An aerial photograph of a snow-covered mountain range. The mountains are rugged and covered in a thick layer of white snow. A valley runs through the center of the range, with a winding road or path visible. The sky is a clear, pale blue. The overall scene is serene and majestic.

# FloeNet: a mass-conserving emulator of the GFDL sea ice model

Polar climate working group meeting, Feb 5<sup>th</sup>

Will Gregory, Mitch Bushuk, James Duncan, Elynn Wu, Adam Subel, Spencer Clark, Bill Hurlin, Jeremy McGibbon, Brian Henn, Troy Arcomano, W. Andre Perkins, Anna Kwa, Ollie Watt-Meyer, Alistair Adcroft, Chris Bretherton, Laure Zanna

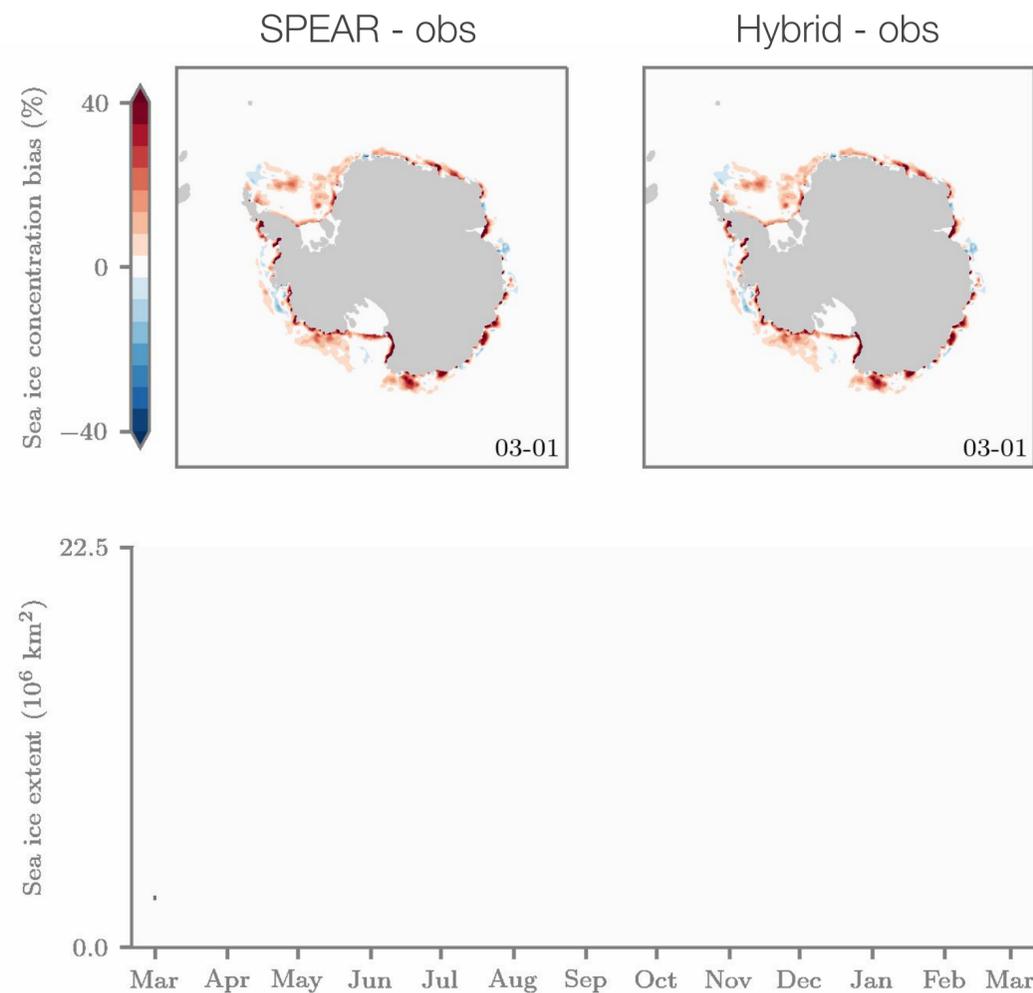
# Update from last year's PCWGM: Papers published on hybrid sea ice modeling

SCIENCE ADVANCES | RESEARCH ARTICLE

OCEANOGRAPHY

## Advancing global sea ice prediction capabilities using a fully coupled climate model with integrated machine learning

William Gregory<sup>1\*</sup>, Mitchell Bushuk<sup>2</sup>, Yong-Fei Zhang<sup>3</sup>, Alistair Adcroft<sup>1</sup>, Laure Zanna<sup>4,5</sup>, Colleen McHugh<sup>6</sup>, Liwei Jia<sup>2</sup>



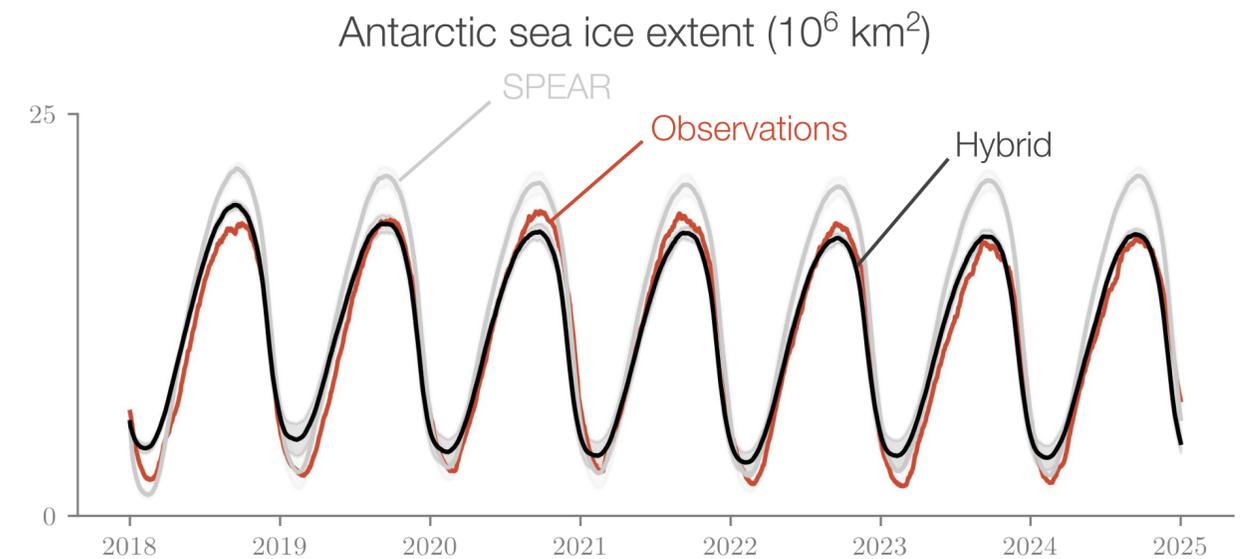
arXiv > physics > arXiv:2510.22676

Physics > Atmospheric and Oceanic Physics

[Submitted on 26 Oct 2025]

## A Framework for Hybrid Physics–AI Coupled Ocean Models

Laure Zanna, William Gregory, Pavel Perezhogin, Aakash Sane, Cheng Zhang, Alistair Adcroft, Mitch Bushuk, William Chapman, Alex Connolly, Danni Du, Kelsey Everard, Fabrizio Falasca, Renaud Falga, David Kamm, Et Simpson, Linus Vogt, Jiarong Wu



# Machine-learning models are making headway as climate model emulators

Auto-regressive climate emulators use their predictions as next-step inputs and apply this iteratively to rollout simulations.

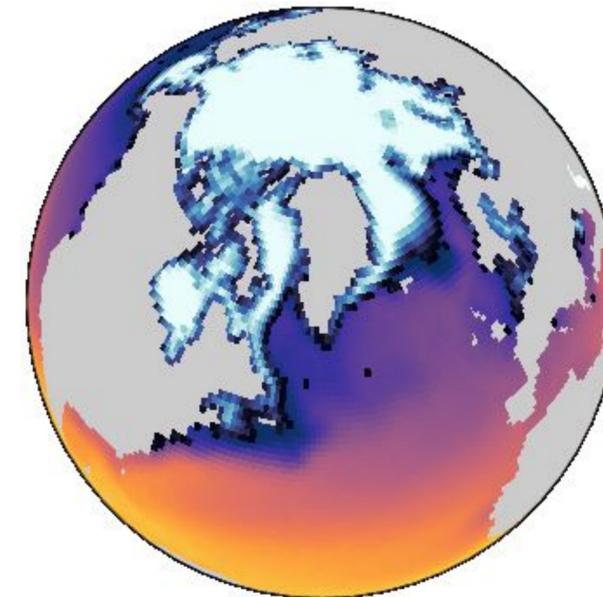
$$x_{t+\Delta t} = f(x_t)$$


New climate emulator 'SamudrACE' couples 3D atmosphere emulator 'ACE' with 3D ocean emulator 'Samudra'

SamudrACE emulates the GFDL CM4 model

CM4 throughput: **16 SYPD** on 5535 CPU cores

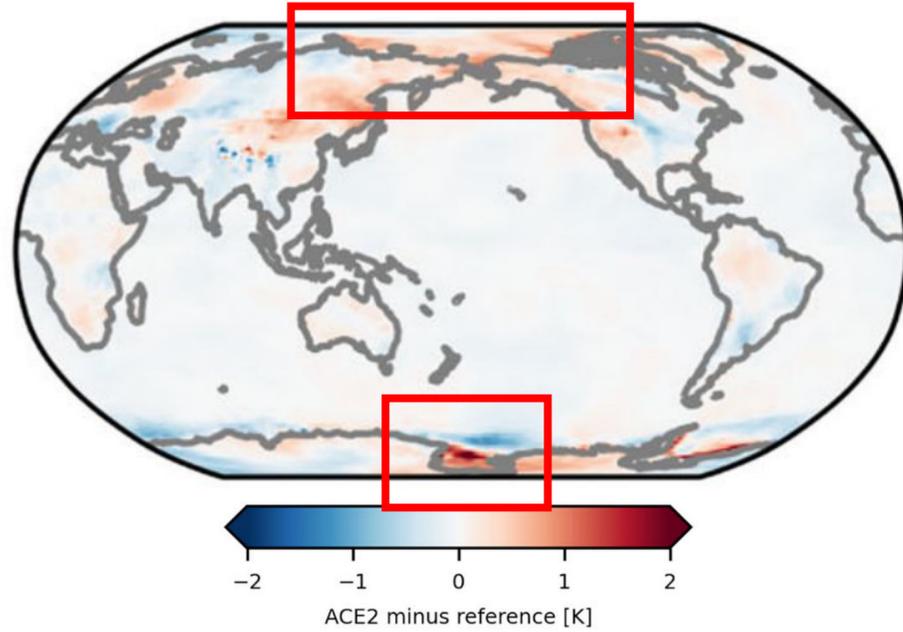
SamudrACE throughput: **1500 SYPD** on 1 GPU



Duncan, .., **Gregory** et al.  
SamudrACE: Fast and accurate coupled climate modeling with 3D ocean and atmosphere emulators. *arXiv (in review at GRL)*. 2025

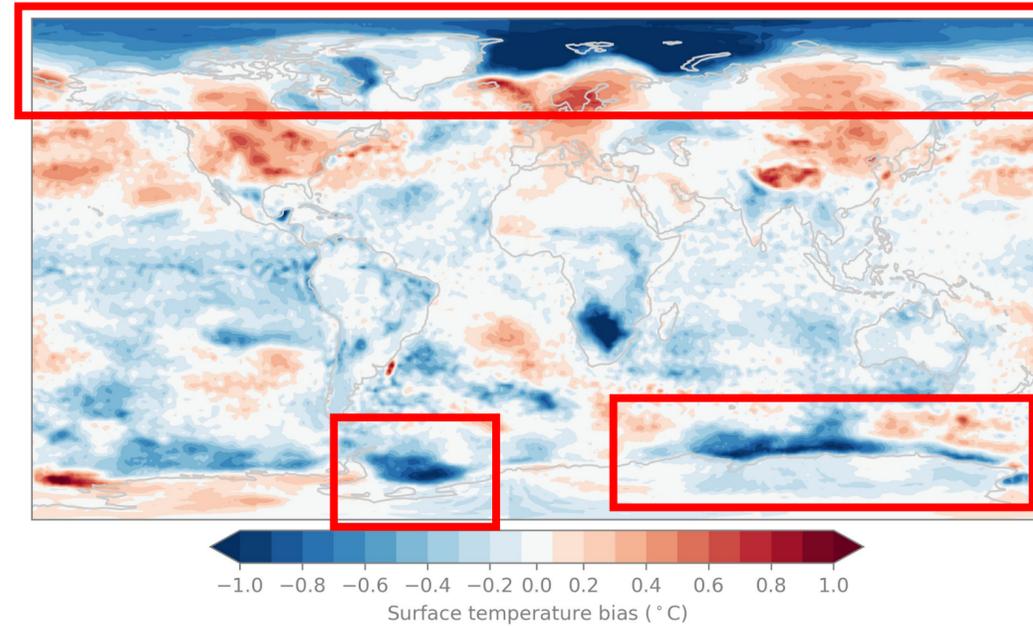
# Current generation atmospheric emulators have residual polar biases

ACE2



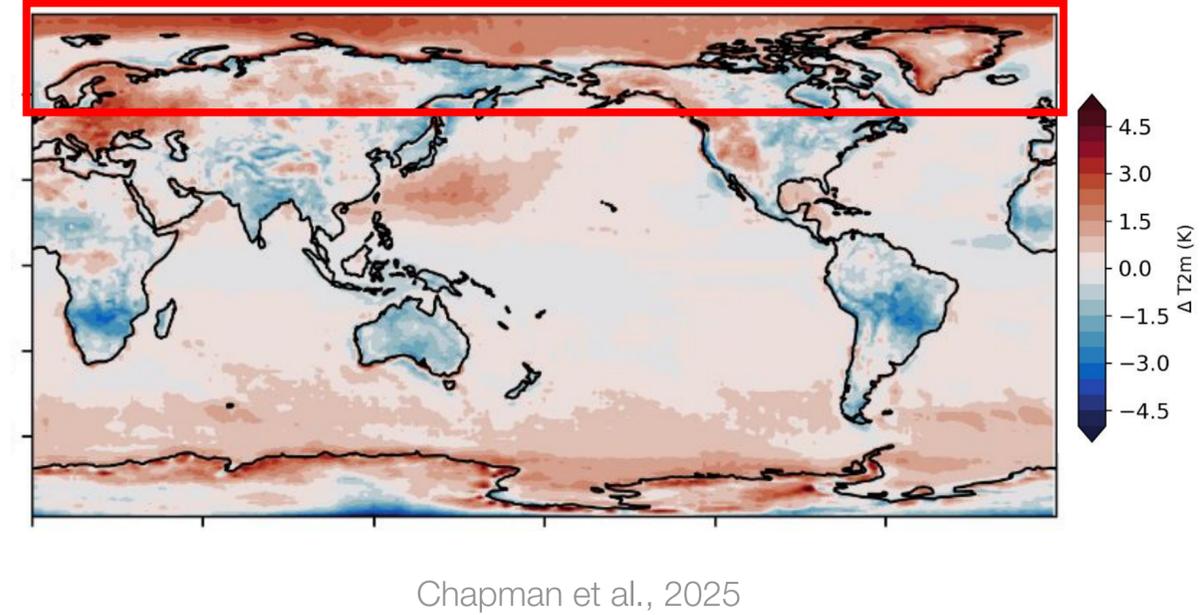
Watt-Meyer et al., 2025

SamudrACE



Duncan et al., 2025

CAMulator



Chapman et al., 2025

$$T2m_{t+\Delta t} = f(T2m_t, siconc_t)$$

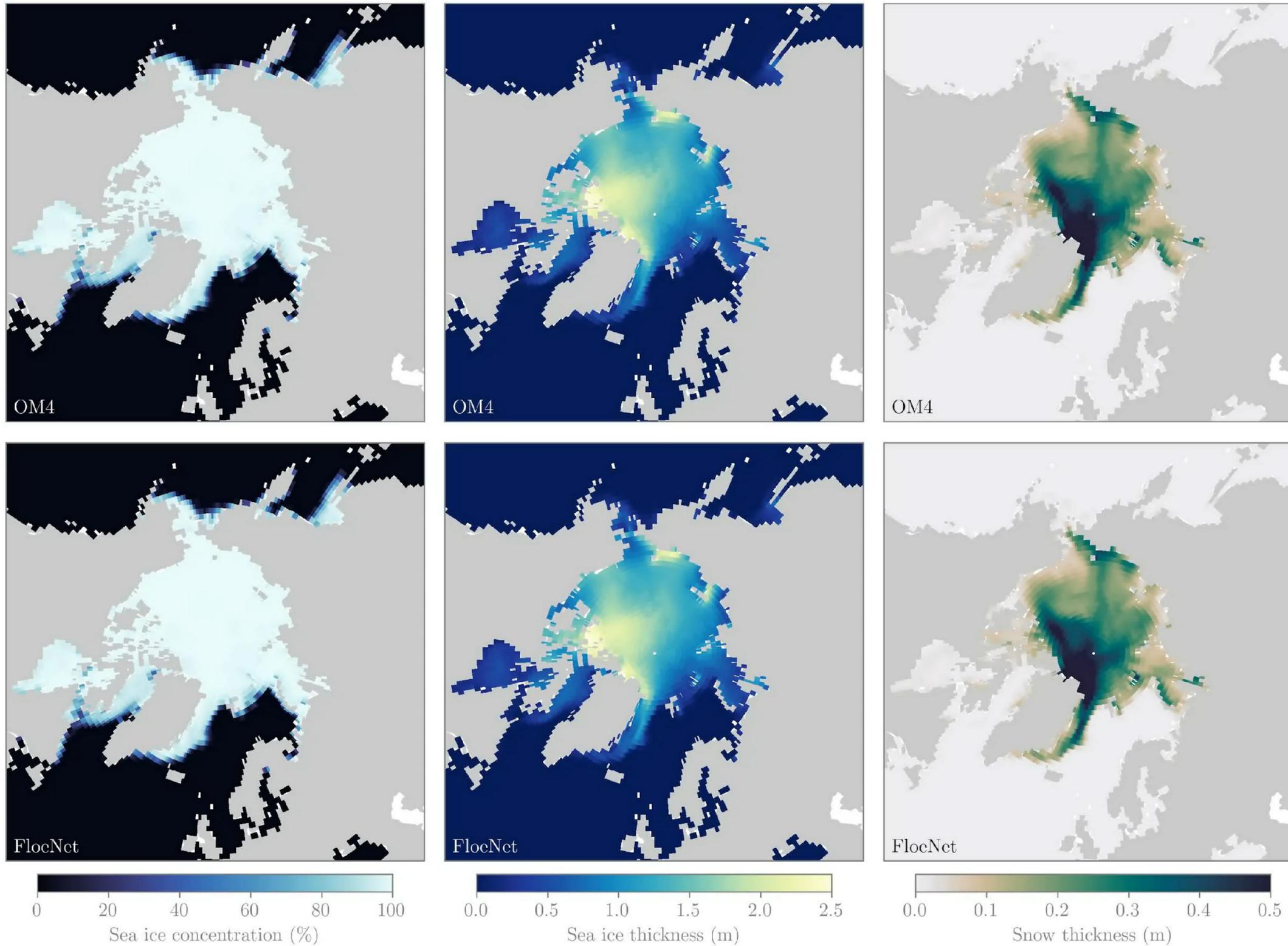
$$T2m_{t+\Delta t}, siconc_{t+\Delta t} = f(T2m_t, siconc_t)$$

$$T2m_{t+\Delta t} = f(T2m_t, siconc_t)$$

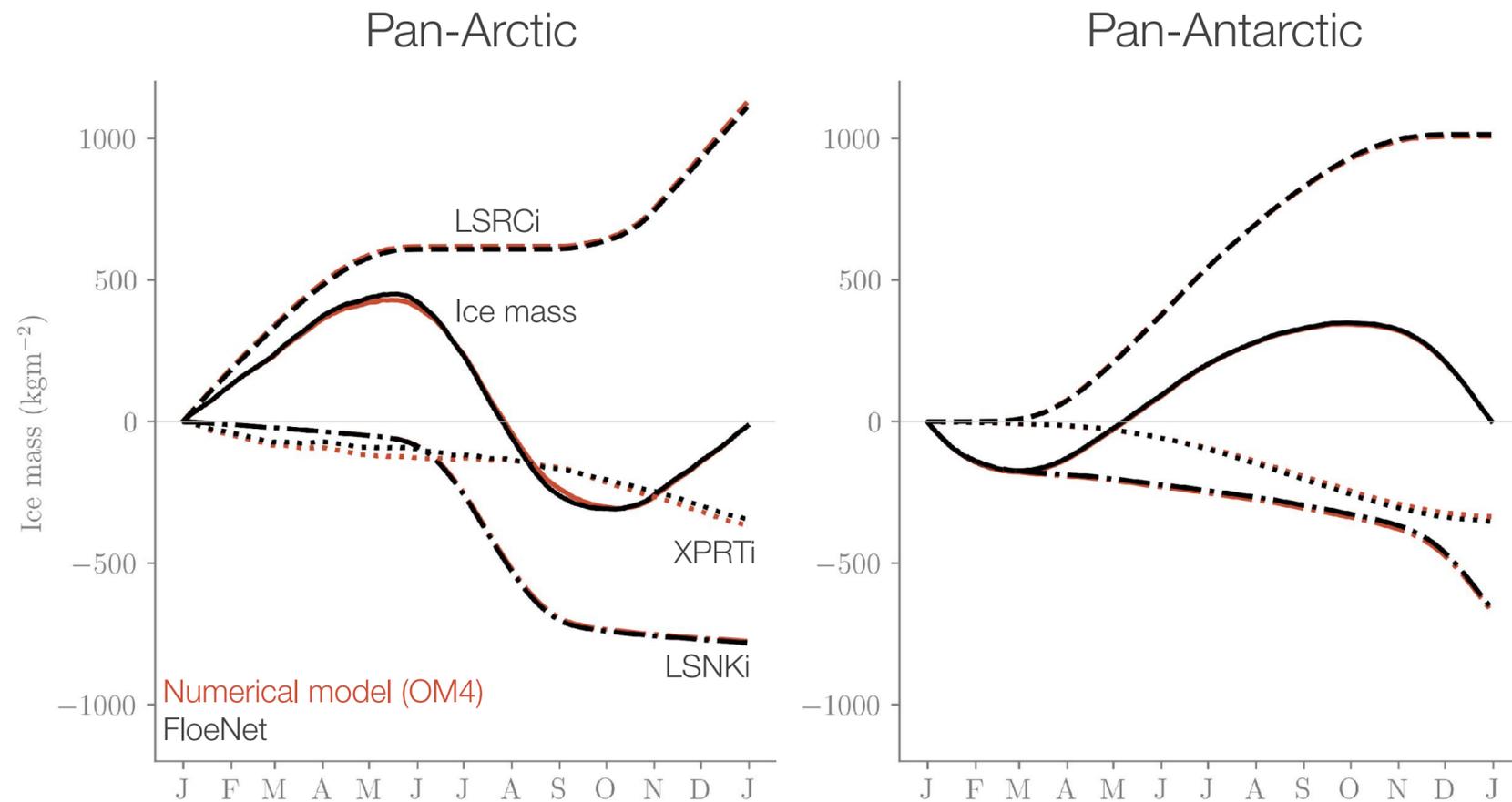
Could a sophisticated sea ice emulator improve surface polar climate biases in atmosphere and/or ocean emulators?

# Introducing FloeNet: a global sea ice emulator architecture

2007-01-01 06:00:00



# FloeNet accurately captures ice and snow dynamics/thermodynamics



The area/mass budget can be summarized by local sources and sinks due to thermodynamics, plus local ice convergence/divergence due to dynamics:

$$x_{t+\Delta t} = x_t + \Delta t (\delta x_{\text{source}} + \delta x_{\text{sink}} + \delta x_{\text{transport}})$$

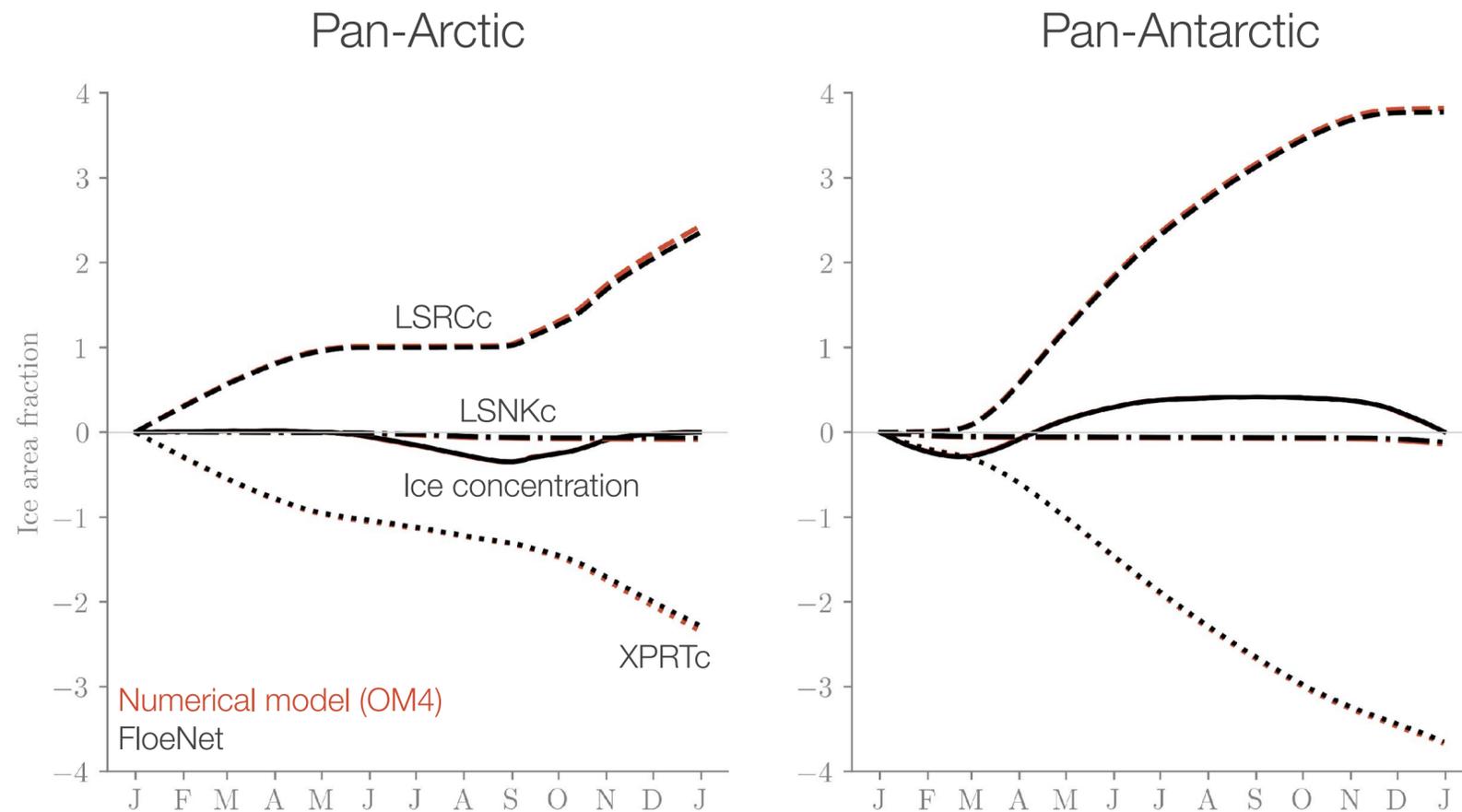
## SIS2 to CICE

$$\text{LSRCi} = \rho_i \cdot \max(dvidtt, 0.0)$$

$$\text{LSNKi} = \rho_i \cdot \min(dvidtt, 0.0)$$

$$\text{XPRTi} = \rho_i \cdot dvidtd$$

# FloeNet accurately captures ice and snow dynamics/thermodynamics



The area/mass budget can be summarized by local sources and sinks due to thermodynamics, plus local ice convergence/divergence due to dynamics:

$$x_{t+\Delta t} = x_t + \Delta t (\delta x_{\text{source}} + \delta x_{\text{sink}} + \delta x_{\text{transport}})$$

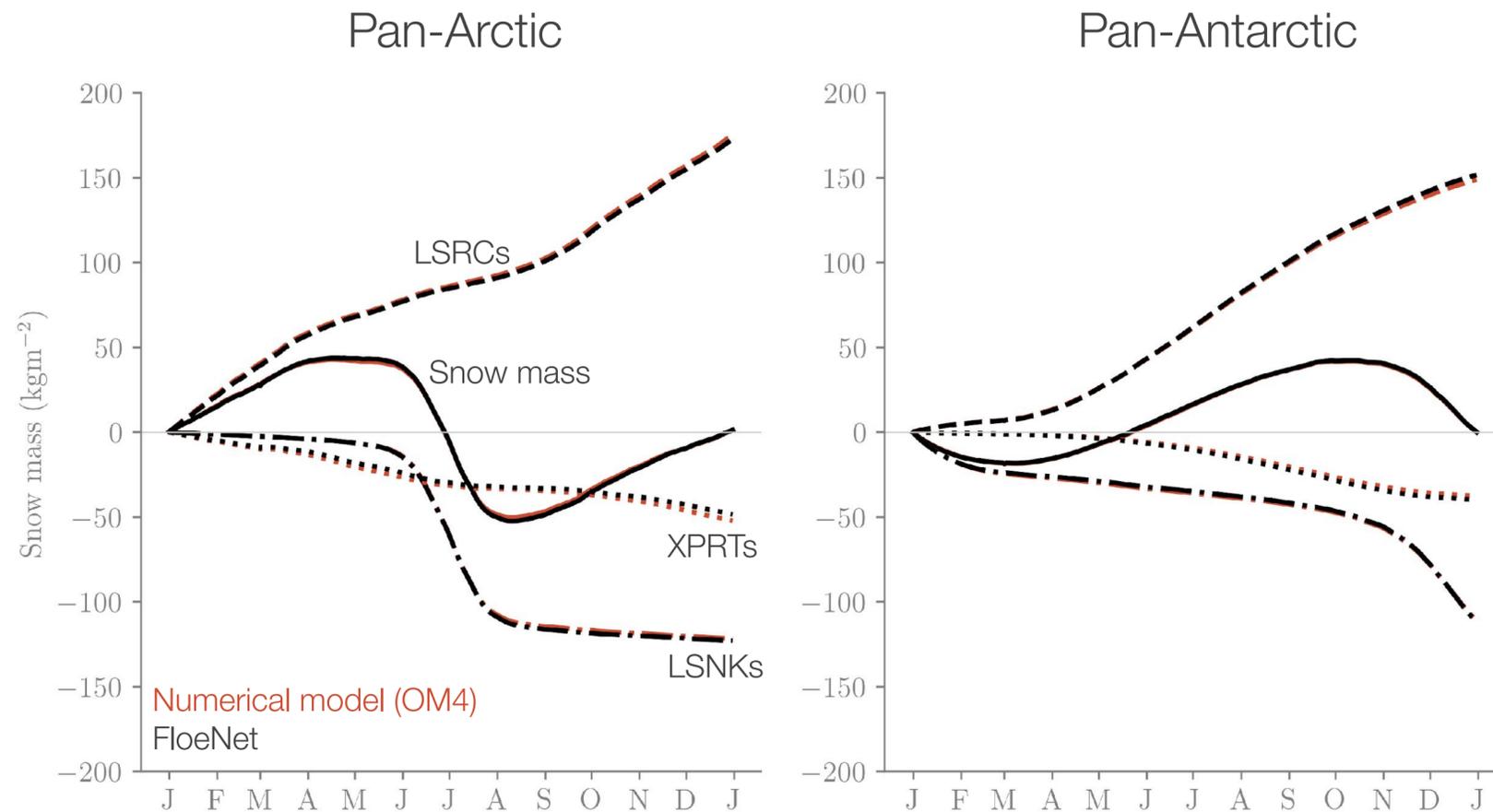
## SIS2 to CICE

$$\text{LSRCc} = \max(\text{daidtt}, 0.0)$$

$$\text{LSNKc} = \min(\text{daidtt}, 0.0)$$

$$\text{XPRTc} = \text{daidtd}$$

# FloeNet accurately captures ice and snow dynamics/thermodynamics



The area/mass budget can be summarized by local sources and sinks due to thermodynamics, plus local ice convergence/divergence due to dynamics:

$$x_{t+\Delta t} = x_t + \Delta t (\delta x_{\text{source}} + \delta x_{\text{sink}} + \delta x_{\text{transport}})$$

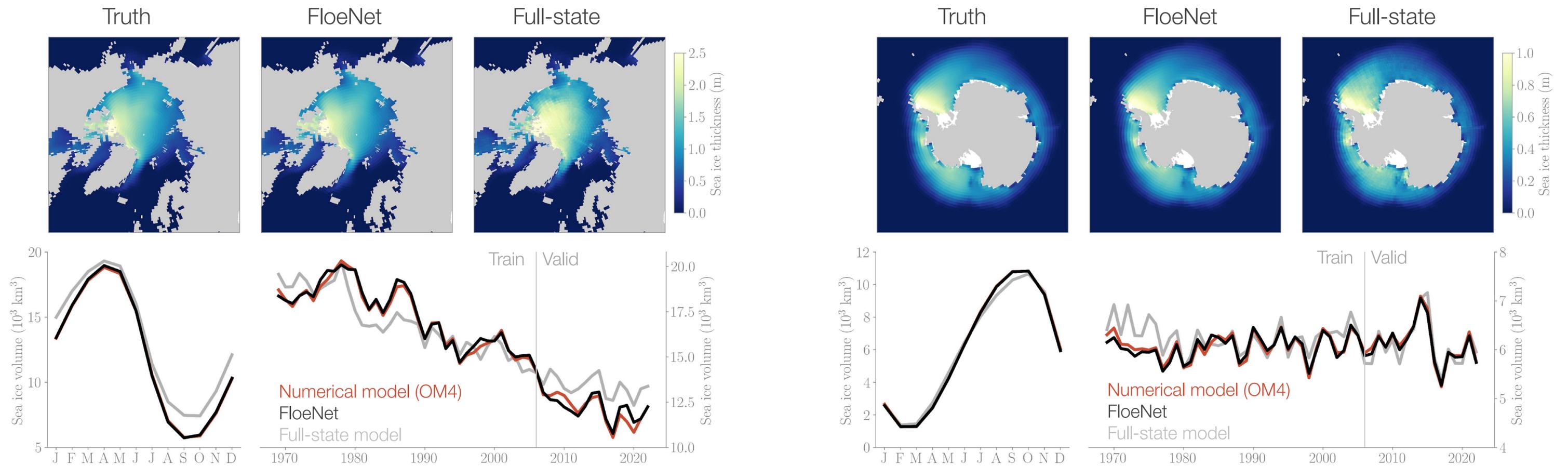
## SIS2 to CICE

- LSRCs = ?
- LSNKs = ?
- XPRTs = ?

# FloeNet outperforms a non-conservative baseline under the same present-day forcing

Baseline “Full-state” model

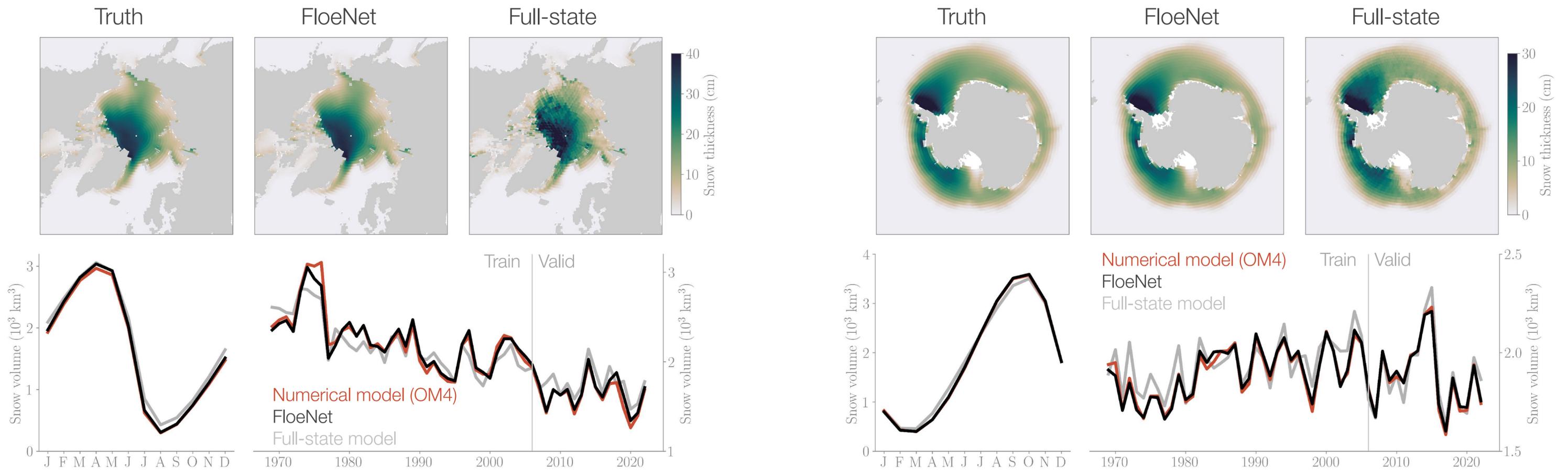
$$\text{simass}_{t+\Delta t}, \text{siconc}_{t+\Delta t}, \text{sisnmass}_{t+\Delta t}, \text{siu}_{t+\Delta t}, \text{siv}_{t+\Delta t} = f(\text{simass}_t, \text{siconc}_t, \text{sisnmass}_t, \text{siu}_t, \text{siv}_t, \mathbf{F}_t)$$



# FloeNet outperforms a non-conservative baseline under the same present-day forcing

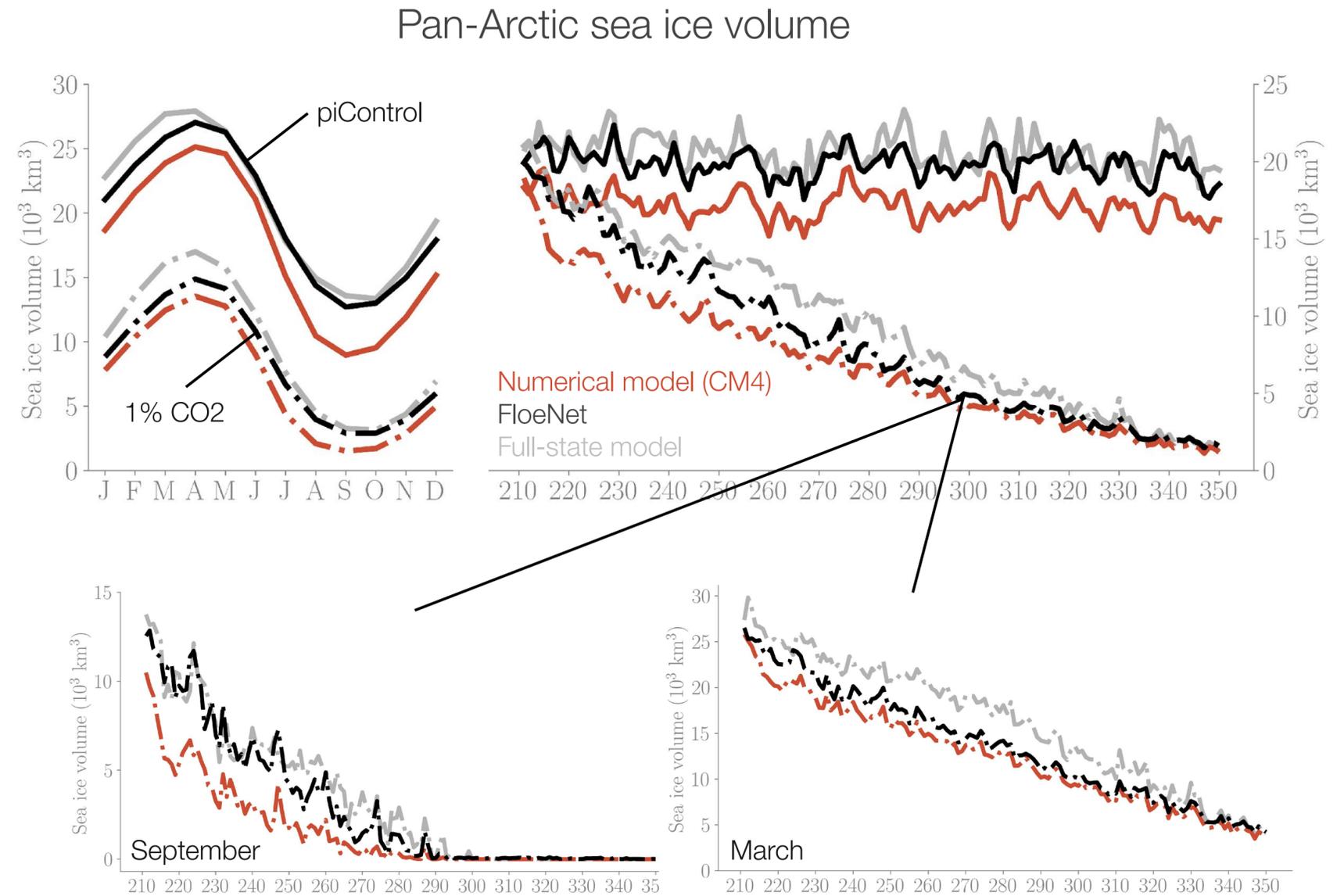
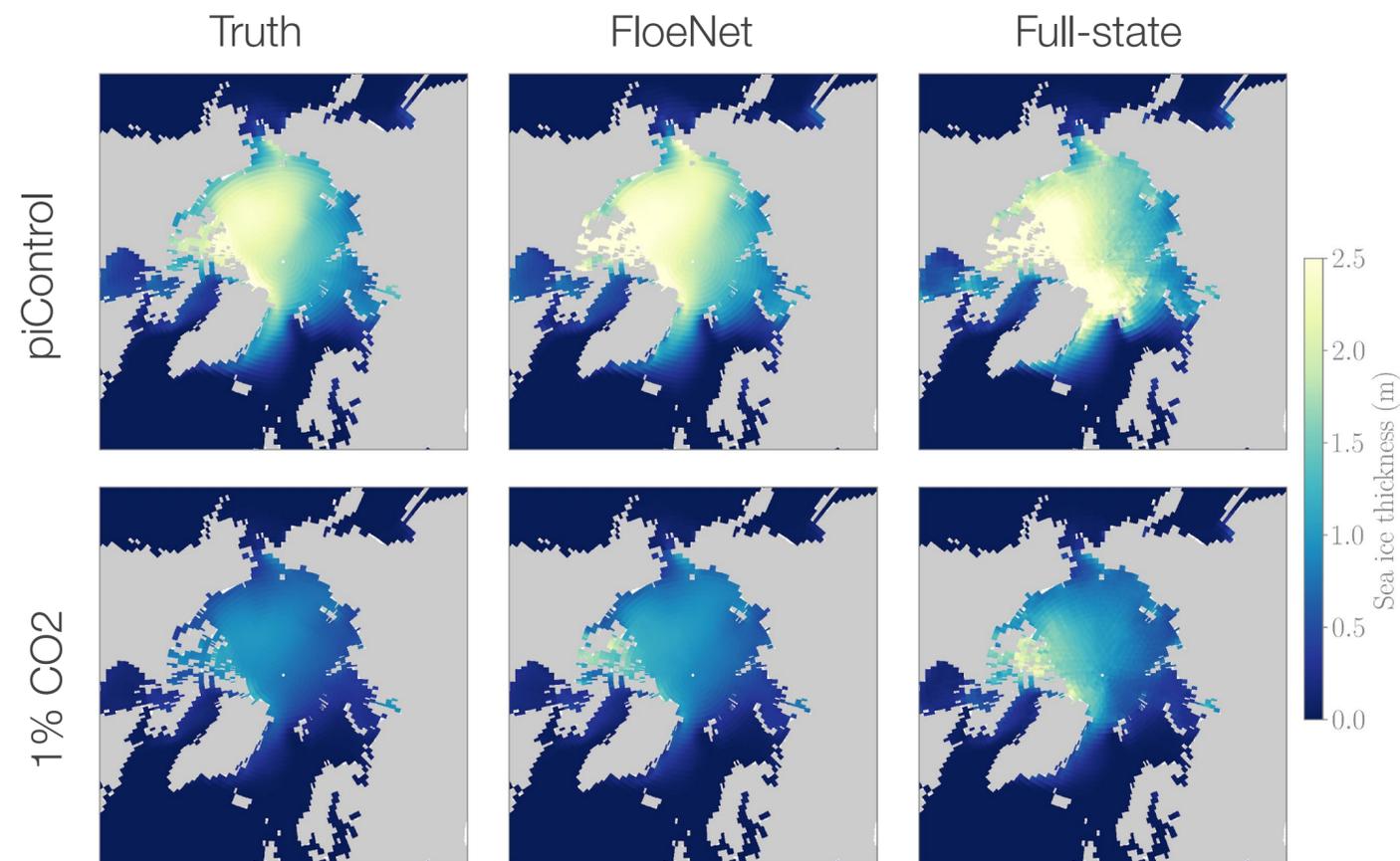
Baseline “Full-state” model

$$\text{simass}_{t+\Delta t}, \text{siconc}_{t+\Delta t}, \text{sisnmass}_{t+\Delta t}, \text{siu}_{t+\Delta t}, \text{siv}_{t+\Delta t} = f(\text{simass}_t, \text{siconc}_t, \text{sisnmass}_t, \text{siu}_t, \text{siv}_t, \mathbf{F}_t)$$



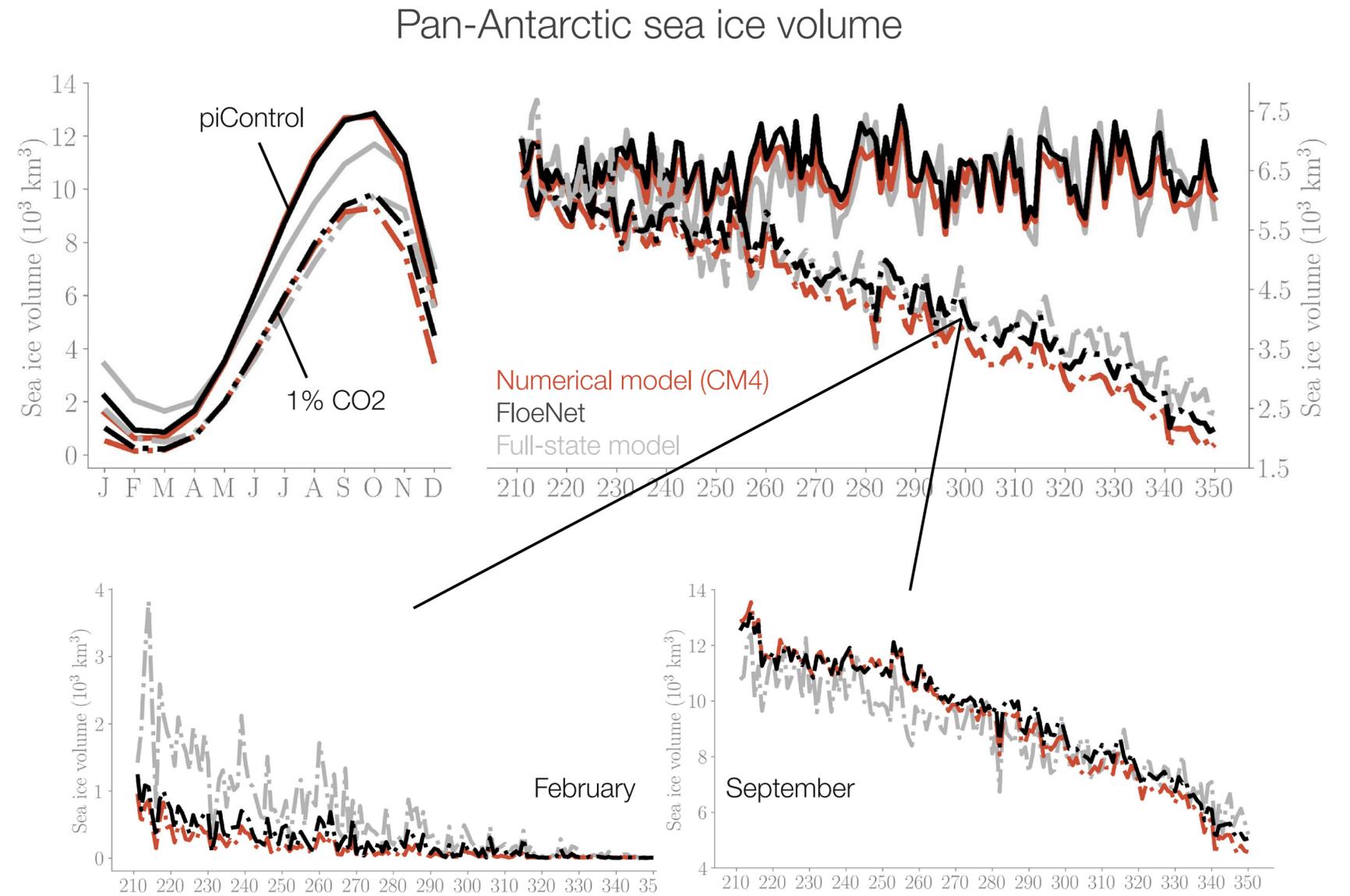
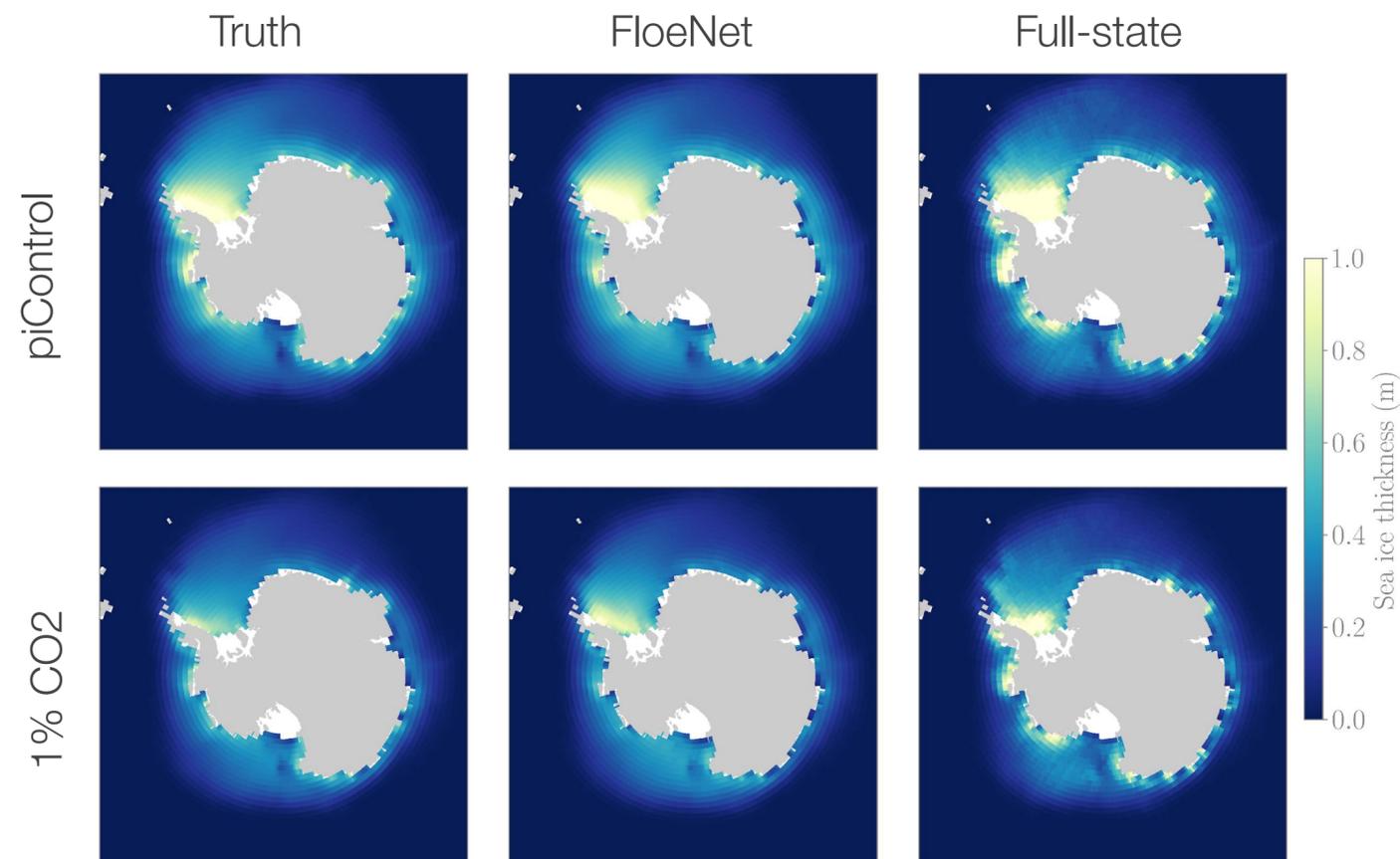
# Emulators can generalize relatively well to piControl and 1% CO2 forcing

Emulators are trained on reanalysis-forced ice-ocean (OM4) simulation and evaluated under piControl and 1% CO2 forcing from CM4 runs

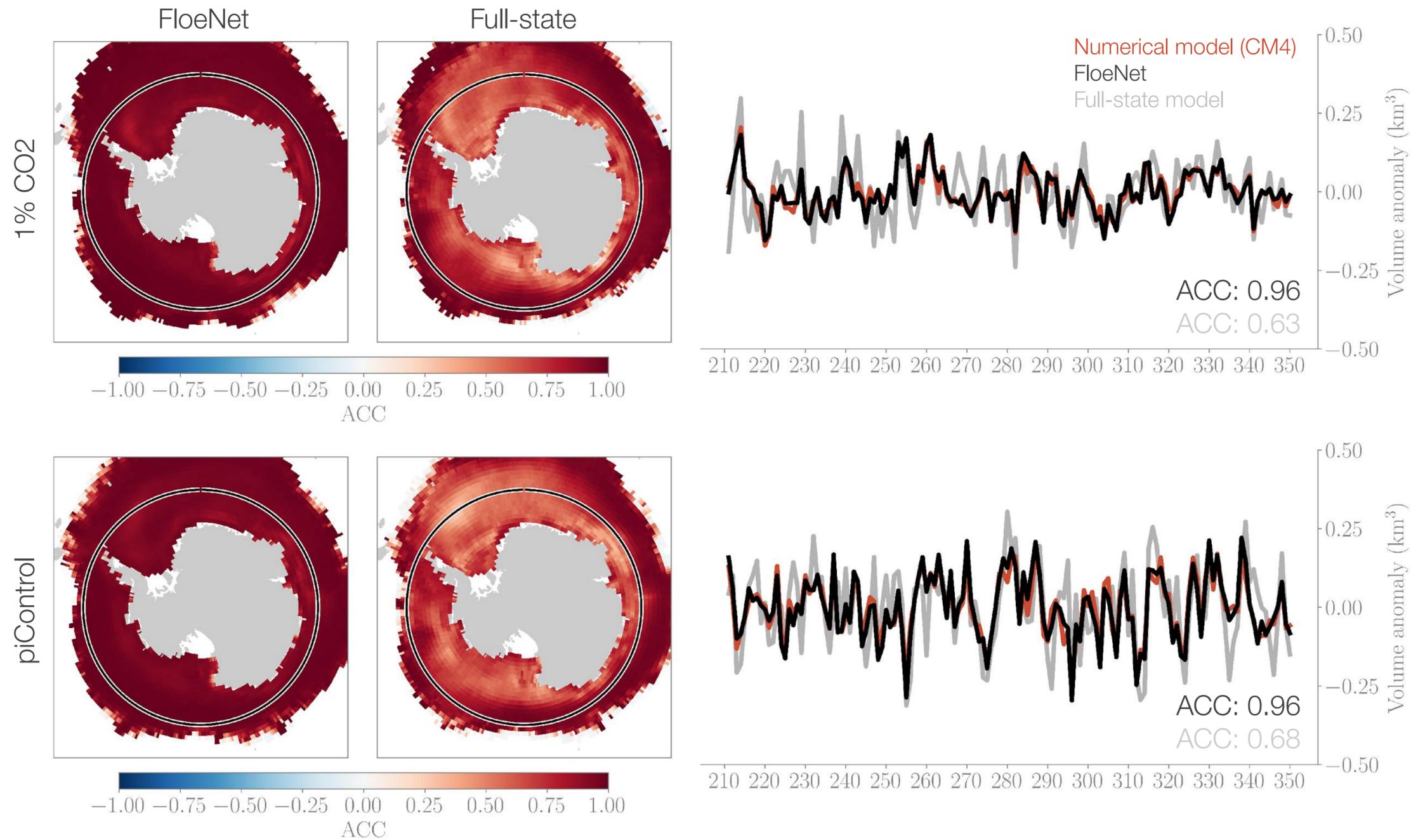


# Emulators can generalize relatively well to piControl and 1% CO2 forcing

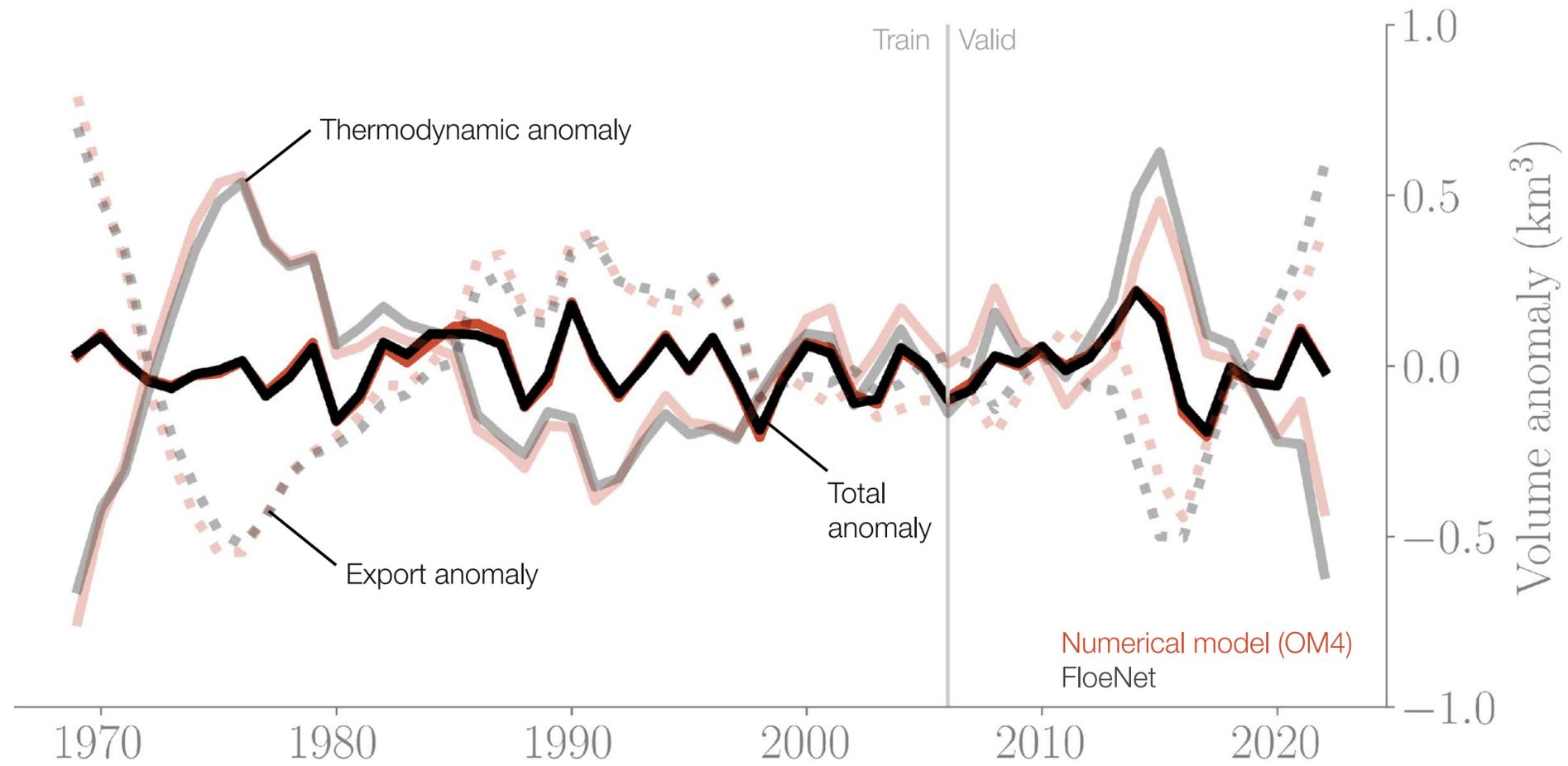
Emulators are trained on reanalysis-forced ice-ocean (OM4) simulation and evaluated under piControl and 1% CO2 forcing from CM4 runs



# FloeNet accurately captures inter-annual sea ice variability under different climates



# FloeNet gets sea ice volume anomalies for the right reasons



# We're hoping FloeNet can be a useful tool for the emulator community

FloeNet is an accurate global sea ice emulator, trained here on the GFDL sea ice model, SIS2

FloeNet can produce a 140-year simulation in ~4.5 hours on 1 GPU

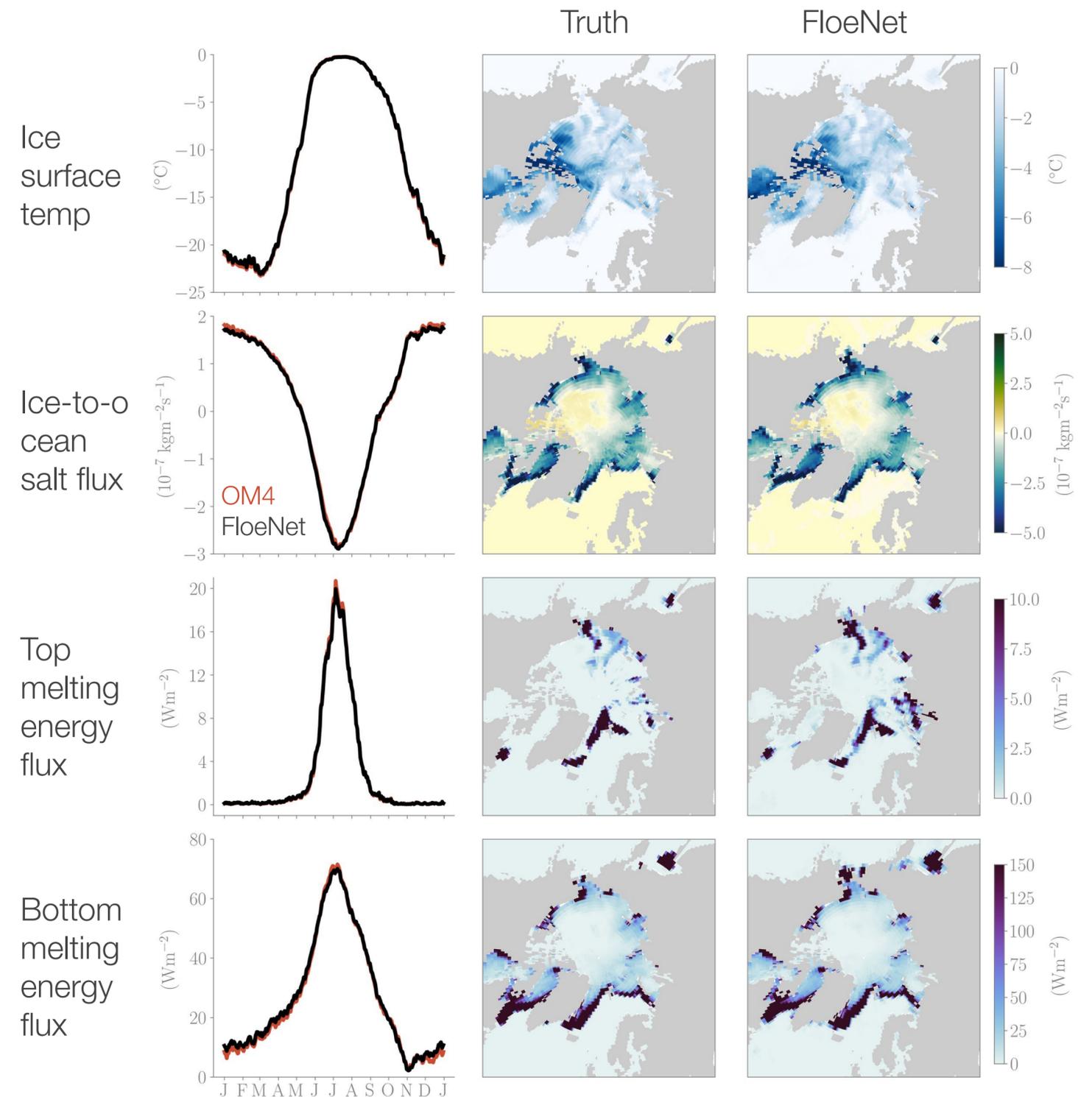
FloeNet also predicts useful variables for ice-atmosphere and ice-ocean coupling

## Next steps

Write up results!

Couple FloeNet to SamudrACE

Work towards an energy- and salt-conserving formulation



Thank you!

# FloeNet's complete set of input and output variables

## CMOR field name

siconc  
 simass  
 sisnmass  
 sitemptop  
 max(sidmassth,0.0)  
 min(sidmassth,0.0)  
 sidmassdyn  
 sisndmasssnf + max(sisndmasssubl,0.0)  
 sisndmassmelt + min(sisndmasssubl,0.0) + sisndmasssi  
 sisndmassdyn  
 max(sidconcth,0.0)  
 min(sidconcth,0.0)  
 sidconcdyn  
 siflsaltbot  
 ?  
 ?  
 siflswdtop  
 sifllwdtop  
 siflsenstop  
 sifllatstop  
 sisndmasssnf  
 sistrxdtop (tauuo [from ocean] where siconc<0.15)  
 sistrydtop (tauvo [from ocean] where siconc<0.15)  
 siflsensbot  
 zos [from ocean]  
 sistrxubot (tauuo [from ocean])  
 sistryubot (tauvo [from ocean])

Name	Description	Type	Time def.
siconc	sea ice area fraction [0-1]	prognostic	6-hour snapshot
simass	sea ice mass [kgm <sup>-2</sup> ]	prognostic	6-hour snapshot
sisnmass	snow mass [kgm <sup>-2</sup> ]	prognostic	6-hour snapshot
TS	ice-surface skin temperature [°C]	prognostic	6-hour snapshot
LSRCi	sea ice mass source [kgm <sup>-2</sup> s <sup>-1</sup> ]	prognostic	6-hour mean
LSNKi	sea ice mass sink [kgm <sup>-2</sup> s <sup>-1</sup> ]	prognostic	6-hour mean
XPRTi	sea ice mass transport [kgm <sup>-2</sup> s <sup>-1</sup> ]	prognostic	6-hour mean
LSRCs	snow mass source [kgm <sup>-2</sup> s <sup>-1</sup> ]	prognostic	6-hour mean
LSNKs	snow mass sink [kgm <sup>-2</sup> s <sup>-1</sup> ]	prognostic	6-hour mean
XPRTs	snow mass transport [kgm <sup>-2</sup> s <sup>-1</sup> ]	prognostic	6-hour mean
LSRCc	sea ice area source [s <sup>-1</sup> ]	prognostic	6-hour mean
LSNKc	sea ice area sink [s <sup>-1</sup> ]	prognostic	6-hour mean
XPRTc	sea ice area transport [s <sup>-1</sup> ]	prognostic	6-hour mean
SALTF	ice-to-ocean salt flux [kgm <sup>-2</sup> s <sup>-1</sup> ]	prognostic	6-hour mean
TMELT	top melting energy flux [Wm <sup>-2</sup> ]	diagnostic	6-hour mean
BMELT	bottom melting energy flux [Wm <sup>-2</sup> ]	diagnostic	6-hour mean
SWDN	downward shortwave radiation [Wm <sup>-2</sup> ]	forcing	6-hour mean
LWDN	downward longwave radiation [Wm <sup>-2</sup> ]	forcing	6-hour mean
SH	sensible heat flux [Wm <sup>-2</sup> ]	forcing	6-hour mean
LH	latent heat flux [Wm <sup>-2</sup> ]	forcing	6-hour mean
SNOWFL	rate of snow fall [kgm <sup>-2</sup> s <sup>-1</sup> ]	forcing	6-hour mean
FA_X	zonal wind stress above sea ice [Pa]	forcing	6-hour mean
FA_Y	meridional wind stress above sea ice [Pa]	forcing	6-hour mean
BHEAT	ocean-to-ice heat flux [Wm <sup>-2</sup> ]	forcing	5-day mean
SSH	sea-surface height [m]	forcing	5-day mean
FW_X	zonal ice-ocean stress [Pa]	forcing	5-day mean
FW_Y	meridional ice-ocean stress [Pa]	forcing	5-day mean

For constraining dynamics

For constraining thermodynamics