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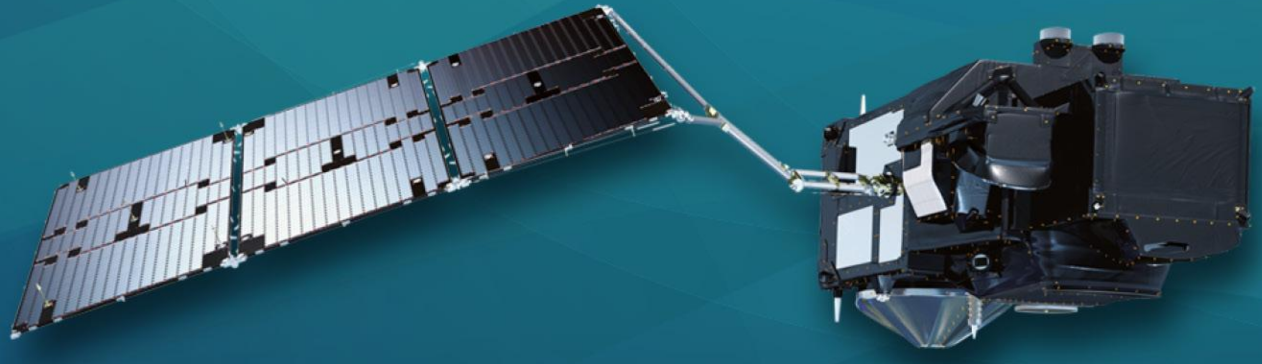


9th Sentinel-3 Validation Team meeting 2026

30 March–01 April 2026 | ESA–ESRIN | Frascati (Rome), Italy

Estimation of Sea Ice Concentration and Snow Depth using Sentinel-3 MWR brightness temperatures and altimeter synergies

A. Saint Georges-Chaumet [1], A. Feufeu [1], L. Amarouche [1], S. Fleury [2], A. Di Bella [3], M. Scagliola [3], F. Borde [3]

[1] CLS, [2] LEGOS, [3] ESA

LEGOS

CLS COLLECTE LOCALISATION SATELLITES

Context

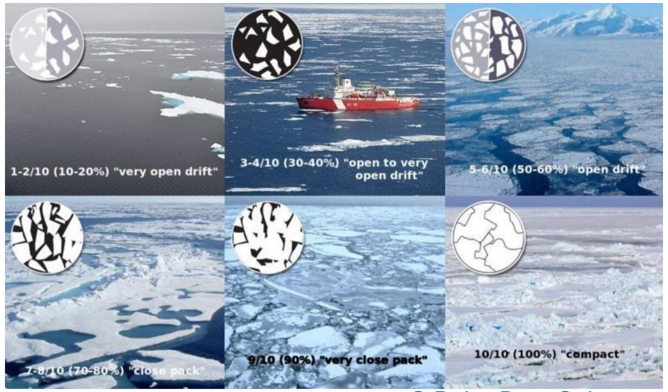
- **Sea Ice Concentration or Sea Ice Fraction (SIC)**
  - Relative amount of ocean covered by sea ice (%)
  - **Important for climate services and for navigation in sea-ice regions**
  - Used as an input for Freeboard and Sea Ice Thickness estimation **(key indicator)**:

    Sea Ice Concentration → Sea ice/leads classification →
    Sea Ice Freeboard estimation → Sea Ice Thickness estimation
  - Currently, interpolated at the altimeter measurement time and location from the OSI-SAF model

- **Snow Depth on sea ice (SD)**
  - Height of snow cover on sea ice in meters
  - In altimetry, SD is used for sea ice thickness estimation from freeboard
  - An error of few tens of cm in the freeboard estimation **can lead to an error of several meters in the Sea Ice Thickness estimation.**

- **Rationale :**

Radiometer data, collocated with altimeter measurements, could provide **more accurate SIC & SD** in space and time, compared to the use of external models.



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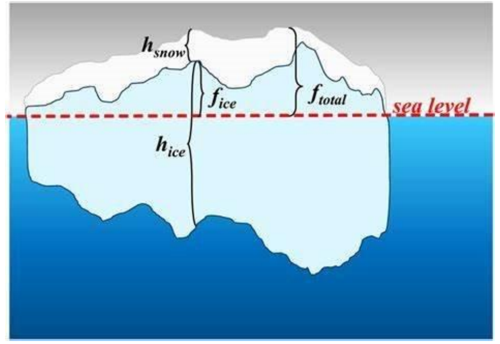


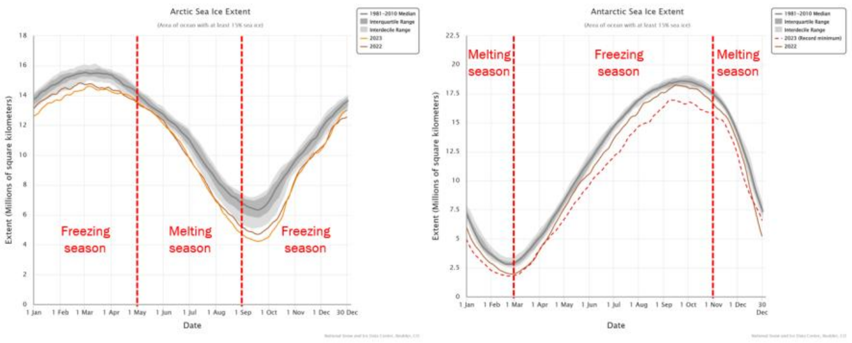
© Webster et al. (2021)

Illustration of SIC (top) and SD (bottom) variables.

Webster, Melinda & Duvivier, Alice & Holland, M. & Bailey, D.. (2021). Snow on Arctic Sea Ice in a Warming Climate as Simulated in CESM. Journal of Geophysical Research: Oceans. 126. e2020JC016308. doi: 10.1029/2020JC016308.

SIC estimation

- **Algorithms from literature**
  - 22 algorithms published by ESA Sea Ice Climate Change Initiative (SICCI)
  - 5 compatible with Sentinel-3 MWR channels
    => focus on the One-channel and Bootstrap in frequency mode algorithms
  - Best performances from Boostrap-F after adaptation of seasonality:
    no seasonality → Summer/Winter → Melting/Freezing

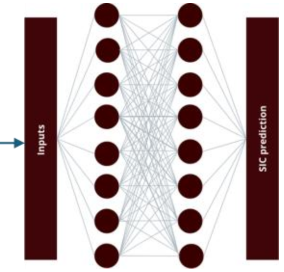


Sea Ice Extent with highlighted definitions of freezing and melting seasons for the Arctic (left) and the Antarctic (right)

- **Comparison with neural network (NN) for reproducing OSI-SAF data**
  - Comparison with NN integrating altimeter data
  - **NN shows the best performances,** mainly driven by brightness temperatures

Architecture of the SIC neural network: 2 fully connected layers of 8 neurons

TB_{23}
TB_{36}
σ_0
$var_{50}(\sigma_0)$



- TB_{23}: Radiometer 23.8 GHz brightness temperature
- TB_{36}: Radiometer 36.5 GHz brightness temperature
- σ_0 or $S0$: Altimeter backscatter coefficient
- $var_{50}(\sigma_0)$ or $var50S0$: σ_0 variance over a 50s rolling window
- $GR_{3623} = \frac{TB_{36}-TB_{23}}{TB_{36}+TB_{23}}$: « Gradient ratio »

Dataset	Category	Algorithm	RMSE (%)	MAE (%)	bias (%)	CC
Both hemispheres Full year 2022	Bootstrap	Global_B	7,36	4,53	0,77	0,964
		LoSW_B	7,23	4,46	-0,64	0,967
		LoMF_B	6,99	4,28	-0,88	0,970
	Neural Network	Global_TB23/TB36	7,01	4,45	-0,71	0,965
		Global_TB23/TB36/S0/VAR50S0	6,82	4,32	-0,84	0,996
		LoMF_TB23/TB36/S0/VAR50S0	**6,44**	**3,94**	**-0,61**	**0,970**

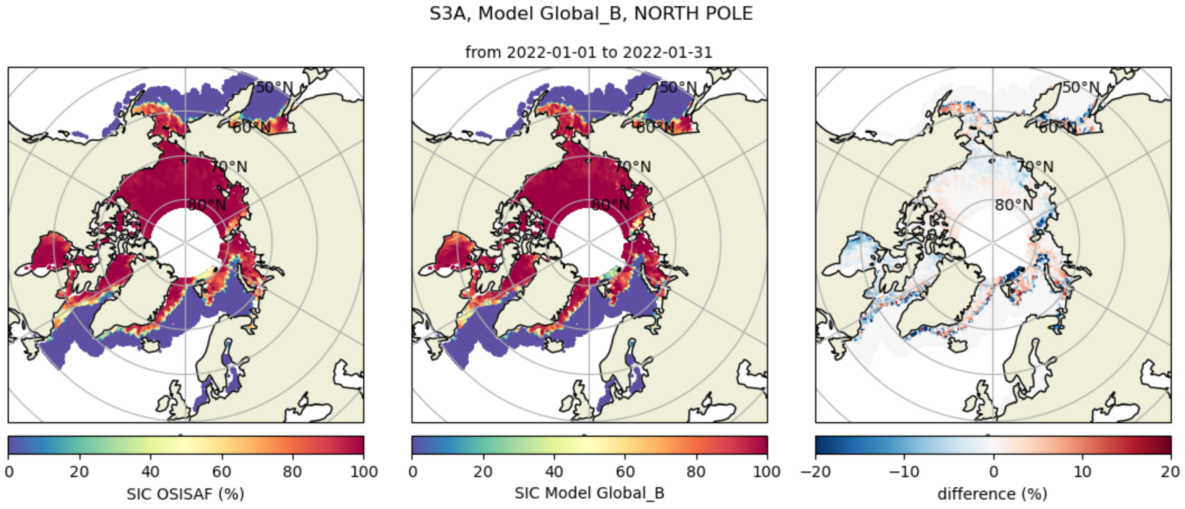
Summer/ Winter

Melting/ Freezing

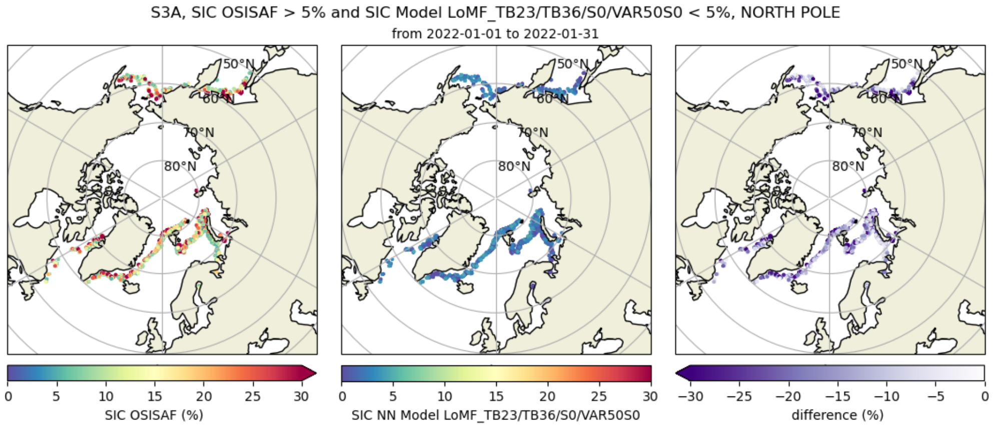
Performance scores for all the SIC retrieval algorithms developed during this study, on both hemispheres for the year 2022. The best overall scores are highlighted in green, while the best bootstrap scores are highlighted in light green.

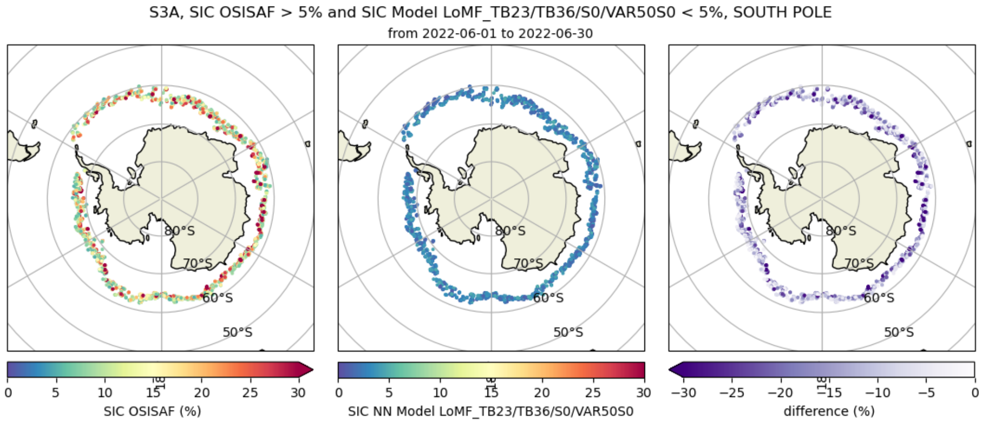
SIC estimation

- **Mapping results**
  - On areas where SIC~0% or SIC~100% (most of the dataset), Gradient Ratio and NN reproduce OSI-SAF correctly
  - **=> A slight improvement in MAE and RMSE implies large improvement in precision (e.g., Bootstrap RMSE=6.99 → NN RMSE=6.44)**
  - Mapping where OSI-SAF and the NN model differ: SIC OSISAF > 5% and SIC NN <5% (ie. when the NN model identifies open drift whereas OSI-SAF detects more or less packed ice)
  - **Sea ice edges stand out**, with differences up to 40 points. Which model is right ?



Maps of SIC estimates by OSI-SAF model (left), the Global Bootstrap algorithm (center) and their difference (right).



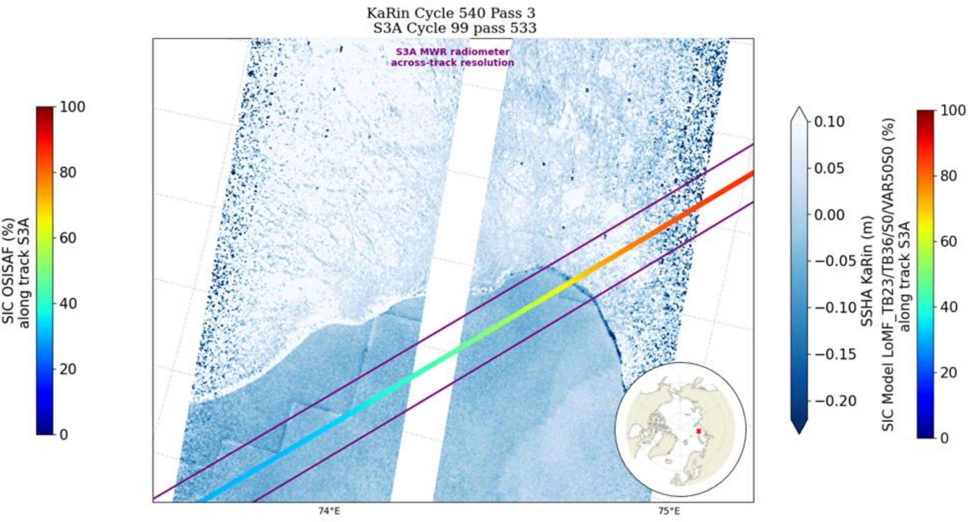


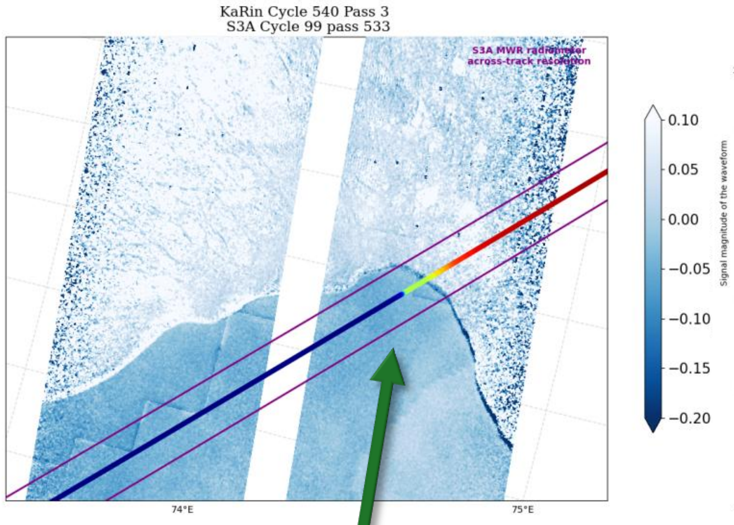
Maps of SIC estimates by OSI-SAF model (left) the neural network (center) and their difference (right) in areas where SIC OSISAF > 5% and SIC NN <5%, for January 2022 in the Arctic (left) and June 2022 in the Antarctic (right)

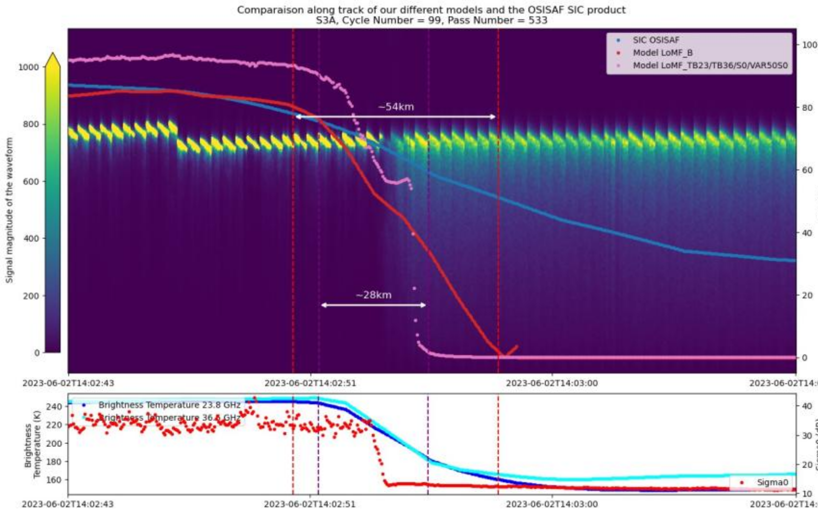
SIC estimation

- **Crossover analysis**
  - Crossovers between SWOT and Sentinel-3A, selected in the Marginal Ice Zone
  - Comparison of NN estimates with OSI-SAF shows **a very significant improvement** of product resolution, especially near the **sea ice edges and for detecting small structures**.

Comparison of SIC data along S3A track given by interpolated OSI-SAF model (left) and estimated by the neural network (center), at a S3A and SWOT crossover point (cycle 99 pass 533 and cycle 540 pass 3 resp.). Background image corresponds to SWOT SSHA. Along track comparison of SIC estimates in the same situation are also shown (right)





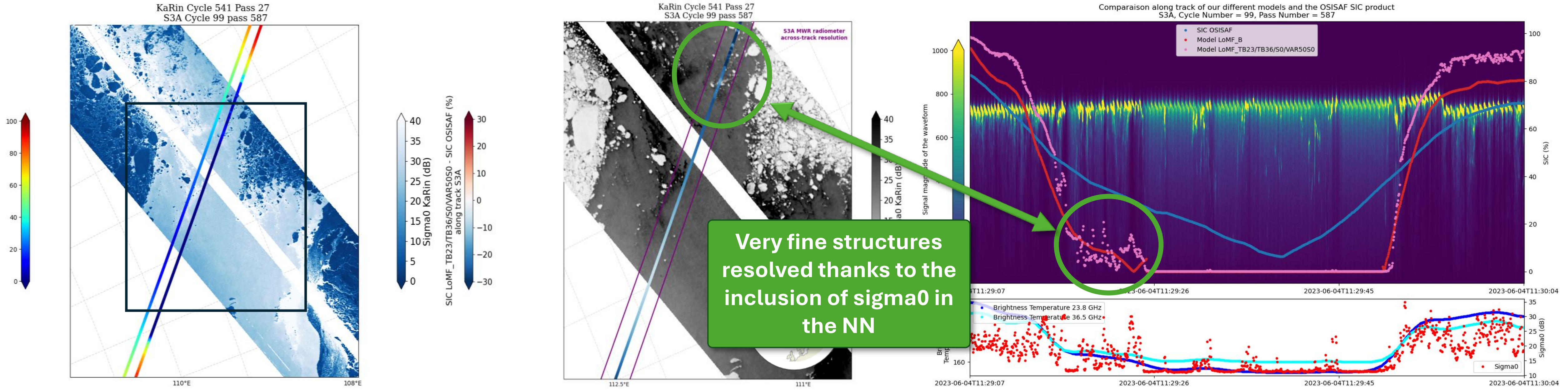


Significant improvement wrt OSI-SAF in sea ice edge detection

SIC estimation

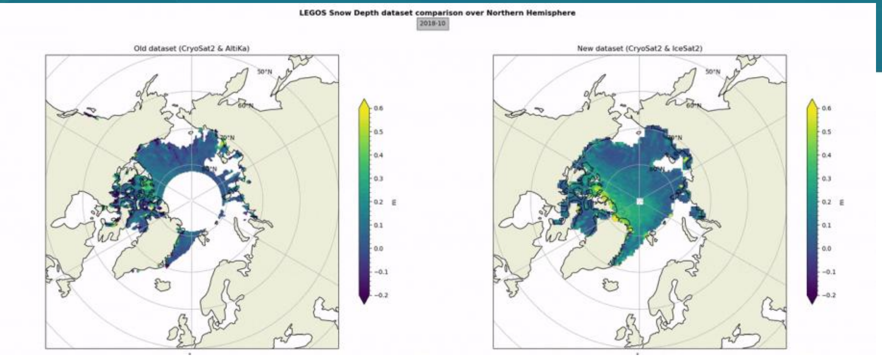
- **Crossover analysis**
  - Crossovers between SWOT and Sentinel-3A, selected in the Marginal Ice Zone
  - Comparison of NN estimates with OSI-SAF shows **a very significant improvement** of product resolution, especially near the **sea ice edges and for detecting small structures**.

Comparison of SIC data along S3A track given by interpolated OSI-SAF model and estimated by the neural network (left) their difference (center), at a S3A and SWOT crossover point (cycle 99 pass 587 and cycle 541 pass 27 resp.). Background image corresponds to SWOT sigma0. Along track comparison of SIC estimates in the same situation are also shown (right)



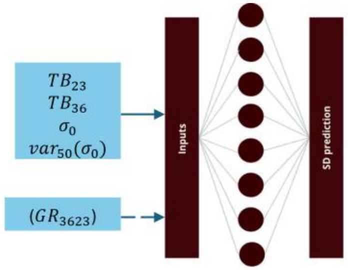
SD estimation

- **Two different reference datasets for neural networks**
  - SD derived by difference between Ka/Ku or LASER/Ku freeboards, from SARAL/CryoSat2 or IceSat2/CryoSat2 respectively.
  - Monthly SD maps provided by LEGOS, interpolated along S3A track
  - Training accomplished on a set of complete years
    One full year set apart for evaluation purposes: 2017 for Ka/Ku, 2019 for La/Ku
- **Algorithms from literature and neural networks**
  - Compatibility with Sentinel-3 data => Gradient Ratio
  - **NNs perform the best,** significant improvement wrt Gradient Ratio
  - The neural networks **reproduce correctly their reference data**, most of the distributions are centered around the correlation line.



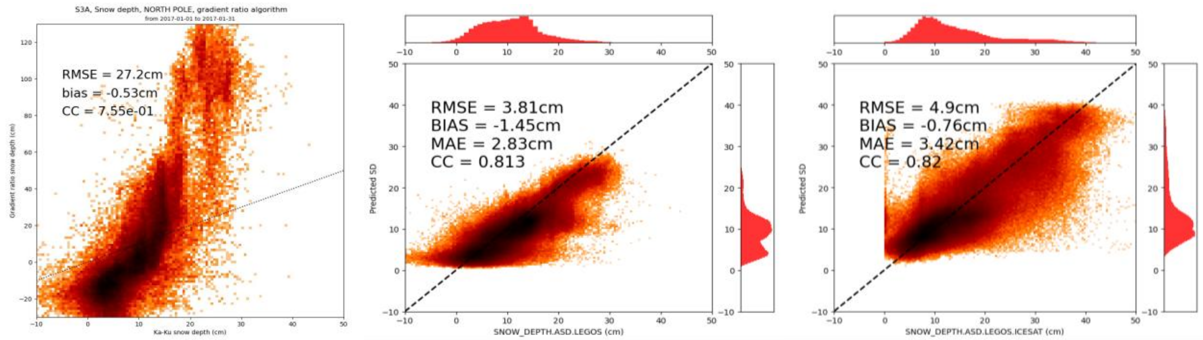
Animation of the Arctic SD monthly grids of Ka/Ku reference dataset (left) and La/Ku reference dataset (right), along the common timeframe (2018 to 2022)

Architecture of the SD neural network:
1 fully connected layer of 8 neurons



Algorithm	RMSE (cm)	MAE (cm)	Bias (cm)	CC
Gradient Ratio Algorithm (GR)	27.2	/	-0.53	0.755
NN with Ref. Ka/Ku Snow Depth (SD_TB23_TB36_S0_VAR50S0)	3.81	2.83	-1.45	0.813
NN with Ref. La/Ku Snow Depth (NewSD_TB23_TB36_S0_VAR50S0)	4.90	3.42	-0,76	0.82

Table of performance indicators of the neural networks for the whole evaluation dataset (2017 for GR and Ka/Ku, 2019 for La/Ku)



2D histograms of SD predicted by algorithm vs the reference data for the whole evaluation dataset
Left: Gradient Ratio, year 2017 Center: NN (Ka/Ku), year 2017 Right: NN (La/Ku), year 2019

SD estimation

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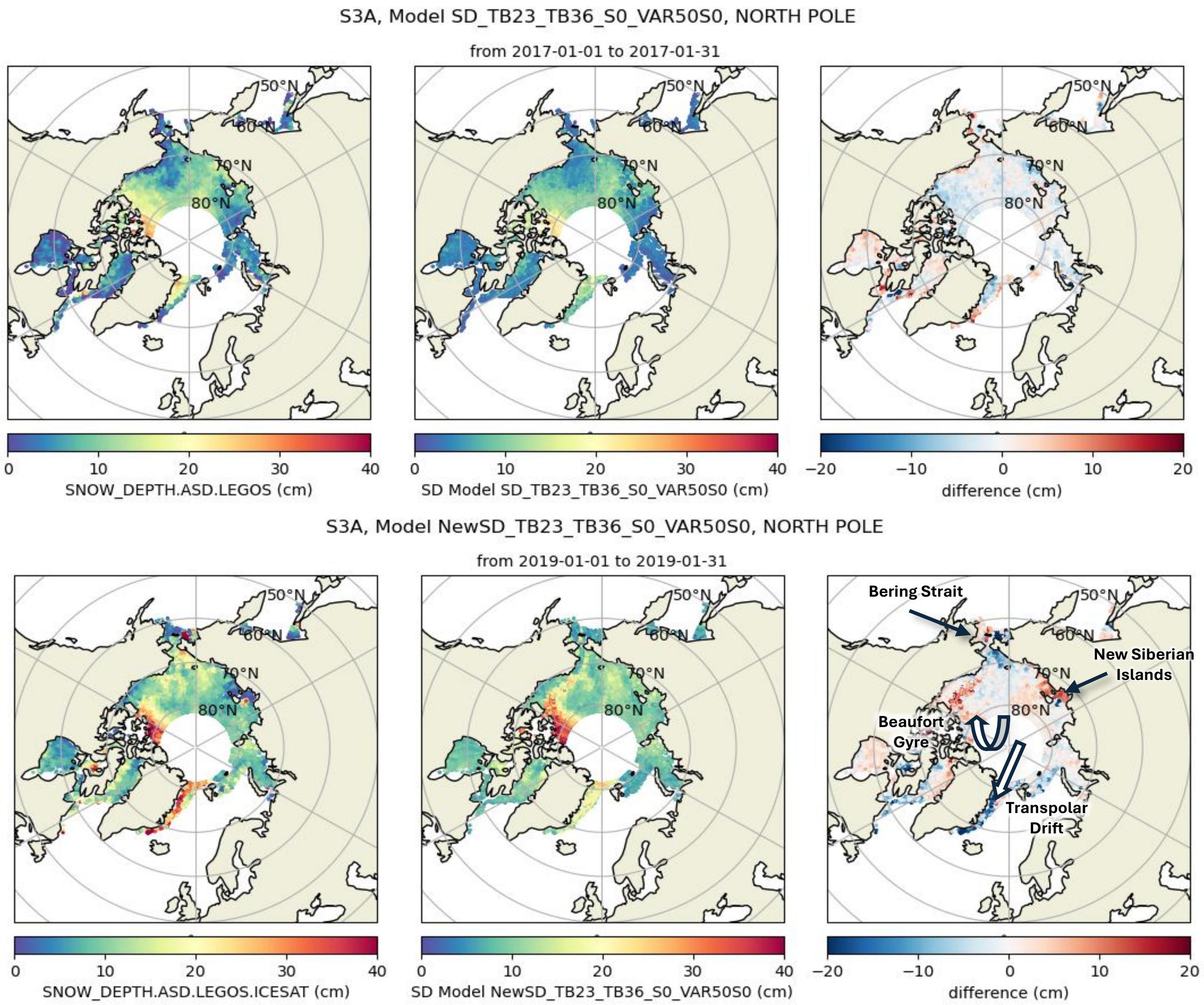
- **Mapping results**
  - Overall, **good reproduction** by the NNs of their respective reference data.
  - Ka/Ku NN shows smooth variations close the Ka/Ku reference data
  - Some difficulty to estimate high SD values
  - La/Ku NN shows interesting behavior in the Beaufort Gyre (precise spiral patterns)
  - In some areas, struggles to reproduce extreme values (Transpolar Drift, New Siberian Islands, Bering Strait…).

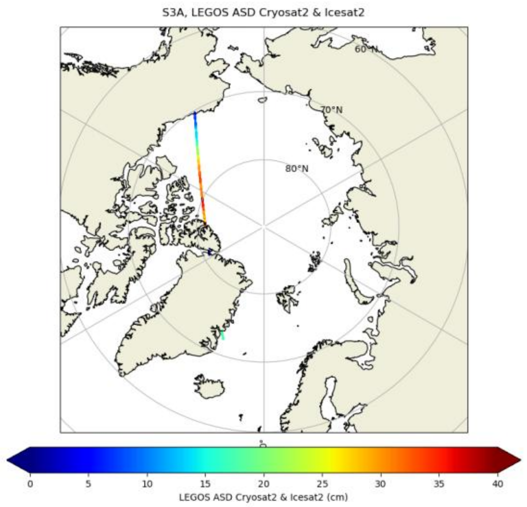


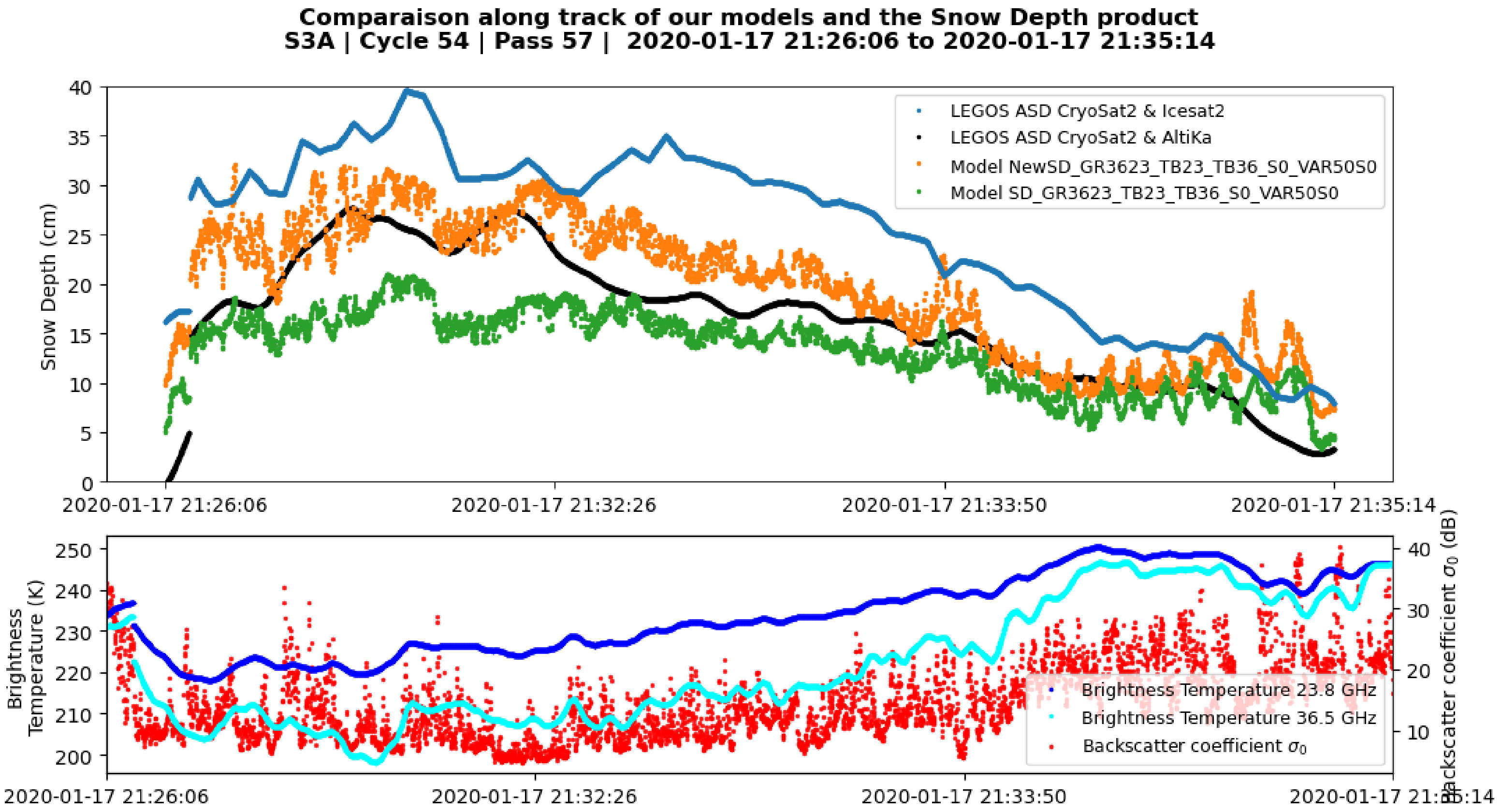
Maps of SD reference data interpolated over S3A tracks (left), SD data predicted by neural network model (center) and their difference (right)
Top: Ka/Ku, January 2017 Bottom: La/Ku, January 2019

SD estimation

- **Along-track comparisons**
  - S3A cycle 54 pass 57. NNs reproduce both Ka/Ku and La/Ku data correctly, especially over the Beaufort Gyre.

La/Ku SD reference data interpolated along the S3A track, during cycle 54 and pass 57



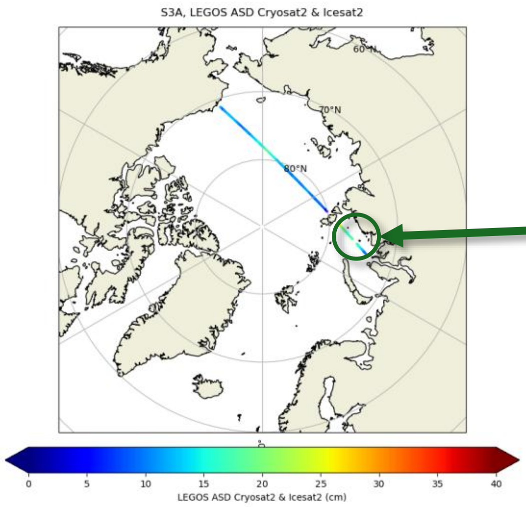


Cycle 54 pass 57 along track comparison of NN SD predictions and reference data, with NN input variables.
Top: La/Ku reference (blue), NN trained on La/Ku (orange)
Ka/Ku reference (black), NN trained on Ka/Ku (green)
Bottom: TB_{23} (dark blue), TB_{36} (teal),
σ_0 (red), $Var_{50}(\sigma_0)$ (green)

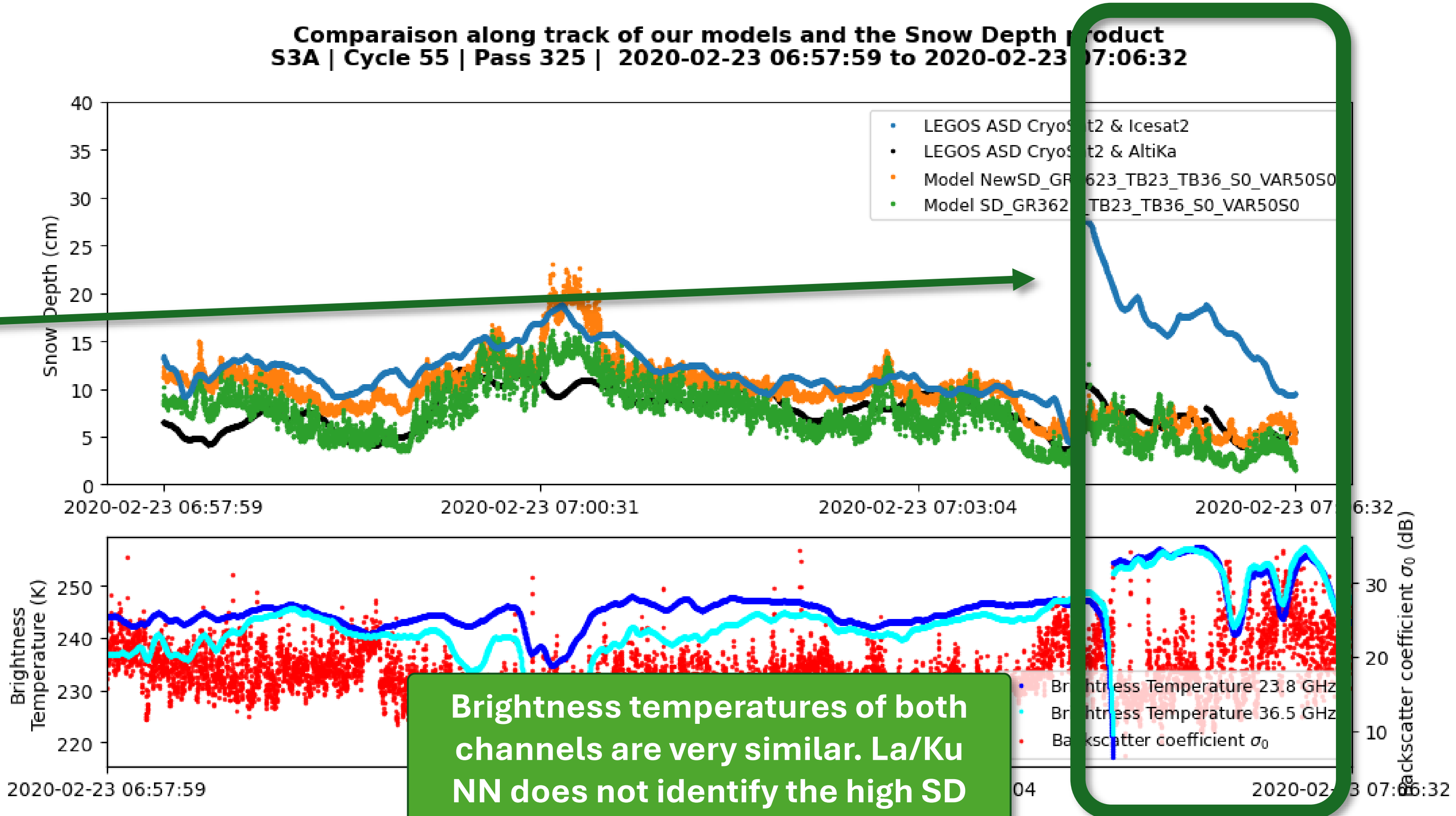
SD estimation

- **Along-track comparisons**
  - S3A cycle 52 pass 1. **NN reproduces La/Ku SD over the most part** but struggles over the Kara Sea, where it produces results very close to Ka/Ku.

La/Ku SD reference data interpolated along the S3A track, during cycle 52 and pass 1



Cycle 52 pass 1 along track comparison of NN SD predictions and reference data, with NN input variables.
Top: La/Ku reference (blue), NN trained on La/Ku (orange)
Ka/Ku reference (black), NN trained on Ka/Ku (green)
Bottom: TB_{23} (dark blue), TB_{36} (teal),
σ_0 (red), $Var_{50}(\sigma_0)$ (green)



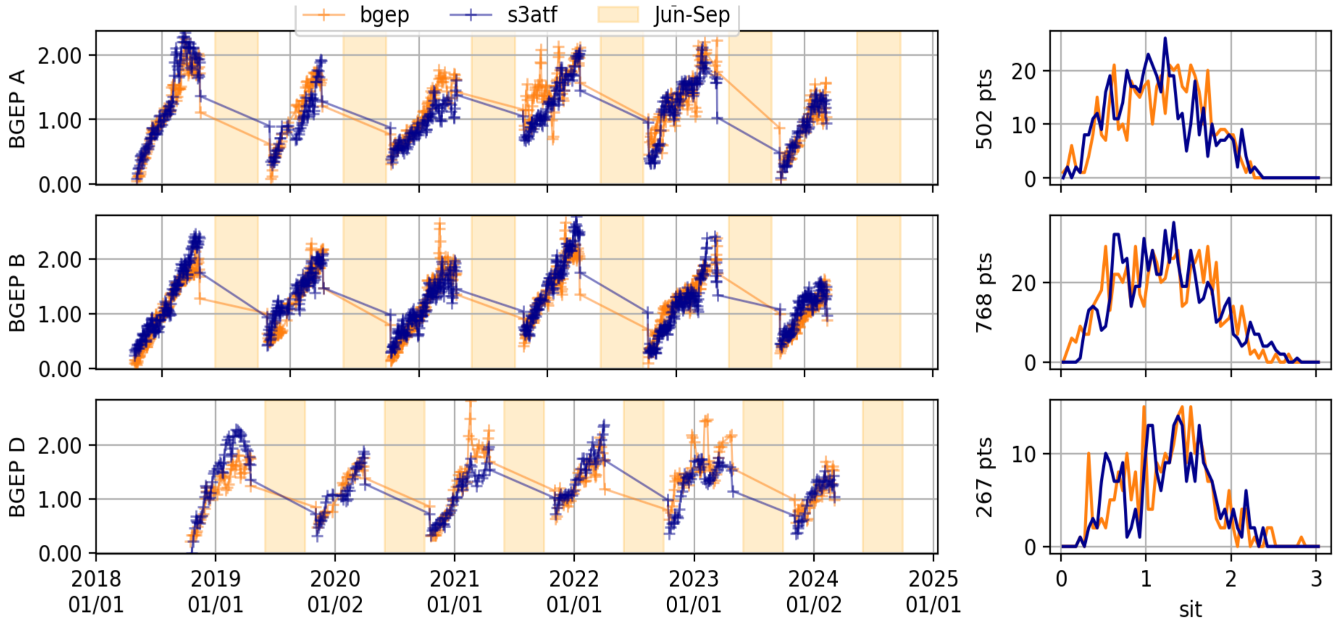
Brightness temperatures of both channels are very similar. La/Ku NN does not identify the high SD (more in line with Ka/Ku SD)

SD estimation

- Comparison to other SD data
  - **Operation IceBridge** airborne campaigns
  - **Beaufort Gyre Exploration Project** mooring data
    - Moorings measure draft (immerged ice part)
    - 3 mooring locations: A, B & D (Beaufort Sea, North of Alaska)
    - Combining with SD values gives an estimation of freeboard and Sea Ice Thickness
    - Freeboard and SIT obtained with different combinations are compared with official products from S3A and IceSat2
    - **NN performs the best** for both variables (here results for SIT are presented)

Courtesy of Sara Fleury @ LEGOS

Sea Ice Thickness
(BGEP + NN SD) versus S3 ATF



Timeseries of Sea Ice Thickness obtained with BGEP + NN snow depth with Sentinel-3A official SIT product, at the location of Mooring A (top), B(center) and D (bottom). Histograms of estimations are given on the right plot

Comparison to IS2 SIT		R	Bias (m)	RMSE (m)	STD (m)	slope
BGEP draft	CCI snow depth	0.62	-0.026	0.567	0.049	0.91
	Ka/Ku SD	**0.86**	0.007	0.296	0.024	**0.95**
	La/Ku SD	0.83	0.010	0.296	0.025	0.90
	NN trained on La/Ku SD	**0.86**	**0.004**	**0.273**	0.023	0.90

Comparison of Sea Ice Thickness obtained with BGEP + various snow depths with IceSat2 official SIT product, at all moorings combined

BGEP data were collected and made available by the Beaufort Gyre Exploration Program based at the Woods Hole Oceanographic Institution (https://www2.whoi.edu/site/beaufortgyre/) in collaboration with researchers from Fisheries and Oceans Canada at the Institute of Ocean Sciences

Conclusions & Perspectives

- **Conclusions**
  - Adaptation of literature algorithms and development of two new algorithms based on NN for estimating SIC and SD.
  - The NNs allow leveraging **the collocation of radiometer data with altimeter data** .
  - The new developed algorithms provide **better performances** in comparison to those from literature that were developed for radiometers designed to study sea ice.
  - Comparison of NN estimates of SIC with OSI-SAF shows a very significant improvement of **product resolution**, especially near the **sea ice edges and for detecting small structures**.
  - Using Beaufort Gyre Exploration Project mooring data allowed using our new SD estimates to derive freeboard and sea ice thickness. **NN performs better when comparing with official products from S3A and IceSat2**
  - **Promising results** for these first algorithms with MWR channels, a radiometer not designed especially to study sea ice, and a margin for improvement !
- **Perspectives**
  - **For SIC and SD**
    - The methods developed in this study are applicable to **SWOT and to future CRISTAL and S3NGT**.
    - In our analysis we used MWR 23 and 36 GHz channels. New radiometer frequency channels are/will be available with these new missions : we will **assess the contribution of the 18 and 89 GHz**.
  - **Next step: Sea Ice Thickness**
    - Assess the use of similar synergies to estimate thin Sea Ice Thickness and how they complement altimetry (thin SIT).

Thank you for your attention !