Revisiting the role of air-sea heat flux on the transformation of Atlantic Water along the rim current system in the Nordic Seas

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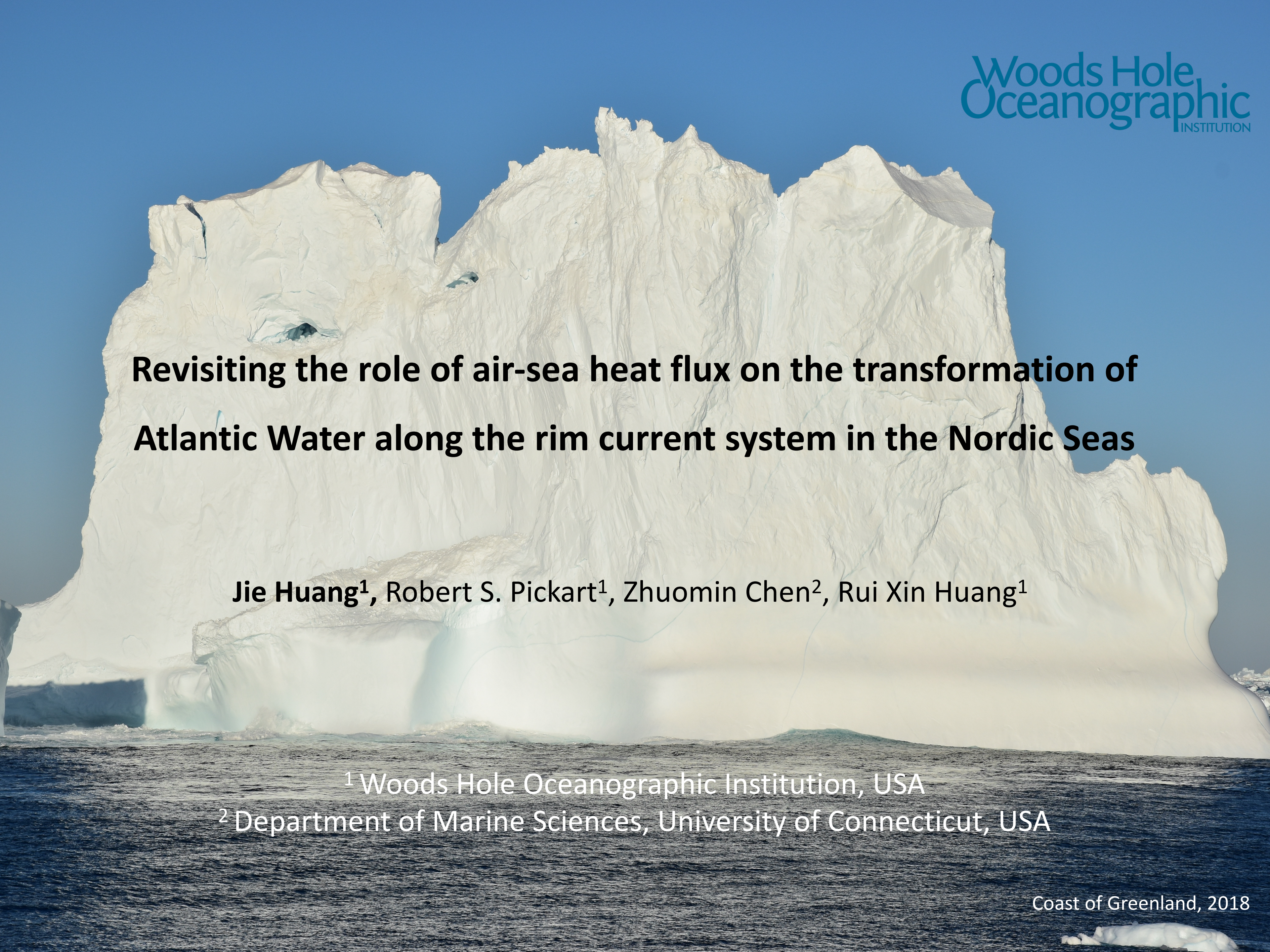


Coast of Greenland, 2018

Background: Early Scheme in 1990s

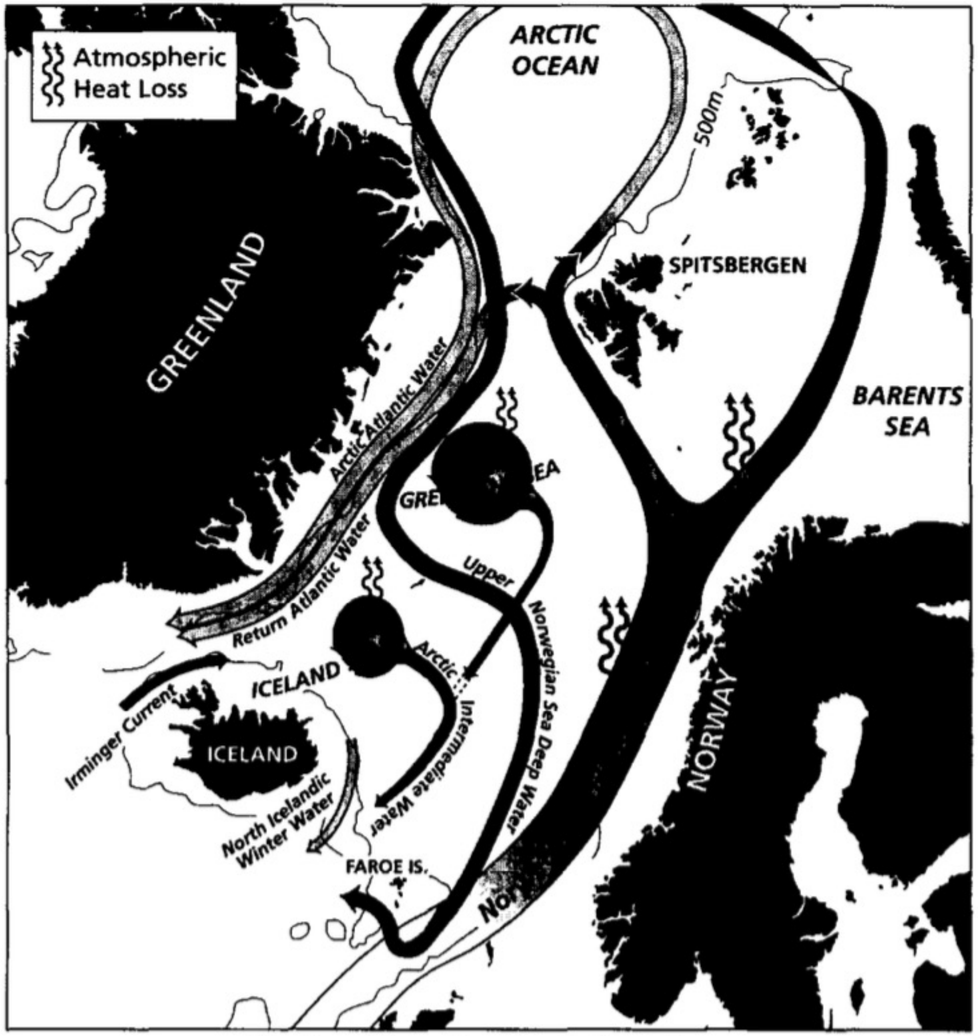
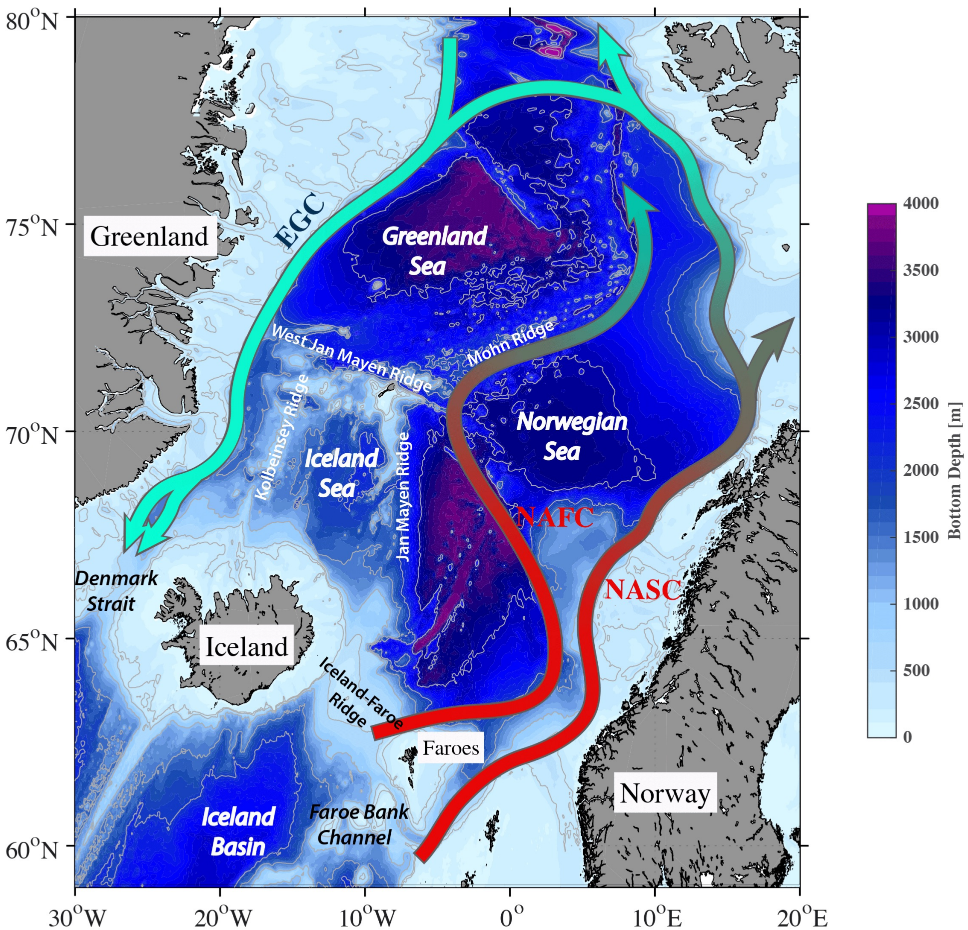


Fig. 2. Alternative circulation scheme.

Mauritzen, 1996

- The warm and salty Atlantic Water is gradually transformed into cold and dense overflow water as it circulates along the rim current system in the Nordic Seas, due to the ocean heat loss to the atmosphere.

Background: recent changes

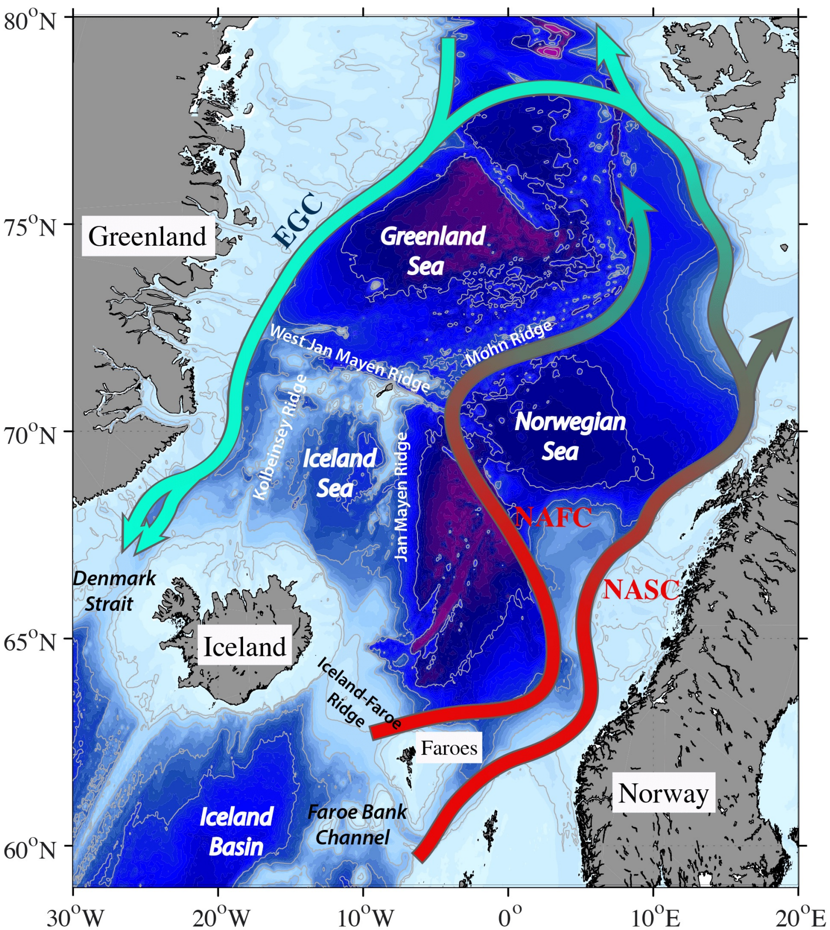


Schematic circulation of rim current system, modified from Huang et al., 2020

- Retreat of sea ice (e.g., Våge et al., 2018; Moore et al., 2022)
- Reduction of ocean heat loss to atmosphere (e.g., Moore et al., 2015)
- Increase of heat transport from subpolar North Atlantic (e.g., Tsubouchi et al., 2021)
- Increase of freshwater flux from Arctic Ocean (e.g., de Steur et al., 2018)

Revisit the role of air-sea heat flux on the transformation of AW along this system.

Outline



Schematic circulation of rim current system, modified from Huang et al., 2020

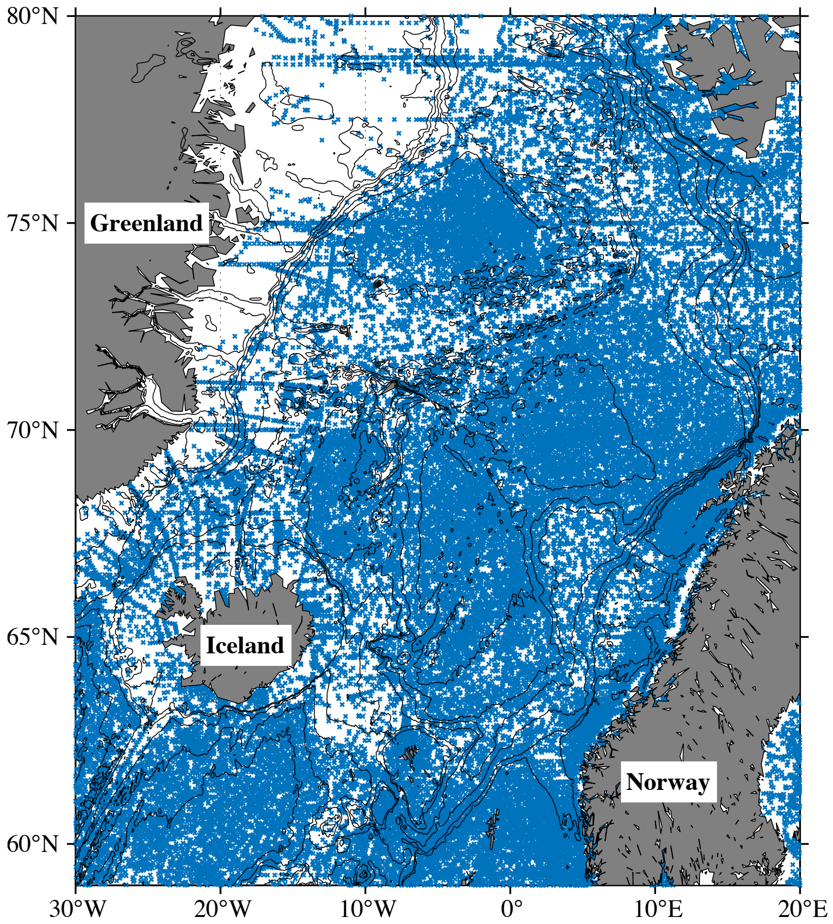
Focus on the rim current system:

- Norwegian Atlantic Slope Current (NASC)
- Norwegian Atlantic Front Current (NAFC)
- East Greenland Current (EGC)

Outline

- Atlantic Water (AW) pathways
- Along-pathway transformation of AW
- Quantifying the contribution of air-sea heat flux to the transformation of AW
- Long-term variability

Data



Hydrographic data coverage 1993-2018

Time period: 1993-2018

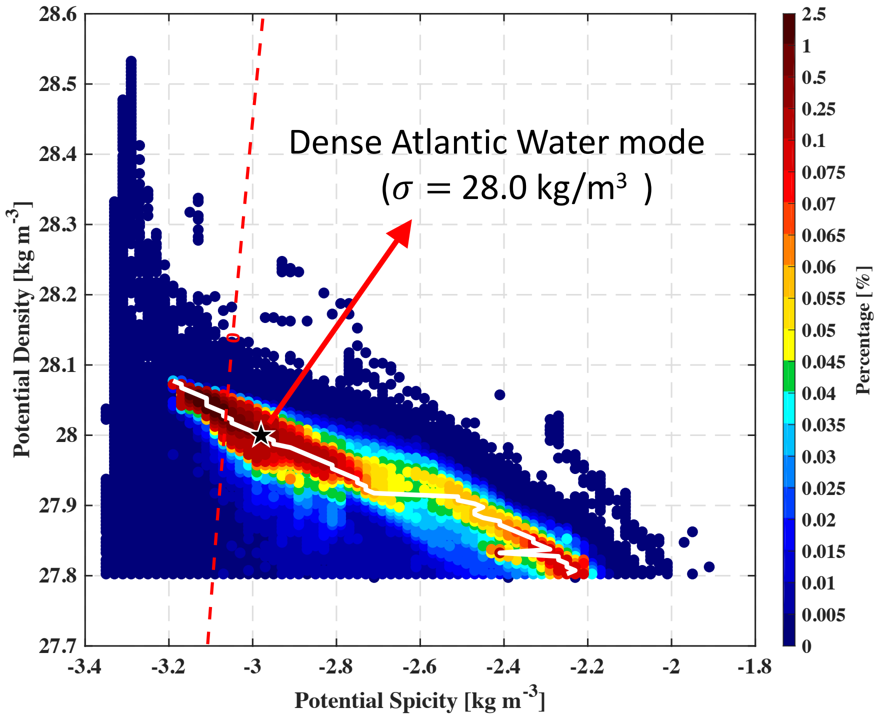
- Historical hydrographic dataset (see Huang et al. 2020 for details of data source).
- GLORYS 3-D velocity product, based on NEMO model, assimilated with several observations, with daily and 1/12 ° resolution.
- CMEMS satellite surface velocity data, with daily and 1/4 ° resolution.
- Direct velocity observations from historical cruises, moorings and gliders.
- ERA5 air-sea heat flux and wind stress product, with 3-hours and 1/4 ° resolution

Results I: Determine AW pathways (sigma-pi distance metric)

Sigma-pi distance metric:

$$D_{1,2} = \sqrt{(\sigma_{0,1} - \sigma_{0,2})^2 + (\pi_{0,1} - \pi_{0,2})^2}$$

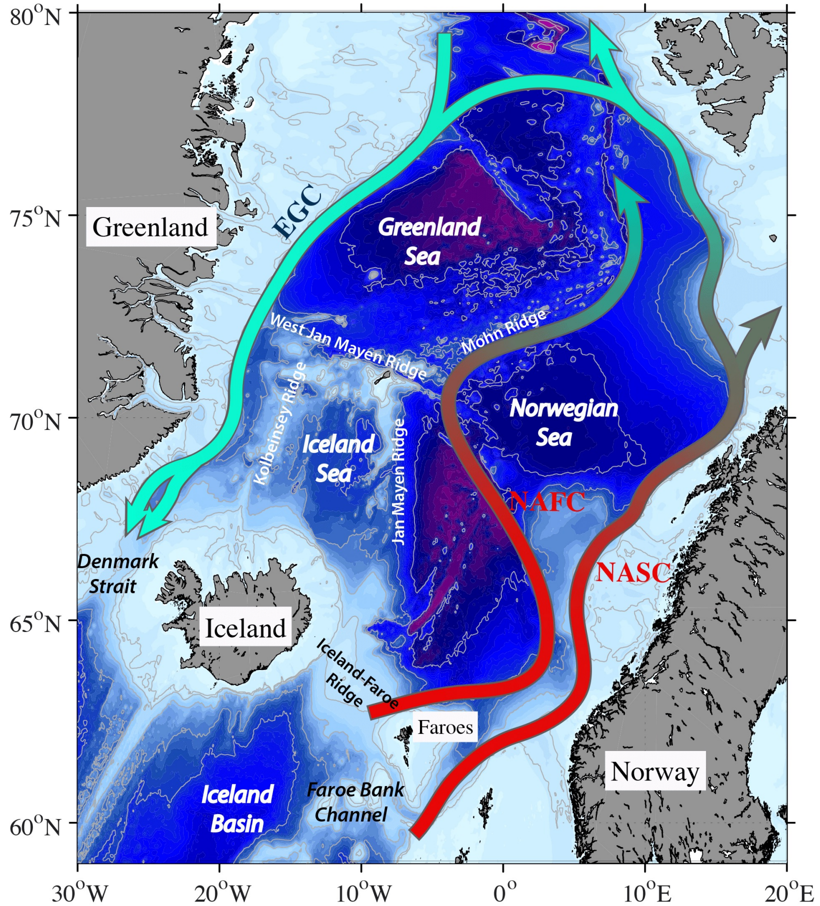
Dense Atlantic Water mode ($\sigma_{0,1}, \pi_{0,1}$) , Any other water parcel ($\sigma_{0,2}, \pi_{0,2}$), see Huang et al. (2020) for details.



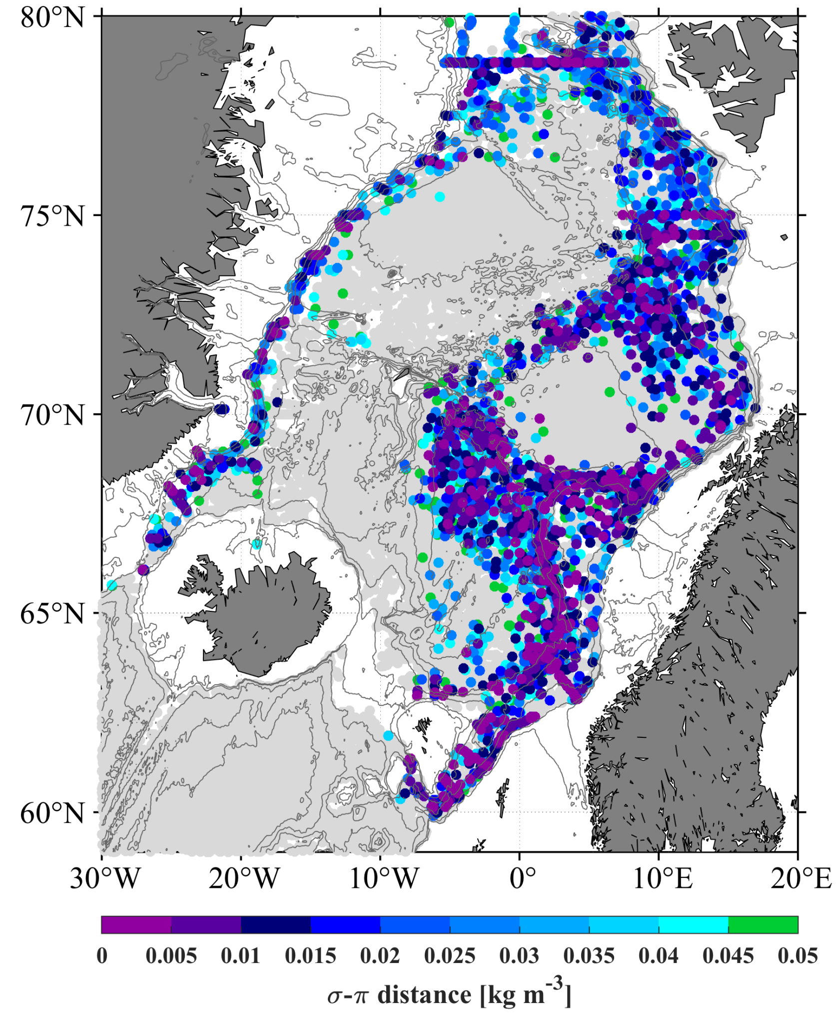
Occurrence percentage of water mass in the Nordic Seas (depth<850m, σ >27.8 kg/m³) in sigma-pi coordinate

Results I: Determine AW pathways (sigma-pi distance metric)

Schematic pathways



Distribution of small (< 0.05 kg/m³) sigma-pi distance at 550-600 m



2005-2018

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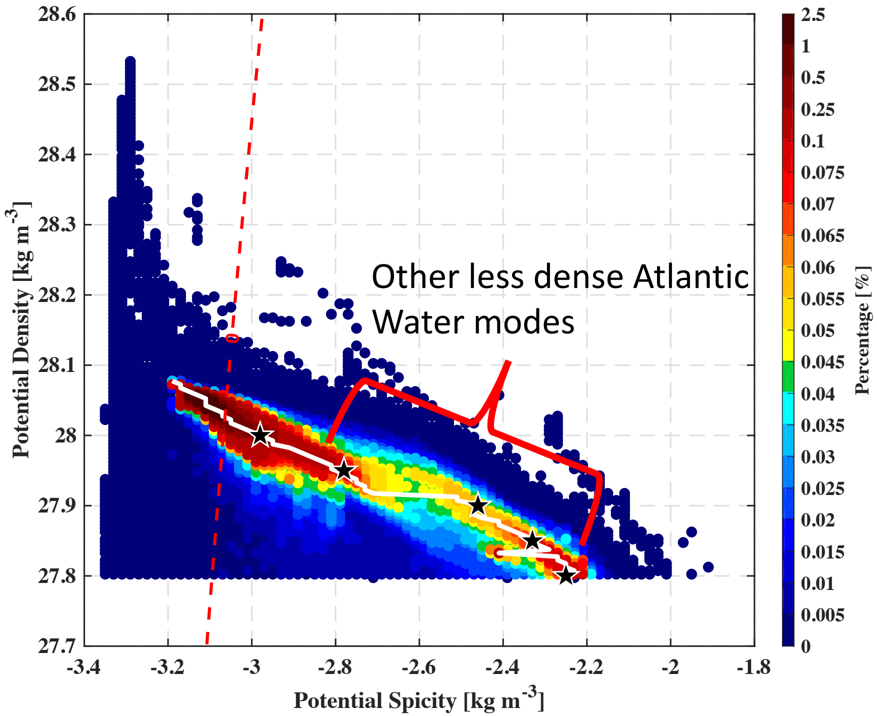

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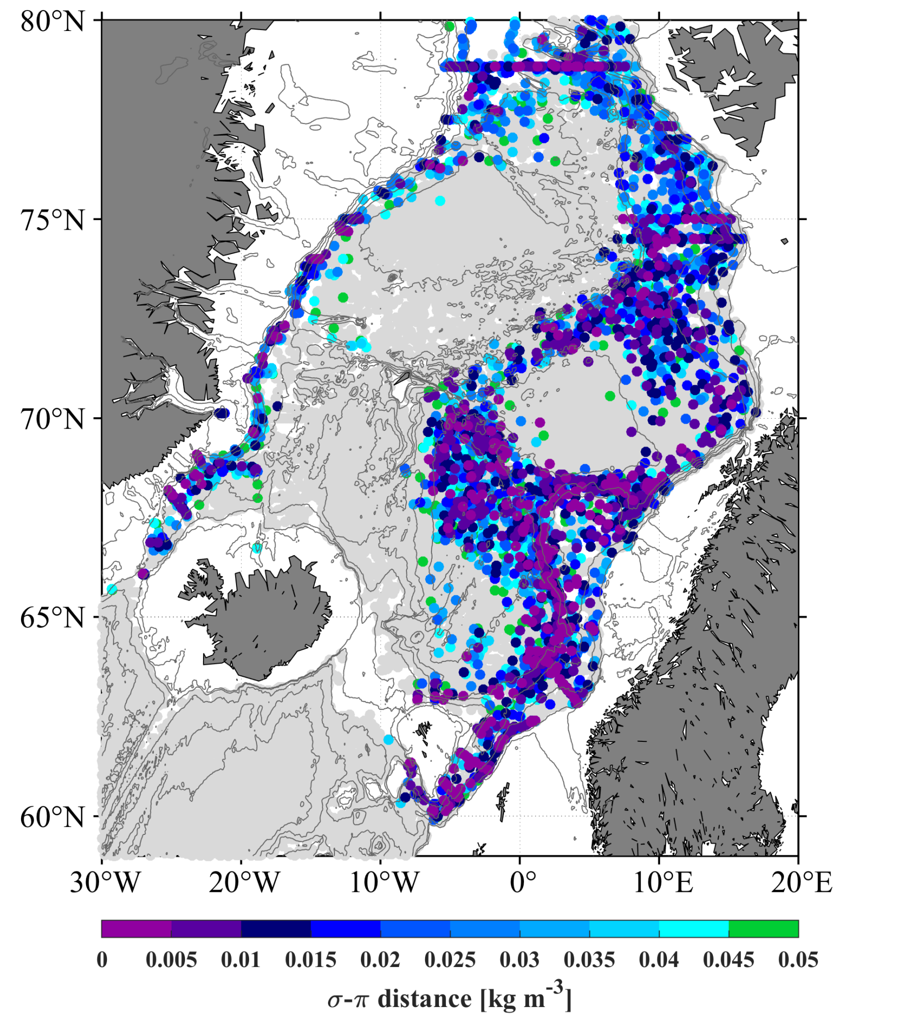
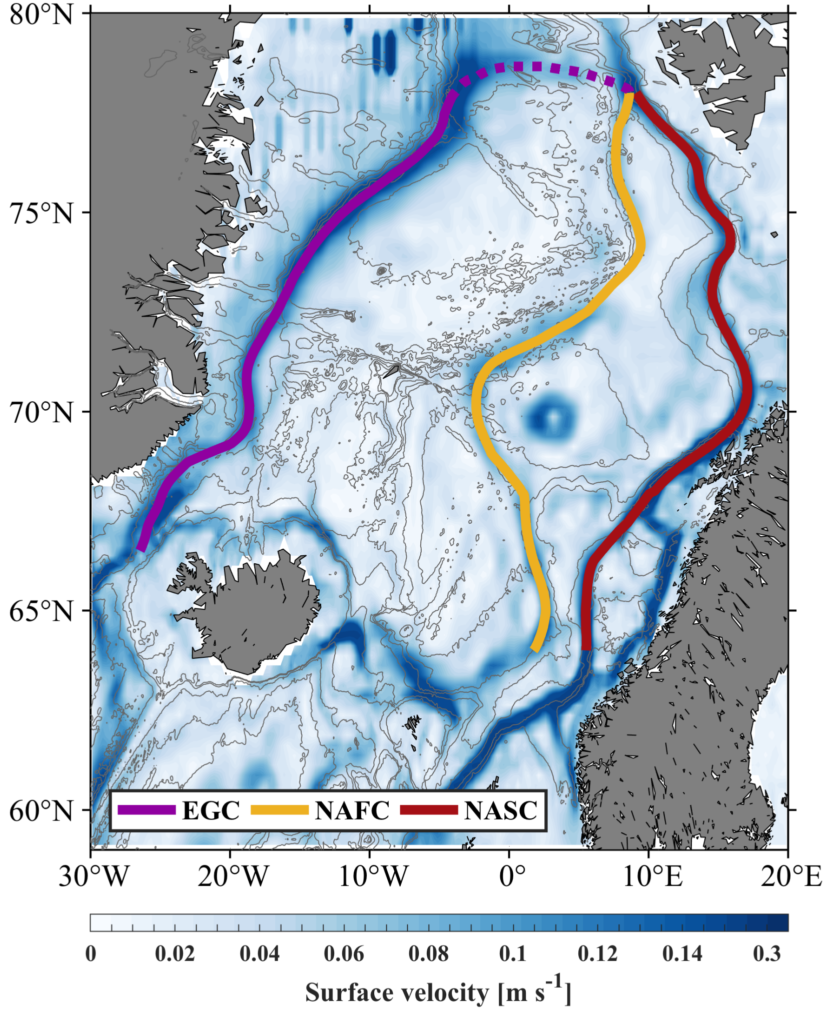


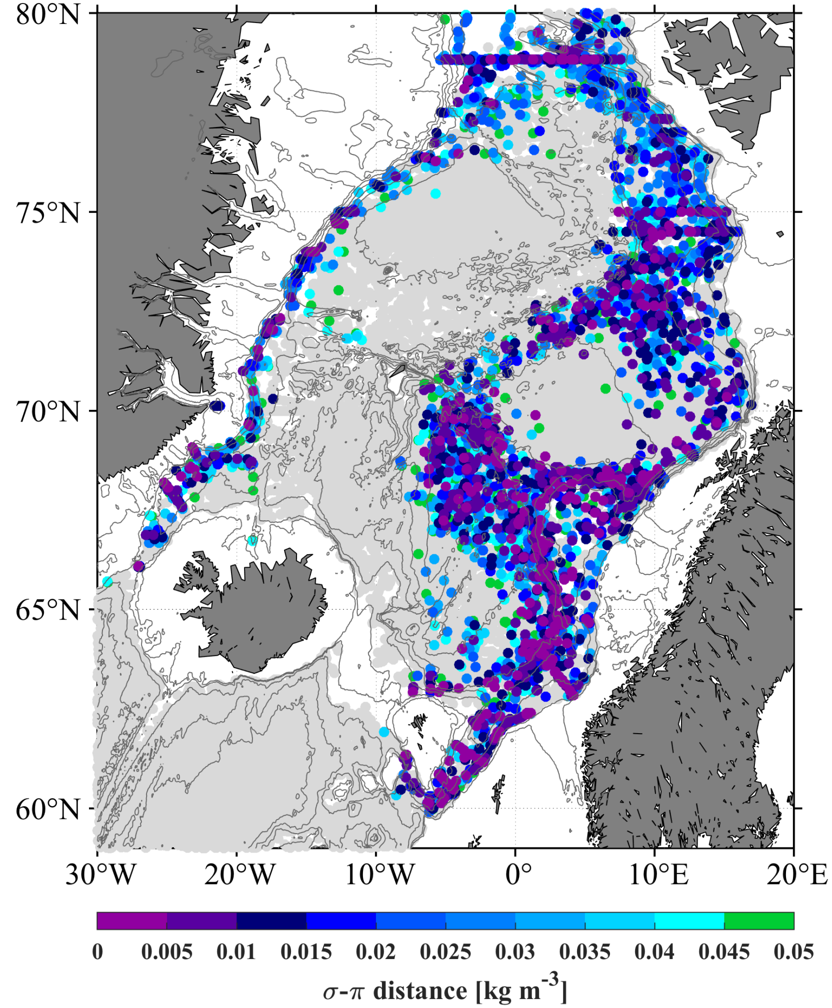
2005-2018

Results I: Determine AW pathways (surface geostrophic velocity)

Mean of satellite and GLORYS surface velocity



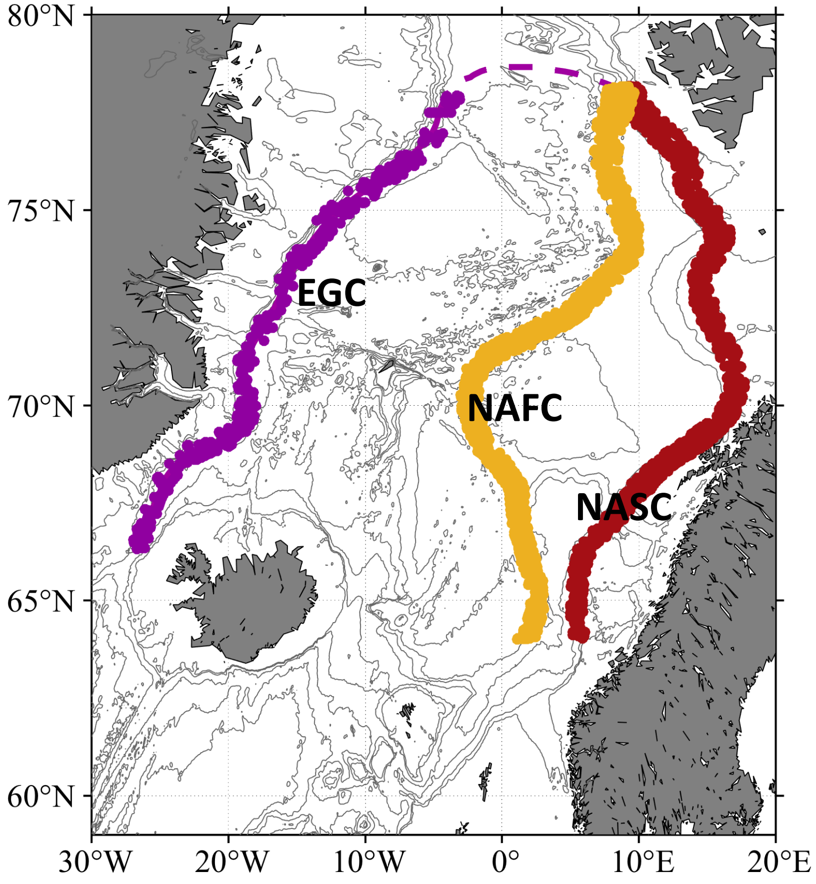
Distribution of small (<0.05 kg/m^3) sigma-pi distance at 550-600 m



➢ The pathways are determined by maxima in the surface velocity field.

2005-2018

Results II: Along-pathway transformation of AW

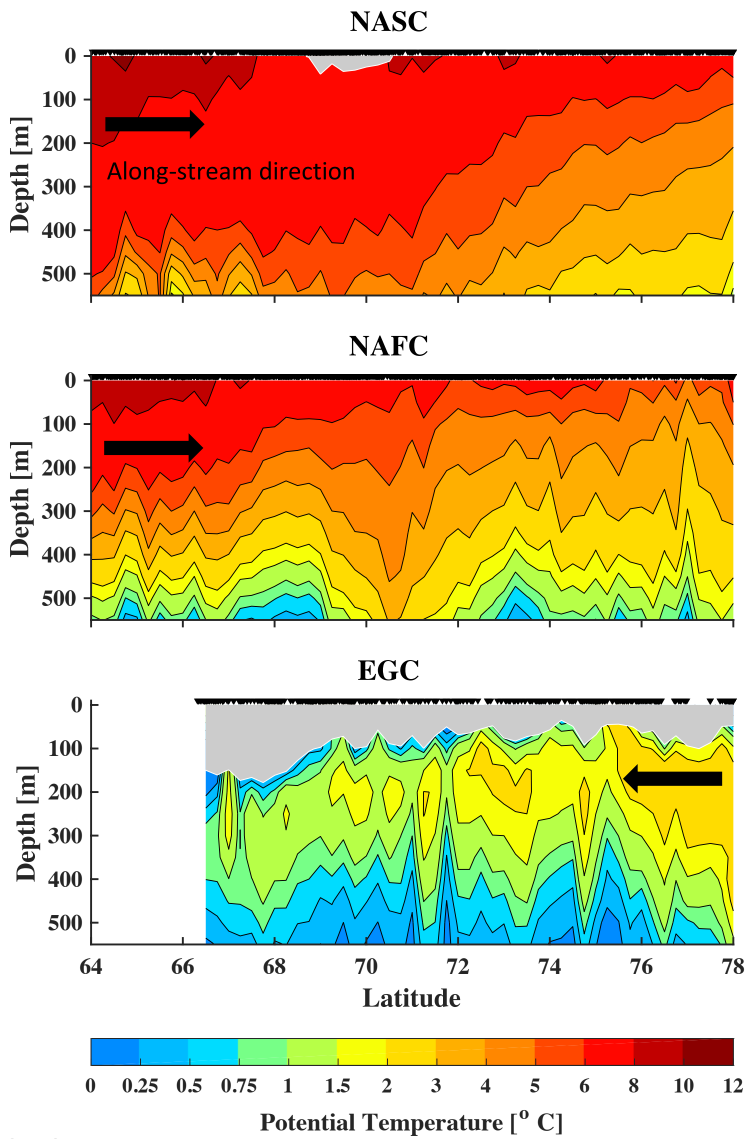


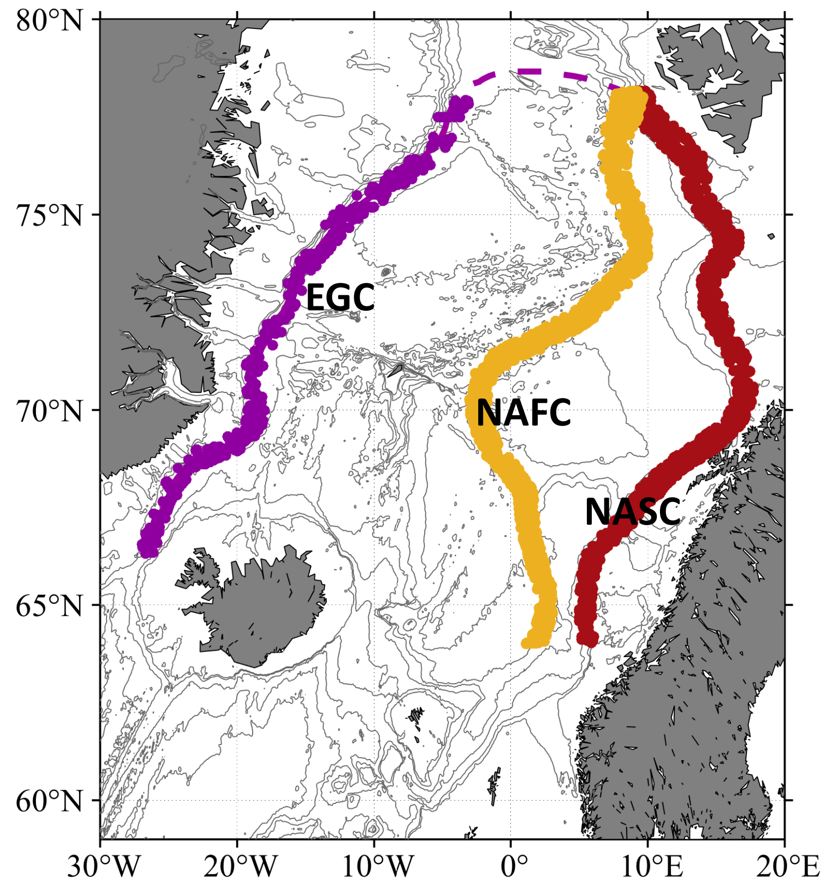
Distribution of historical hydrographic profiles close to the pathways (distance to the pathways < 25 km)

2005-2018

Results II: Along-pathway transformation of AW

Vertical sections of temperature

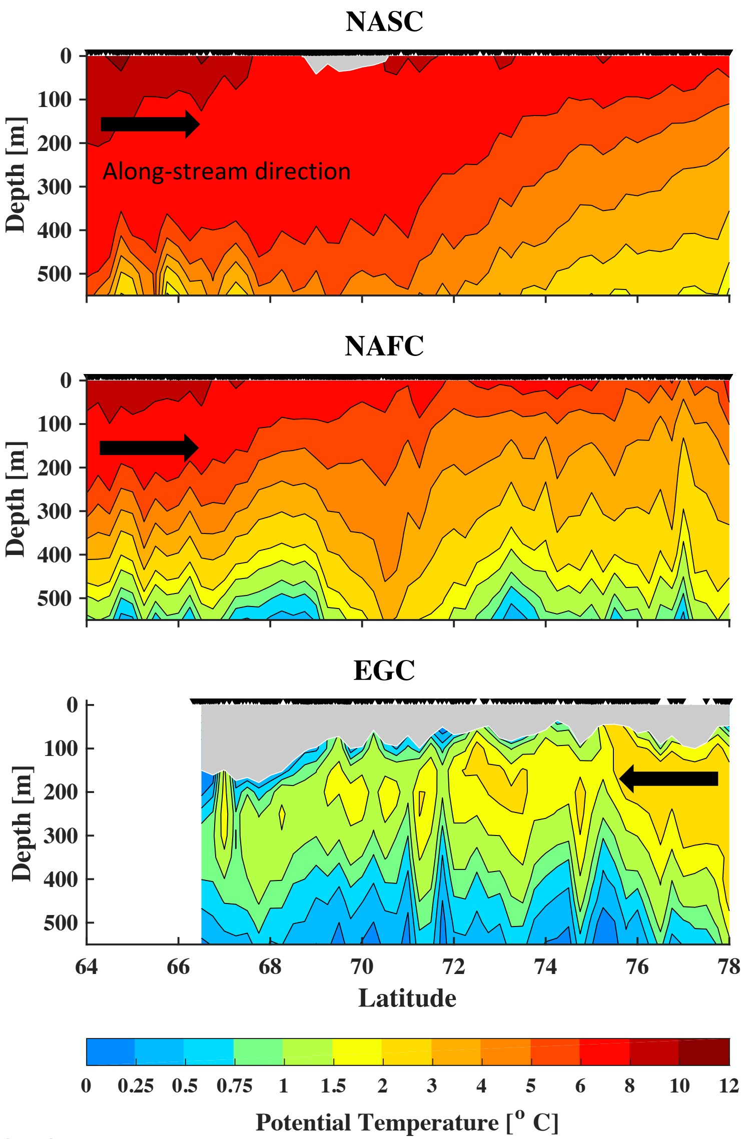




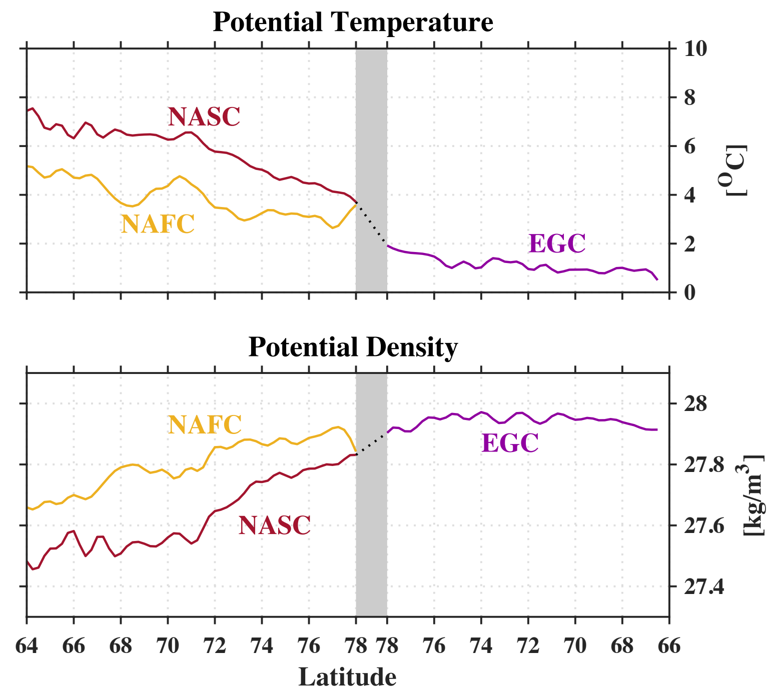
2005-2018

The polar surface water layer (defined by $\theta < 0$ °C, salinity < 34.5, $\sigma < 27.7$ kg/m^3) is excluded in the vertical sections (shown in gray).

Results II: Along-pathway transformation of AW



Depth-mean change of AW layer along NASC, NAFC and EGC



- The densification of AW primarily occurs along the NASC and NAFC in the eastern Nordic Seas, where cooling in temperature dominates the change.

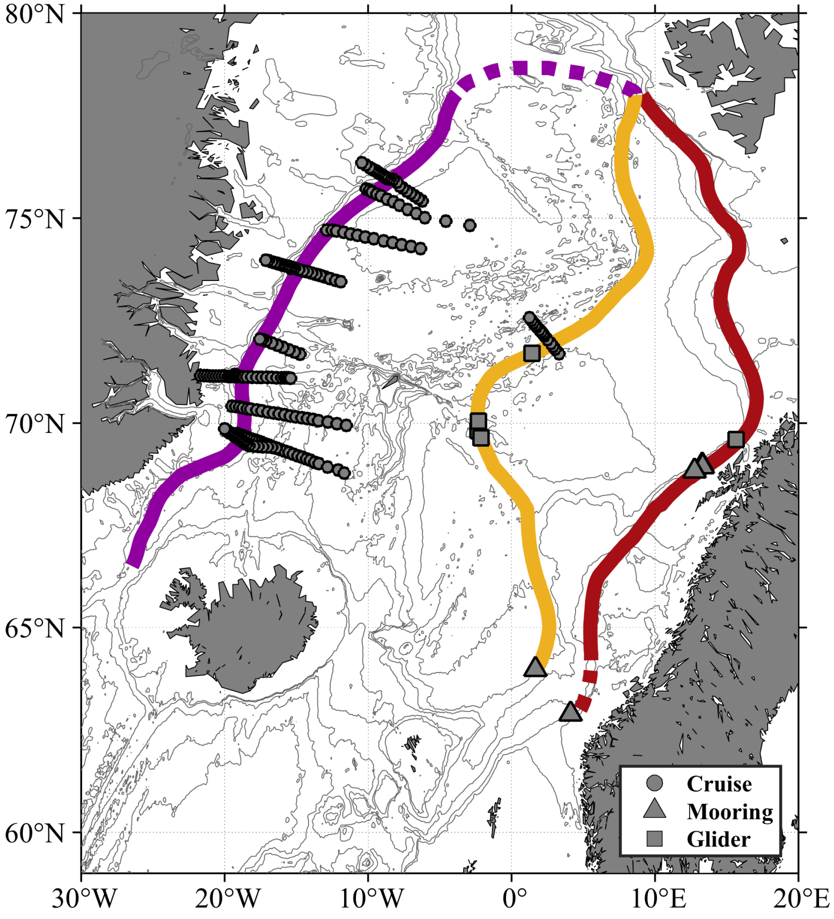
2005-2018

Outline

- Atlantic Water (AW) pathways
- Along-pathway transformation of AW
- **Quantifying the contribution of air-sea heat flux to the transformation of AW**
- Long-term variability

Results III: GLORYS reanalyzed 3-D velocity field

Comparison between GLORYS mean velocity and direct historical velocity observations

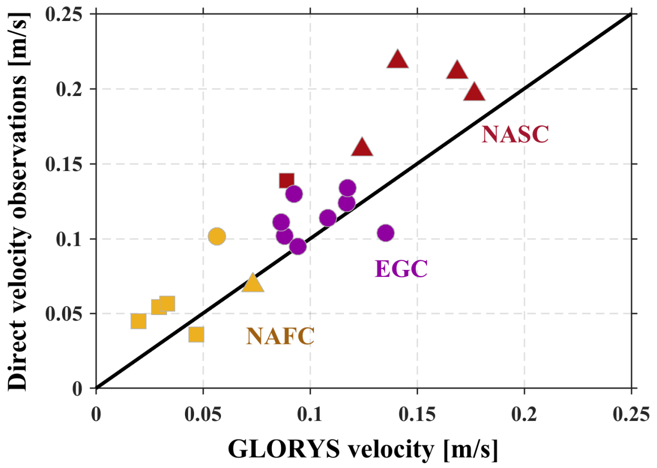


Distribution of historical velocity observations

Cruise velocity (0-550 mean): JCR 2012 (Håvik et al. 2012), PROVOLO 2016-2017 (Bosse et al. 2019), IGP 2018 cruises (Huang et al. 2021).

Mooring velocity (100-550 mean): Svinøy transect 2005-2015 (from Dr. Kjell Arild Orvik), PROVOLO 2016-2017 moorings (Fer et al. 2020).

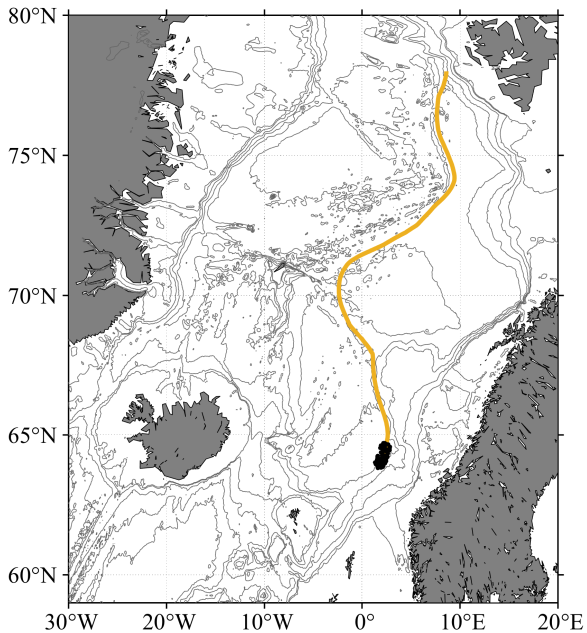
Glider velocity (0-1000 mean): Lofoten basin 2012-2014, PROVOLO 2016-2017 gliders (from Norgliders, GFI, University of Bergen).



2005-2018

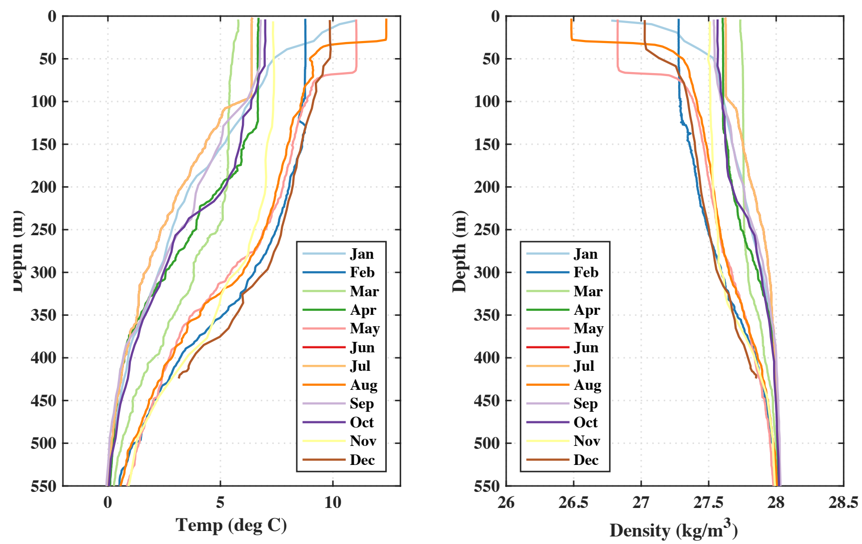
Results III: Quantifying the contribution of air-sea heat flux

Location of profiles (N=155, 64-64.5°N)

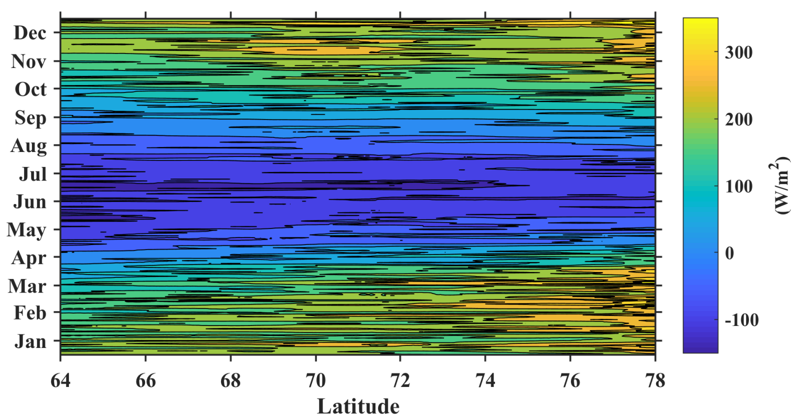


PWP (Price-Weller-Pinkel) model simulation

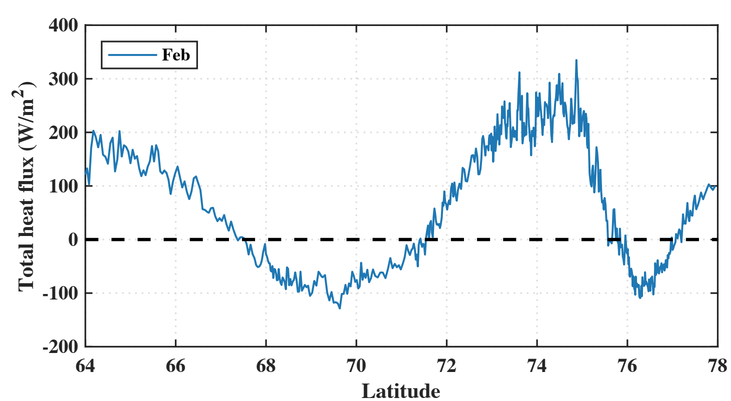
Initial conditions: monthly mean profiles in the south portion of pathway



Air-sea heat loss from ERA5:



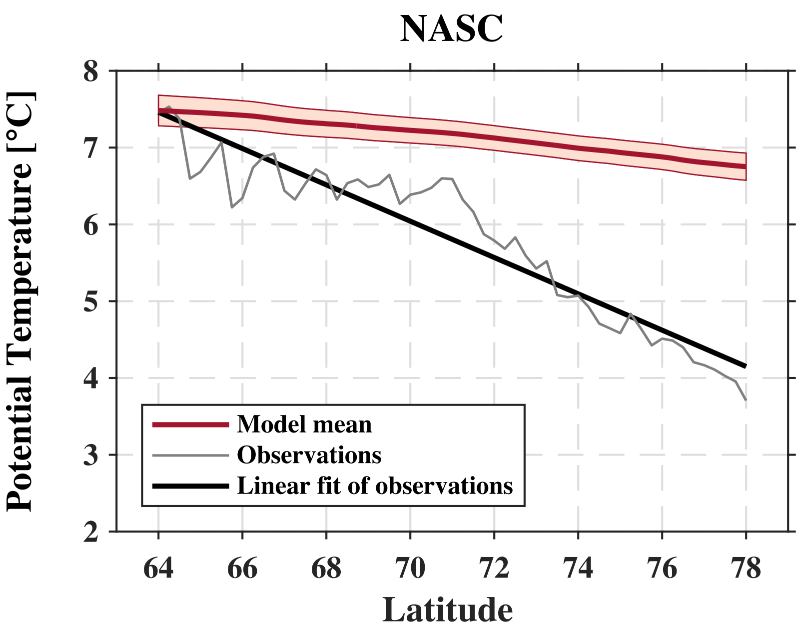
Examples of forced air-sea heat loss for a profile starts in February:

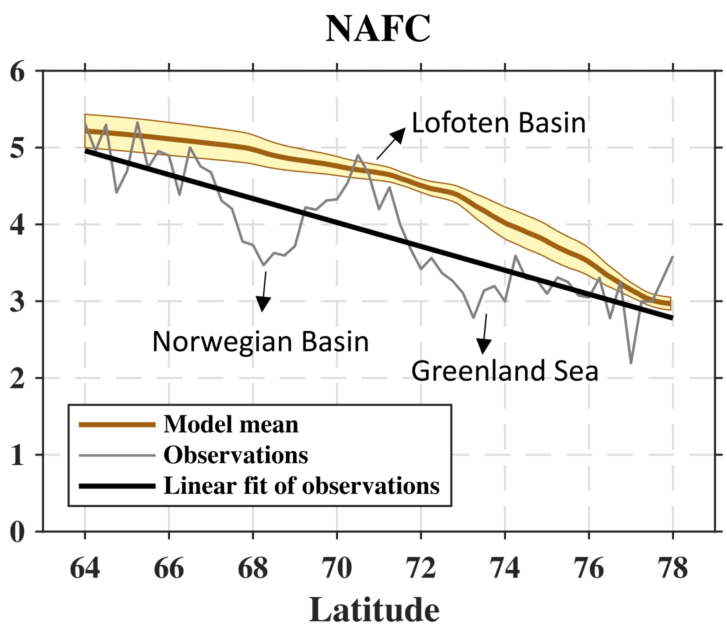


Results III: Quantifying the contribution of air-sea heat flux

(Norwegian Atlantic Slope Current)

(Norwegian Atlantic Front Current)





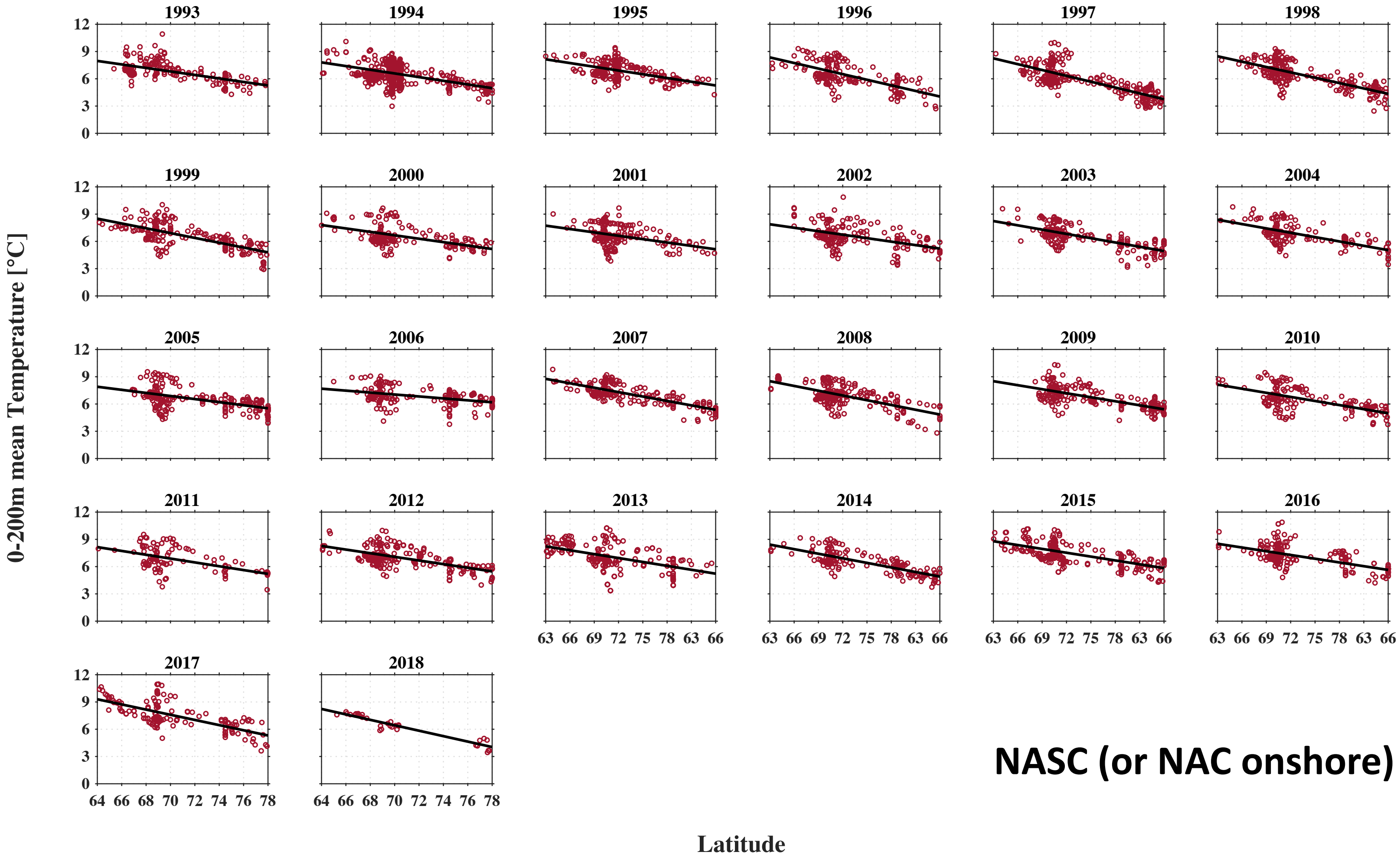
- This demonstrates that air-sea heat flux accounts almost entirely for the net cooling of AW along the NAFC. By contrast, other processes (e.g. lateral transfer of heat) appear to dominate the temperature change of AW along the NASC.

Outline

- Atlantic Water (AW) pathways
- Along-pathway transformation of AW
- Quantifying the contribution of air-sea heat flux to the transformation of AW
- **Long-term variability**

Results IV: Long-term variability

For each year, a linear fit (y=a*x+b, x is latitude, y is 0-200 m mean temperature) was used to obtain the net cooling (a*Δx) of AW along the current.



NASC (or NAC onshore)

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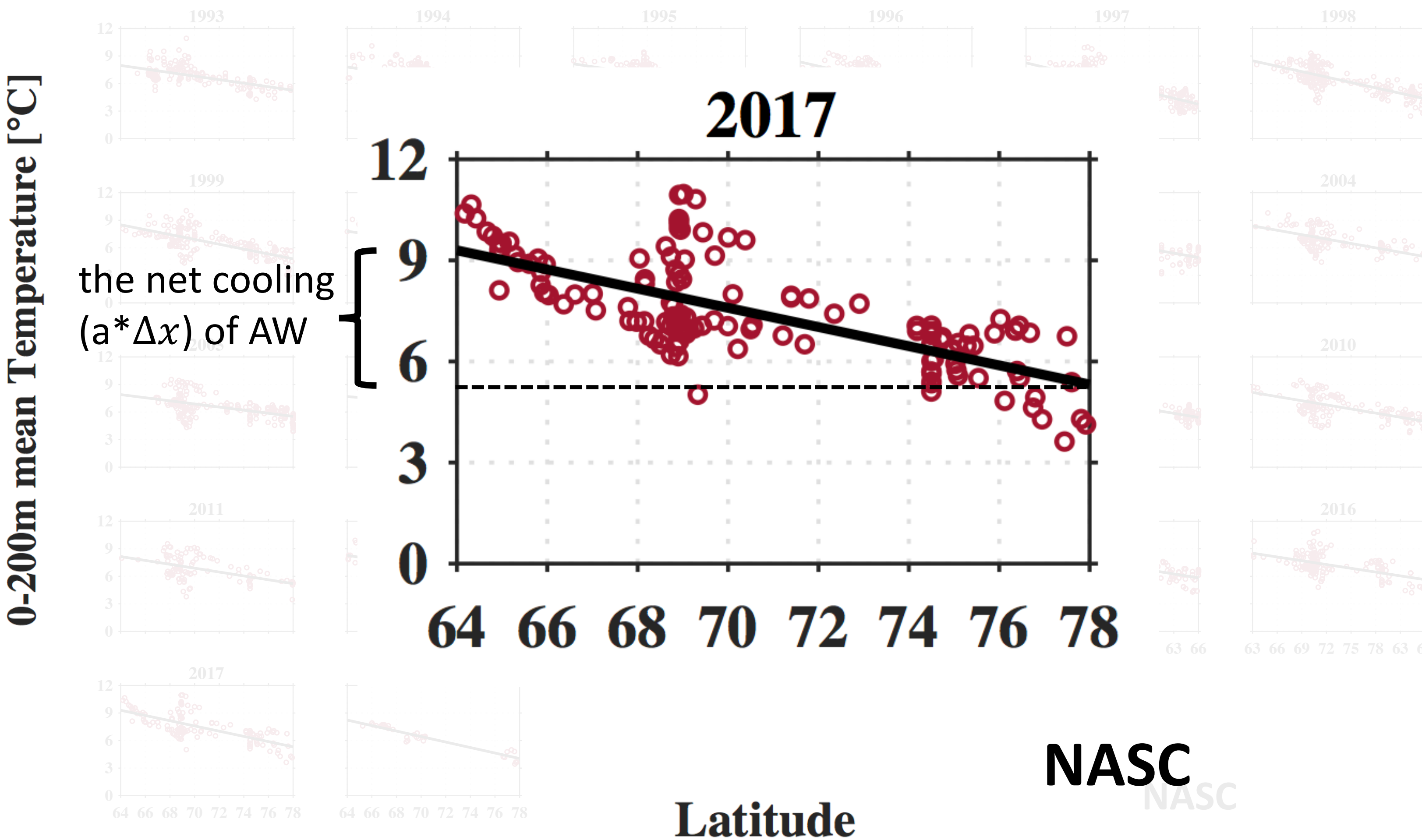
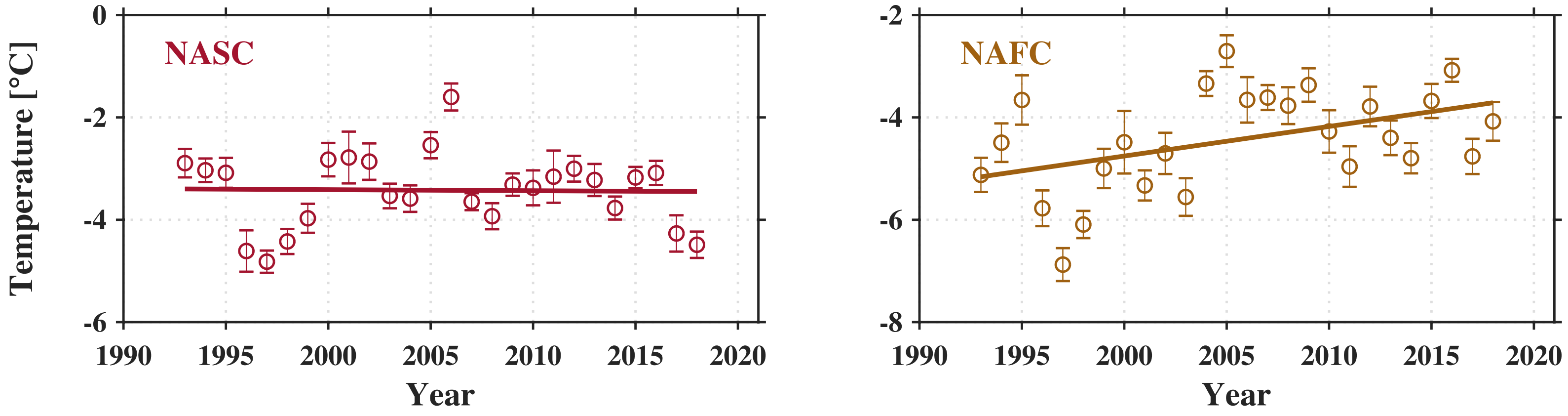


Results IV: Long-term variability

Long-term change of the net cooling of AW (0-200m layer) along two NAC branches



- There is a long-term reduction (1.5 ± 0.6 °C, P value in *t-test* =0.02) in the net cooling of AW along the NAFC. Such a long-term trend was not found for the NASC (P value in *t-test* > 0.1).

Results IV: Long-term change of air-sea heat flux

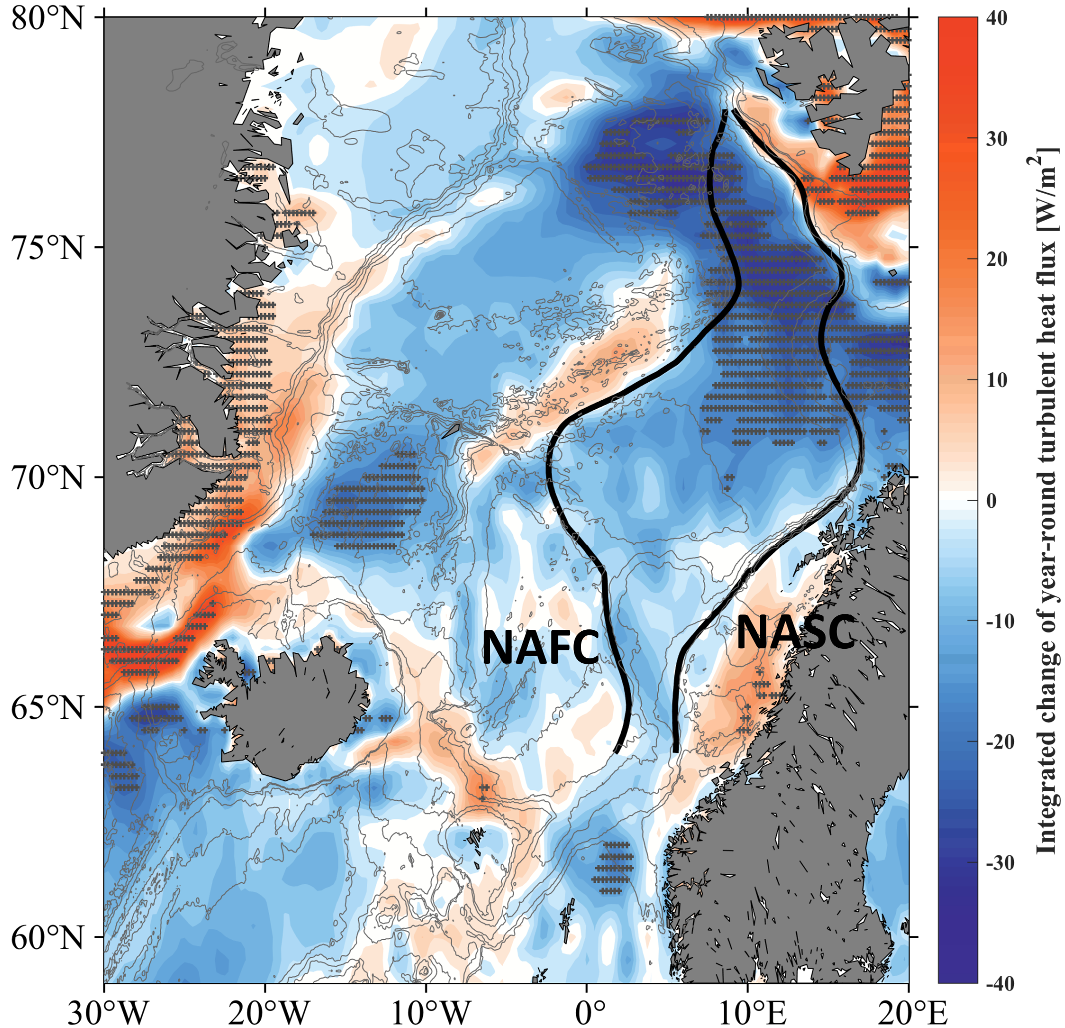
At each grid point, a linear fit (y=a*t+b, t is year, y is the year-round mean turbulent heat flux from ERA5) was used to obtain the long-term change of turbulent heat flux (a*Δt) .

The net change of turbulent heat flux

1993-2018

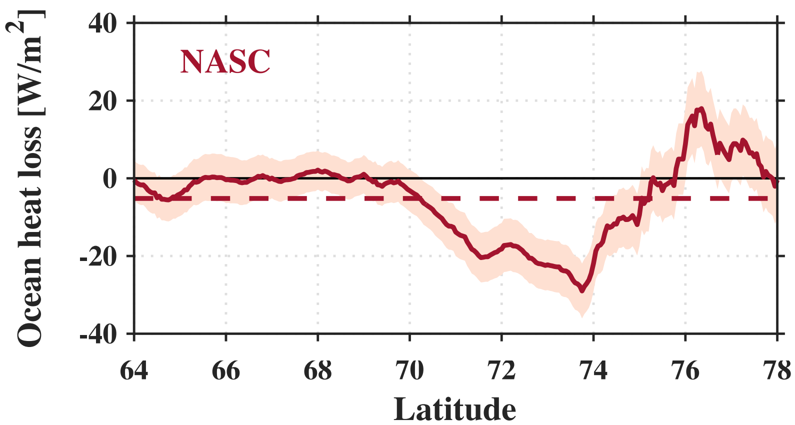
Blue: reduction of ocean heat loss

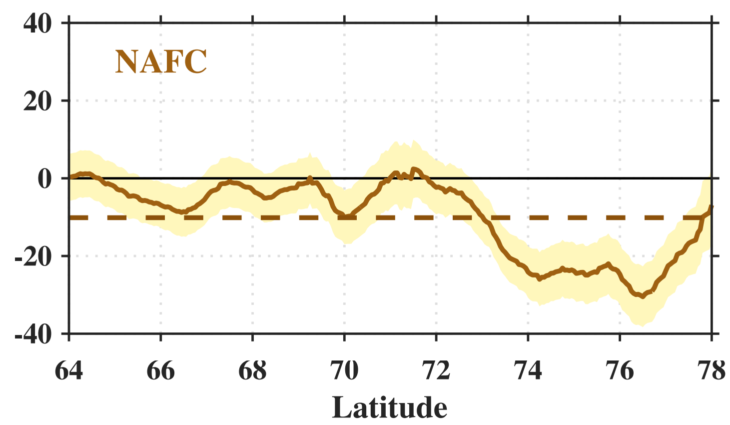
The crosses indicate the significant values



Results IV: Long-term change of air-sea heat flux

Long-term change of ocean heat loss (total turbulent heat flux, from ERA5)





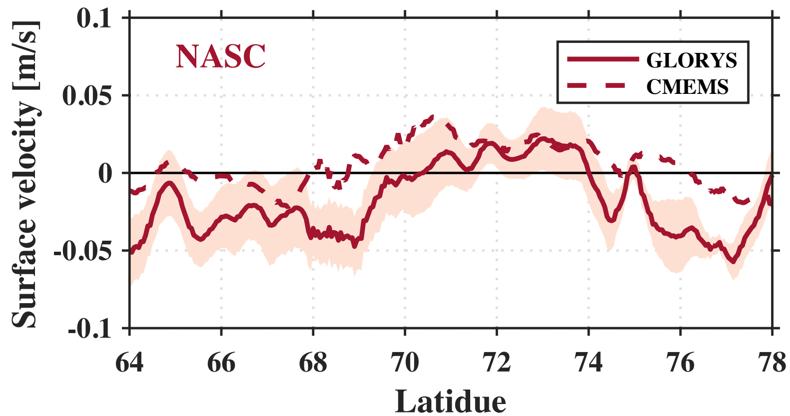
Dashed line: meridional mean

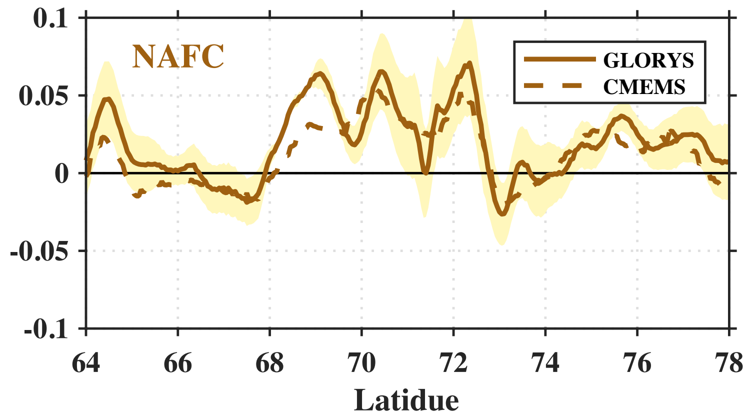
Reduction of ocean heat loss (pathway-mean) was found for the two currents (can potentially contribute to a reduction in the net cooling of AW for the two currents).

Results IV: Long-term change of along-stream velocity

Long-term change of ocean heat loss (total turbulent heat flux, from ERA5)

Long-term change of the along-stream velocity at surface (from GLORYS and CMEMS)





Decrease of along-stream velocity

Increase of along-stream velocity

An increase of along-stream velocity could potentially contribute to a reduction in the net cooling of AW along the NAFC!

Results IV: PWP model for the long-term variability

Use the PWP model to quantify how the long-term changes of air-sea heat flux and along-stream velocity impact the cooling of AW

Four experiments with the same initial conditions:

1. Long-term mean heat flux and along-stream velocity (control run)
2. Long-term mean + change of heat flux, and long-term mean along-stream velocity
3. Long-term mean heat flux, and long-term mean + change of along-stream velocity
4. Long-term mean + change of heat flux and along-stream velocity

Results IV: PWP model for the long-term variability

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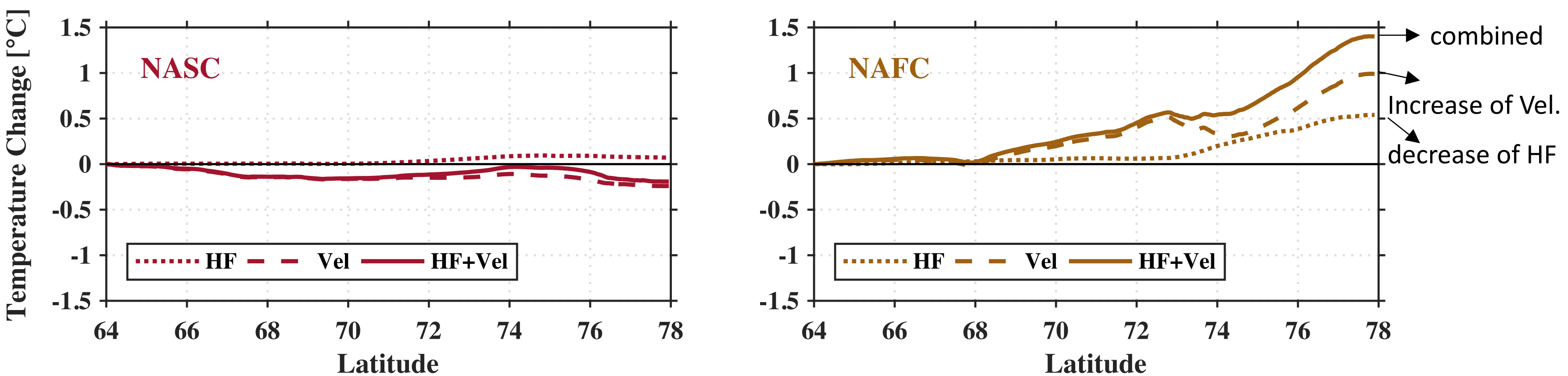
Temperature change compared with control run



The positive temperature change indicates a reduction in the net cooling of AW!

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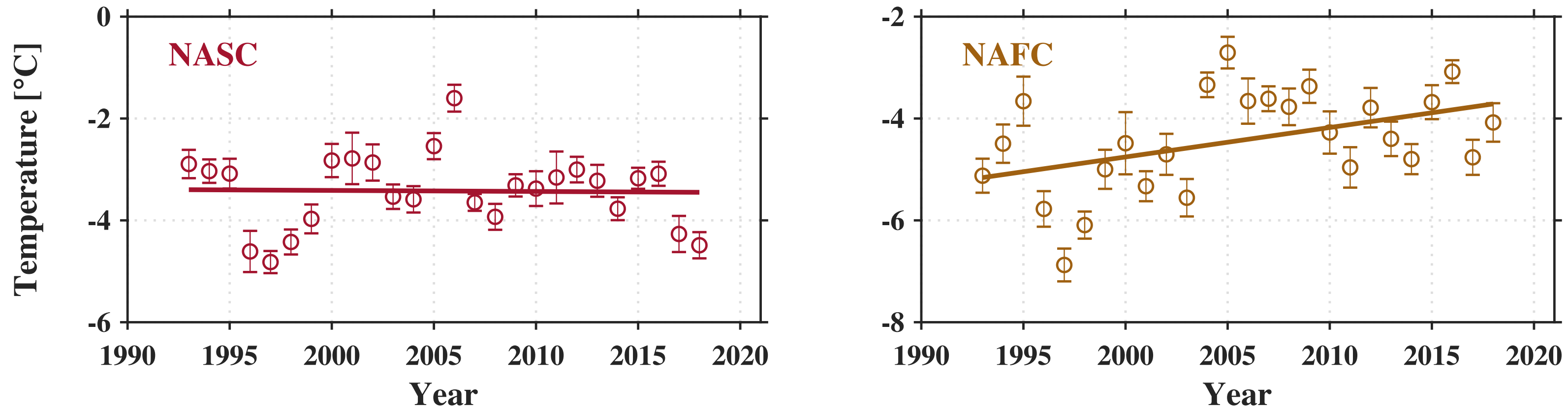
Long-term change of the net cooling of AW (0-200m layer) along two NAC branches



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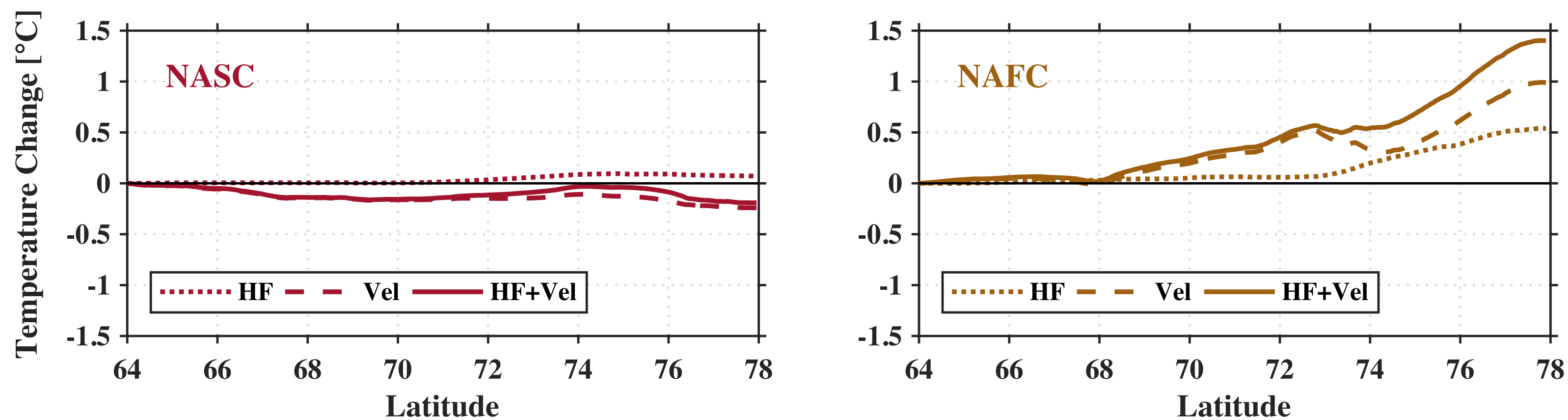

The positive temperature change indicates a reduction in the net cooling of AW!

Summary

- Here we use historical hydrographic data, together with satellite data and a velocity reanalysis product to study the role of air-sea heat flux on the transformation of AW along the rim current system in the Nordic Seas.

- The densification of AW was primarily found to occur along the two branches of Norwegian Atlantic Current (NASC and NAFC) in the eastern Nordic Seas, where cooling in temperature dominates the change.

- The contribution of air-sea heat flux to this cooling was estimated by using a one-dimensional mixing model in an advective framework. This demonstrates that air-sea heat flux accounts almost entirely for the cooling of AW along the NAFC. By contrast, lateral transfer of heat appears to dominate the temperature change of AW along the NASC.

- Our results reveal that air-sea heat fluxes play different roles on the transformation of AW along its pathways in the Nordic Seas.