorov (2022)*

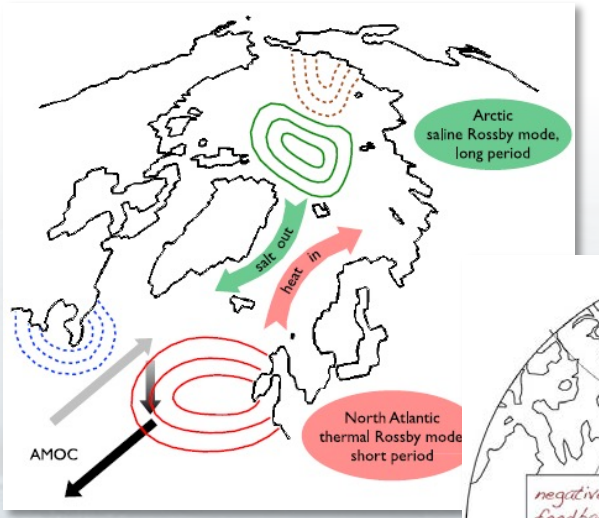


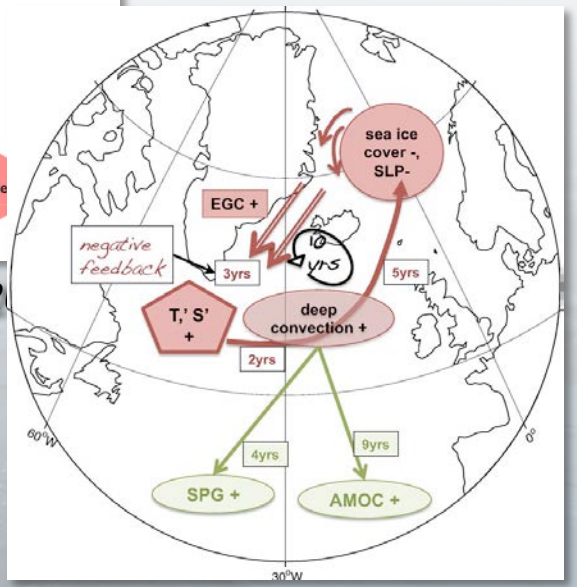
# Two-way Interactions Between Arctic and AMOC

**Is there evidence for two-way interactions between sea ice and AMOC?**

- Other mechanisms have been proposed
  - Jungclaus et al. (2005)
  - Frankcombe & Dijkstra (2011)
  - Escudier et al. (2013)




*Frankcombe & Dijkstra (2*




*Escudier et al. (2013)*