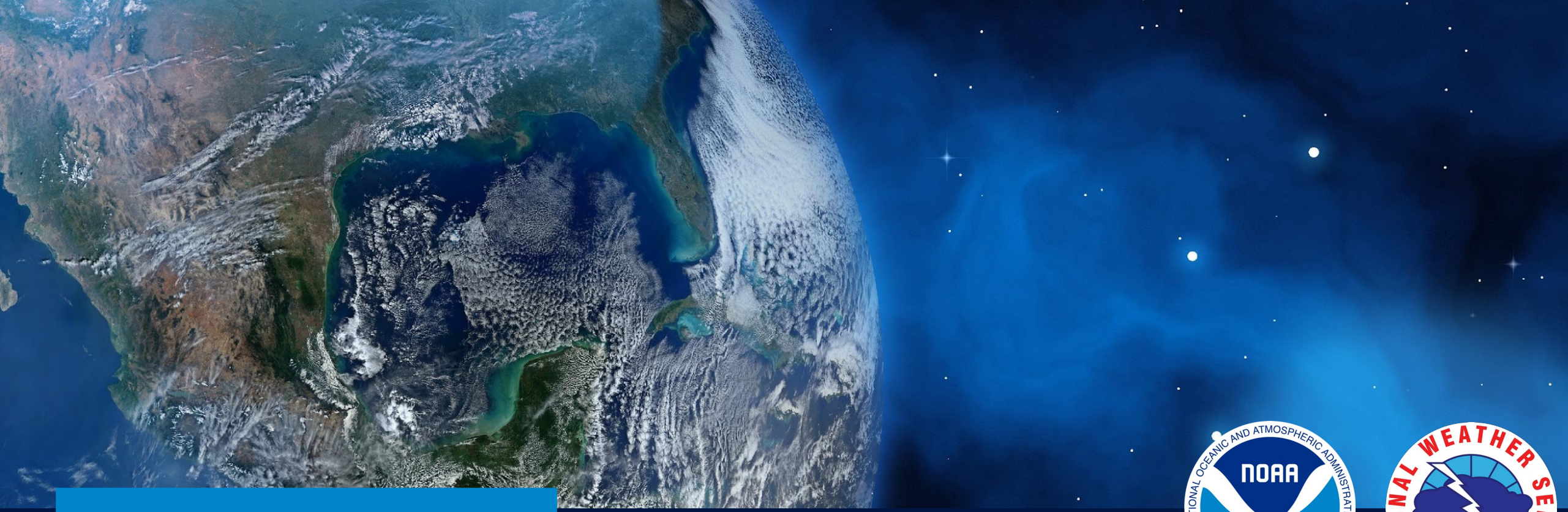


Updated Sea-Ice Initialization in JEDI SOCA for the Global Forecast System

Improving CICE6 Initial Conditions and Sea-Ice Forecasts in UFS

NOAA NWS Office of Modeling and Development

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U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service

Unified Forecast System (UFS) Coupled Model Configuration

Global Forecasting System (GFSv17):

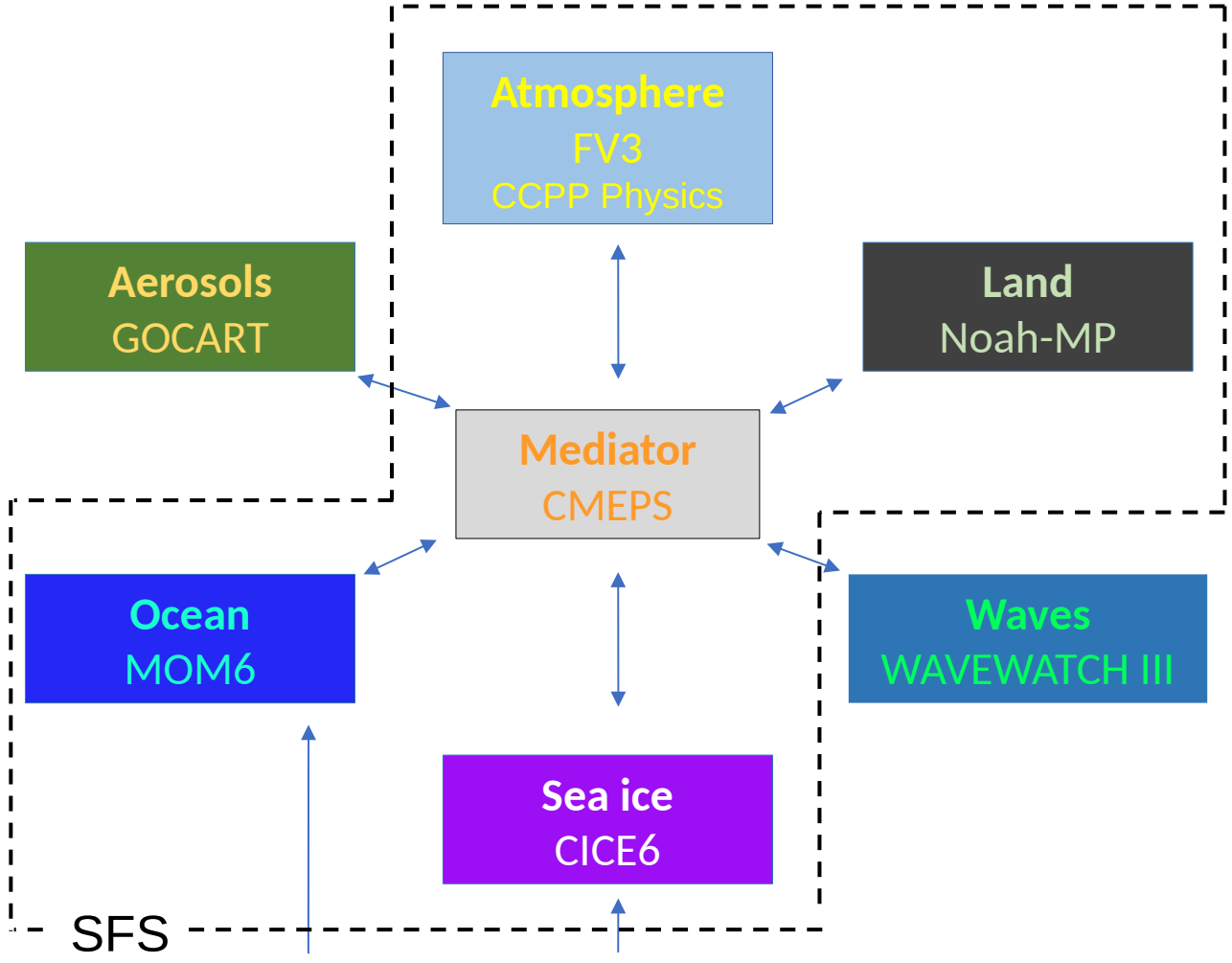
- **Ocean:** MOM6, tripolar 0.25°
- **Sea Ice:** CICE6, tripolar 0.25°
- **Atmosphere:** FV3, "cubed" C1152 (~50km)

Seasonal Forecasting System (SFS Beta 2.0):

- **Ocean:** MOM6, tripolar 0.25°
- **Sea Ice:** CICE6, tripolar 0.25°
- **Atmosphere:** FV3, "cubed" C192

CICE6 Configuration

Parameters	GFSv17	SFS (Test configurations)
Ice layers	7	7
Snow layers	1	1
Ice thkn categories	5	5
Thermodynamics	mushy	mushy
Therm. Conduct.	MU71	bubbly
Rheology	EVP	EVP
Ponds	Level-ice pond scheme	Topographic pond scheme
Snow physics	Off	Snow metamorphism & ITD

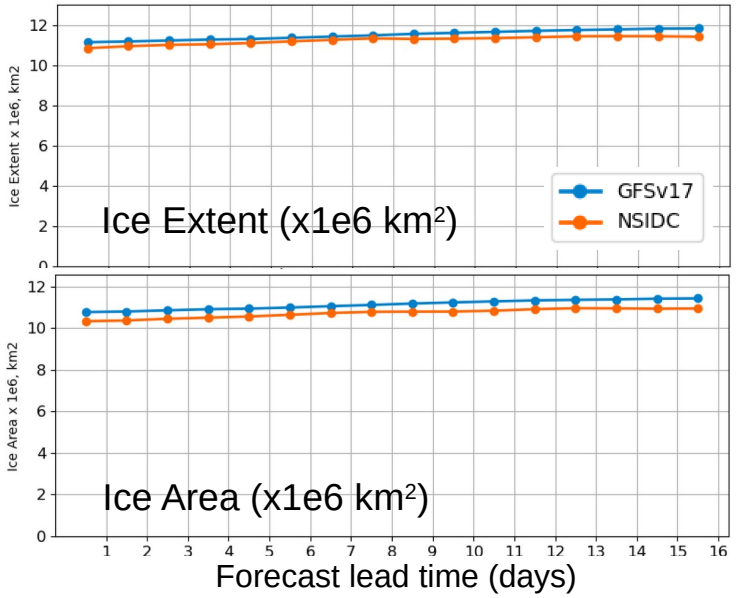


GFSv17: Initial state provided by JEDI/SOCA

Sea ice observations: ice fractional area (concentration) from AMSR2

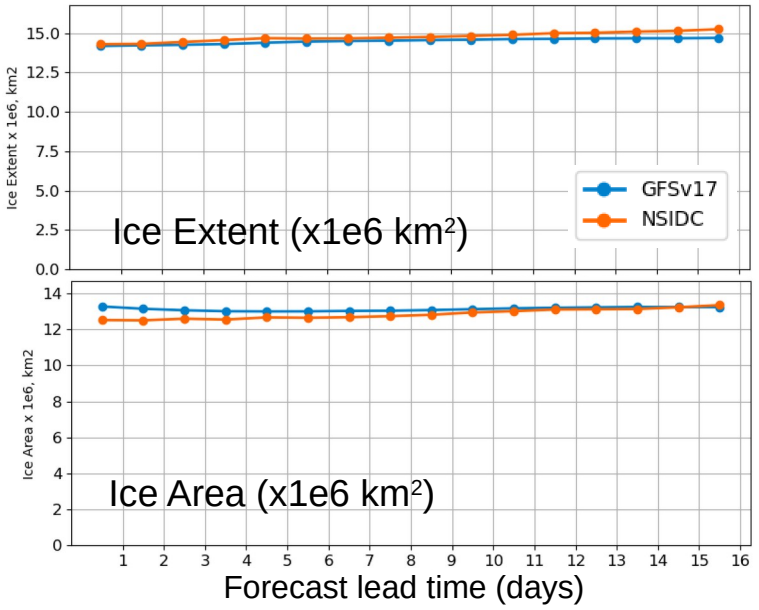
GFSv17 Retrospective Forecasts: Winter Sea Ice

Arctic Ocean

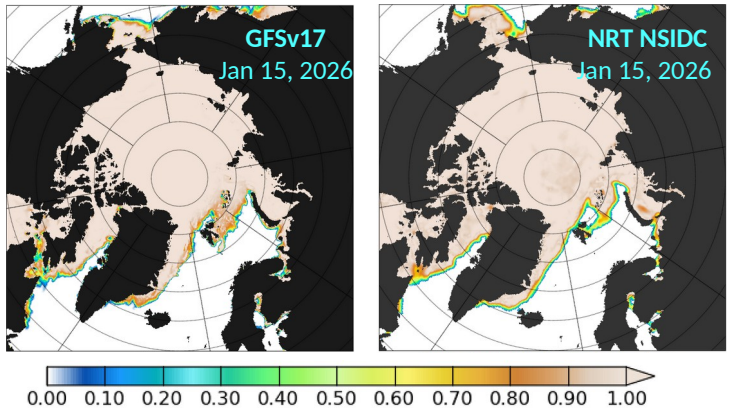


- GFSv17 predicts realistic ice concentration in both hemispheres.
- Accurate prediction of ice concentration and ice edge.
- Slow growing RMSE; outperforms persistence in the Southern Ocean.
- Other variables also look realistic during winter in both hemispheres.

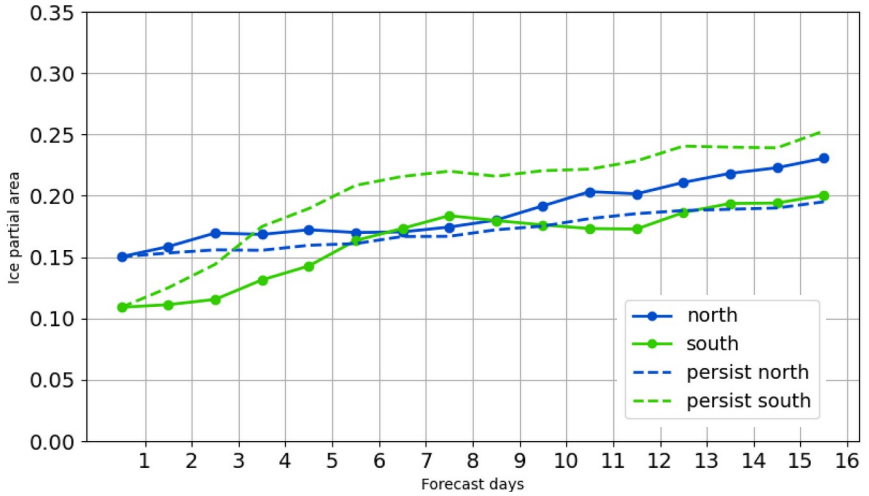
Southern Ocean



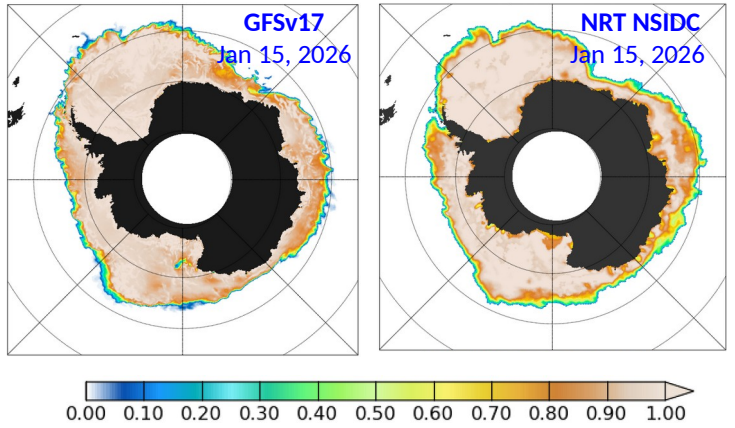
Ice Concentration, FDAY=16



RMSE of ice concentration
GFSv17 vs NRT NSIDC (Winter)

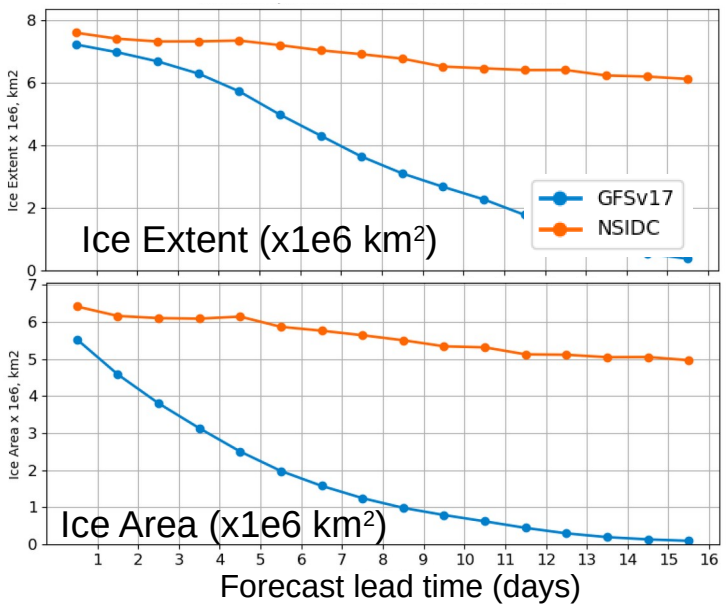


Ice Concentration, FDAY=16



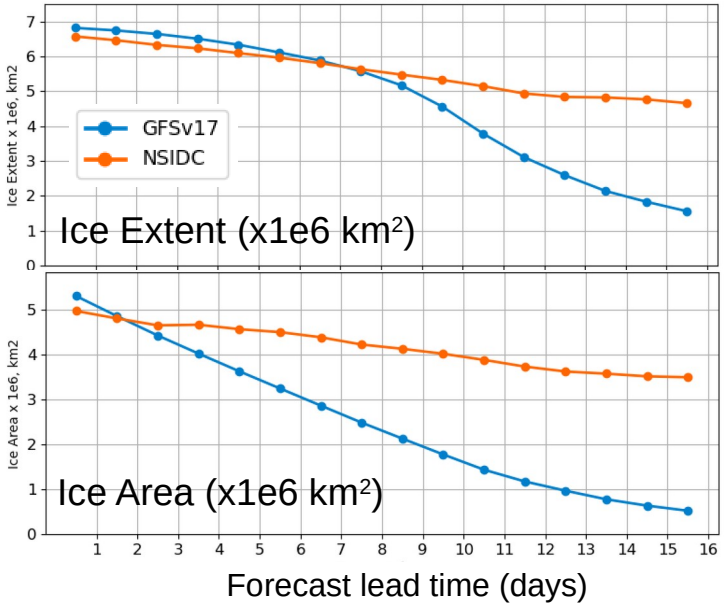
GFSv17 Retrospective Forecasts: Summer Sea Ice

Arctic Ocean

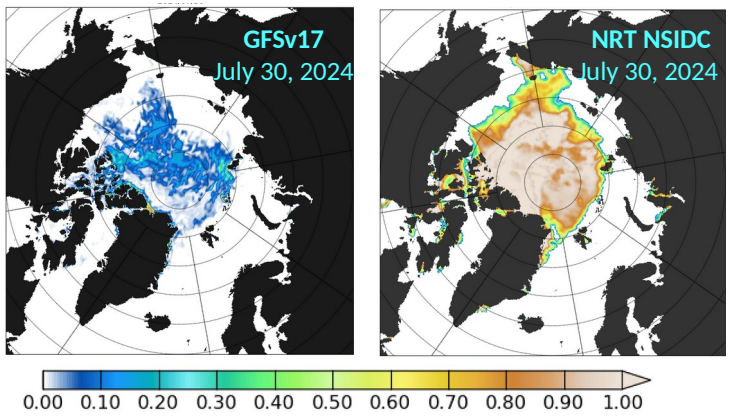


- GFSv17 underpredicts ice concentration in both hemispheres.
- Ice in the Arctic Ocean undergoes substantial melting.
- In both hemispheres: Fast growing RMSE; the forecasts underperform compared to persistence.

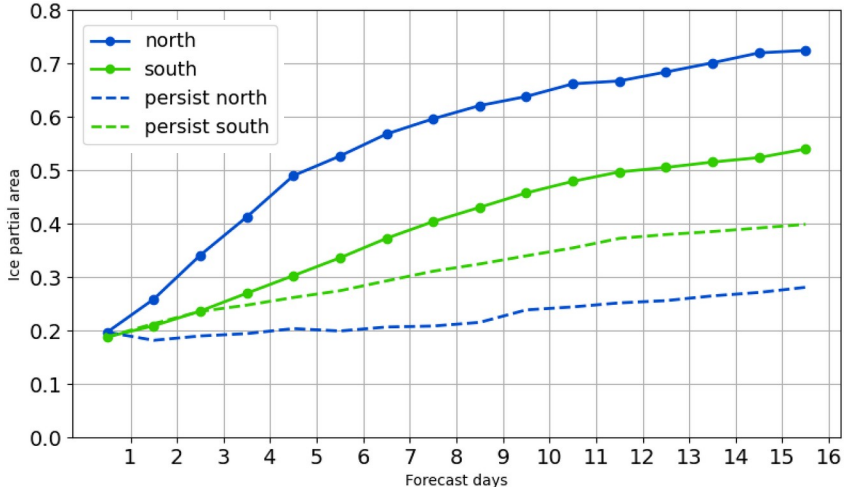
Southern Ocean



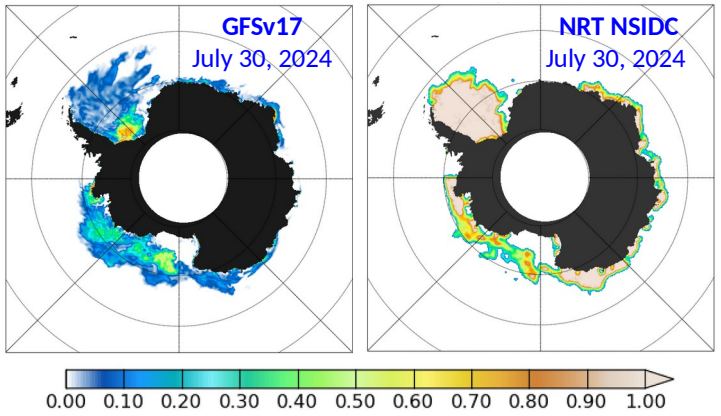
Ice Concentration, FDAY=16



RMSE of ice concentration
GFSv17 vs NRT NSIDC (Summer)

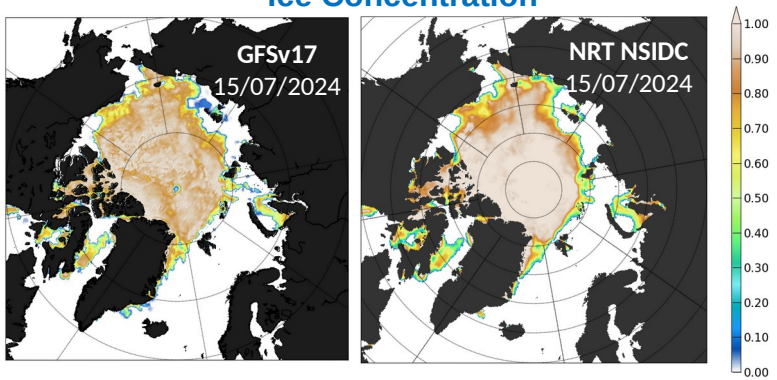


Ice Concentration, FDAY=16

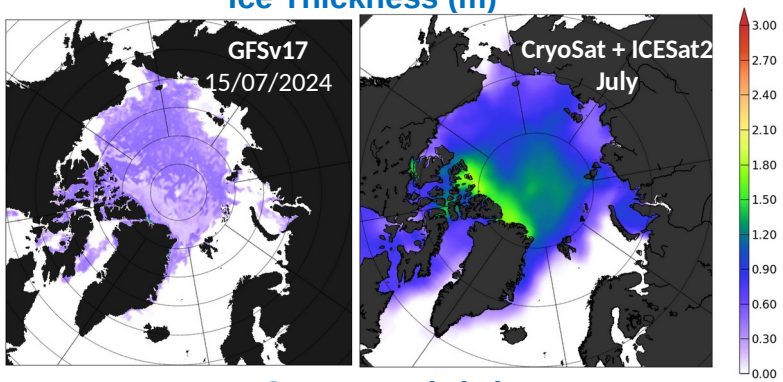


Sea Ice Initial Conditions: A Source of Large Forecast Errors

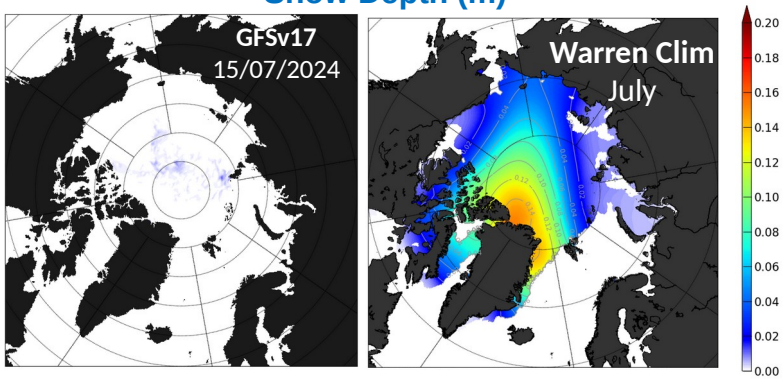
Ice Concentration



Ice Thickness (m)



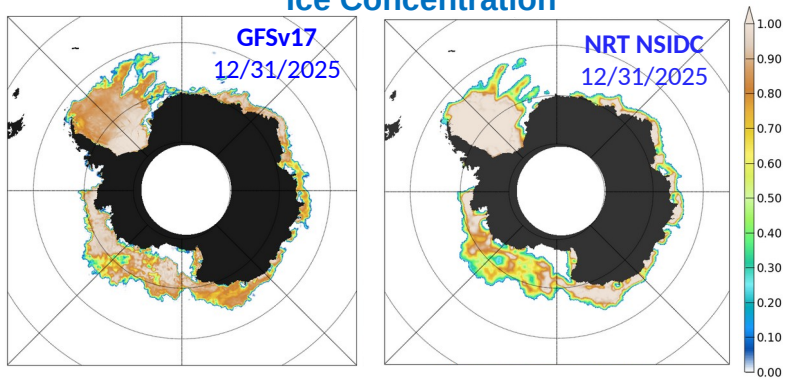
Snow Depth (m)



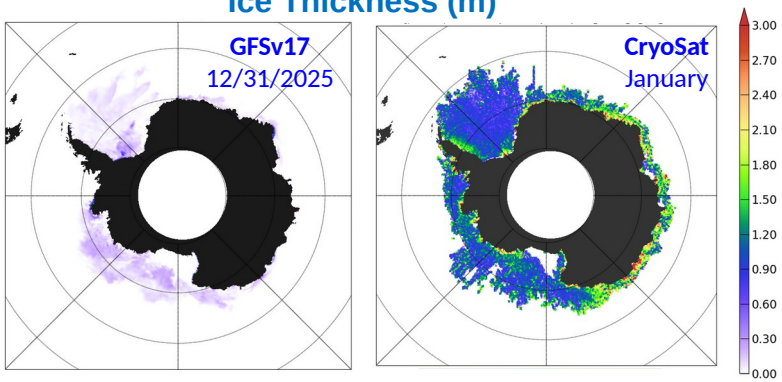
Sea ice IC during melt season in GFSv17:

- **Ice concentration:** provided from SOCA
  - Accurately captures the ice edge and spatial distribution.
- **Ice thickness and snow depth:** currently unconstrained in GFSv17 and inherited from the background
  - During the melt season, errors accumulate from cycle to cycle, leading to progressively underestimated ice thickness and snow depth.
  - After several forecast cycles during the melt season, sea ice is initialized with unrealistically thin ice and little to no snow cover.

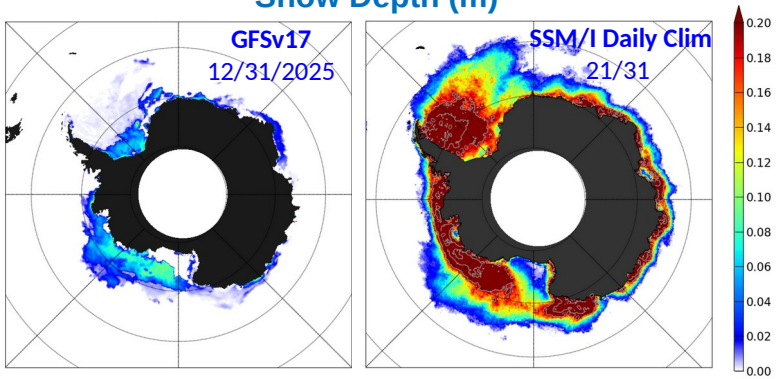
Ice Concentration



Ice Thickness (m)



Snow Depth (m)



Direct Insertion
of Sea Ice Variables into the Initial State

Direct Insertion Algorithm

Ice Concentration

- Insert and redistribute ice concentration across ice thickness categories, preserving total ice volume and target ice area in the grid cell
- Adjust ice / snow / ocean surface T_{sfc}
  - "ice à no ice":
  - "ice à ice", "no ice à ice":

Ice Thickness

- Insert and redistribute target ice volume (m^3/m^2) across ice categories preserving target total ice volume and ice area in the grid cell
- Update S profile in ice layers
- Update ice enthalpy in ice layers
- Update snow depth: $h_{snow} > h_{snow_min}$
- Update snow enthalpy

Ocean surface temperature (MOM6)

- In the ice-covered grid cells:

Snow Depth

- Insert and redistribute target snow volume (m^3/m^2) across ice categories preserving total snow volume in the grid cell
- Update snow enthalpy to maintain thermodynamic consistency
- Update surface ice enthalpy to prevent rapid snow melt at ice/snow interface
- Check ice-snow interface height relative to sea level, to prevent snow-to-ice transition during the 1st step
  - Redistribute snow volume across categories capable of supporting additional load
  - Where needed: Incrementally increase ice thickness in the affected categories until ice-snow interface is restored at / above sea level

Concept: Mapping Ice Variables into the sea ice model state space

Goal: Distribute input state variables across ice thickness categories given the following constraints:

- Preserve target ice partial area:

Input ice partial area $\longrightarrow$ $a_{ice} = \sum_{n=1}^{N_{cat}} a_i(n)$ Redistributed ice partial area should conserve the input partial area

- Preserve target ice volume:

Input ice "thickness" = ice volume per unit grid cell area (m^3/m^2) $\longrightarrow$ $v_{ice} = \sum_{n=1}^{N_{cat}} h_i(n) \cdot a_i(n)$ Redistributed ice thickness should conserve the input ice volume

- Positivity constraint:

,

- Redistributed ice thickness should be within the category bounds:

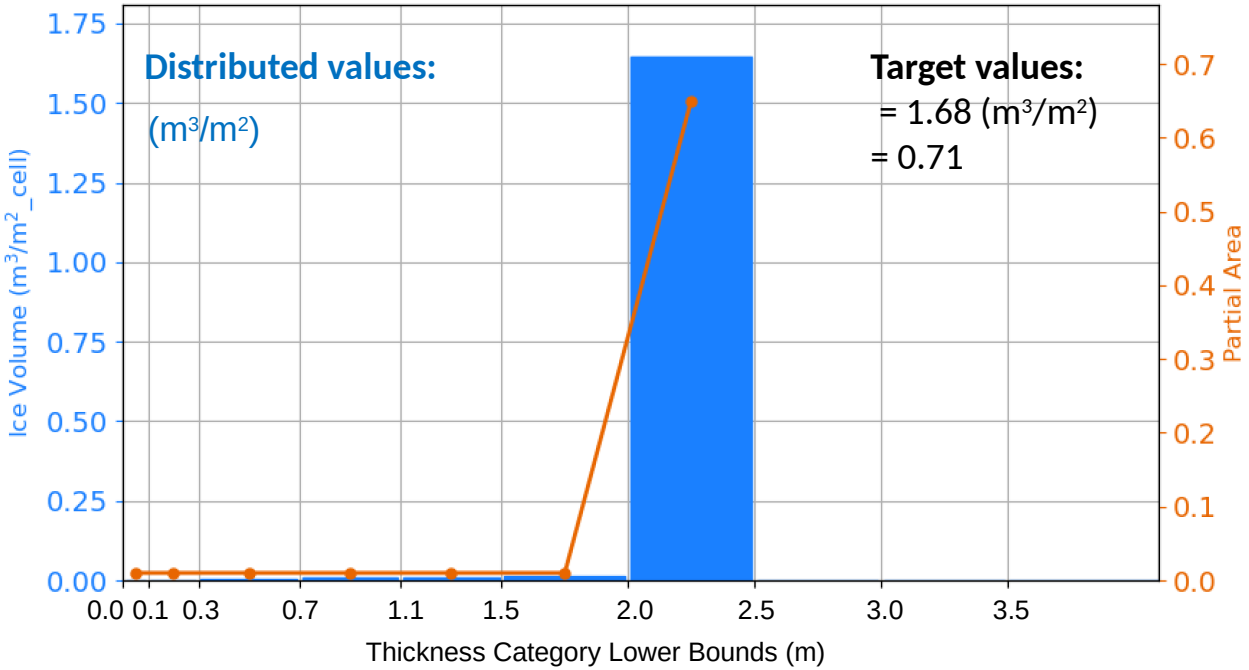
- For optimization, an objective function can be formulated, e.g.:

$$J = \sum_{n=1}^{N_{cat}} \left(a_i(n) - \widetilde{a}_i(n) \right)^2$$ where is initial guess of partial area distribution

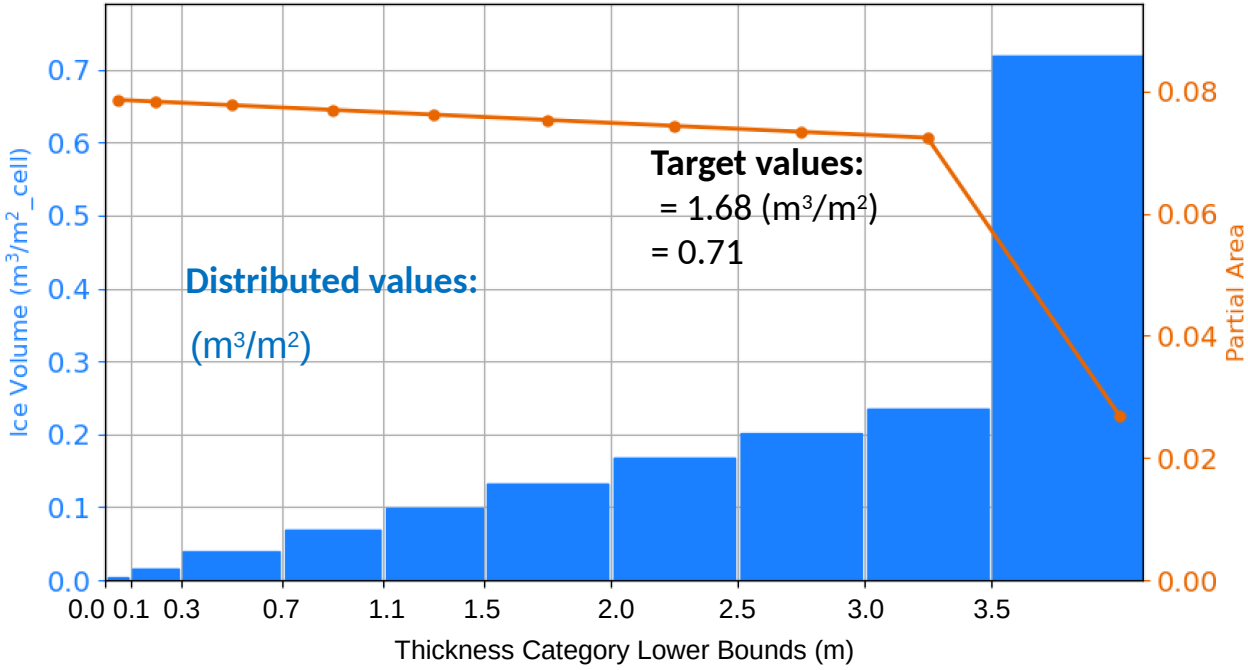
Examples of Ice Redistribution Algorithms

- **Task:** Redistribute the input ice volume per unit area (= 1.68 m^3/m^2) and partial area (= 0.71) across the ice thickness categories while satisfying prescribed constraints
- Examples shown for a 10-category sea ice configuration

Thick-to-thin redistribution



Iterative Constrained Optimization



The algorithm is described in Dukhovskoy et al., GMD, 2026
https://doi.org/10.5194/egusphere-2026-955

Forecasts with Updated Sea Ice Initial Conditions

- Summer season retrospective forecasts
- **Model configuration:** coupled MOM6-CICE6 forced by GFSv16 GDAS atmospheric fields
- Use the direct insertion algorithm for updating sea ice initial state

Test Experiments: Direct Insertion of Sea-Ice Fields

Control run: Replicates the GFSv17 retrospective forecast
Test experiments: Initialized with an updated sea-ice state (summer seasons)

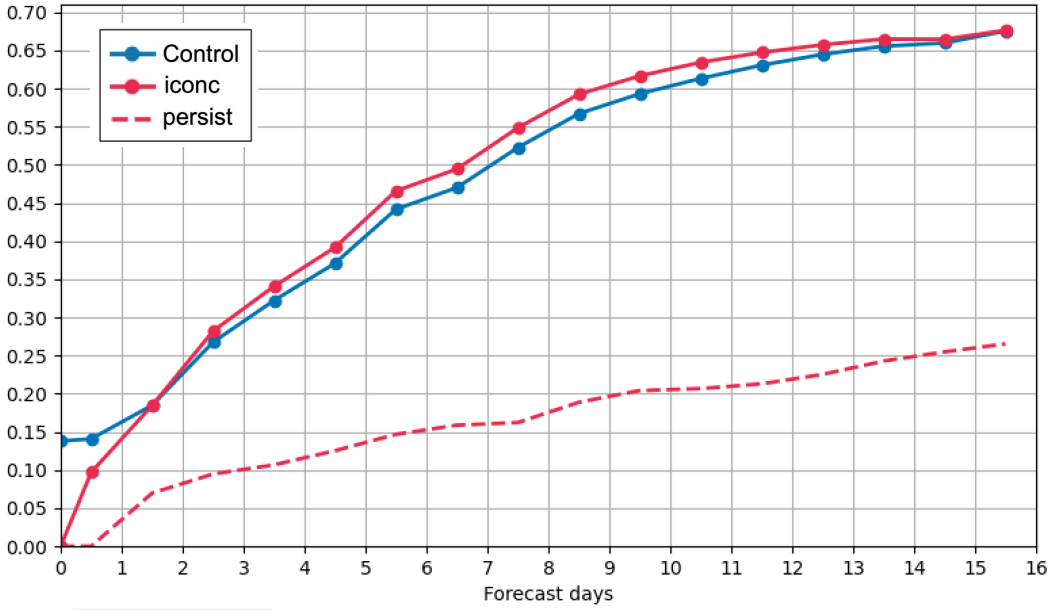
Target Sea-Ice Fields Used for Insertion

Region	Ice Concentration	Ice Thickness "Climatology"	Snow Depth on Sea Ice
Southern Ocean	Daily NRT NSIDC (*)	CryoSat-2 (2010-2021), gridded monthly sea-ice thickness (Fons et al., 2022, 10.5281/zenodo.7327710)	Daily maps of the snow depth on the floating sea ice from SSM/I observations (1992-2007), Markus & Cavalieri, 1999
Arctic Ocean	Daily NRT NSIDC (*)	• CryoSat-2 + SMOS (2019-2024, winter), AWI gridded sea-ice thickness product (Ricker et al., 2017) • AVHRR (*indirect, OTIM-based estimate; 2016-2025*) NOAA NCEI, CDR AVHRR APP-X, version 2 • ICESat-2 (2019-2021, May-August), monthly gridded summer sea-ice thickness, (Petty, 2025, https://doi.org/10.5281/zenodo.18004849)	EWG Atlas ("Warren climatology", Warren et al., 1999)

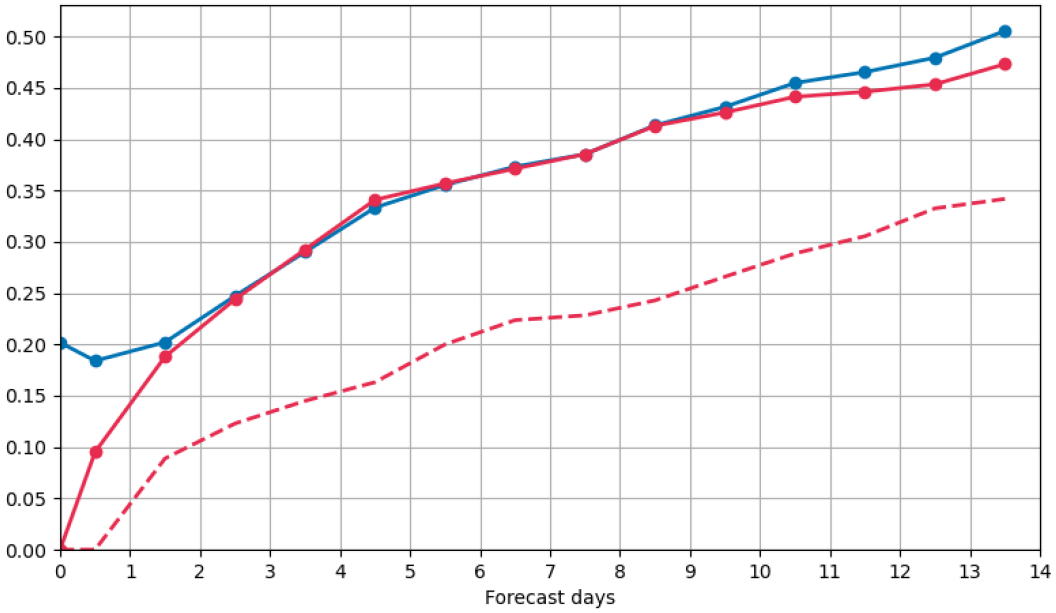
(*) For testing purposes, NRT NSIDC data are treated as "truth" observations. In practice, AMSR2 data are used in GFSv17.

Updated Ice Concentration: Short-Lived Impact

Arctic Ocean
2025/07/04 – 2025/07/19



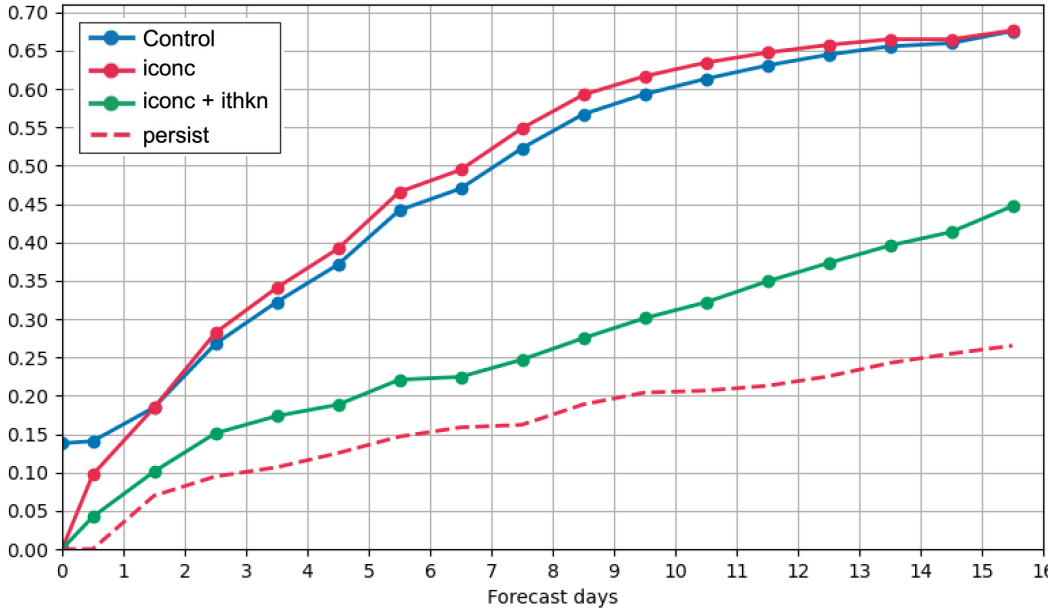
Southern Ocean
2025/01/03 – 2025/01/16



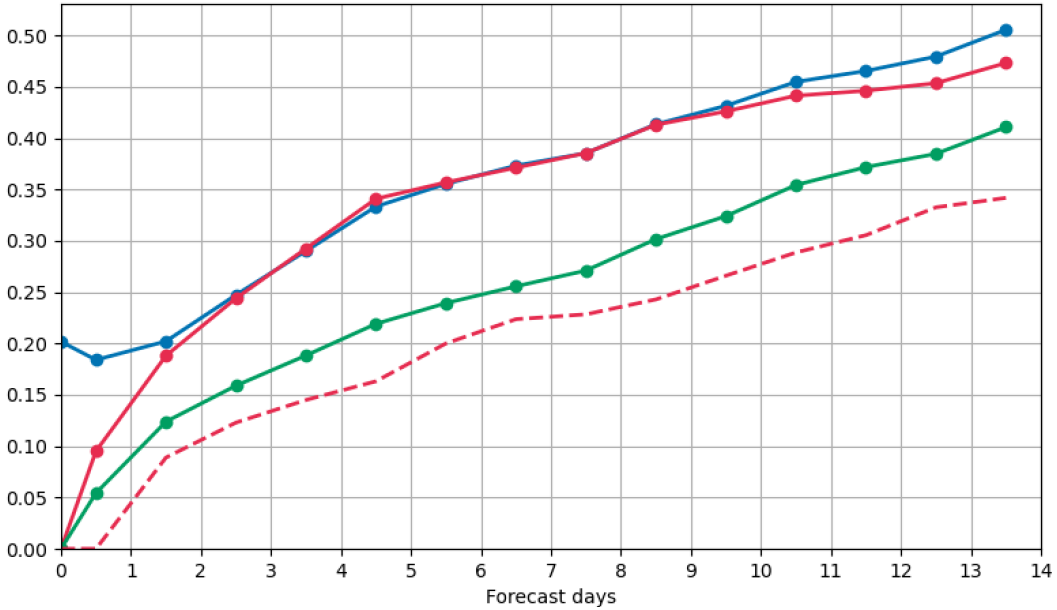
- In both hemispheres, corrected initial ice concentration has a short-lived improvement of the model forecast
- After 2 days, the model returns to the control trajectory
- Persistence outperforms both forecasts

Updated Ice Concentration + Ice Thickness

Arctic Ocean
2025/07/04 – 2025/07/19



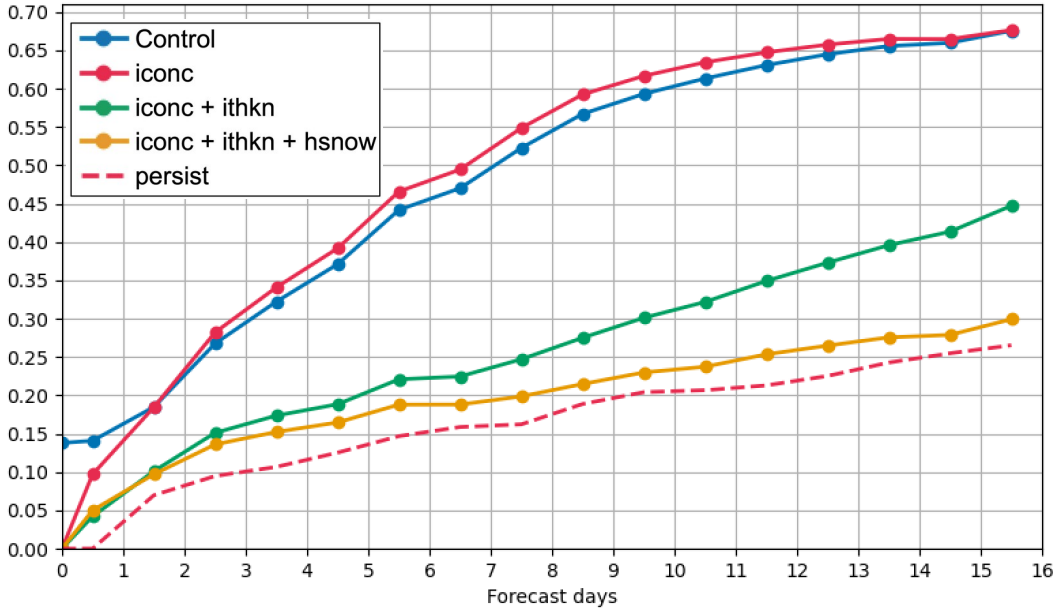
Southern Ocean
2025/01/03 – 2025/01/16



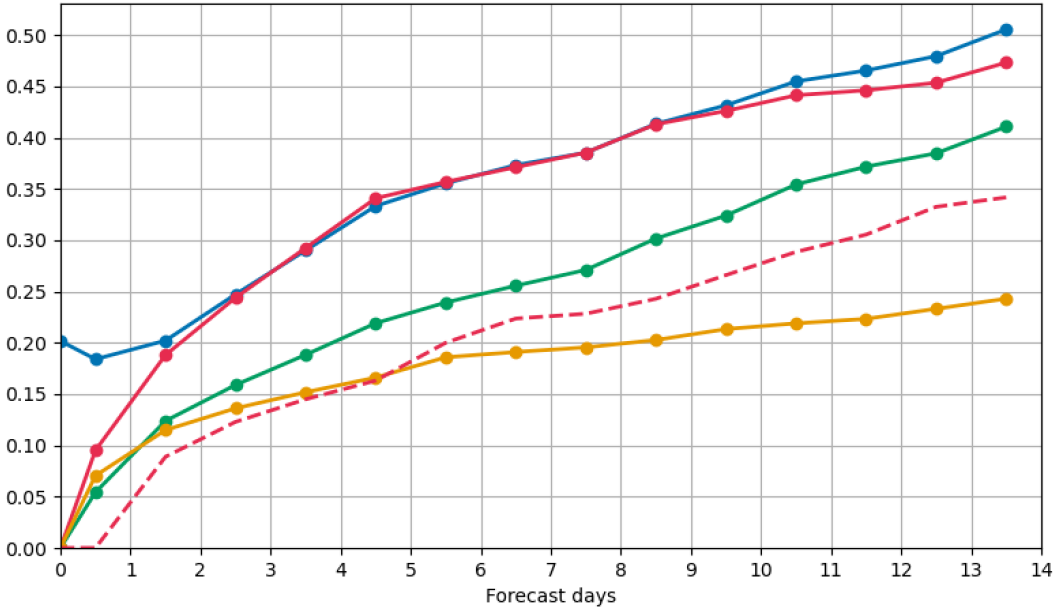
- In both hemispheres, corrected initial ice concentration and ice thickness substantially improve forecast skill.
- The improvement persists throughout the forecast period.
- Persistence outperforms the model forecasts.

Updated Ice Concentration + Ice Thickness + Snow Depth

Arctic Ocean
2025/07/04 – 2025/07/19



Southern Ocean
2025/01/03 – 2025/01/16



- In both hemispheres, corrected initial ice concentration, ice thickness, and snow depth substantially improves forecast.
- The improvement persists throughout the forecast period.
- In the Southern Ocean, the model forecast outperforms persistence after day 5.
- In the Arctic Ocean, persistence still outperforms the model; however, the difference between the two is reduced.

ML Emulator of Ice Thickness

- **Previous experiments:** Ice thickness from satellite-based mean fields.
- **Idea:** Use ML to generate target ice thickness fields based on GDAS / SOCA fields to create sea-ice initial state for the forecast.
- **Training:** Use sea ice reanalysis that can provide physically consistent input fields (predictors)
- **For UFS forecasts:** Use GDAS / SOCA to generate predictors à ML emulator à ice thickness IC

ML Emulator for Sea-Ice Thickness

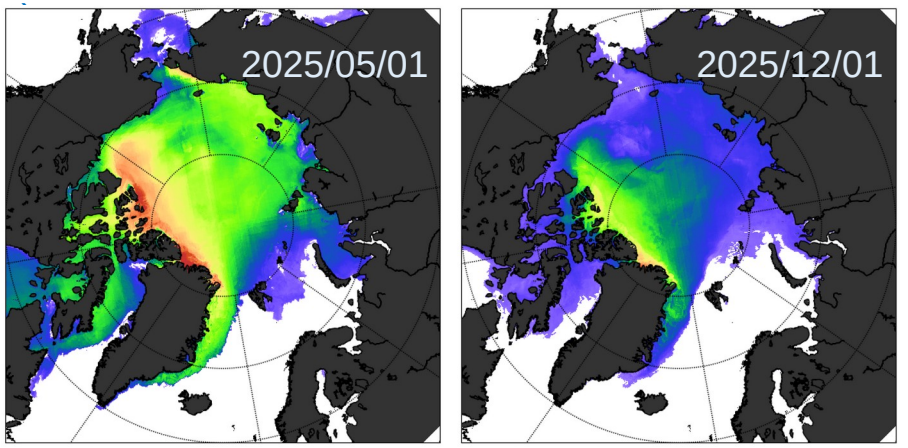
Approach: Gradient Boosting Regressor (max leaf: 63, learning rate: 0.05, max depth: 15)

Training data set: GLORYS ice / ocean fields + ERA5 fields

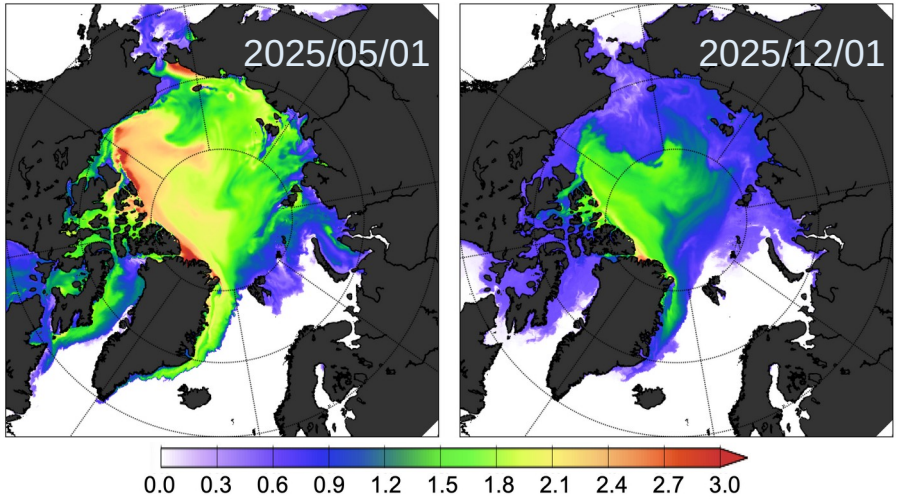
Training data set: 1993-2025, daily fields subsampled at 7-day interval (decorrelation time scal
and a 50-km spatial decorrelation scale, with 80% of the subsampled data

Predictors	Arctic Ocean	Southern Ocean
Year day =	-	-
Geogr. Coord. → spherical coordinates (X, Y, Z)	-	-
Bottom depth () = , -1), if	-0.124 (5)	0.067 (5)
Long-term ice thickness variability (account for long-term trend)	0.27 (3)	0.034 (6)
Ice concentration	0.463 (1)	0.284 (1)
SST	-0.111 (6)	-0.08 (3)
Ice divergence (divU) averaged over decorrelation length scale	0.012 (8)	-0.003 (8)
IFDD (Integrated freeze degree days) =	0.362 (2)	0.145 (2)
IHDD (Integrated heat degree days)=	0.226 (4)	0.072 (4)
T2m	0.048 (7)	0.008 (7)

ML Prediction of Ice Thickness (m)



GLORYS Ice Thickness (m)

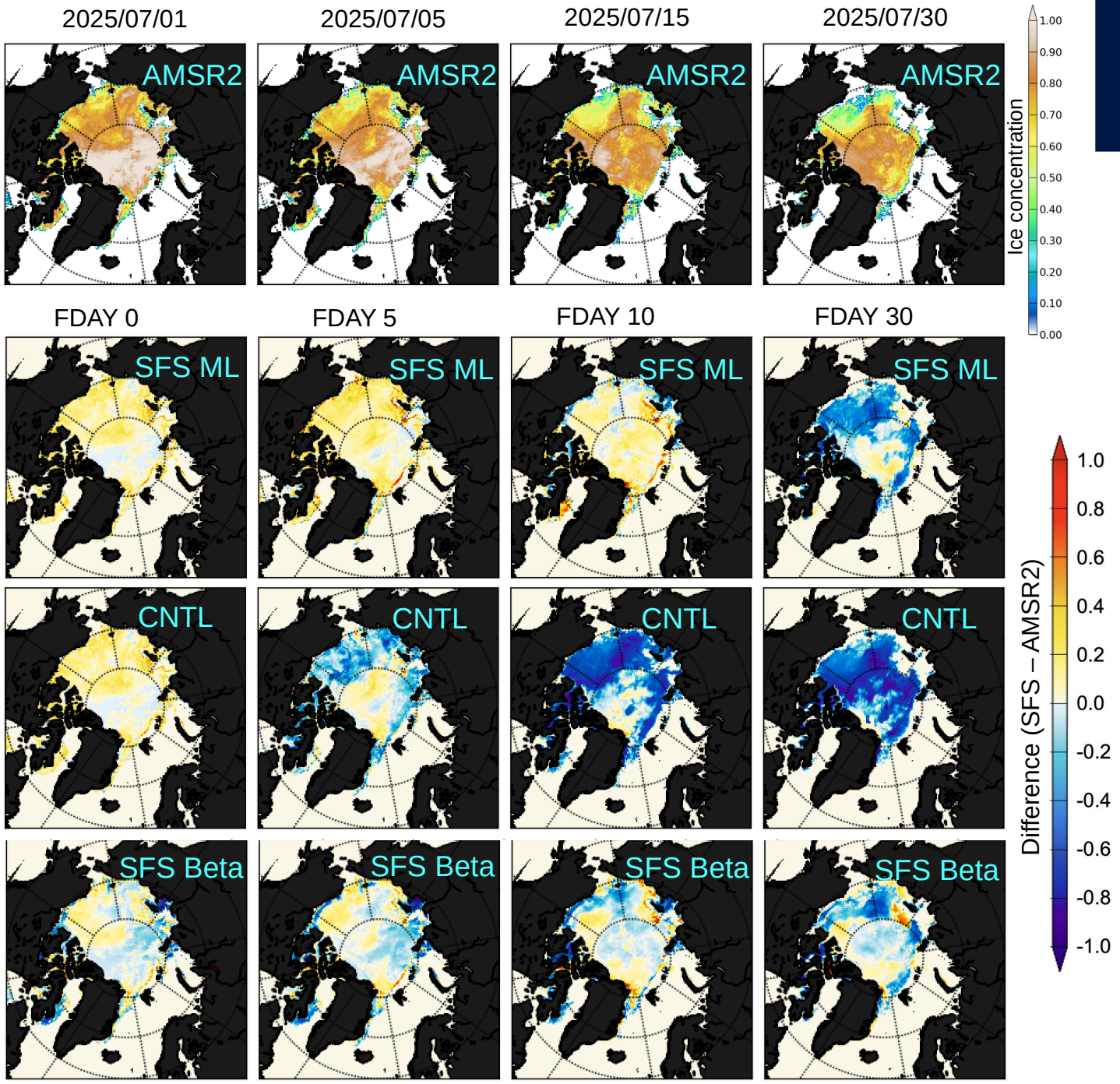


SFS Test Experiments: Sea-Ice Forecast Different CICE6 Initializations

Forecast period: 2025/07/01 – 2025/08/31 (boreal summer)

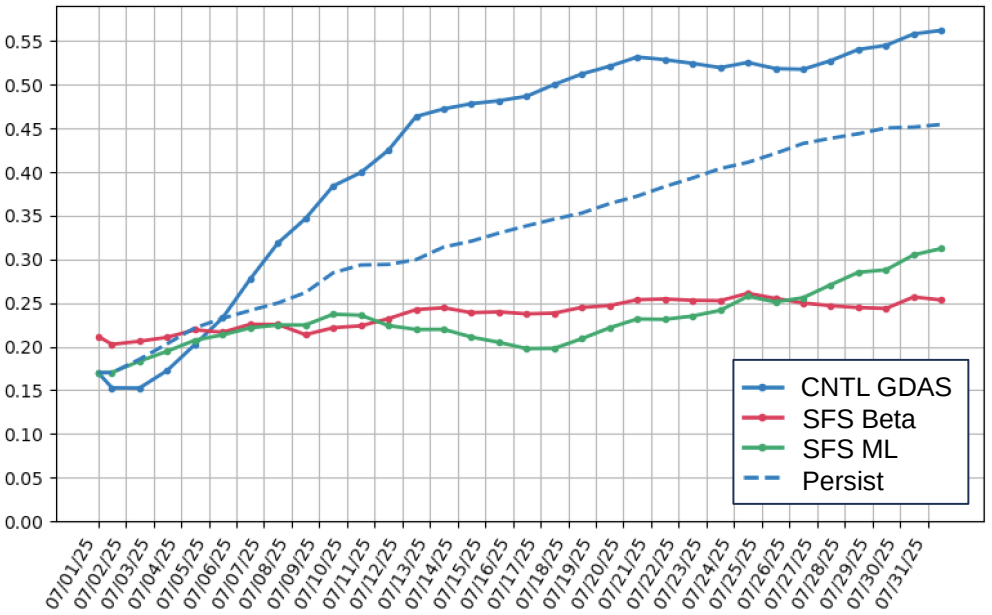
Experiment	Initial State	CICE6 parameters
Control	**Ocean, ice, atmosphere:** GDAS / SOCA analysis	**GFSv17 default**
SFS Beta	NOAA CPC analysis **Ocean / ice:** GLORe **Atmosphere:** CORe	**SFS Beta2.0:** • Melt-pond topography parameterization • Bubbly-brine thermal conductivity • Snow-grain metamorphism • Snow redistribution across the ice-thickness distribution (ITD) • Updated Delta-Eddington radiation parameters • Updated melt-pond geometry
SFS ML	**Atmosphere / Ocean:** GDAS / SOCA **Sea Ice:** • Thickness: ML emulator • Concentration: SOCA • Snow depth: Warren climatology **ML Emulator Input:** GDAS / SOCA	

SFS – AMSR2 Comparison:
Ice Concentration Differences and RMSE

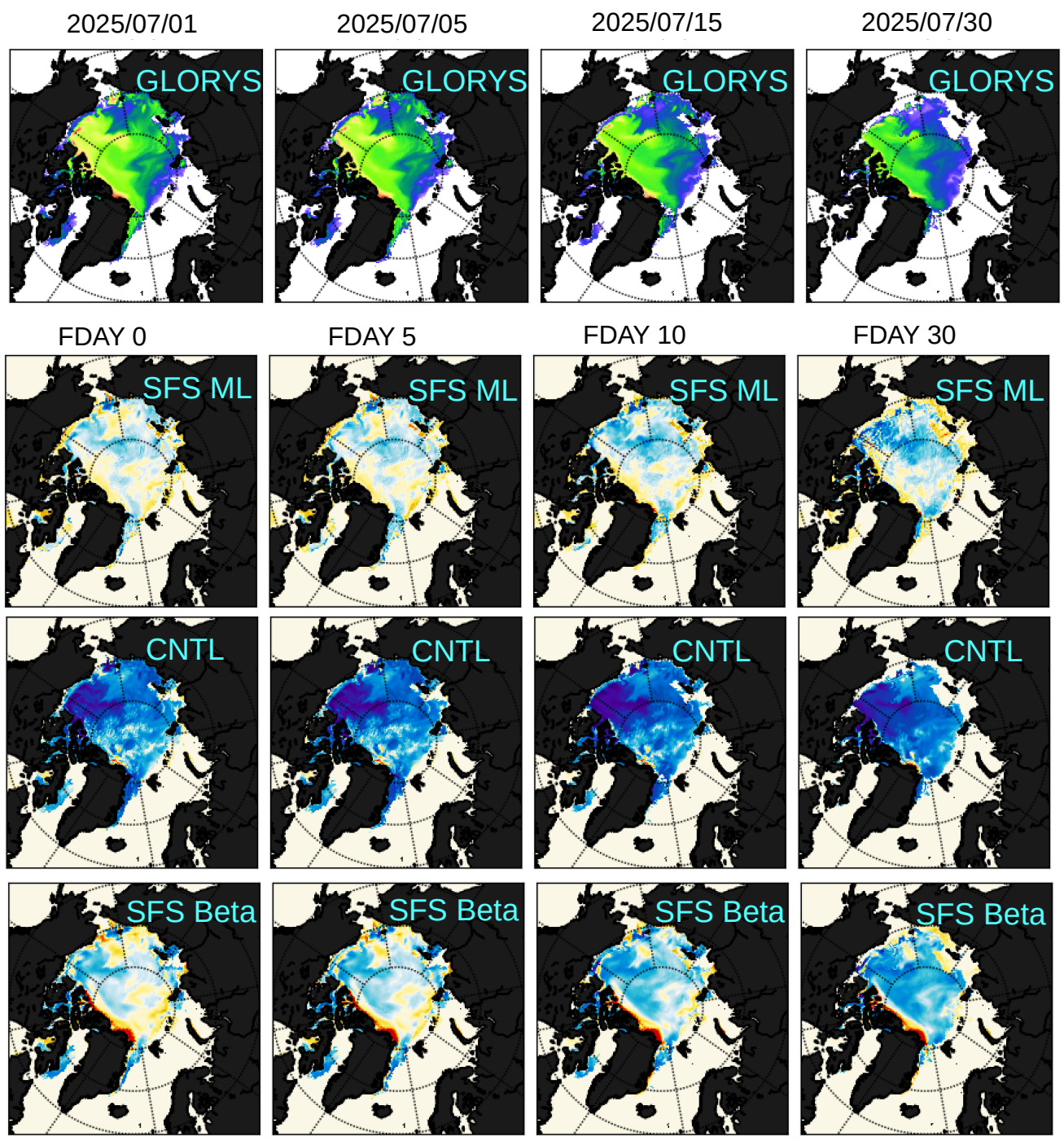


- **SFS ML:** Low RMSE; Outperforms persistence, outperforms CNTL run after FDAY 5, outperforms SFS Beta during the first 3 weeks.
- **Control GDAS:** Low RMSE during the first 5 days, followed by rapid degradation of the forecast skill due to intensive ice melt.
- **SFS Beta:** Gradually increasing RMSE; outperforms persistence after FDAY 5 and CNTL after FDAY 6.

RMSE of ice concentration SFS vs AMSR2

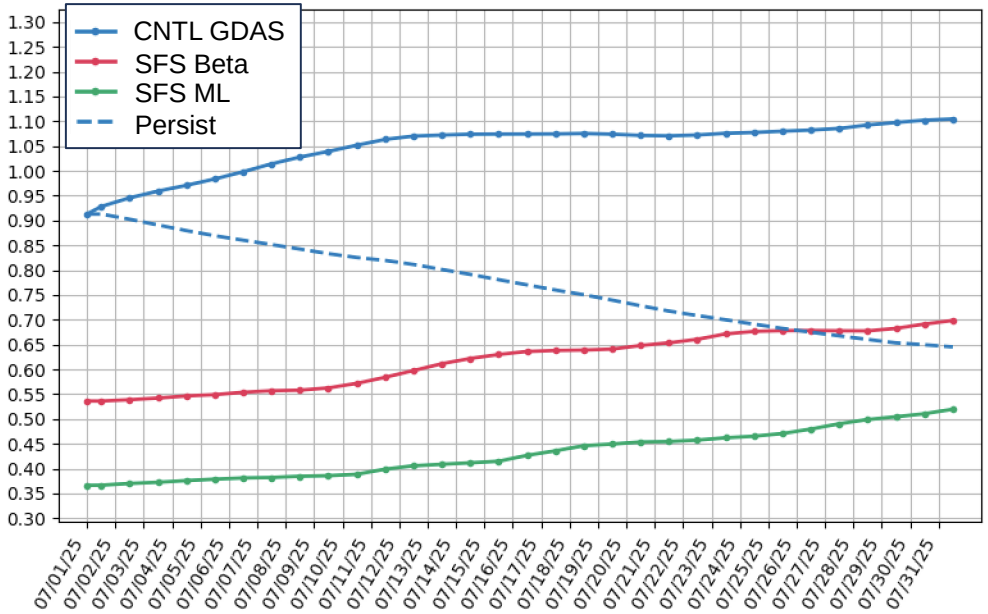


SFS – GLORYS Comparison:
Ice Thickness Differences and RMSE

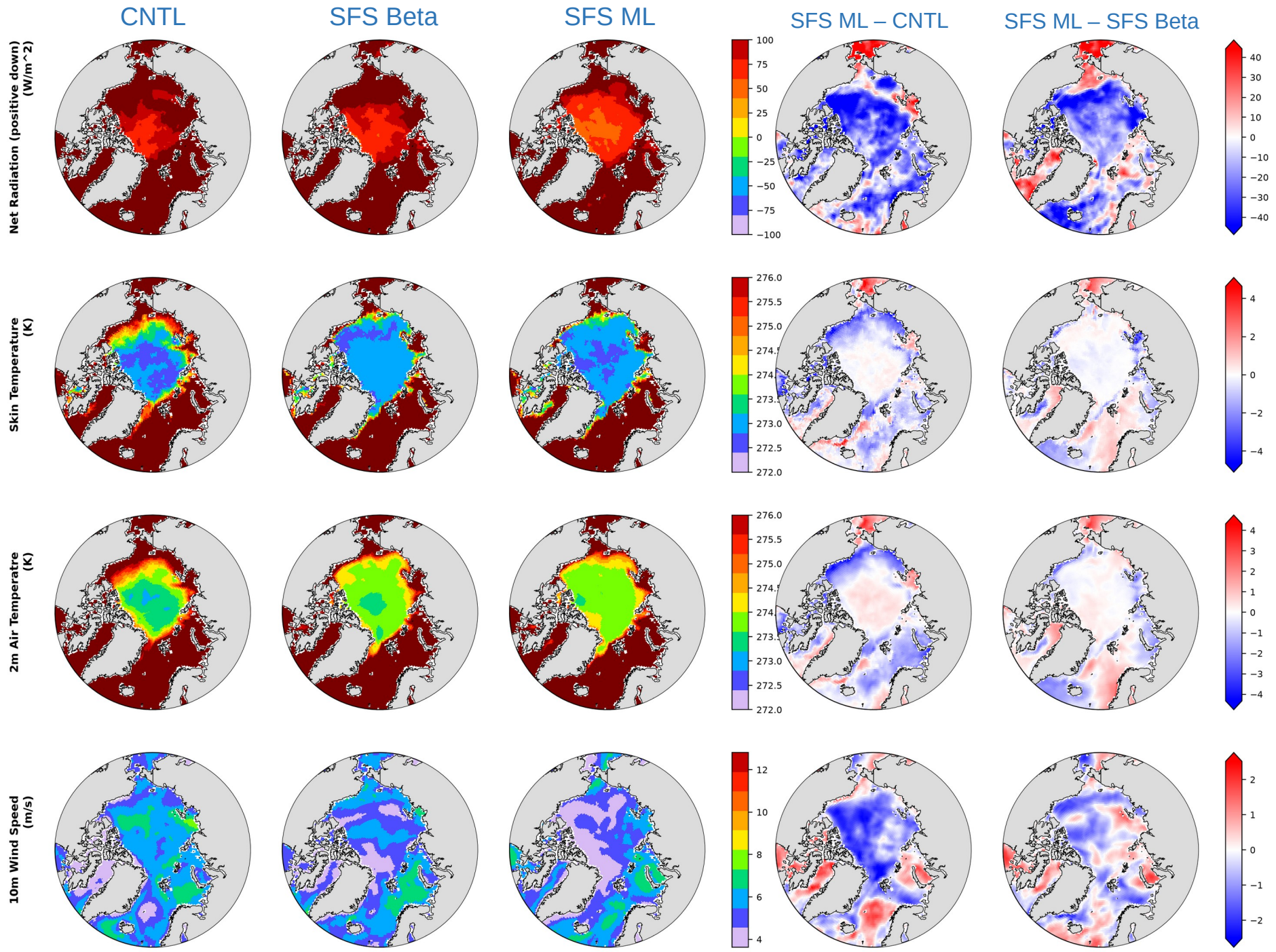


- **SFS ML:** Best overall performance, with the lowest RMSE, outperforming all other forecasts.
- **Control GDAS:** Poorest forecast skill, with high RMSE due to poor initialization and intensive ice melt.
- **SFS Beta:** Performance comparable to SFS ML but with higher RMSE due to larger initialization error.

RMSE of ice thickness (m) SFS vs AMSR2



Response in a Coupled System: Surface Atmospheric Fields
(Averaged FDAYS 10-30)



- Lower net radiative flux to sea ice in SFS ML.
- Colder surface skin temperatures and T2m over the Canadian Shelf in SFS ML compared to CNTL; smaller difference with SFS Beta.
- Lower wind speeds over the interior Arctic in SFS ML compared to CNTL, with a similar pattern in SFS Beta.
- Changes in sea ice characteristics during the forecast have far-reaching impacts that extend beyond the sea ice region into the surrounding atmosphere.

Figure by Lydia Stefanova

Summary

- A robust direct-insertion algorithm has been developed and tested in different model configurations, enabling updates to the initial sea-ice state using analysis or other target fields.
- The algorithm has been implemented in SOCA and is being testing within the UFS workflow.
- Sensitivity experiments demonstrate that constraining ice concentration alone provides short-lived improvements in summer forecasts, whereas correcting ice thickness and snow depth over sea ice (particularly snow depth) substantially extends forecast skill during the melt season in both hemispheres.
- Limited availability of near-real-time sea-ice observations during the melt season remains a major challenge for short- to medium-range forecasting, model validation, and system improvement.
- An ML-based approach for generating initial ice-thickness fields from analysis inputs shows promise for operational forecasting.



Thank you

Questions?

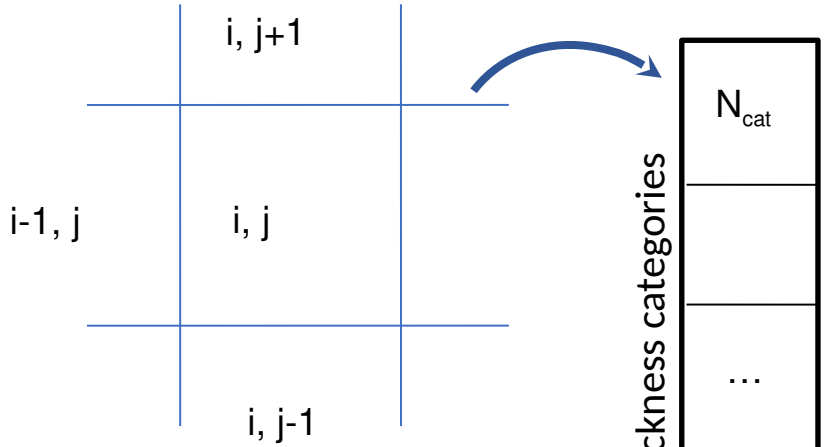
Contact information:

Dmitry Dukhovskoy
NOAA NWS Office of Modeling and Development
dmitry.dukhovskoy@noaa.gov

Extra Slides

Mapping Observed Ice State into the Model State Space

- Sea ice is partitioned into N_{cat} thickness categories, each containing multiple ice and snow layers.
- For each thickness category, the model predicts the evolution of ice thickness, snow thicknesses, and the vertical T profile in response to radiative, turbulent, and conductive heat fluxes.
- Many model state variables are 4D fields or 3D fields, whereas most observational ice fields are 2D:
- Therefore, observational or analysis fields must be mapped into the sea ice model state space before they can be used for initialization



Each ice/snow column is discretized into ice/snow vertical layers

Ice "thickness" [m] for the nth ice category

Volume per unit area [m³/m²]

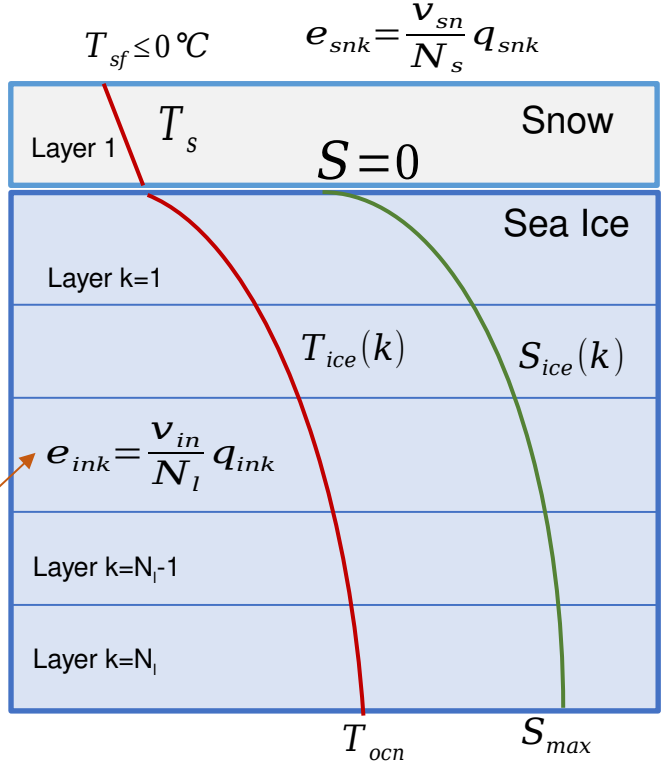
$$h_{in} = \frac{v_{in}}{a_{in}}$$

Partial ice area [m²/m²]

Snow "thickness" [m]

$$h_{sn} = \frac{v_{sn}}{a_{in}}$$

The internal ice energy in layer k



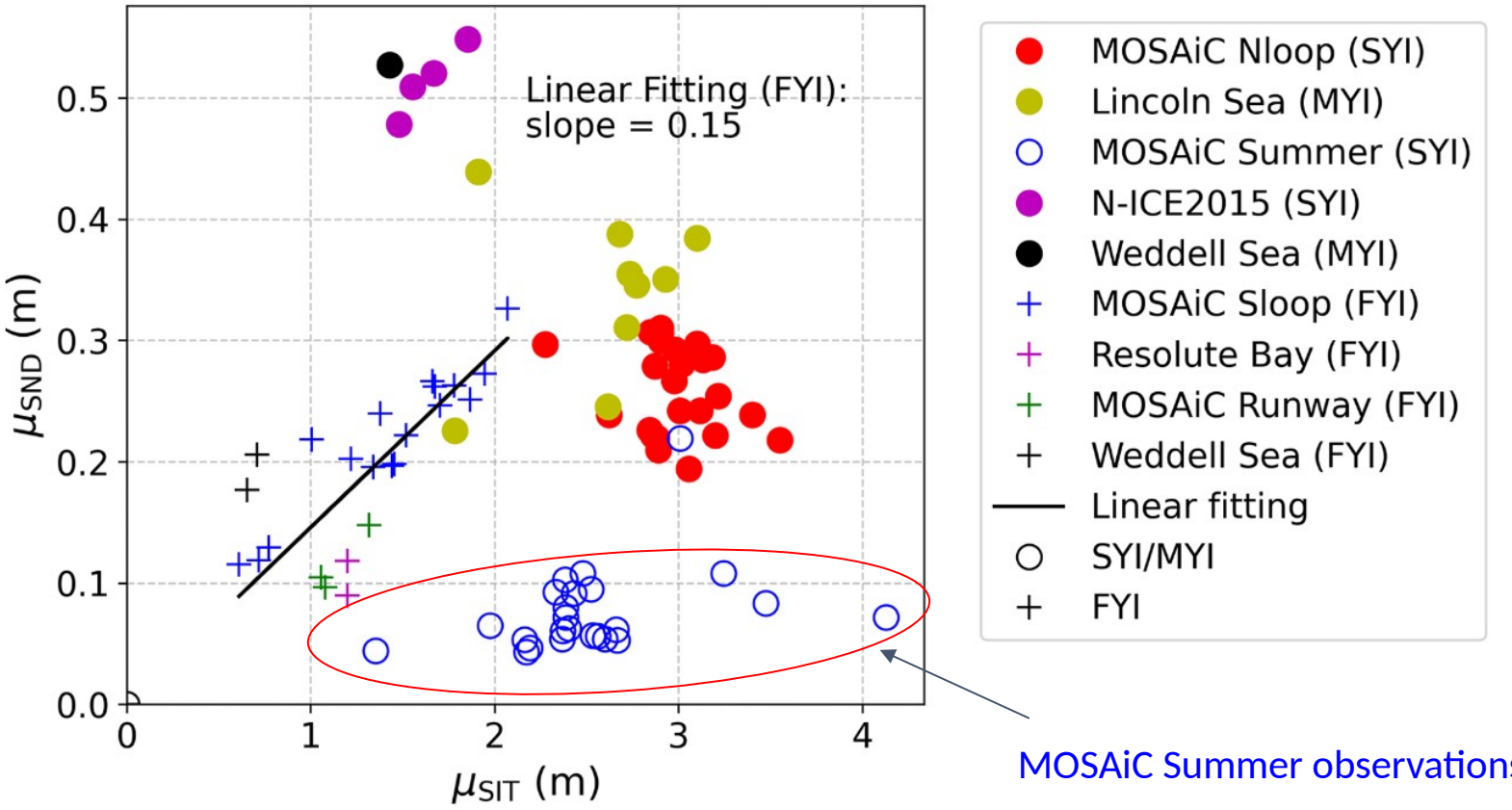
The relationship between the snow depth (SND) and sea ice thickness (SIT) from in situ observations in the Arctic and Southern Oceans

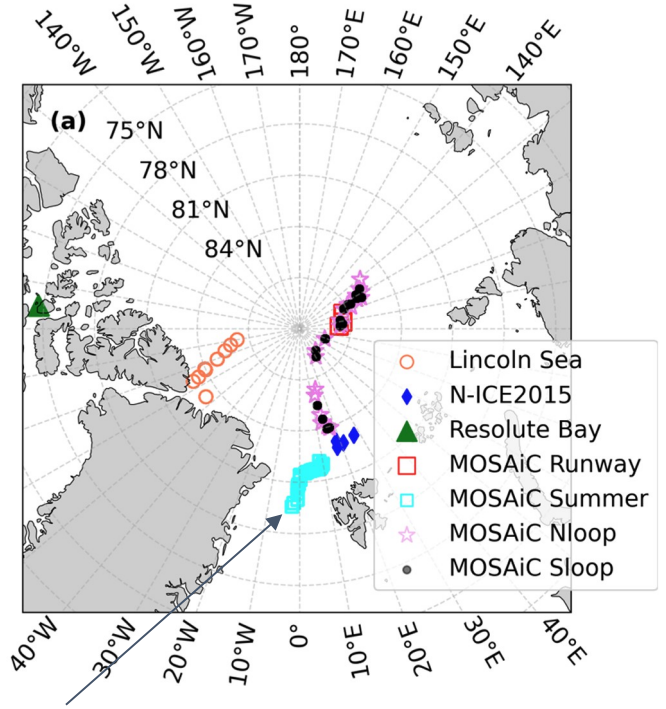
The Cryosphere, 20, 2825–2849, 2026
https://doi.org/10.5194/tc-20-2825-2026
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The Cryosphere

Snow depth distributions on sea ice of different ages and thicknesses from regional field campaigns

Lanqing Huang[1,2], Julienne Stroeve[1,3,4,5], Thomas Newman[1], Robbie Mallett[6], Rosemary Willatt[1], Lu Zhou[7], Malin Johansson[6], Carmen Nab[1,8], and Alicia Fallows[1]





MOSAiC Summer observations, North of Fram Strait AO

There is snow on ice in the Arctic during summer!

- Snow depth ~5-10cm in summer (not bare ice)
- No relationship with ice thickness

Sea ice in Baffin Bay, Candian Coastguard Icebreaker "Amundsen", July 2019



Algae



There is snow on ice in the Arctic during summer!



Melt pond

In summer, the snow cover evolves into a thin, bright, crusted layer that remains highly reflective despite substantial densification.

Bare ice

"Snow" on ice (frost layer or crusted snow)

