Super-resolution of satellite observations of sea ice thickness using diffusion models and physical modeling

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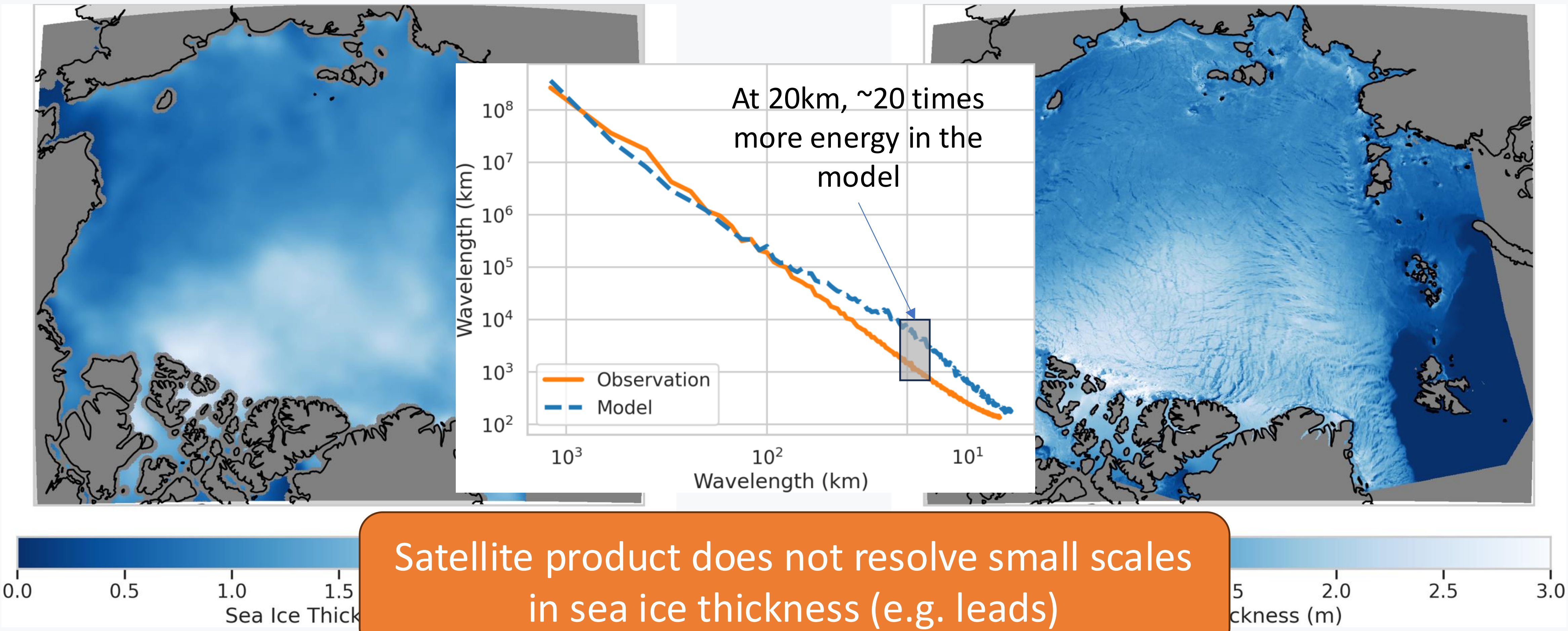
Motivation

Satellite observation product (CS2SMOS)

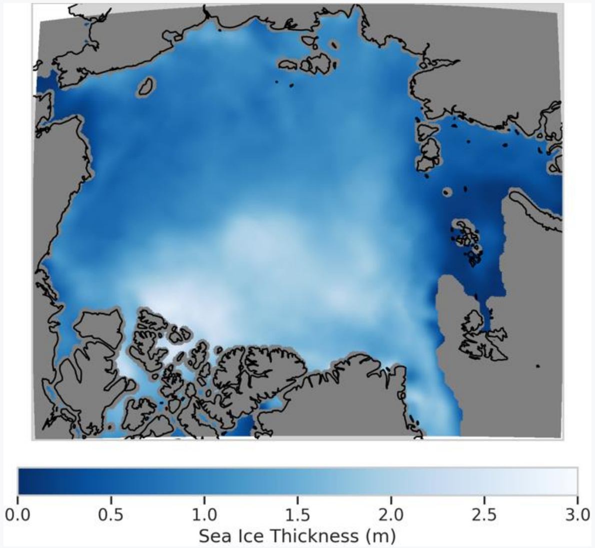
Physical model (NeXtSIM) forecast



Satellite product does not resolve small scales in sea ice thickness (e.g. leads)

Our Objective: downscaling

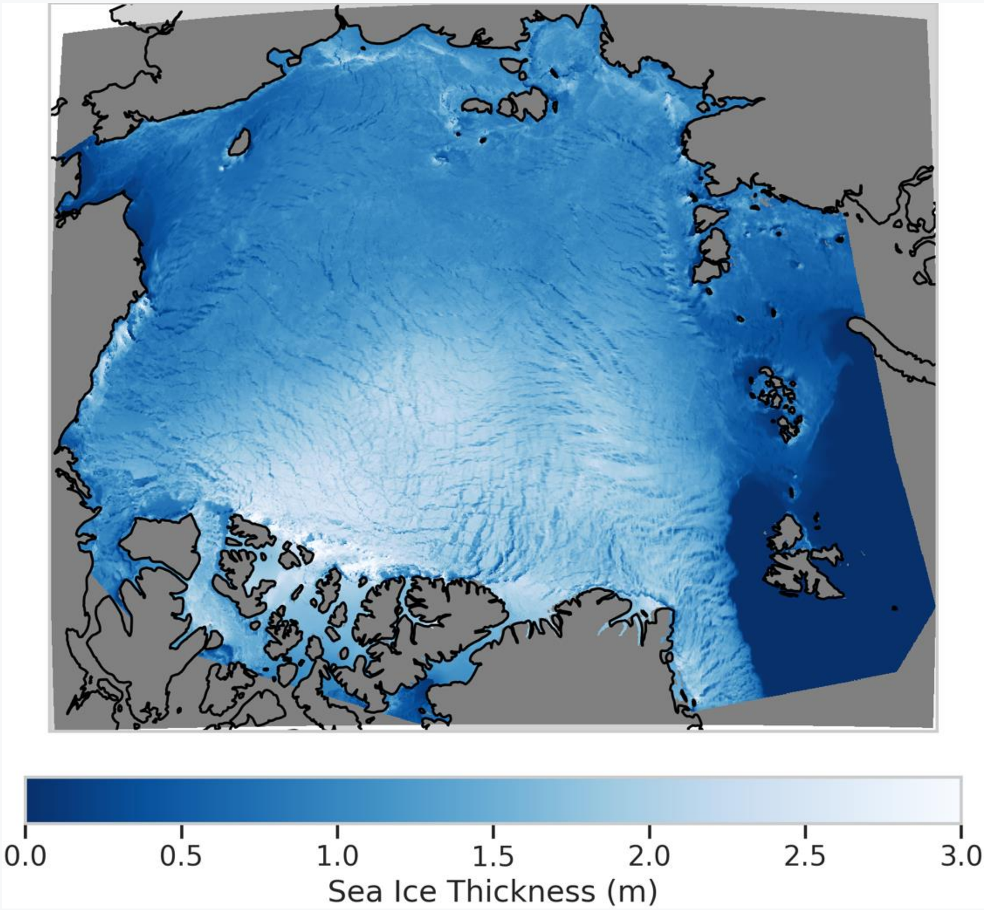
Low-resolution observation



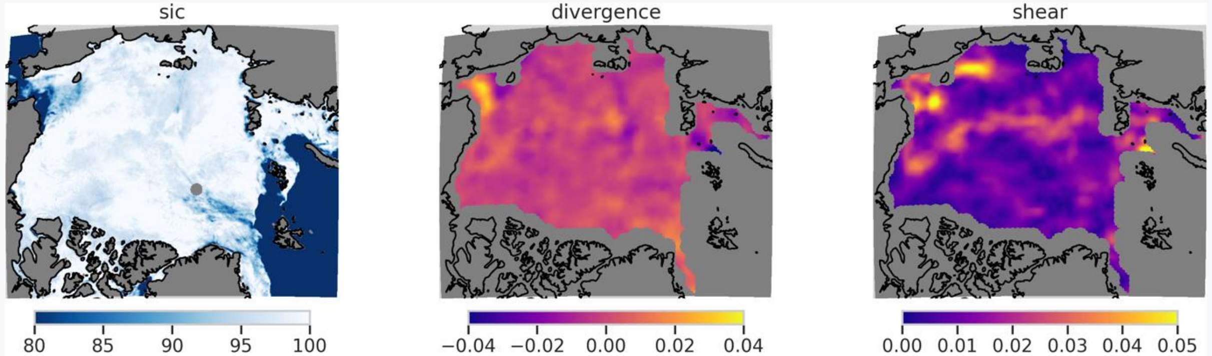
Downscaling Model

Neural network

High-resolution sea ice thickness



+ Other low-resolution observations



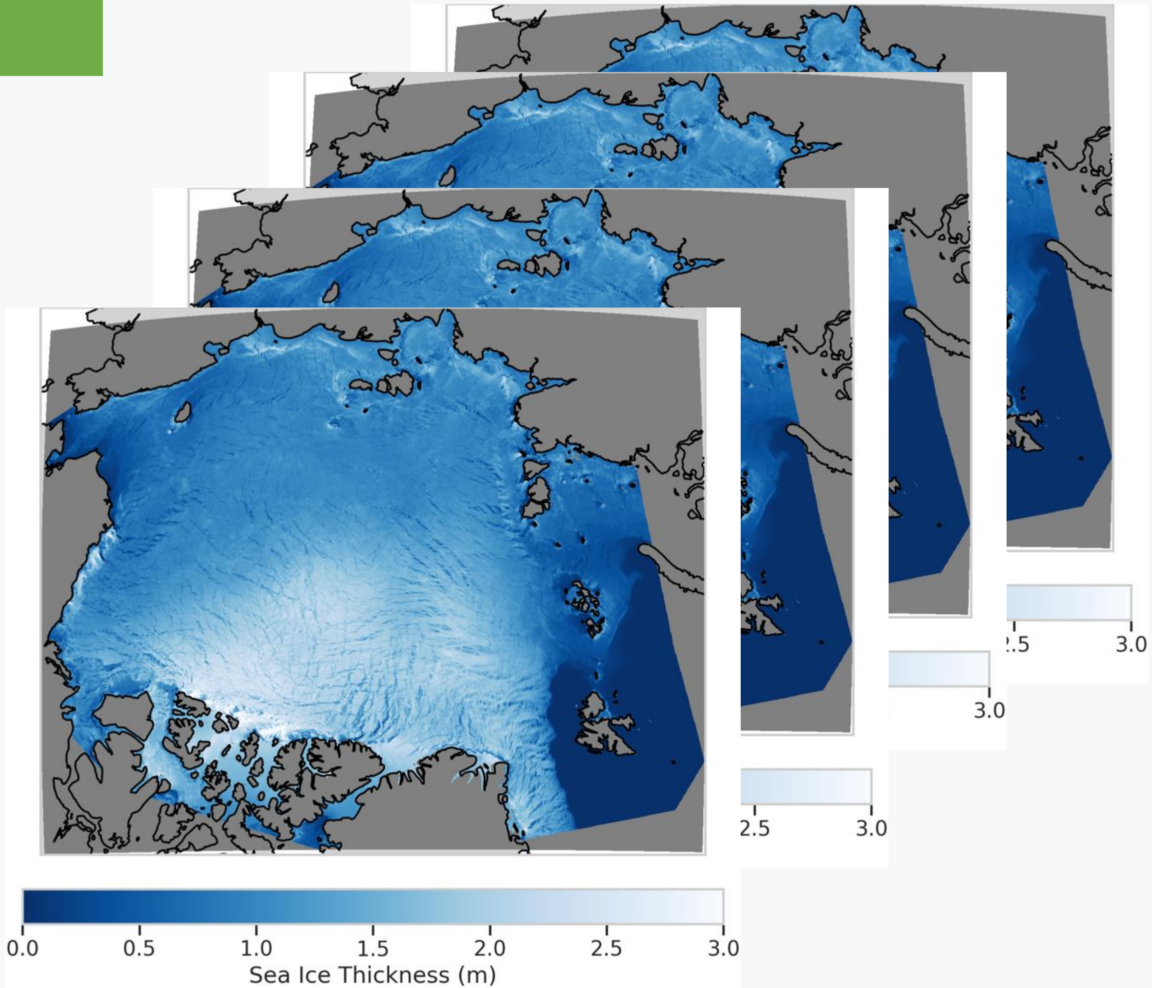
probabilistic

Our Objective: downscaling

x

Low-resolution observations → Downscaling Model → High-resolution sea ice thickness

y



Deterministic downscaling: $y = f(x)$

Probabilistic downscaling: $P(y|x)$

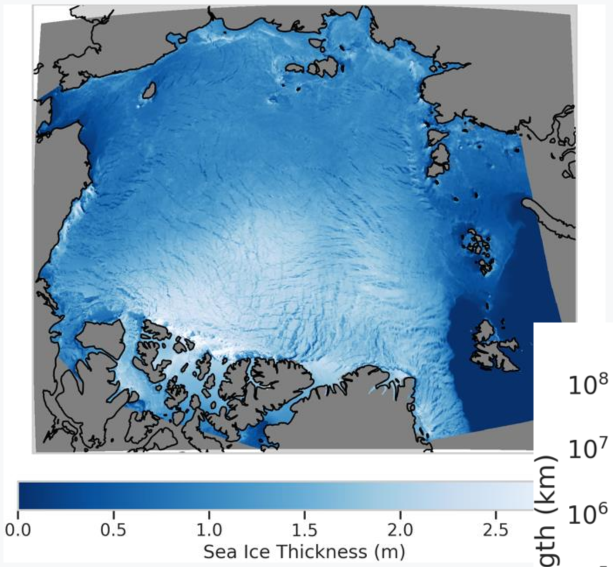
What do we need?

- ✓ A training set of matching pairs of low-resolution/high-resolution fields
- ✓ A probabilistic model
- ✓ Relevant metrics for validation
- ✓ Apply to observation

Dataset constitution

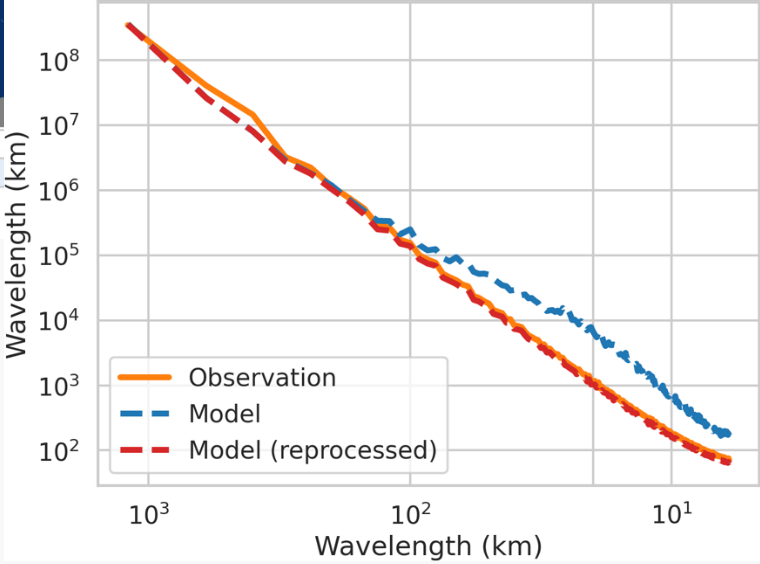
Principle: Using **high-resolution NeXtSIM simulations** [Ólason et al., 2022] and process them to match the resolution of **the observations**.

NeXtSIM sea ice thickness (res ~3km)

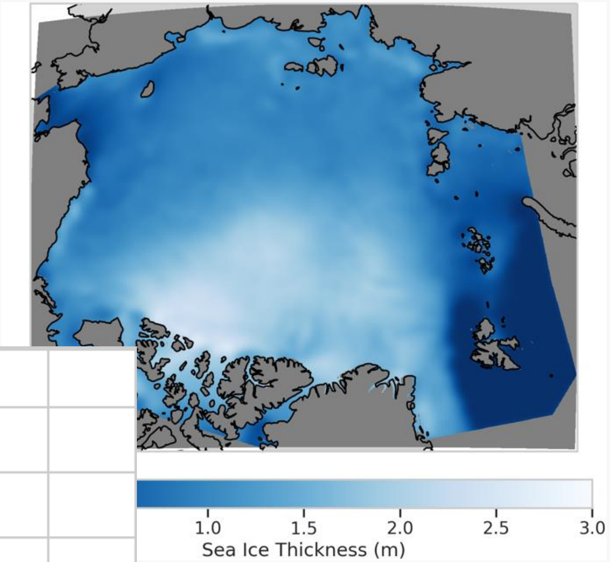


y

Smoothing with a Gaussian kernel (size 33 km)

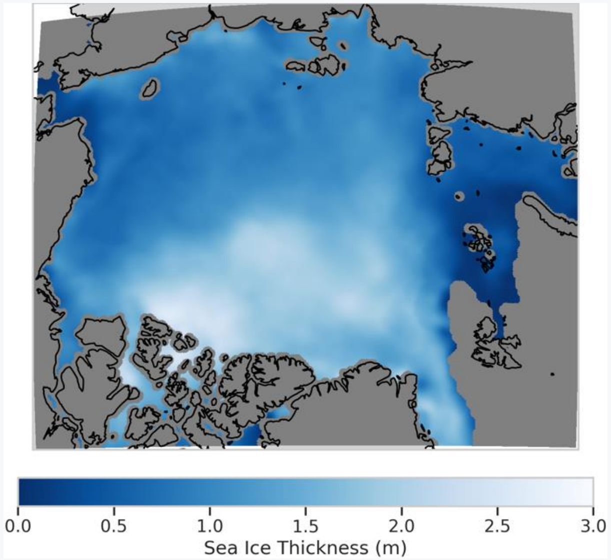


Reprocessed neXtSIM



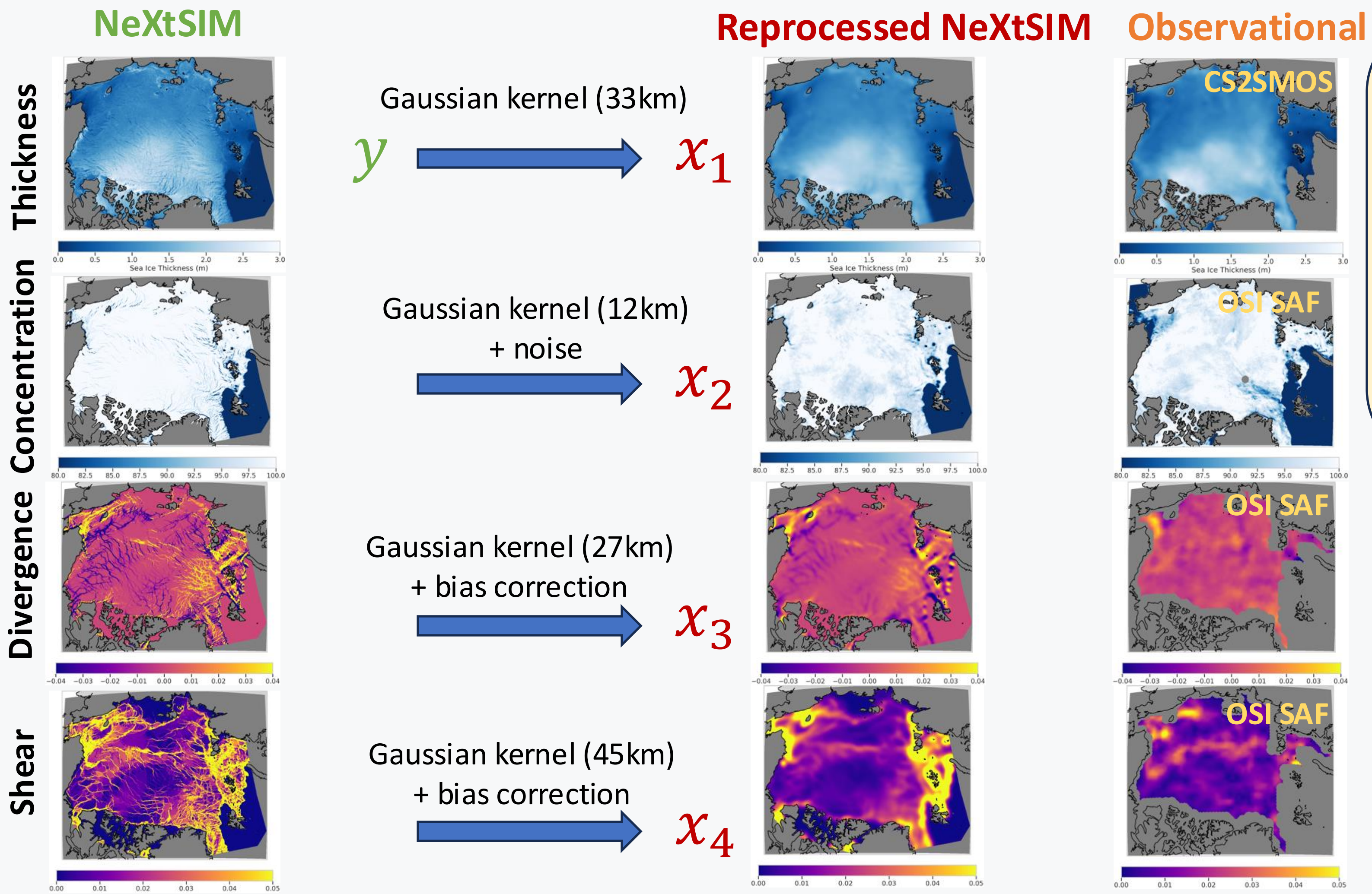
x

CS2SMOS (observational product)



Dataset constitution

Same procedure for Sea Ice concentration, divergence and shear (to be used as input feature)



Dataset: $([x_1, x_2, x_3, x_4], y)$

- ✓ Divergence and Shear are transformed into the total deformation
- ✓ A land mask is added
- ✓ Samples in freezing season:
  - ✓ Training: 2013-2020 (1157 samples)
  - ✓ Validation: 2020-2022 (360 samples)
  - ✓ Test: 2022-2023 (180 samples)

Download the dataset

https://archive.norstore.no/pages/public/datasetDetail.jsf?id=10.11582/2024.00126

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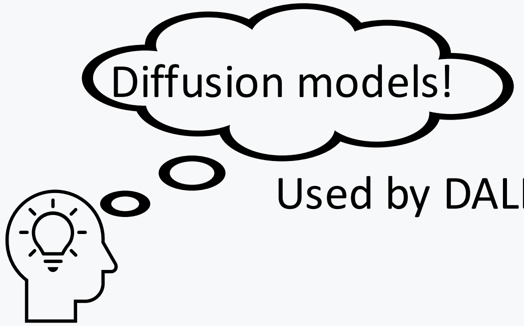
Generative machine learning

Probabilistic downscaling: $P(y|x)$

Generate an ensemble of realization of high-resolution sea ice thickness y knowing low-resolution fields x

x: condition, context, prompt



Used by DALL-E, Midjourney, …

Example of a prompt:
"Realistic image of a ship navigating in the Arctic sea-ice”

https://openart.ai

Generative machine learning

Probabilistic downscaling: $P(y|x)$

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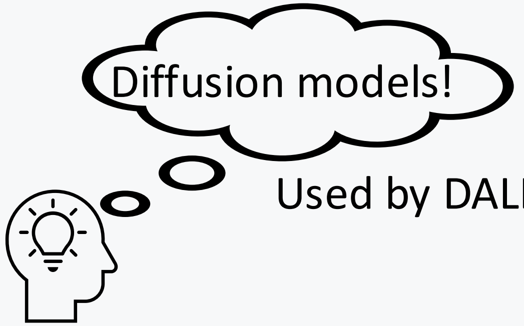
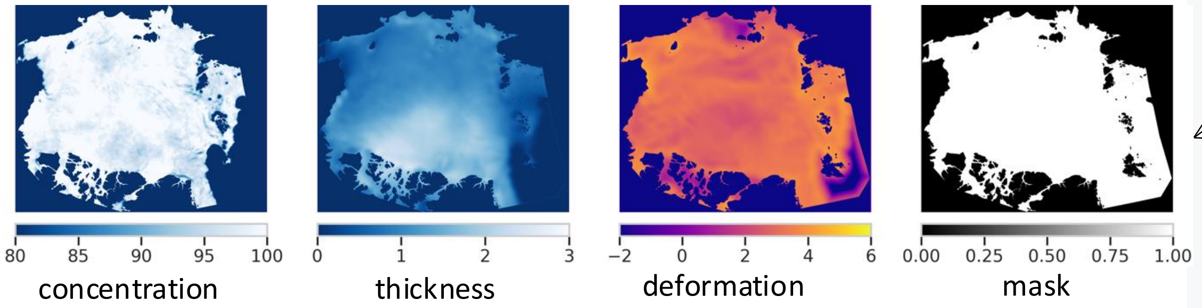
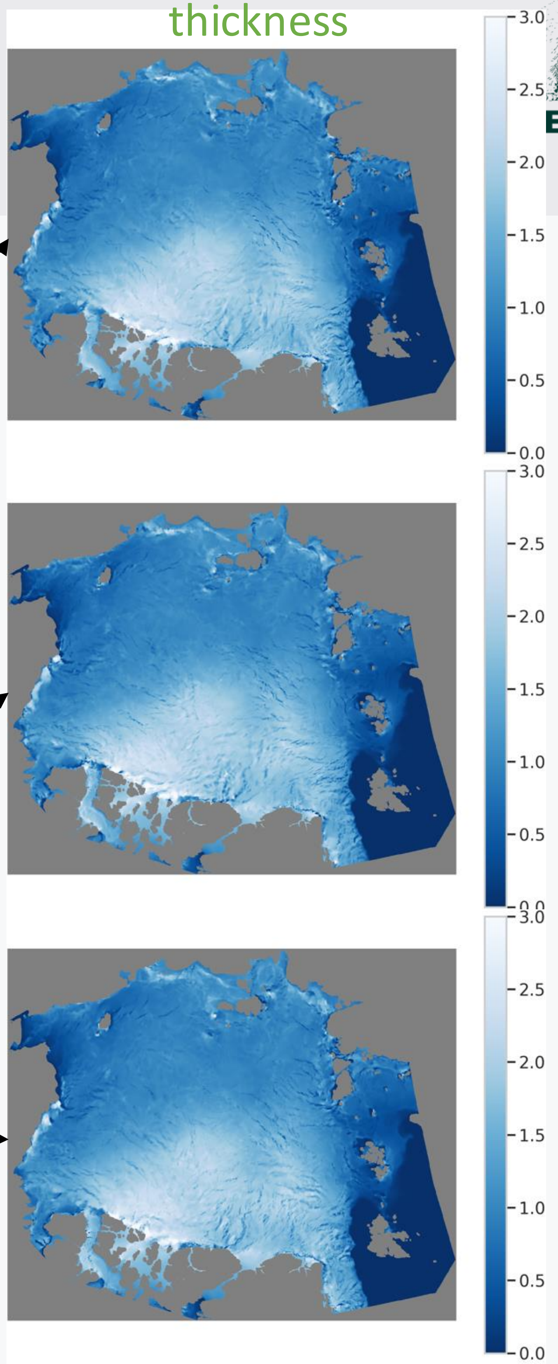


Used by DALL-E, Midjourney, …

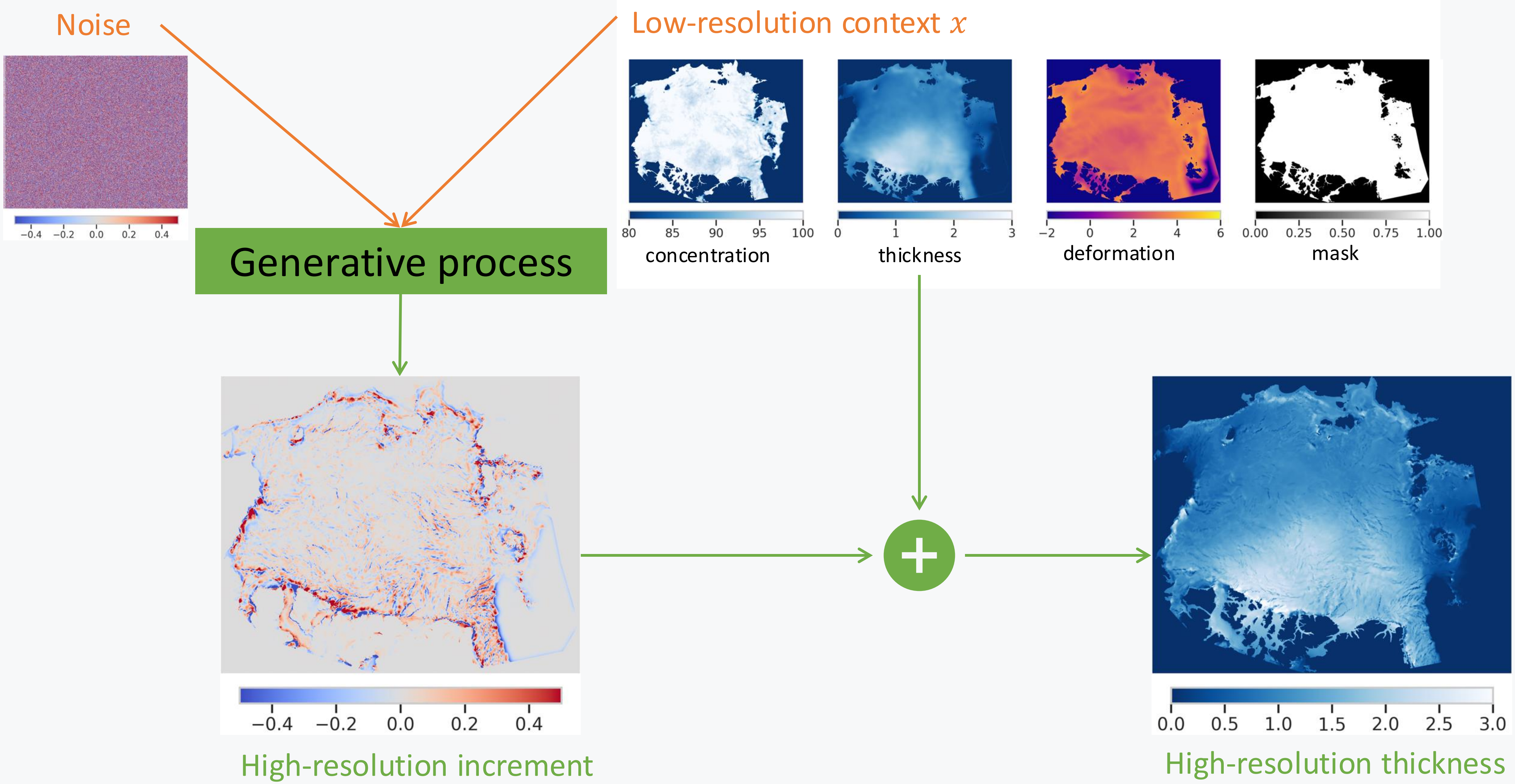
low-resolution context x



High-resolution sea ice thickness

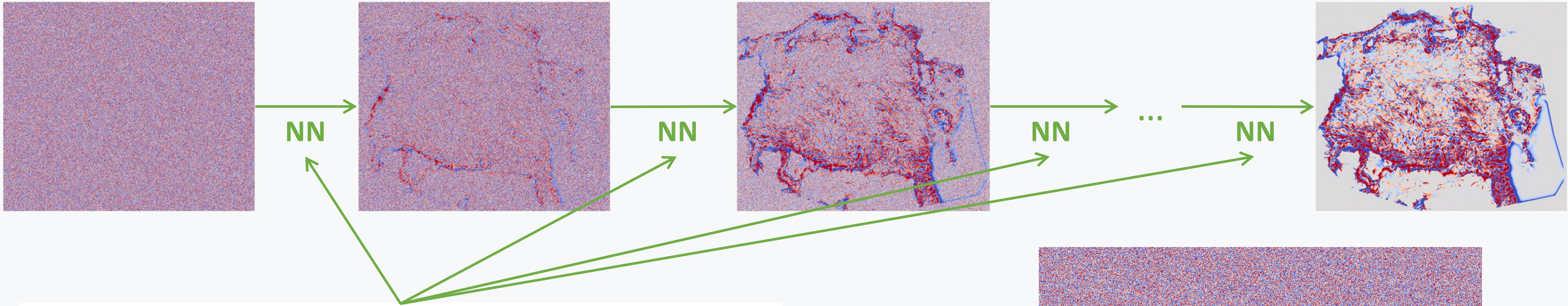


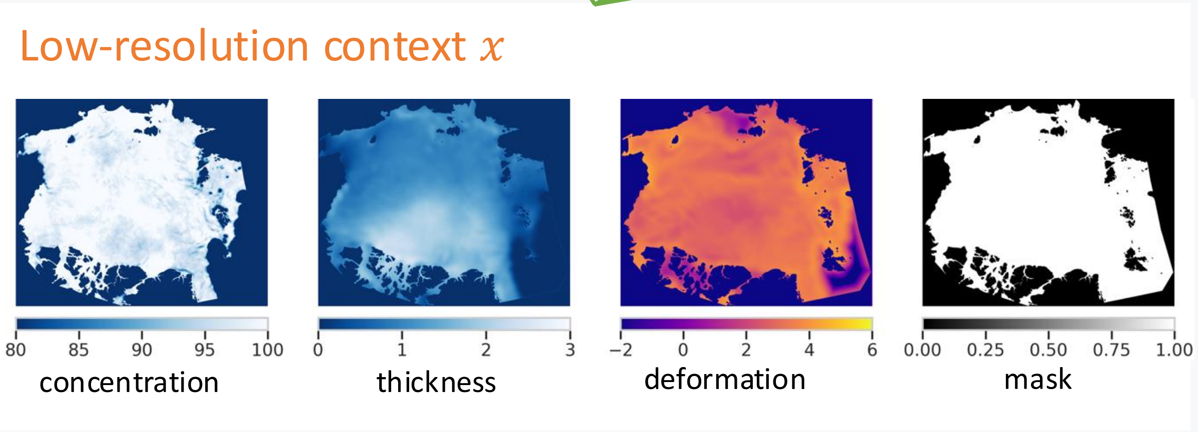
Applying the diffusion model to sea ice super-resolution

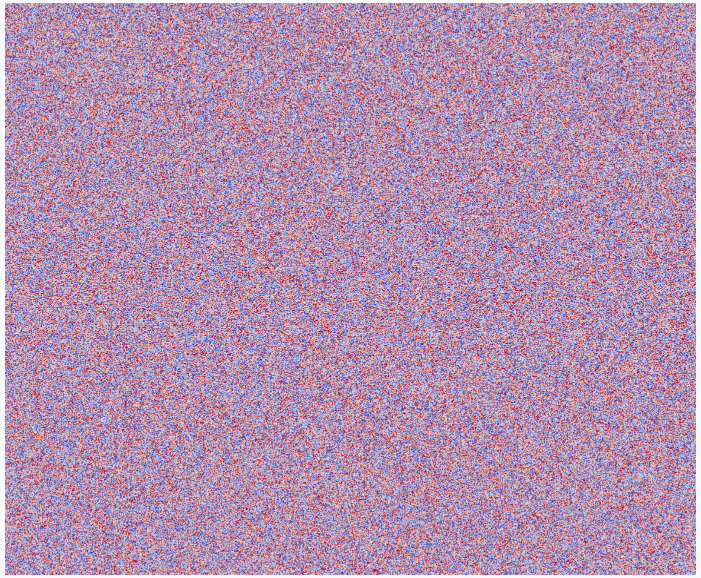


Diffusion models – how do they work?

A **neural network** as a recursive denoiser

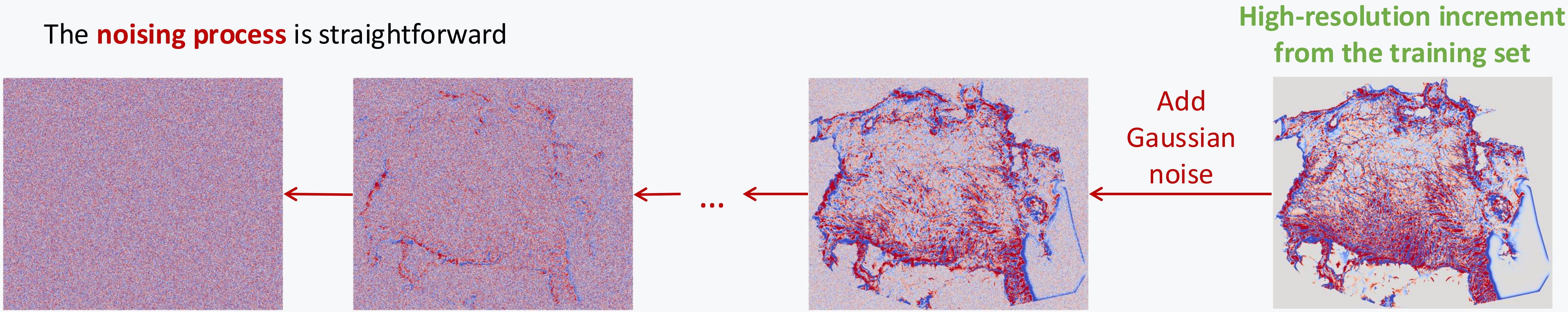




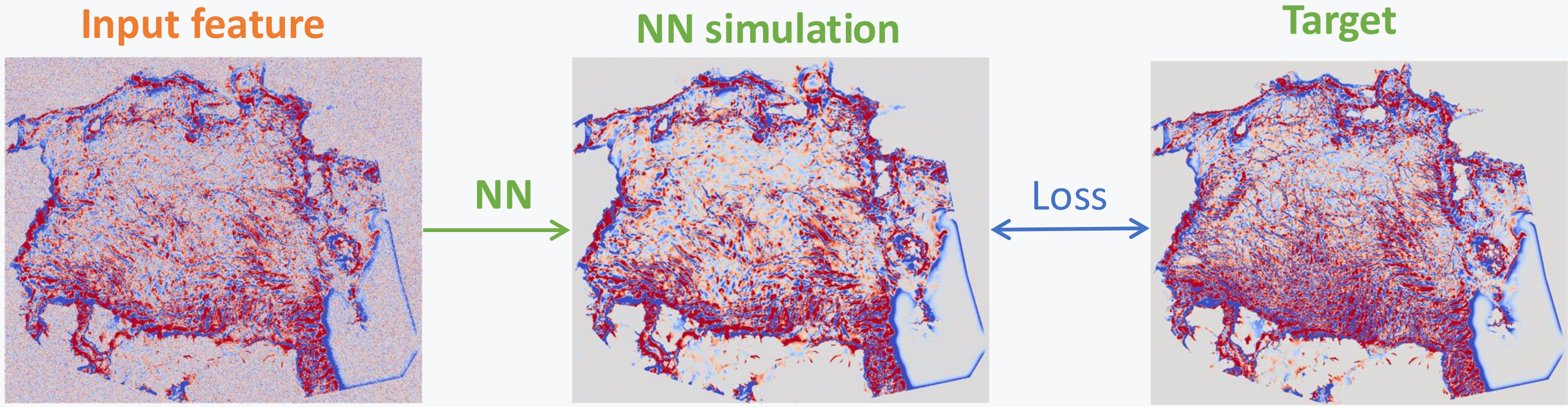


Training a diffusion model

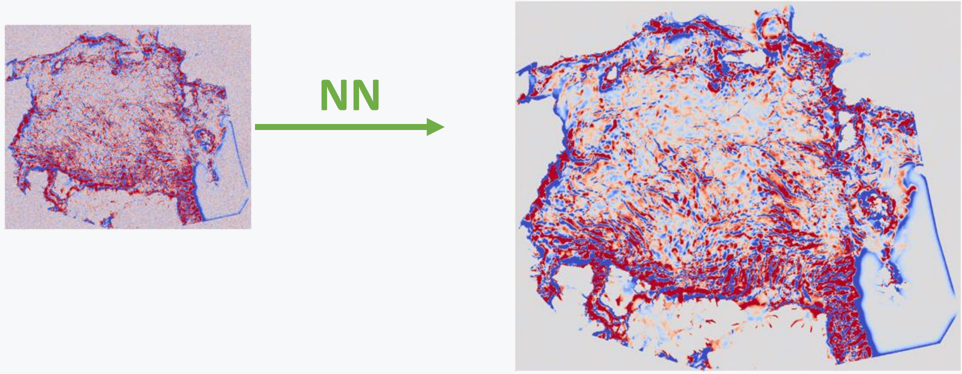
The **noising process** is straightforward

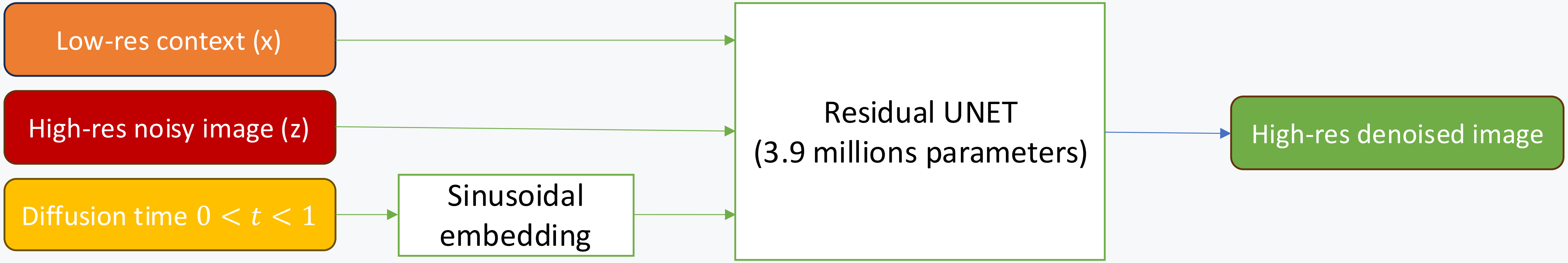


One training sample (draw a level of noise between 0 and 1):



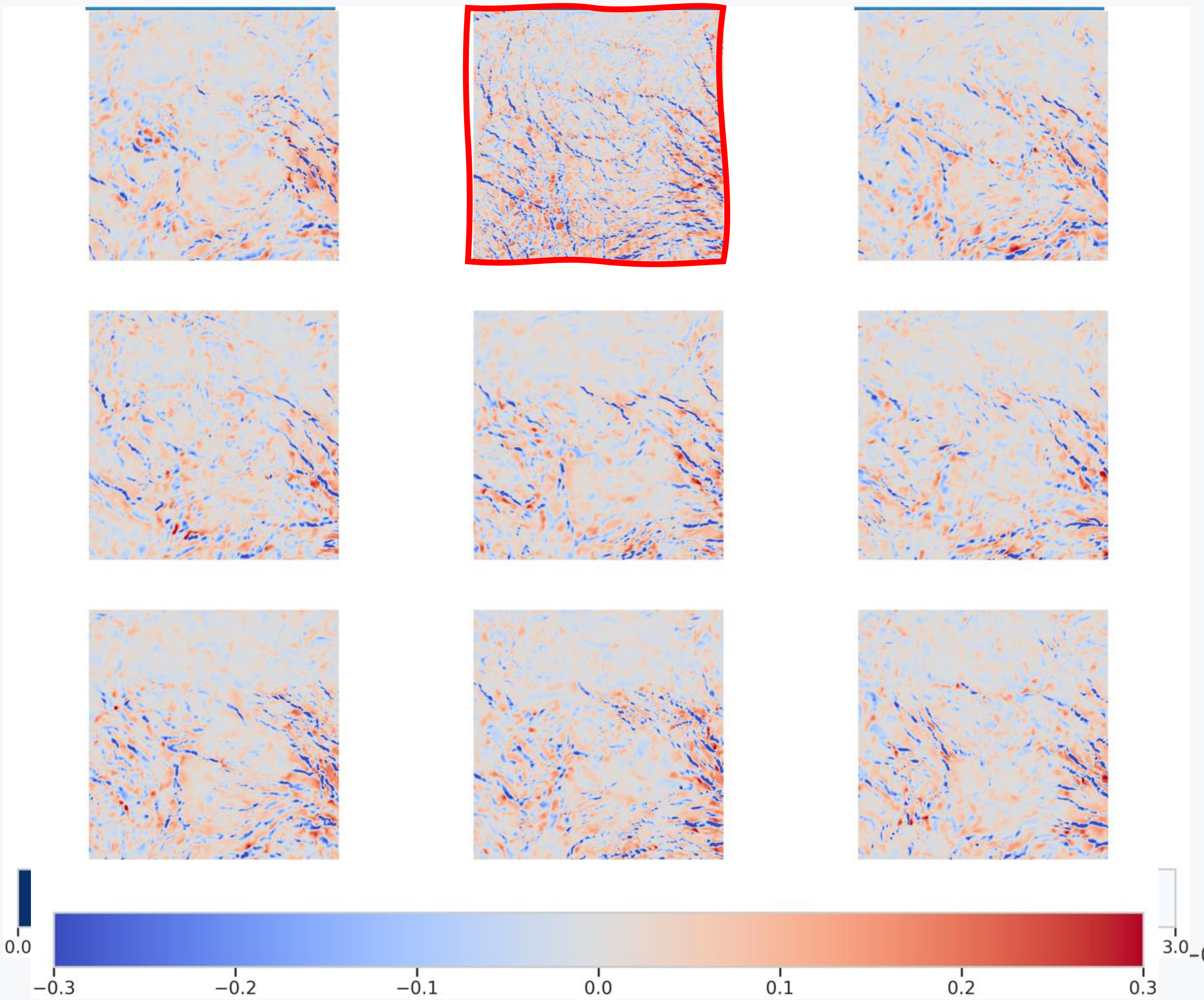
Implementation details

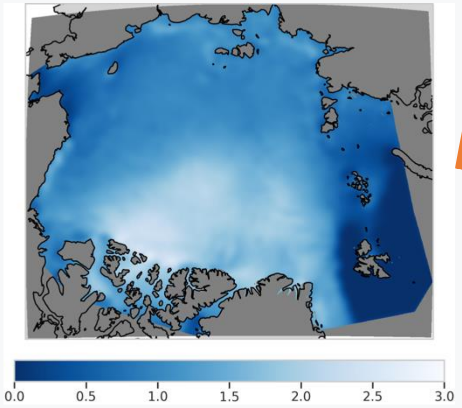




Generation January 1, 2021

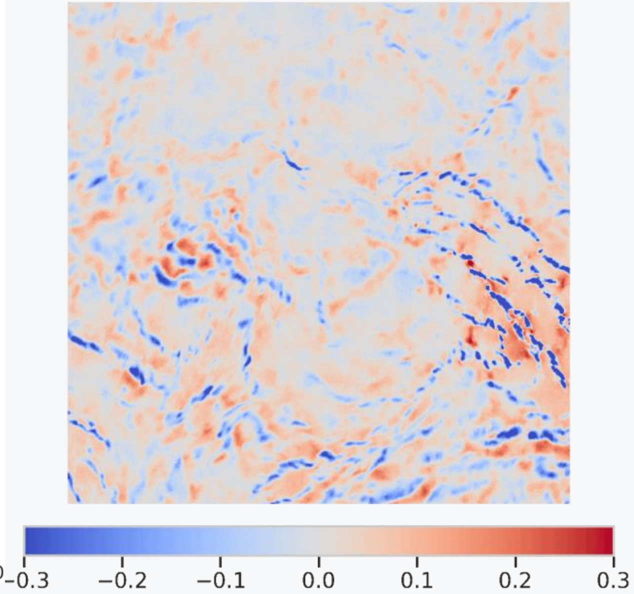
Generated ensemble of sea ice thickness

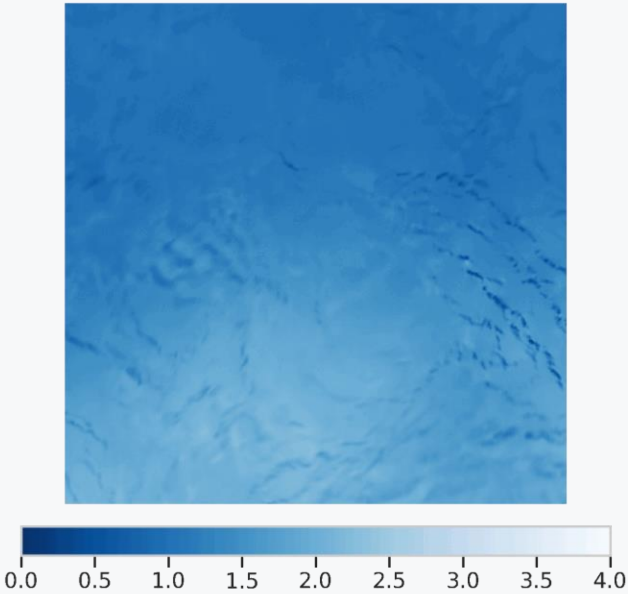




From the low-resolution tickness

SIT mem 0 - 20210101





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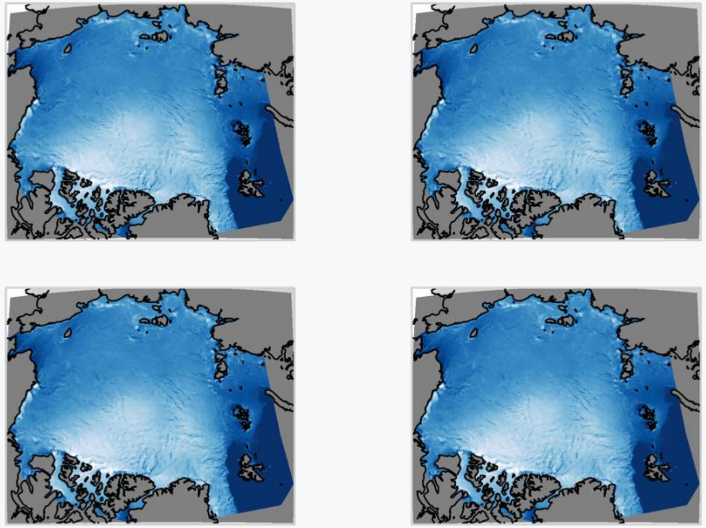
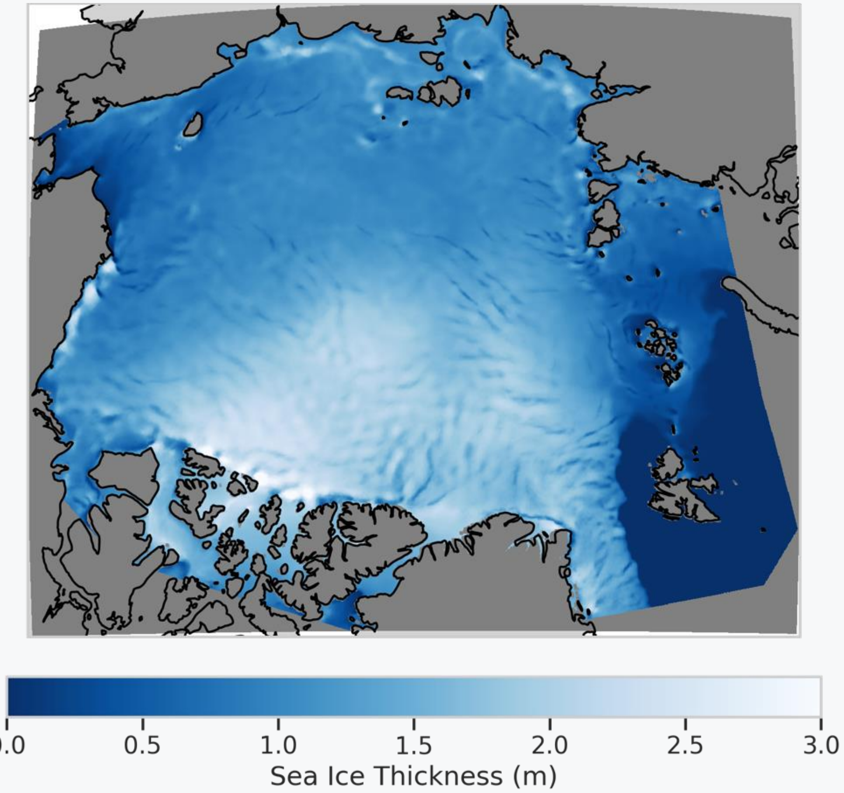
Different “products”

Individual members



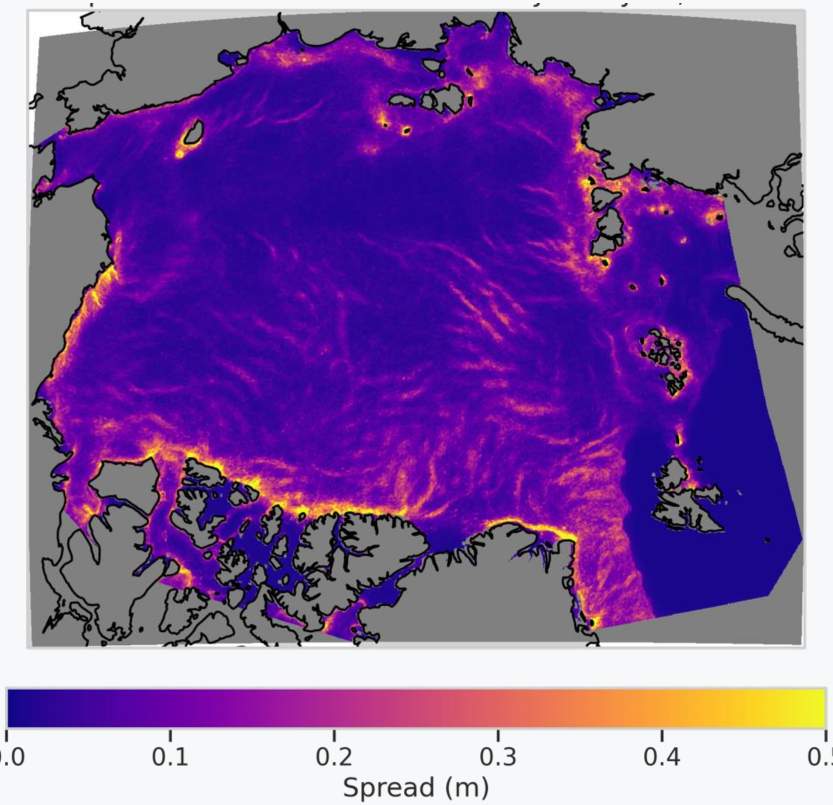
Used to assess
realism

Ensemble mean



Used to assess
accuracy

Spread

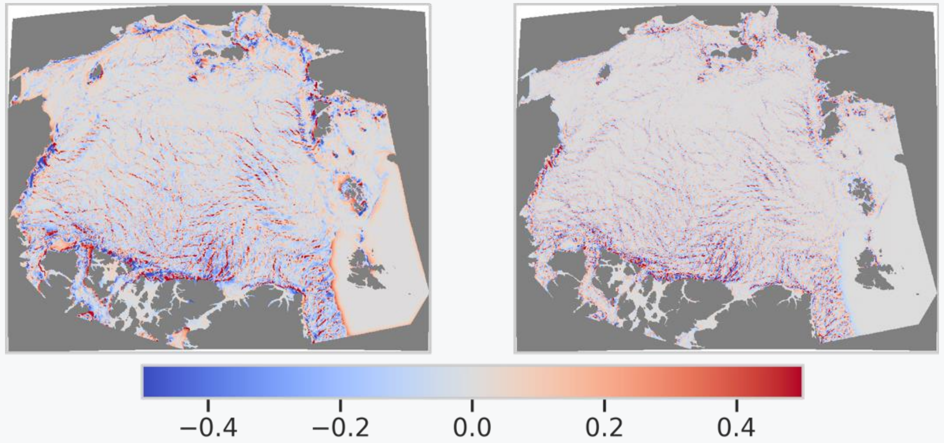


Used to assess
uncertainty

Accuracy of the super-resolution

Error low-resolution

Error AI ensemble mean

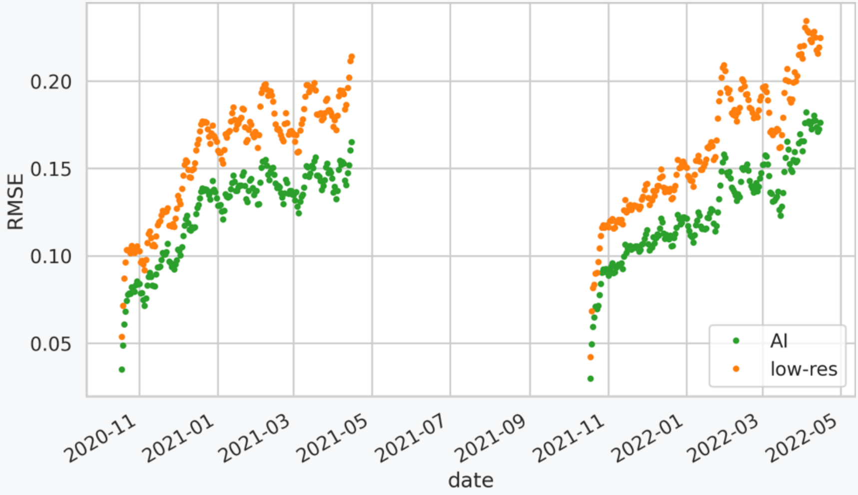


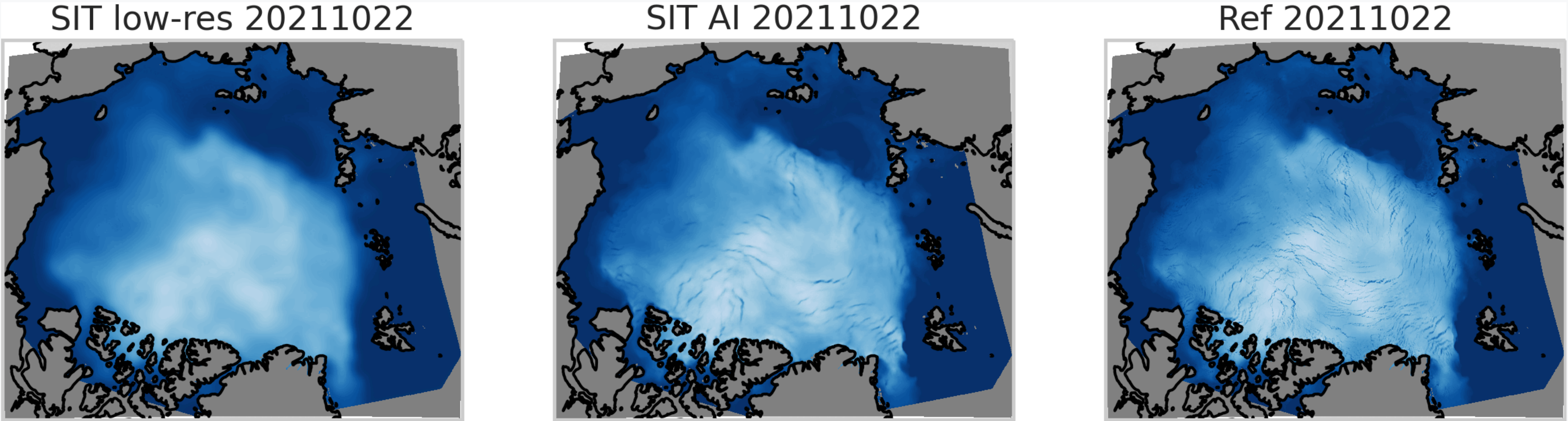
Root-mean square error (RMSE) of:

Low-resolution: 0.16 m

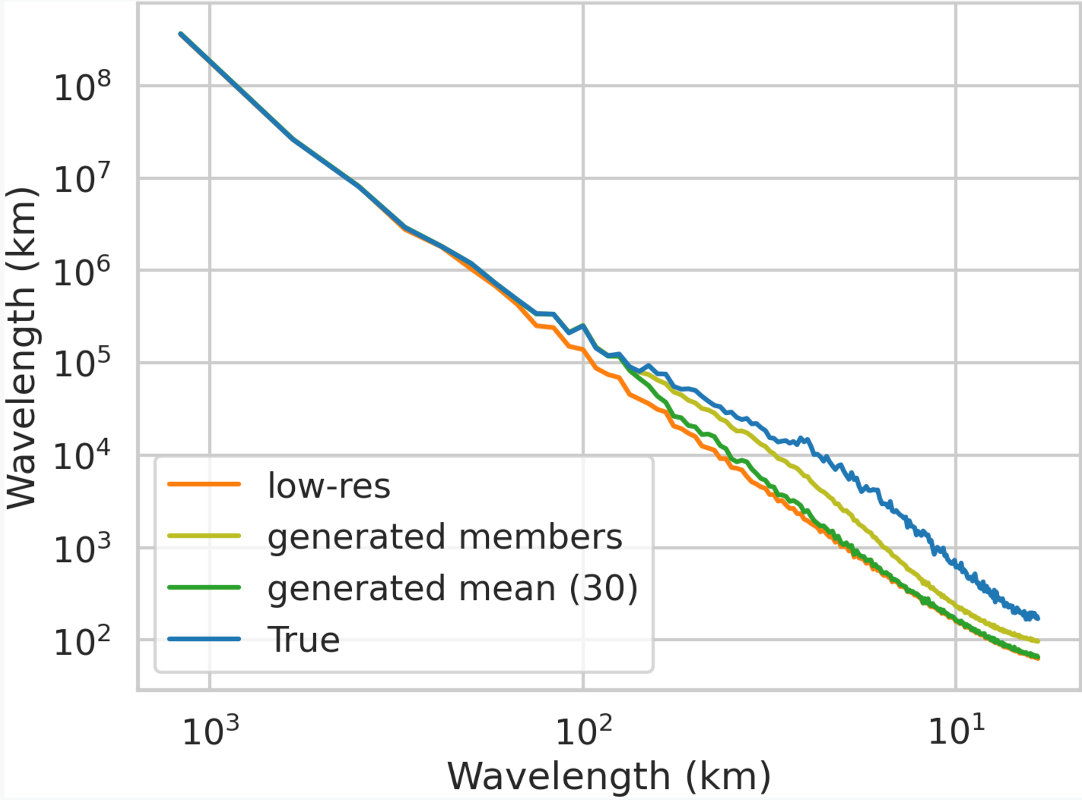
AI product: 0.13 m

Improvement: **20%**

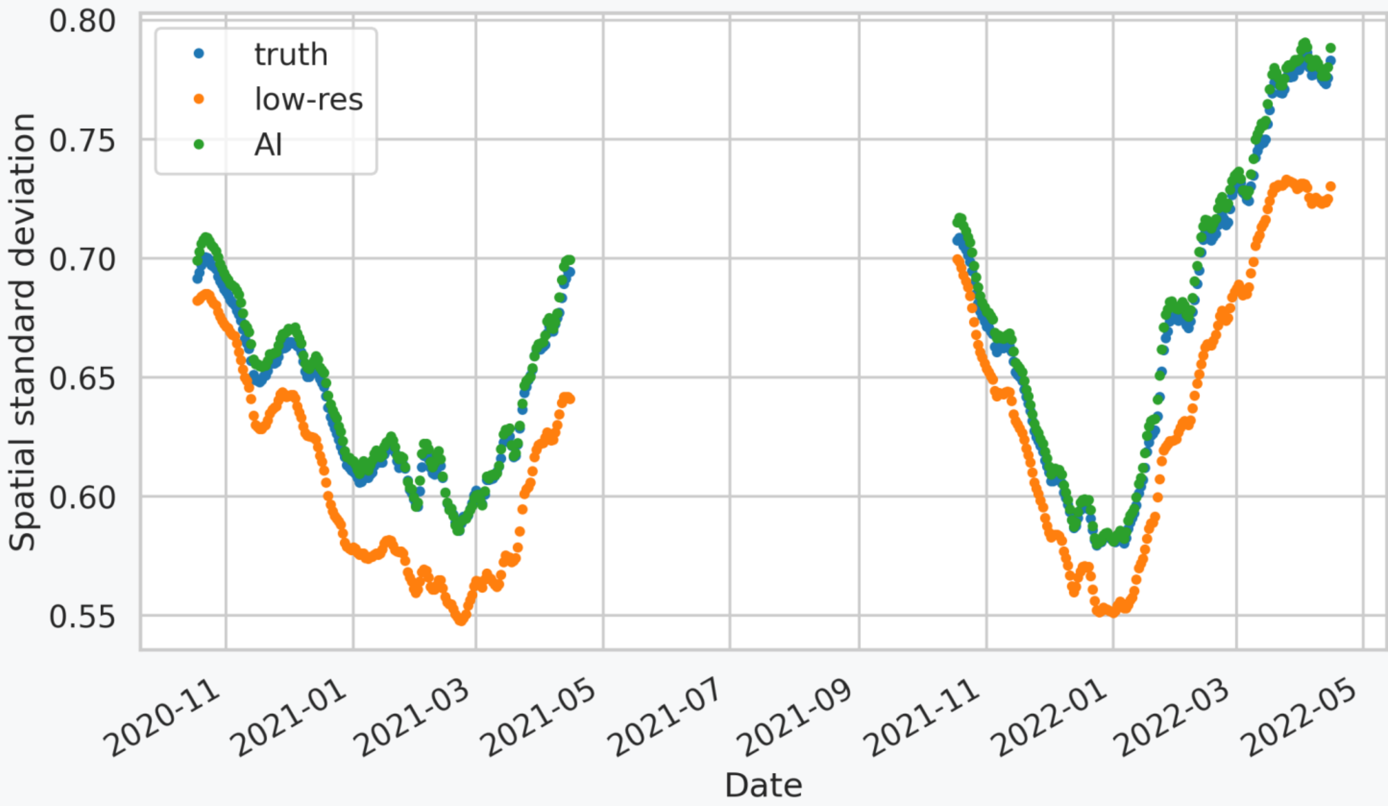




Realism



Wavelength (km)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^3
10^2
10^1
Wavelength (km)
low-res
generated members
generated mean (30)
True



Spatial standard deviation
0.80
0.75
0.70
0.65
0.60
0.55
truth
low-res
AI
2020-11
2021-01
2021-03
2021-05
2021-07
2021-09
2021-11
2022-01
2022-03
2022-05
Date

What do we need?

- ✓ A training set of matching pairs of low-resolution/high-resolution fields
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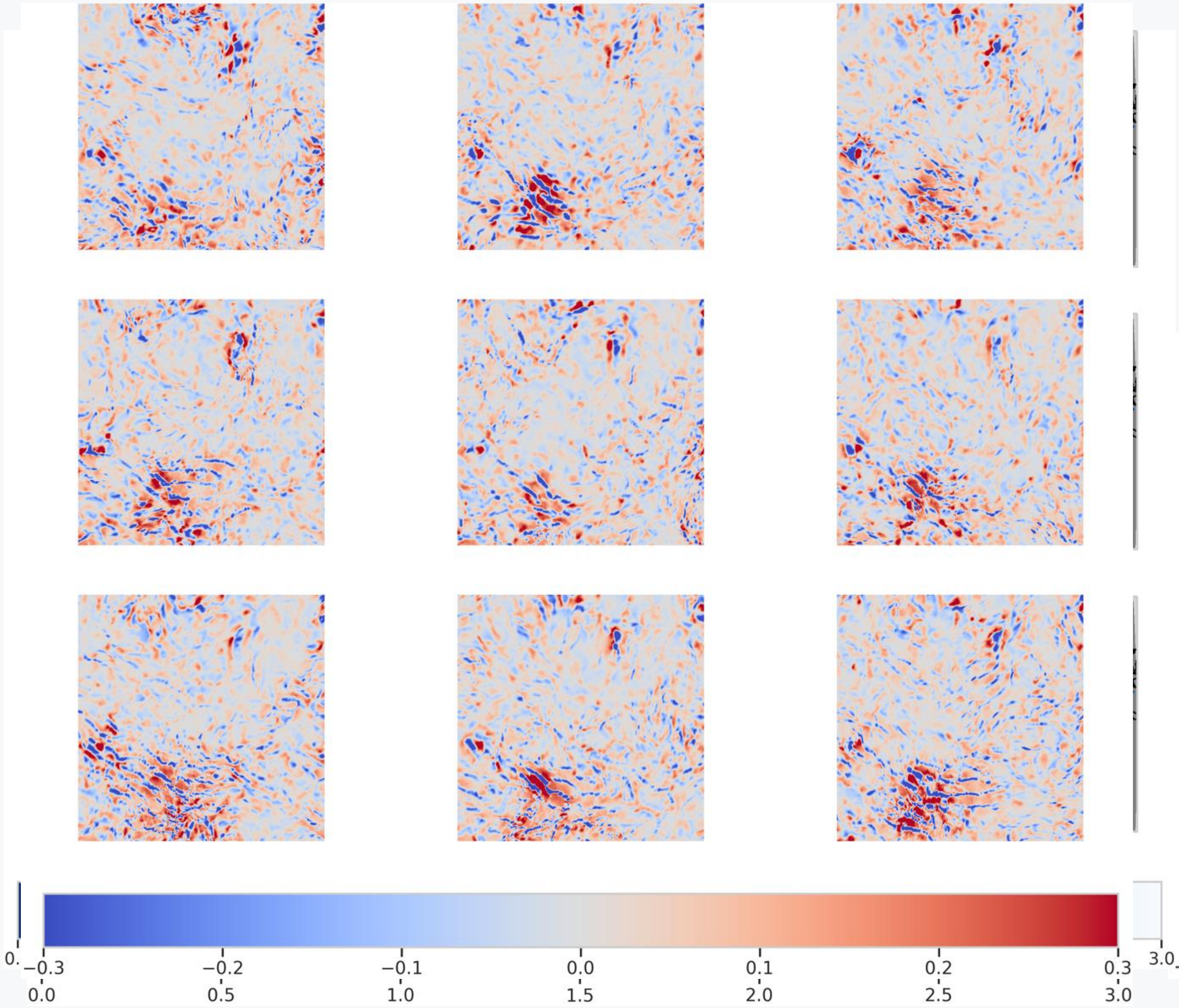
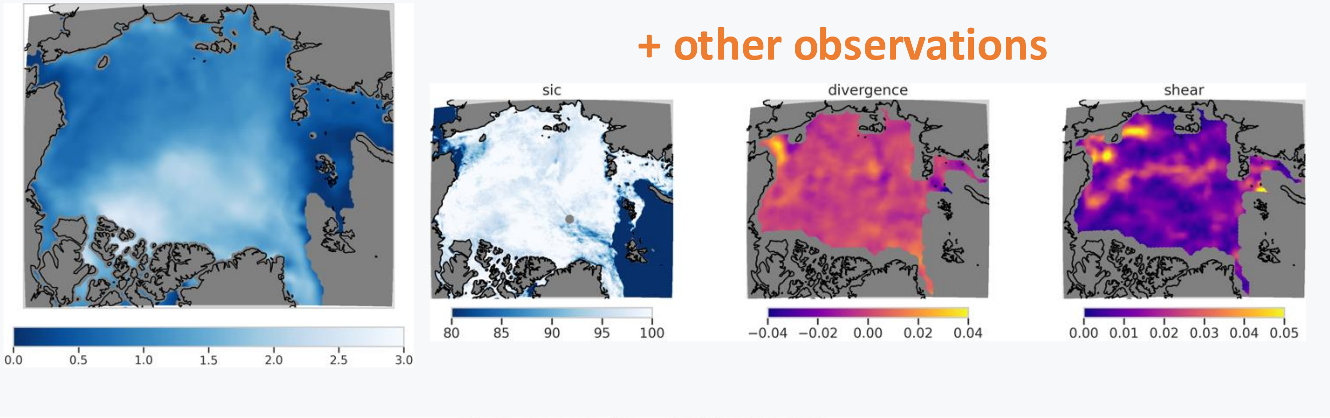
Generation from observations

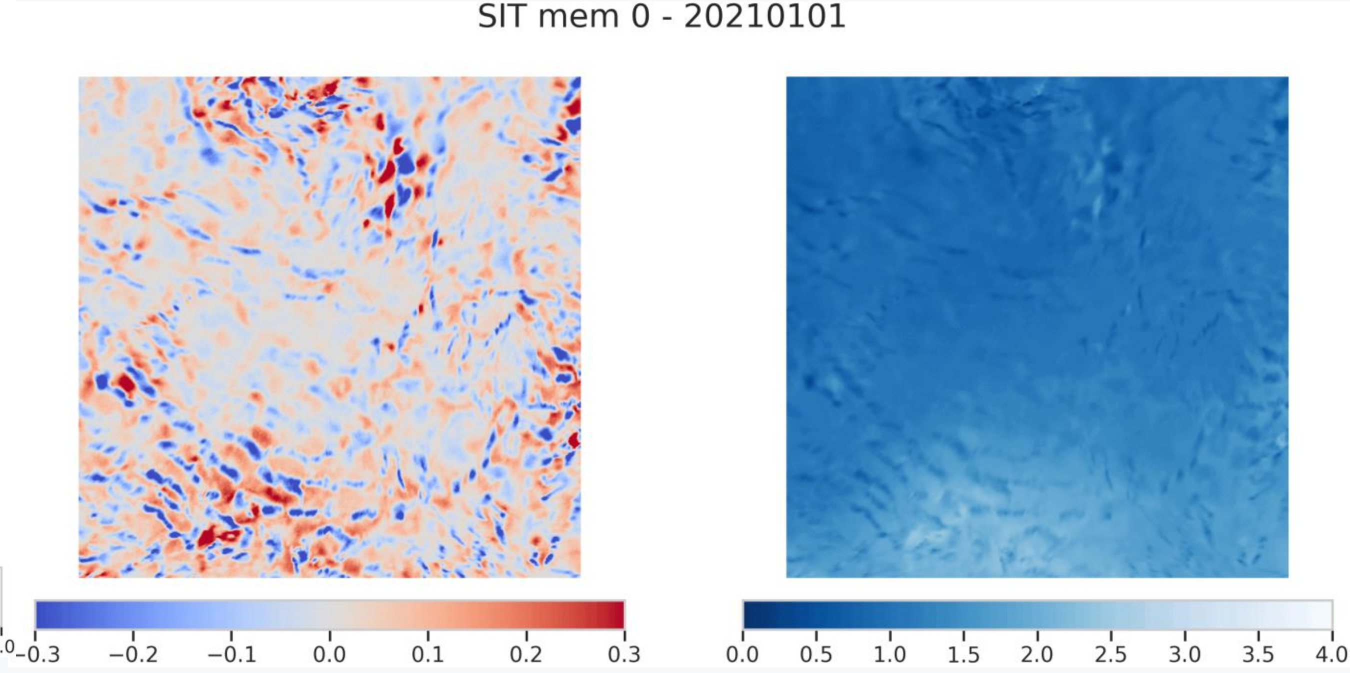
From the low-resolution thickness (CS2SMOS)

Generated ensemble of sea ice thickness



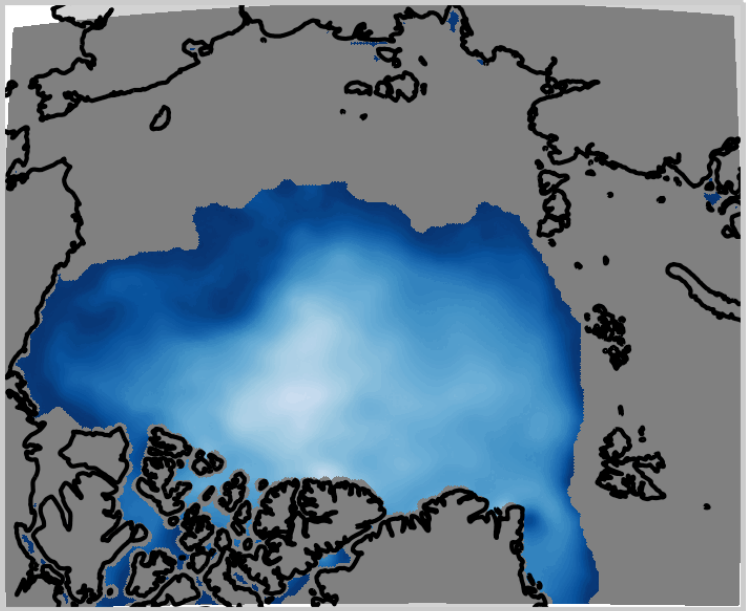
+ other observations



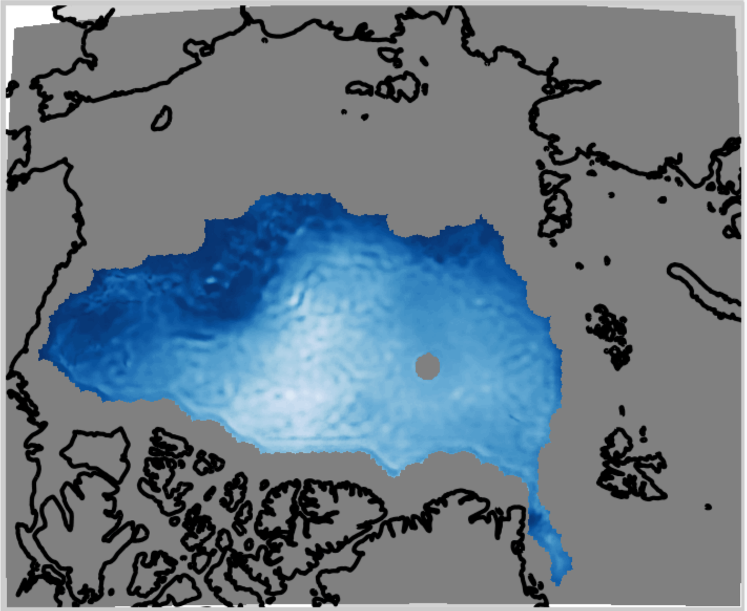


Observations 2020-2021

SIT low-res 20201022

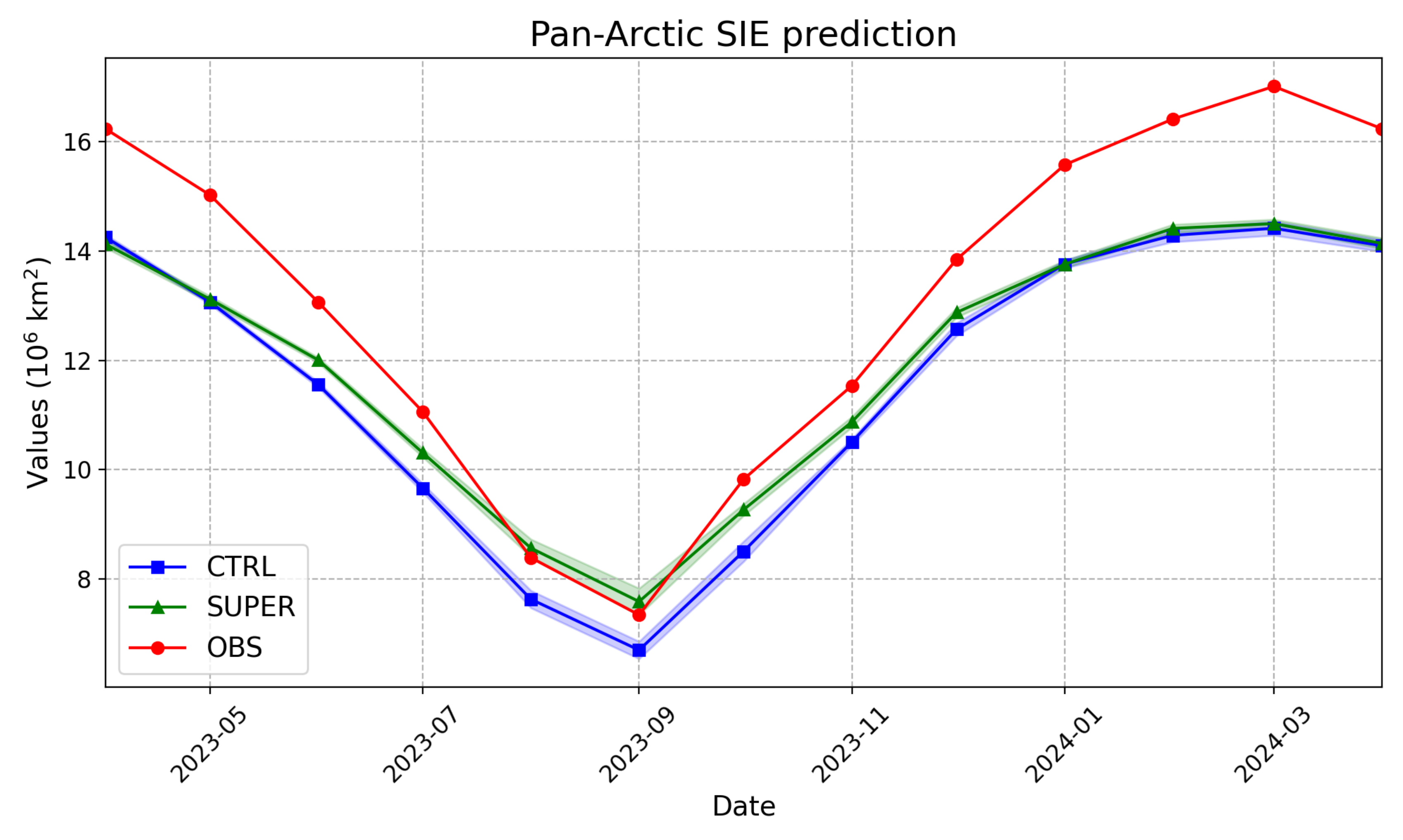


SIT AI 20201022



Case study for prediction from April 2023

CTRL: initialization with SIC and SIT observations (NOAA and CS2SMOS)
SUPER: initialization with category SI observations (SuperICE)
Obs: SIC observations (NOAA)



Courtesy of Yiguo Wang

Take-home message

- **Diffusion models can be used to generate accurate and realistic high-resolution sea ice thickness fields**
    - Better accuracy and better realism compared with low-resolution field
- **A model trained on a realistic physical simulations can be applied, without retraining, on observations** (a few artifacts can appear)
- **Super-resolution using diffusion models can be applied to other sea ice variables** (actually, any geophysical variable)
- The dataset (both physical simulations and AI generation) is available for download

Contact me!

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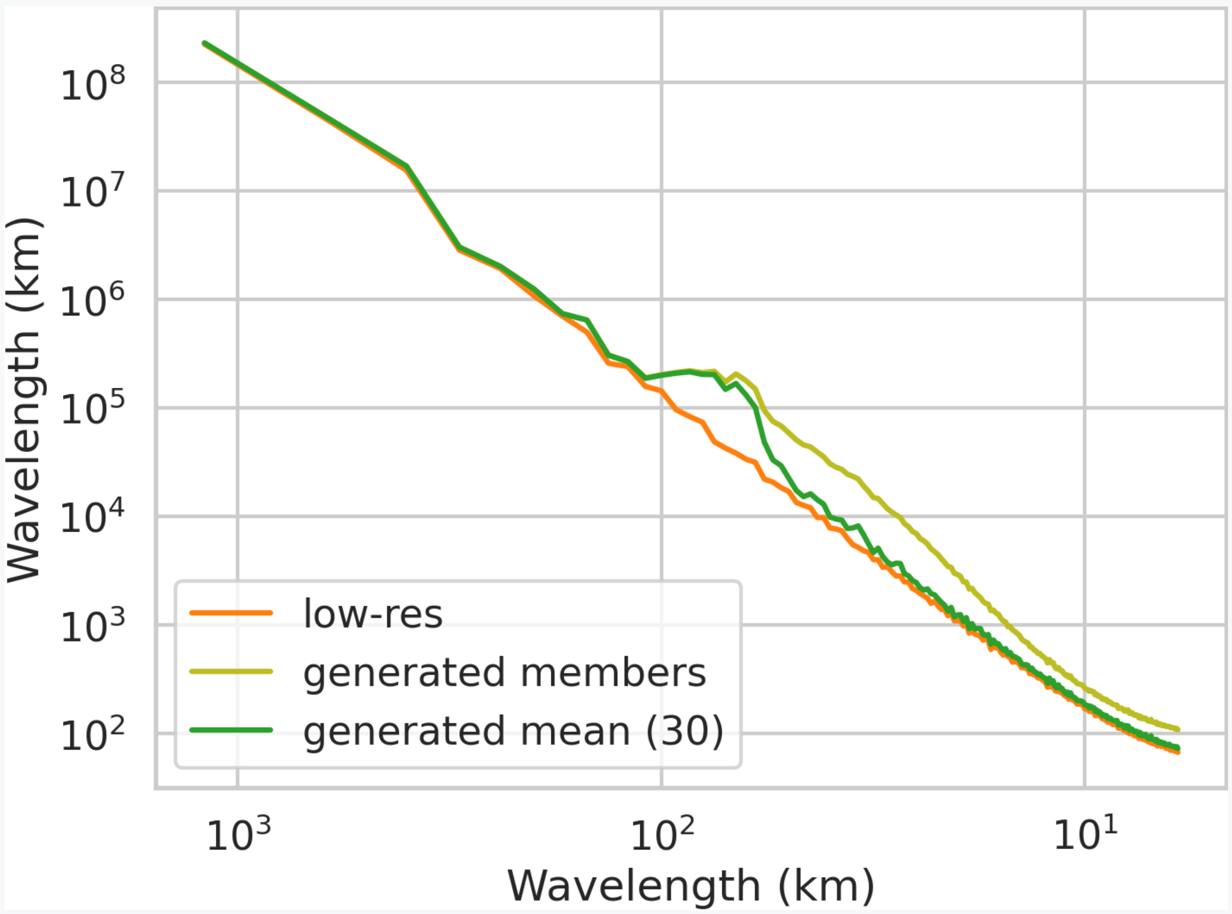
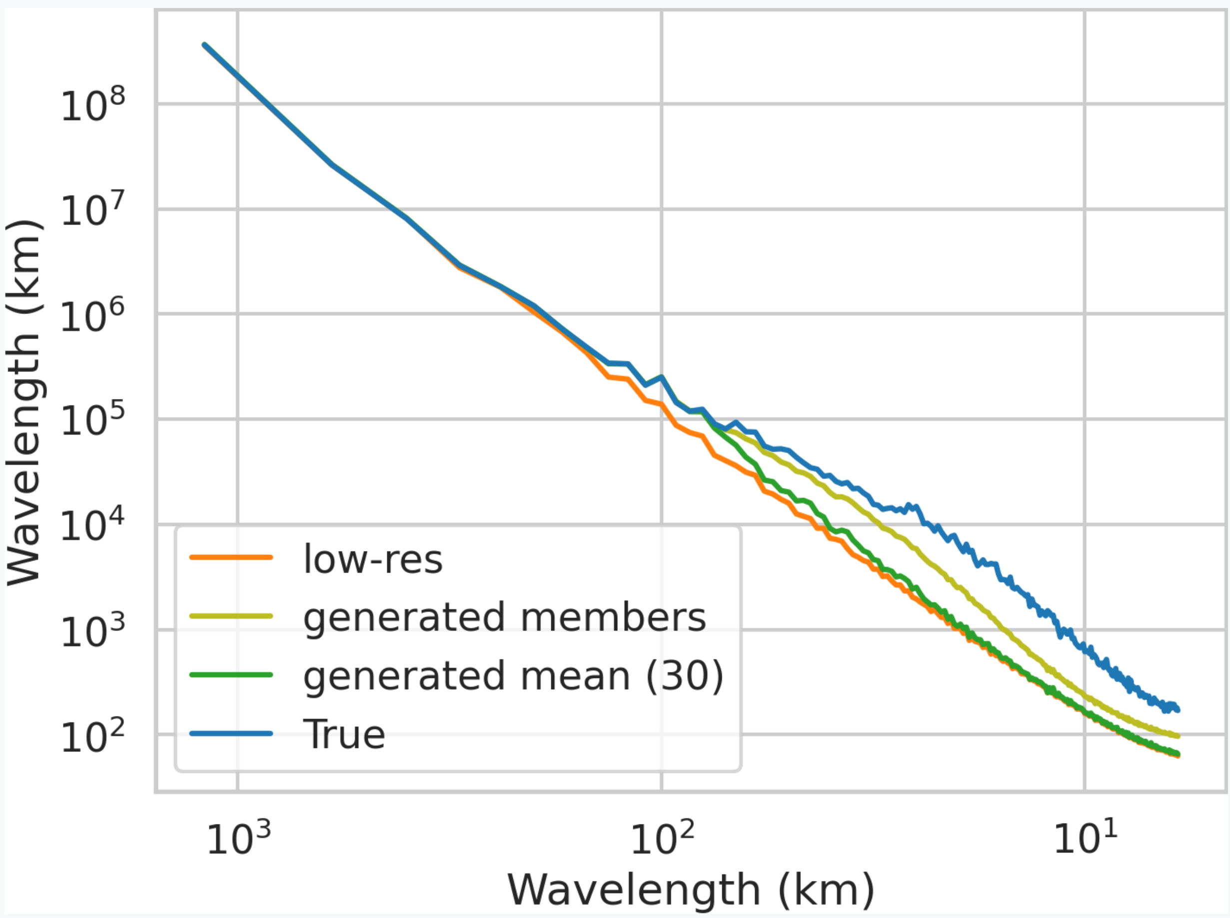
Observation spectrum

Spectrum of the observations reconstruction

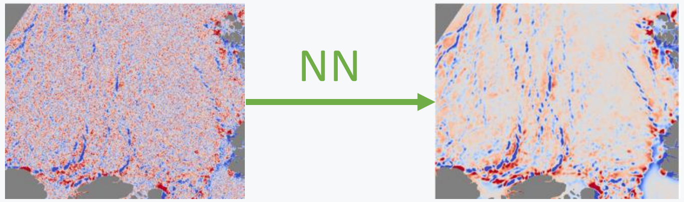


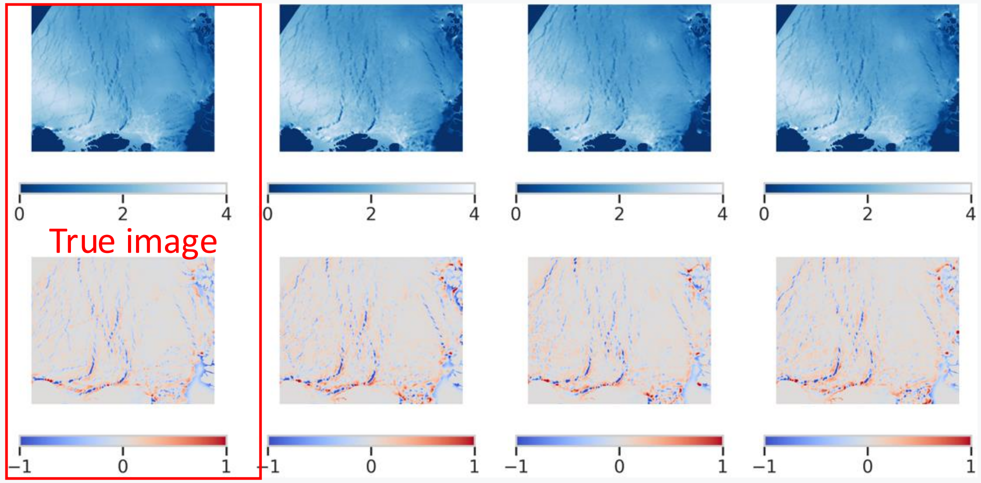
Spectrum of the NeXtSIM reconstruction



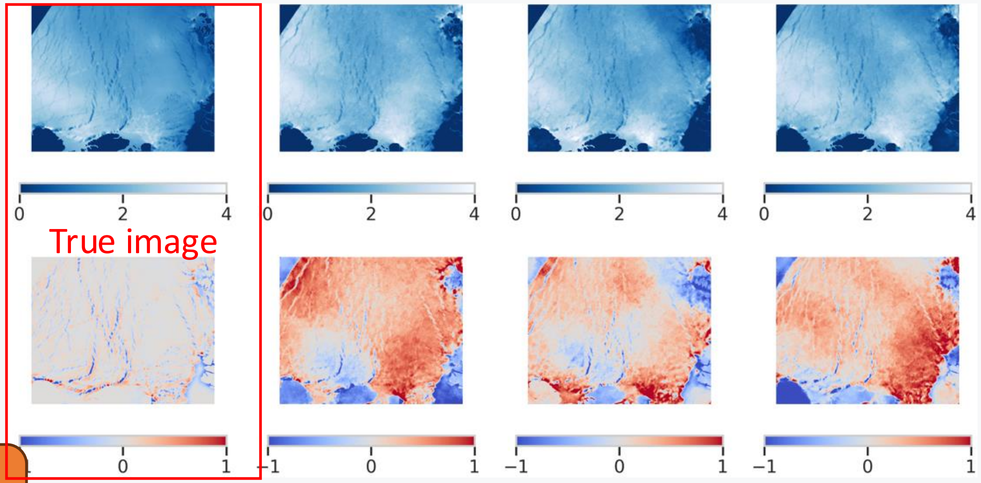
Anomaly Vs full field generation

Anomaly generation





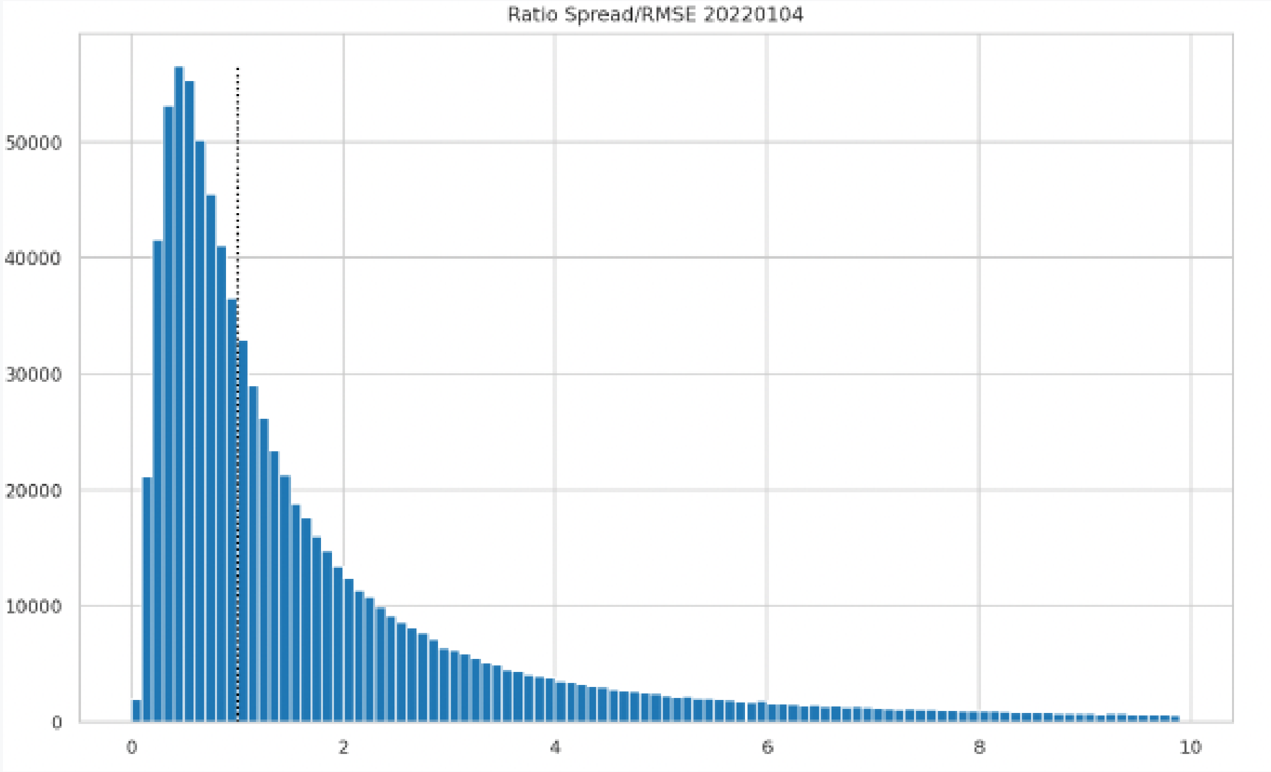
Full-field generation

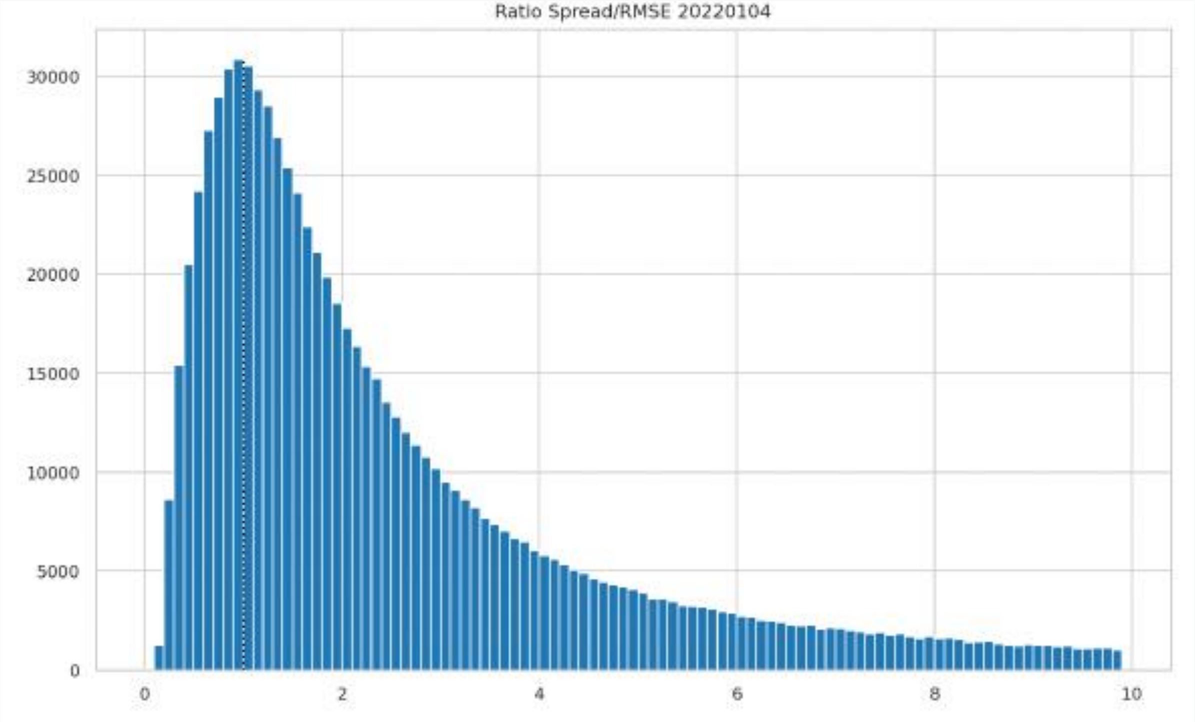


Full-field induces large-scale biases

Ensemble score

Ratio Spread / RMSE

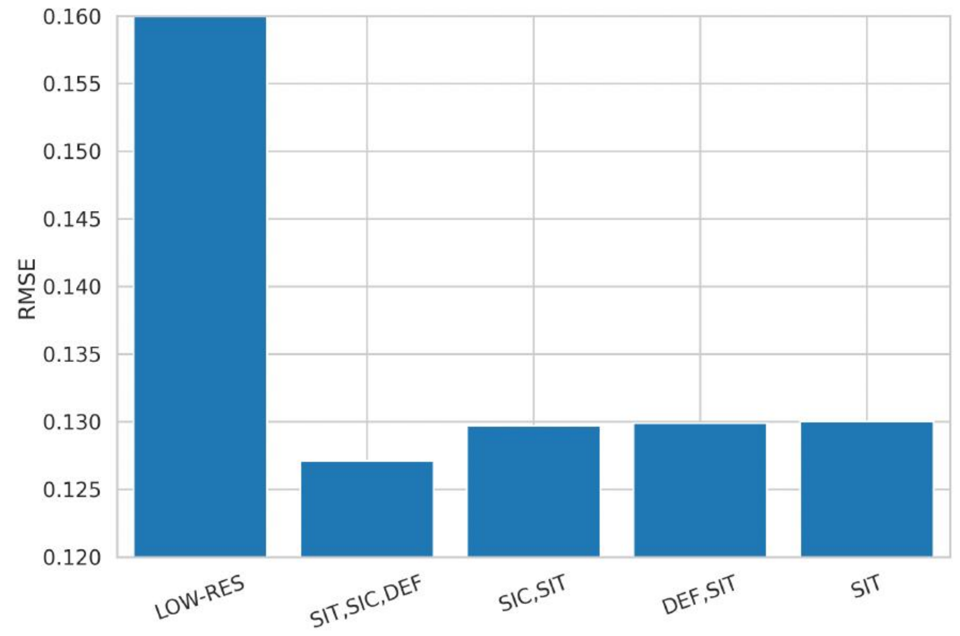


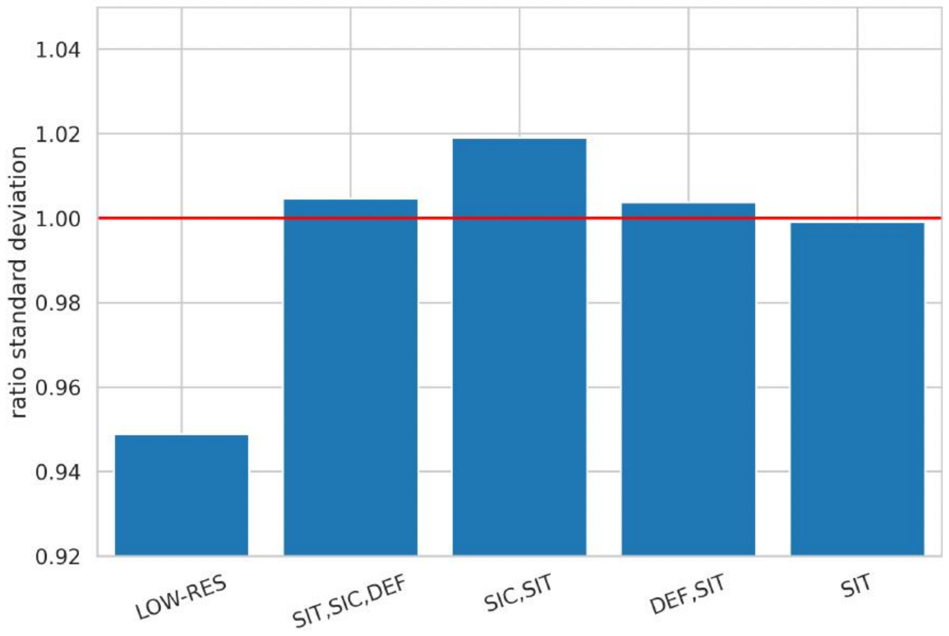


Another training with only thickness and concentration in the context

Input features

Trial	inputs
11	SIC, SIT, DEF
6	SIC, SIT
7	DEF, SIT
8	SIT





Input features