# Ocean and Cryosphere Processes

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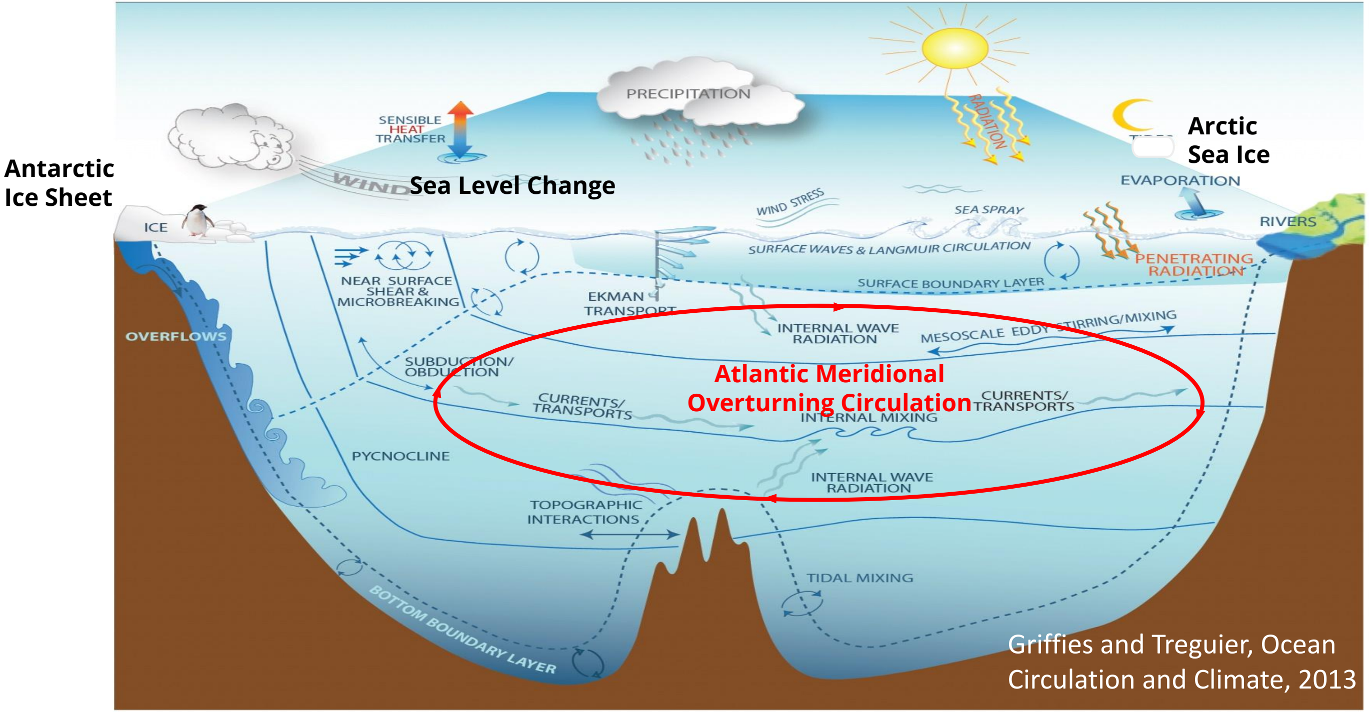
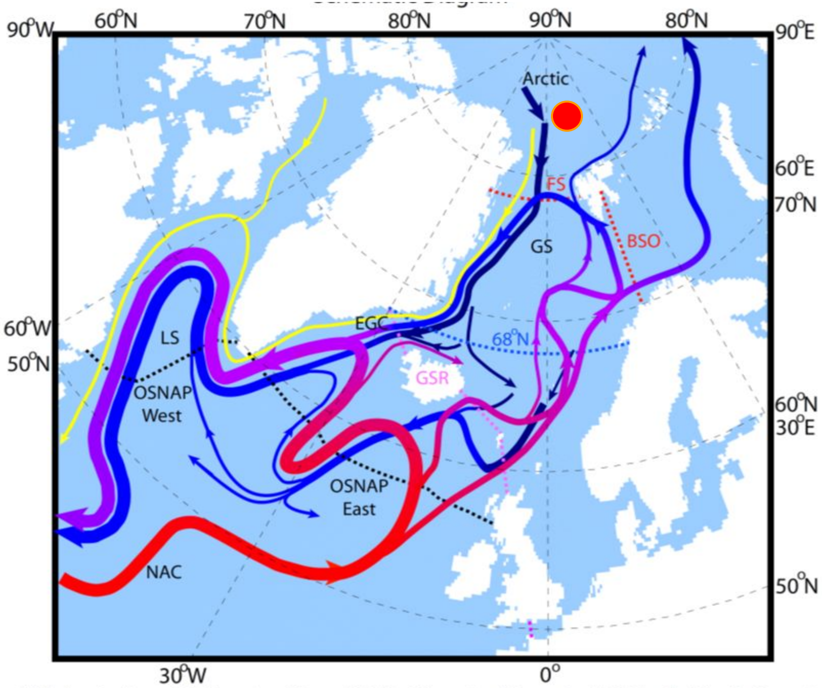
Q2: Concerning NOAA's key mission element of understanding, predicting, and projecting changes in the Earth System, how can GFDL drive further advances in these areas, including extremes and environmental hazards, through scientific innovation based on observations, theory, and modeling? Where are the strengths, gaps, and new frontiers?

# Ocean and Cryosphere Processes are Crucial for Weather, Climate, Sea Level, and Ecosystems




GFDL research on these processes directly advances NOAA's mission to understand and predict changes in climate, weather, ocean, and coasts

# The Arctic Ocean is the Northern Terminus of the AMOC




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

**OSNAP: Overturning in the Subpolar North Atlantic Program**

Schematic of AMOC pathways. Colors of arrows indicate seawater density (light to dense: (yellow-red- purple-violet-blue-dark blue) Red dot designates where the northern extension of the understood AMOC is

The novel result is valuable to predict future AMOC changes and associated climatic, ecological, and economic impacts, and guide modeling and observational efforts

The AMOC affects Sahel/India monsoon, Atlantic hurricane, North American and European heat waves, US east coast sea level and ecosystems, and Arctic sea ice, serving as a major source for decadal predictability

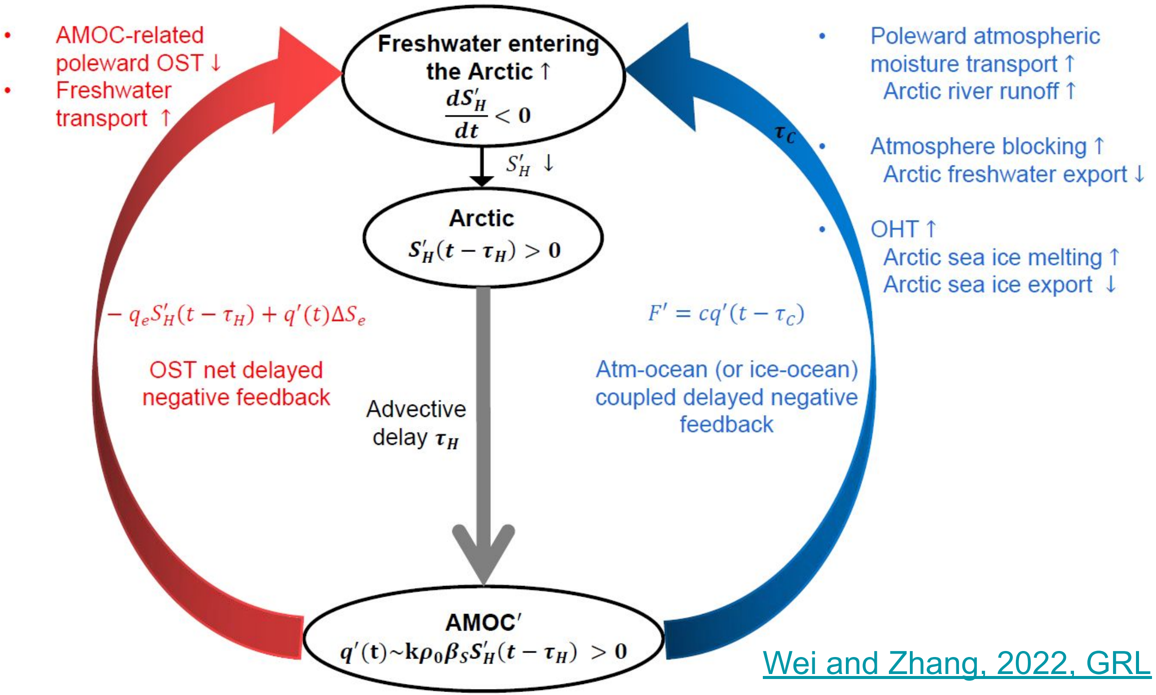
The AMOC is not well observed. GFDL reconstructs the long-term mean AMOC for the first time and points to the key role of the Arctic in the process

Addressing R6 of 2019 GFDL Lab Review

Zhang and Thomas, 2021, Nature Communications Earth & Environment

# Multidecadal AMOC Variability and Associated Two-Way Interactions with the Arctic

## Schematic of the AMOC Delayed Oscillator




Unlike ENSO variability that has been explained through conceptual models, multidecadal AMOC variability (crucial for many regional impacts) is not well understood from theoretical perspective

The conceptual model reveals the AMOC delayed oscillator mechanism and the important role of Arctic salinity anomalies in multidecadal AMOC variability

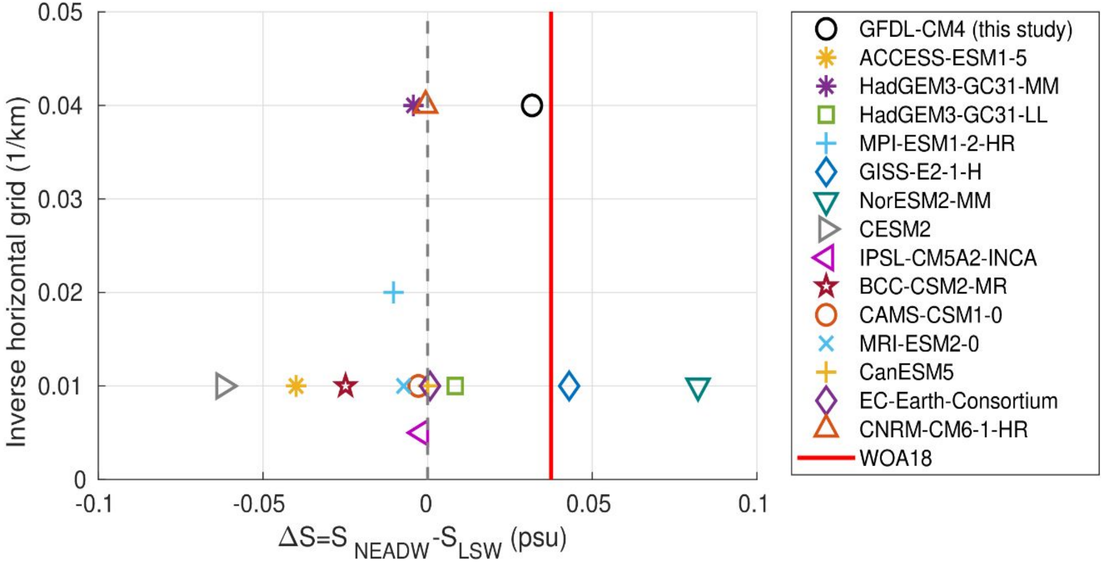
It provides a theoretical framework to explain multidecadal AMOC variability, its two-way interactions with the Arctic, and the diverse periods simulated in climate models

Wei and Zhang, 2022, GRL

Addressing R1 of 2019 GFDL Lab Review

highlighted on AGU EOS (https://eos.org/editor-highlights/arctic-salinity-pushes-the-amoc-swing)

# Important Impact of Iceland-Scotland Overflow on Labrador Sea Deep Convection




**Comparing with CMIP6 models for representing the ISOW-associated NEADW layer in the deep Labrador Sea**, evaluated by the climatological mean salinity difference between the ISOW-associated NEADW layer (2000-2500m) and the core Labrador Sea Water (LSW) layer (1000-1500m) ($\Delta S = S_{NEADW} - S_{LSW}$)

GFDL CM4 used in this study simulates the observed positive salinity difference and has a relatively higher resolution to better resolve the boundary current

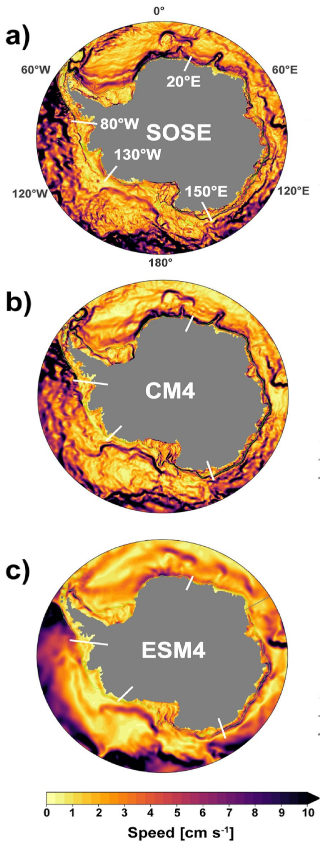
Hence it can simulate the important impact of the weakening/freshening of ISO on the strengthening of the Labrador Sea deep convection

The observed Iceland-Scotland overflow (ISO) associated Northeast Atlantic Deep Water (NEADW) layer in the Labrador Sea is saltier than the Labrador Sea Water layer above, which is not well represented in CMIP6 models

Addressing R1 of 2019 GFDL Lab Review

Wei and Zhang, 2024, Nature Communications

# Southern Ocean Response to Antarctic Ice Sheet Melting

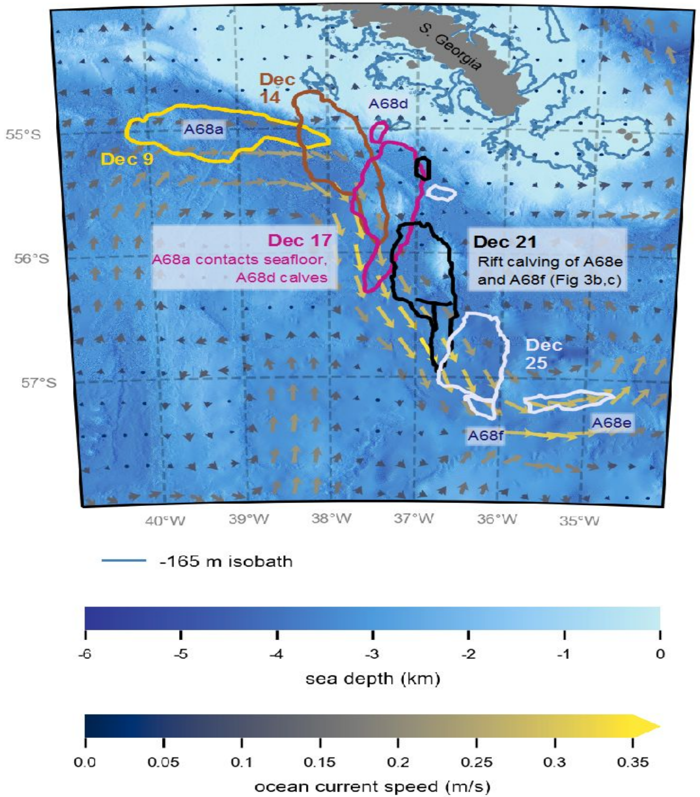



- In response to prescribed Antarctic ice sheet melting, CM4 (1/4°) yields strong subsurface cooling (i.e. a negative feedback to melting), while ESM4 (1/2°) yields strong subsurface warming (i.e. a positive feedback to melting) along the West Antarctic shelf
- The difference is due to the models' differing baseline representation of the Antarctic Slope Current. CM4 simulates a stronger Antarctic Slope Current, while ESM4 simulates a weaker, more diffuse current
- The results show the importance of ocean model resolutions in resolving the Antarctic Slope Current, and the importance of coupling ice sheet to ocean for better estimates of sea level rise and other global changes related to Antarctic ice sheet melting

Figure: Speed (cm/s) depth-averaged over the upper 500 m simulated in the 1/12°Southern Ocean State Estimate (SOSE) (a), GFDL CM4 (b), and GFDL ESM4 (c)

Beadling et al., 2022, JGR-Oceans, one of the top 10 cited papers in JGR-Oceans in 2023

# Antarctic Icebergs and Spatial Distributions of Freshwater Melting




Huth, Adcroft, Sergienko & Khan, Science Advances, 2022

GFDL giant iceberg model simulates the observed breakup of Antarctic iceberg to understand giant iceberg breakup mechanism

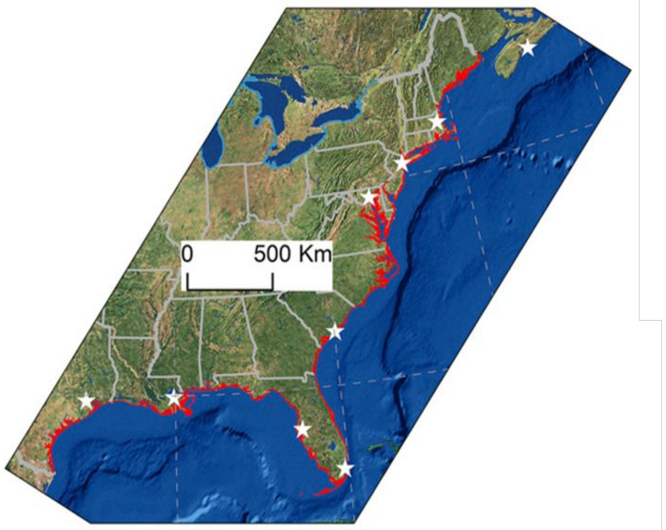
Two breakup events triggered by:

1. Collision with ocean bottom (Dec. 17, 2020)
2. Shear in ocean currents (Dec. 21, 2020, newly discovered breakup mechanism)

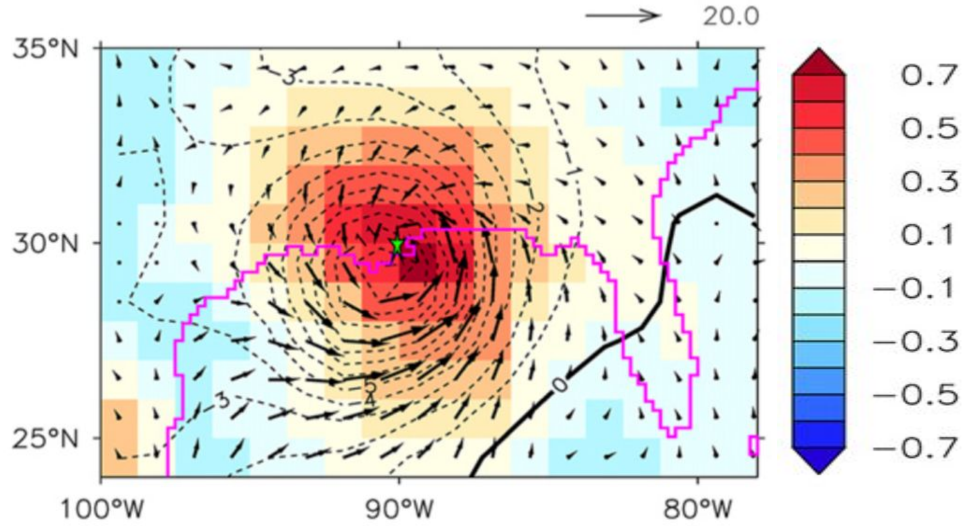
Addressing R6 of 2019 GFDL Lab Review

Figure: Mid-December 2020 Breakup of Iceberg # A68a. The yellow, brown, pink, black, and white outlines show the shape and location of the iceberg through time. As the iceberg collides with the ocean bottom and experiences shear in ocean currents, it breaks apart.

# Storm-related Extreme Sea Level Events




The relatively more frequent extreme sea level events along the US East Coast, particularly **during Nor'Easters,** is linked to the projected decline of the AMOC




GFDL CM4 simulated wind pattern for large surges at New Orleans

Extreme Sea Level events along the Gulf Coast are sensitive to wind anomalies, and therefore **changes in Tropical Cyclone activity**

J. Yin (U. Arizona), S. Griffies, M. Winton, M. Zhao, and L. Zanna (NYU) (2020)

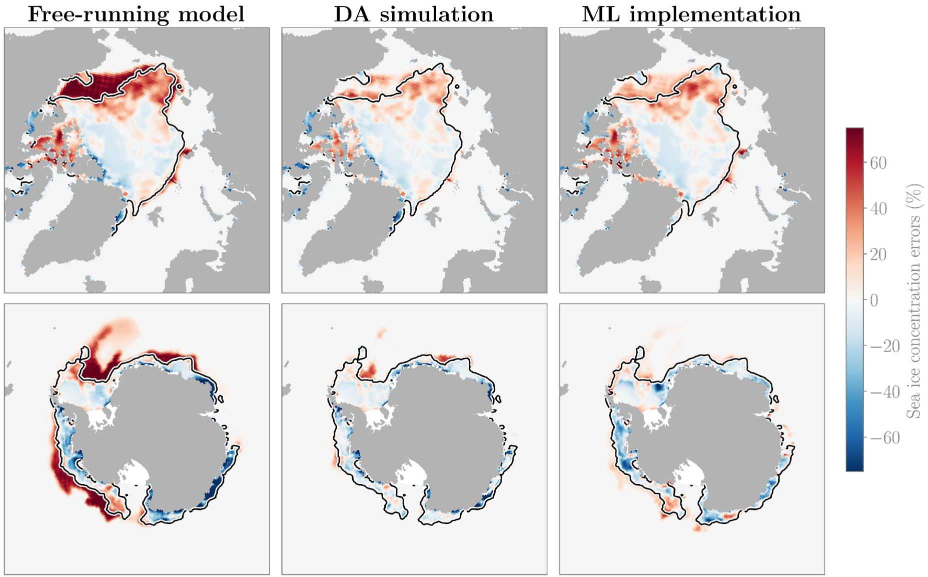
# New Frontier: Machine Learning for Improved Sea Ice Predictions

## GFDL is affiliated with Multiscale Machine Learning In Coupled Earth System Modeling ($M^2$LInES) project funded by Schmidt Science

- Machine Learning can be potentially implemented in improving initial conditions and online bias corrections in seasonal sea ice predictions

$M^2$LInES participants: Princeton/GFDL scientists (Adcroft, Bushuk, Reichl, Lu) and CIMES postdocs (Sane, Gregory, Cheng)

**Correcting ice-ocean simulations with Machine Learned model can significantly reduce sea ice concentration error**




Snapshots of summertime sea ice concentration errors (model minus observations) for the FREE, Data Assimilation (DA) and Machine Learned (ML) ice-ocean simulations (Gregory et al. 2024, GRL)

# Future Directions to Address Challenging Issues

- Without an accurate projection of future AMOC change, we cannot accurately project many societal challenges. It's crucial to reduce uncertainties of projected future AMOC change and associated impacts

- Without an accurate projection of Arctic freshwater release, we cannot accurately project future AMOC change. It's important to improve projections of Arctic freshwater release

- Dynamic coupling of Antarctic/Greenland ice sheets with ocean/atmosphere is necessary for better projections of future sea level rise and freshwater melting-related impacts

- Incorporating AI/ML for research on ocean/cryosphere processes and coupled interactions