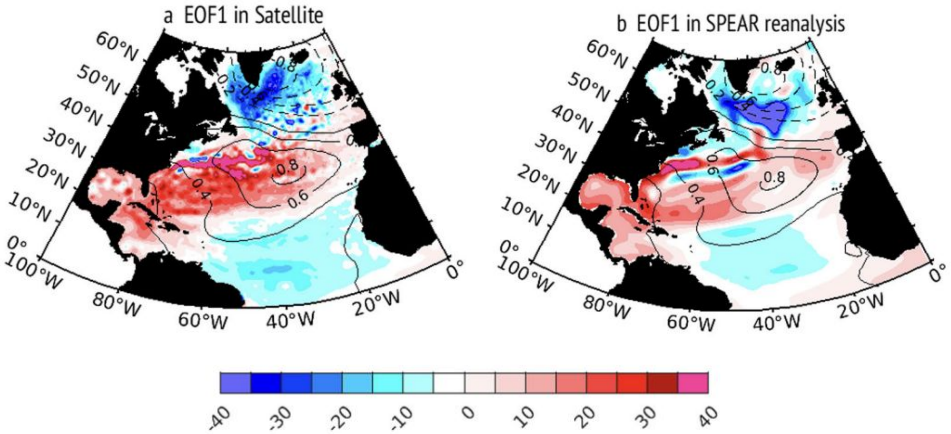
Seasonal to Decadal Variability & Predictability: Oceans & Cryosphere

John Krasting and Mitch Bushuk

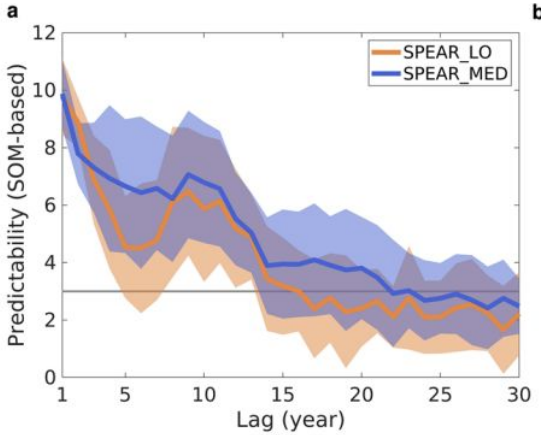
Q2: Concerning NOAA's key mission element of understanding, predicting, and projecting changes in the Earth System, how can GFDL drive further advances in these areas, including extremes and environmental hazards, through scientific innovation based on observations, theory, and modeling? Where are the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

Using SPEAR to predict sea level anomalies

Seasonal prediction models struggle with sea level anomalies, especially along the US East Coast. Recent studies demonstrate that SPEAR has skill on seasonal to decadal timescales



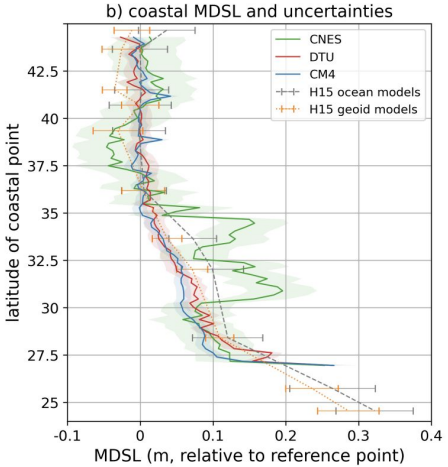
GFDL's SPEAR model captures the observed north-south tripole of sea surface height variability in the North Atlantic - ***Zhang et al. 2024 Nat. Clim. Atm. Sci***



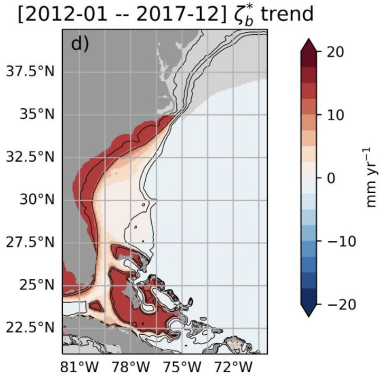
Using self-organizing maps, SPEAR exhibits predictability of N. Atlantic sea level anomalies on decadal timescales - ***Gu et al. 2024, Nat. Clim. Atm. Sci***

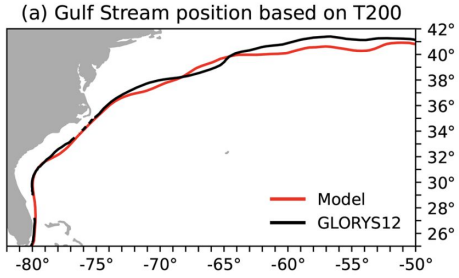
Improving Gulf Stream Representation for Sea Level

The Gulf Stream plays an important role in coastal-open ocean interactions important for sea level, yet global models suffer from common biases in its representation.



Zhao et al. JTECH (in rev.) developed a new three-cornered-hat methodology for using tide gauge data to evaluate ocean models.



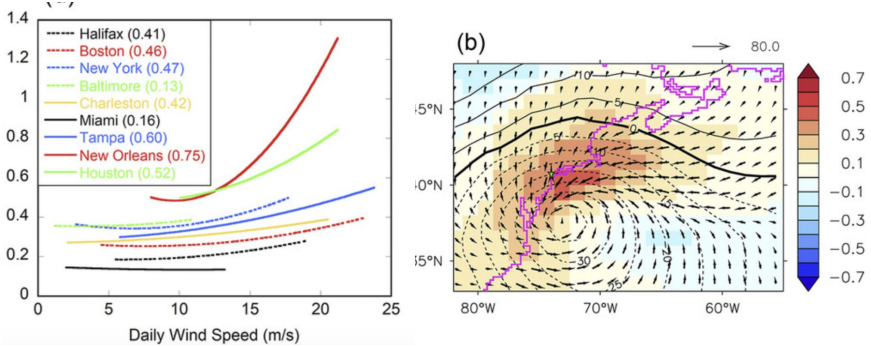


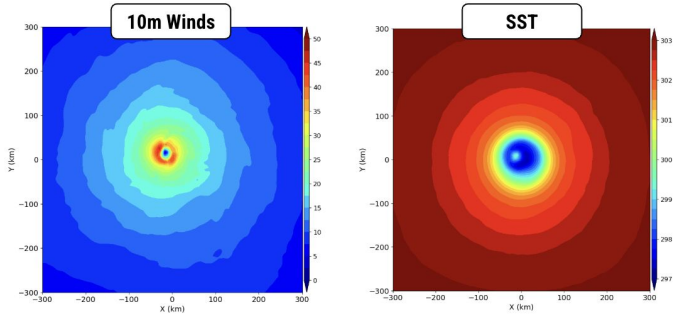
CM4 captures the North-South gradient of sea level better than most global climate models.

Ross et al., 2023 GMD and ***Steinberg et al. 2024, JGR*** Oceans show regional MOM6 configurations (NWA12) ***excel in representing the Gulf Stream***, and found a ***predictable link*** between steric sea level anomalies and offshore subtropical mode water warming.

Simulating Extreme Sea Level Events

Stakeholders are increasingly seeking information on how extreme sea level might change in a warming world.

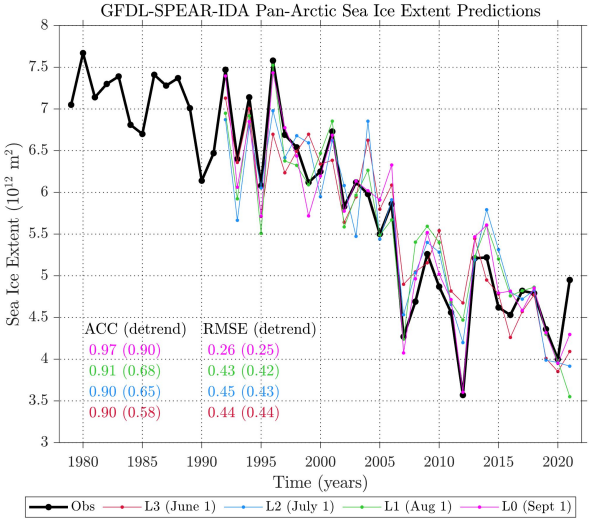


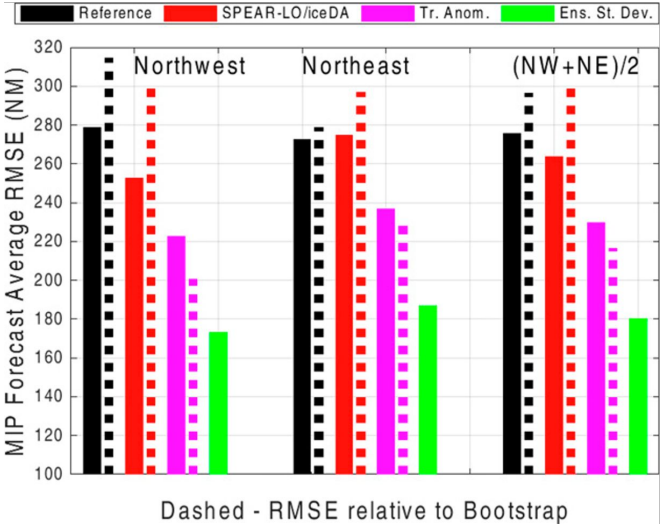


Yin et al. (2020), J. Clim linked future changes in extreme sea level events in CM4 to Nor'easter events while also establishing that stations along the Gulf Coast are sensitive to tropical cyclone wind anomalies. Rising sea levels with a weakening AMOC circulation compounds extremes along the Atlantic and Gulf coasts

As part of work funded by the Bipartisan Infrastructure Law, ***GFDL is developing a coupled 4-km SHiELD and Regional MOM6 configuration along the East Coast*** that incorporates a wave model in order to forecast and study surge and inundation events both now and in the future.

Skillful Seasonal Arctic Sea Ice Predictions with SPEAR



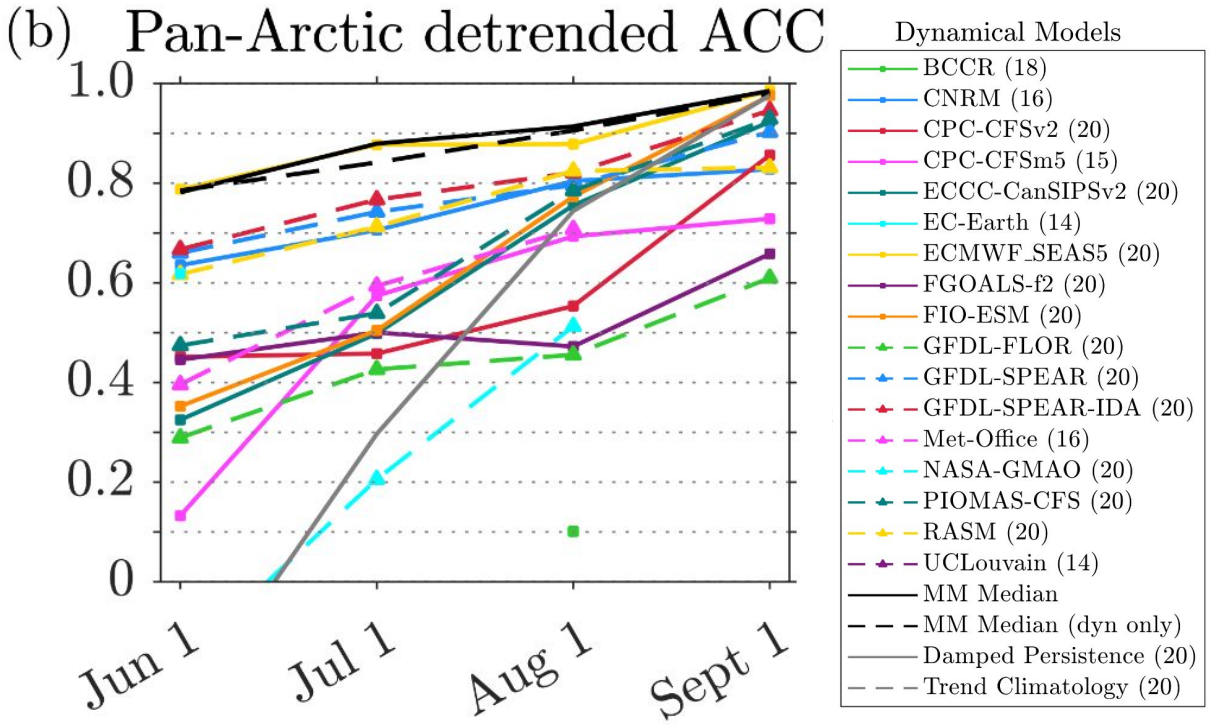


The GFDL SPEAR seasonal prediction system can **skillfully predict Arctic sea ice on the Pan-Arctic, regional, and local scale**[1,2]. GFDL submits **real-time SPEAR predictions** each summer to the Arctic sea ice outlook[3].

SPEAR has prediction **skill for Arctic shipping routes** through summer sea ice in the Northwest and Northeast passages[4].

[1]Bushuk et al. (2022), *J. Climate*; [2]Zhang et al. (2022), *J. Climate*; [3]Blanchard-Wrigglesworth et al. (2023), *GRL*; [4]Winton et al. (2022), *J. Climate*

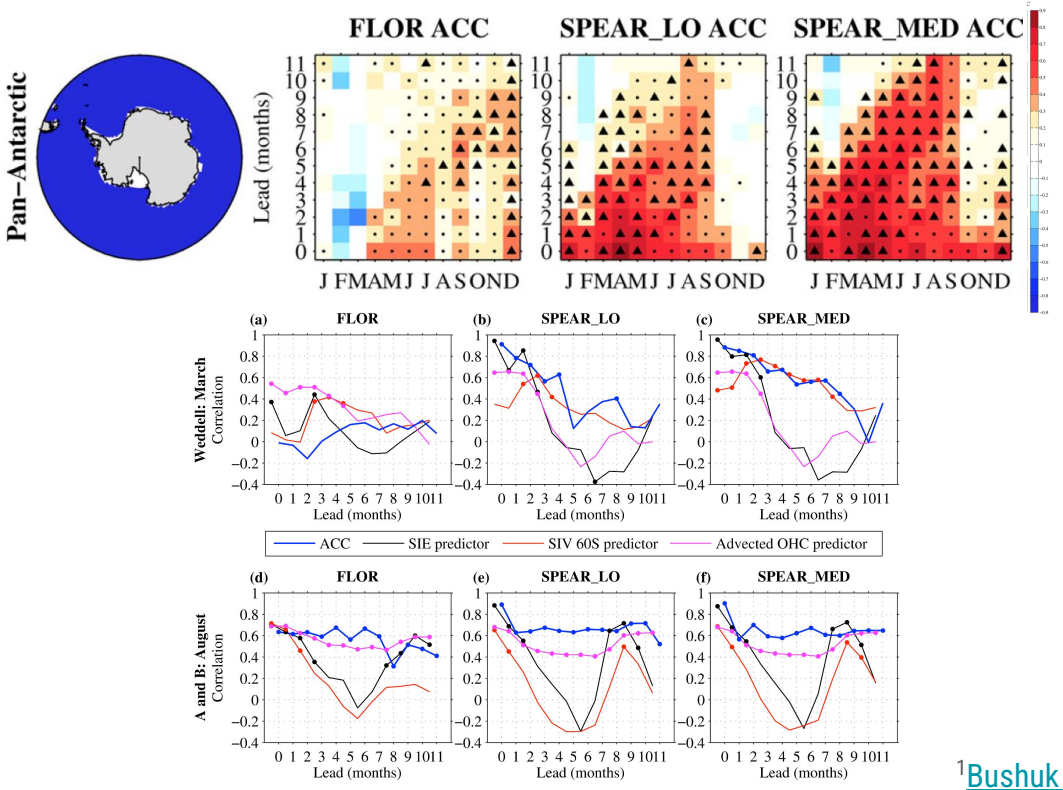
SPEAR is a Top-Performing Sea Ice Prediction System



A recent international intercomparison[1] of seasonal sea ice prediction systems found that **SPEAR systems were the second and third most skillful out of 17 participating dynamical models** (the blue dashed line is the standard SPEAR system; red dashed line is SPEAR with sea ice data assimilation). SPEAR also shows a **notable skill improvement** over GFDL's previous generation prediction system, GFDL-FLOR (green dashed line).

[1] Bushuk et al. (2024), *BAMS*

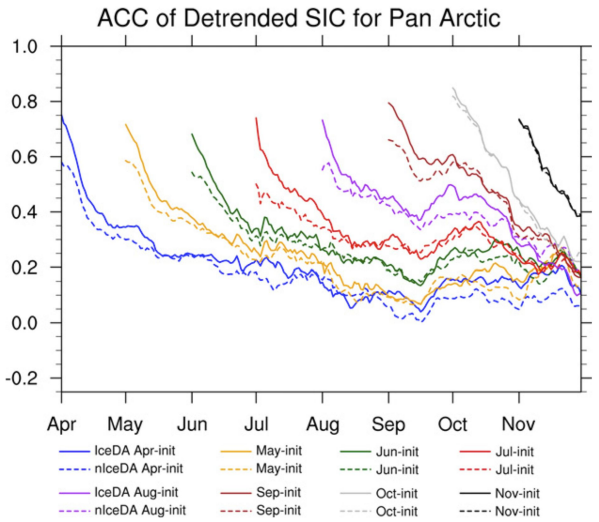
Skillful Seasonal Predictions of Antarctic Sea Ice

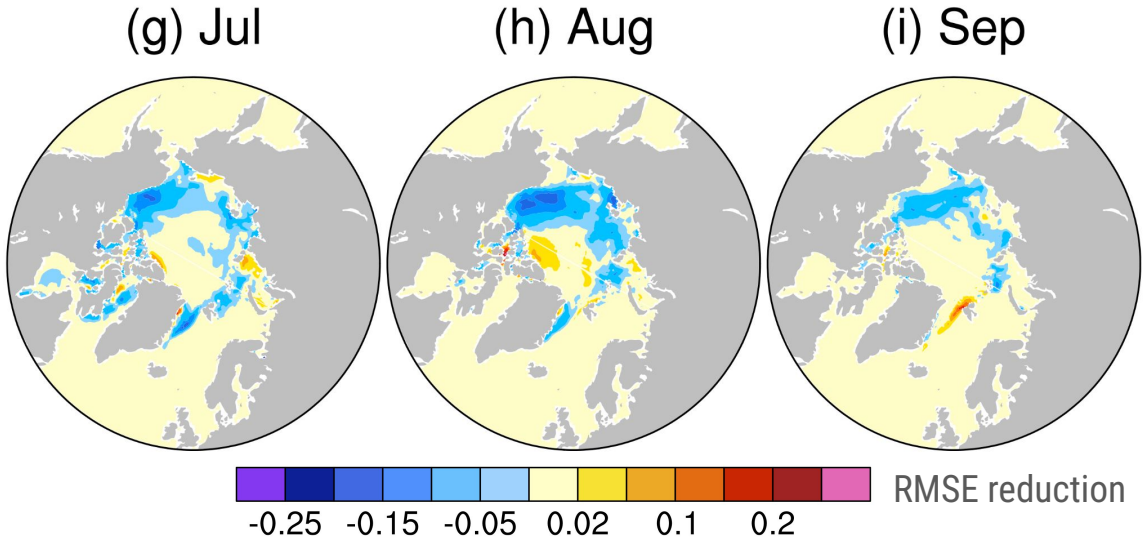


In the **first comprehensive assessment of Antarctic sea ice extent seasonal prediction skill**[1], SPEAR was shown to have skill at predicting both summer and winter sea ice extent anomalies. Summer sea ice prediction skill was primarily attributed to **advection and persistence of sea ice thickness anomalies**. Winter prediction skill was primarily attributed to **advection and persistence of upper ocean heat content anomalies**. GFDL submits SPEAR predictions to SIPN-South, which collects December-initialized predictions of summer Antarctic sea ice[2].

[1]Bushuk et al. (2021), *J. Climate*; [2]Massonnet et al. (2023), *Fron. Mar. Sci.*

SPEAR Sea Ice Data Assimilation System

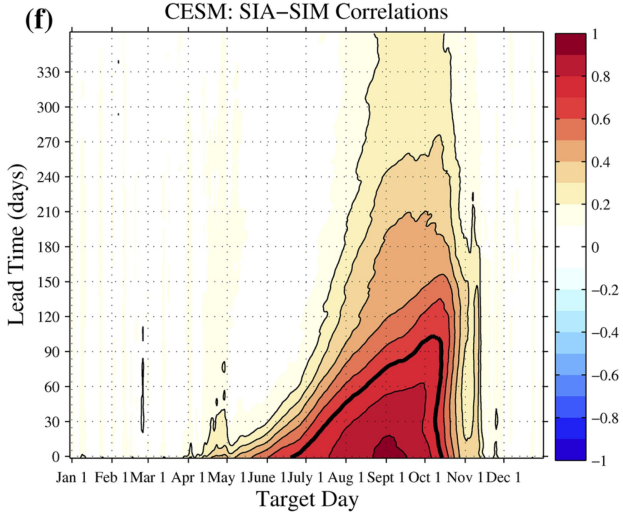


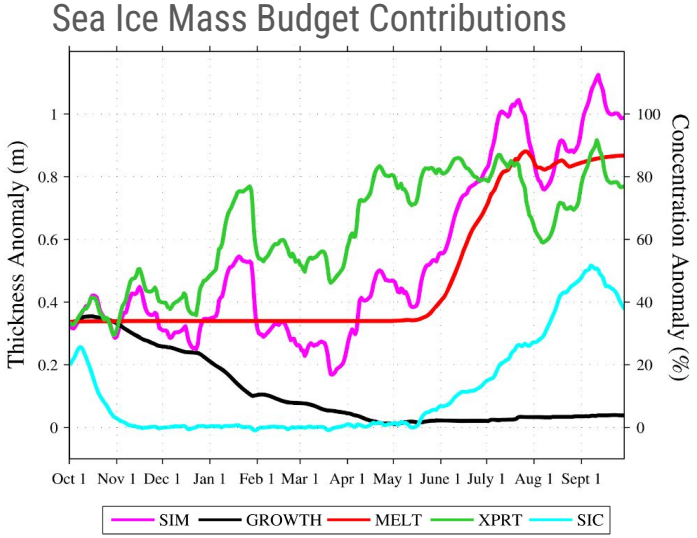


Developed a **novel sea ice data assimilation system** based on an Ensemble Kalman Filter methodology[1]. Assimilation of satellite sea ice concentration observations **improves subseasonal predictions of Arctic[2] and Antarctic[4] sea ice**. Assimilation of satellite sea ice thickness observations **improves seasonal predictions of summer Arctic sea ice[3]**.

[1]Zhang et al. (2021), *J. Climate*; [2]Zhang et al. (2022), *J. Climate*; [3]Zhang et al. (2023), *GRL*; [4]Zhang et al., *in prep for The Cryosphere*

A Spring Predictability Barrier for Summer Sea Ice Predictions

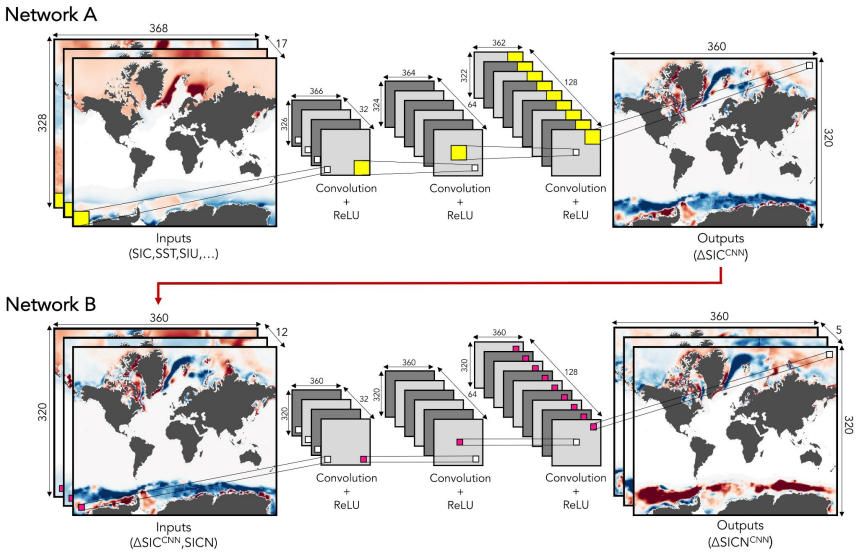


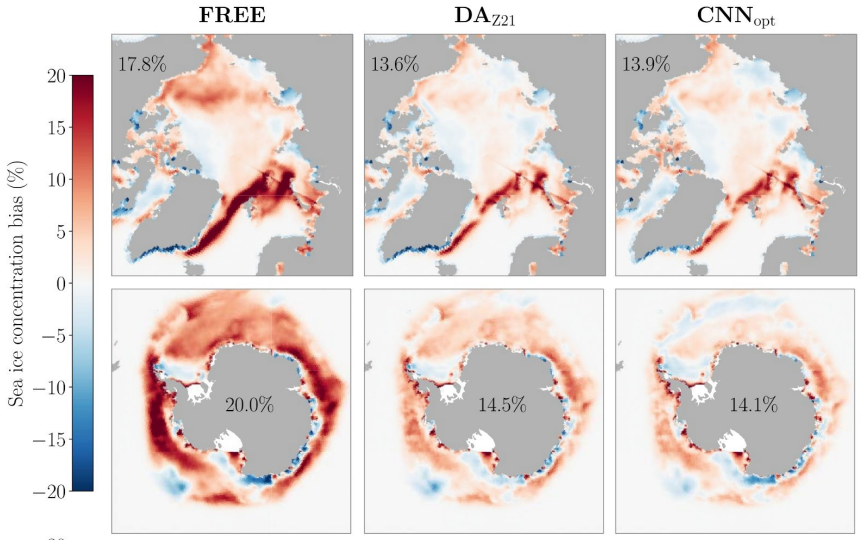


Predictions of summer Arctic sea ice are **limited by a spring predictability barrier**, in which forecast skill drops off substantially for forecasts initialized prior to June 1[1]. The spring predictability barrier results from a competition between **unpredictable variations in sea ice export and thermodynamic growth** in winter and **predictable variations associated with melt onset and ice-albedo feedback** in late spring[2].

[1]Bonan et al. (2019), *GRL*; [2]Bushuk et al. (2020), *GRL*

Improving Sea Ice Models Using Machine Learning





Data assimilation increments provide information on structural model errors. A **convolutional neural network was trained to skillfully predict sea ice data assimilation increments** using local sea ice, ocean, and atmosphere state variables[1]. When applied online as a state-dependent sea ice model correction in free-running global ice-ocean simulations, **the neural network provides a substantial sea ice error reduction in both the Arctic and the Antarctic**[2].

[1]Gregory et al. (2023), *JAMES*; [2]Gregory et al. (2024), *GRL*