

Multi-Frequency Satellite Approaches for Snow on Sea Ice
Polar+ Snow on Sea Ice (PSSI)



Deliverable 5.1:
Impact Assessment Report (IAR)



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Document History

Version	Date	Updated by	Reason
1.a	06/01/2023	Jaakko Seppänen / Heidi Sallila	First draft

Detailed History of Changes

Version	Section	Updated by	Details

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The project website is <http://www.cpom.ucl.ac.uk/snow-on-sea-ice/index.html>

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Table 2 - Met Office model runs. For LEGOS and CPOM, FOAM snow depths are used North of 88N (CryoSat-2 'pole hole').

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Acronyms and Abbreviations

<p> AltiKa – Ka-band Altimeter AMSR-E - Advanced Microwave Scanning Radiometer - Earth Observing System ATBD – Algorithm Theoretical Basis Document AVHRR - Extended Advanced Very High Resolution Radiometer AWI – Alfred Wegener Institute CICE – The Los Alamos Sea Ice Model CRREL - Cold Regions Research and Engineering Laboratory CryoVEx - CryoSat Validation Experiment CS2 – CryoSat-2 DuST – Dual-altimeter Snow Thickness ECMWF – European Centre for Medium-range Weather Forecasts Envisat – Environmental Satellite EO – Earth Observation ERS – European Remote Sensing Satellite ESA – European Space Agency EXPRO – Express Procurement FBEM - Facet-Based numerical Echo Model FMI – Finnish Meteorological Institute FYI – First-Year Ice GLAS – Geoscience Laser Altimeter System IABP – International Arctic Buoy Program IAR – Impact Assessment Report ICESat – Ice, Cloud and land Elevation Satellite IMB – Ice Mass-balance Buoy ITT – Invitation To Tender KO – Kick-Off KuKa – Ku (radar) / Ka (radar) snow thickness product KuLa – Ku (radar) / Laser snow thickness product LEGOS - Laboratoire d’Etudes en Géophysique et Océanographie Spatiales </p>	<p> LIM – Louvain-la-Neuve Sea Ice Model MAF – Management, Administrative and Financial proposal MYI – Multi-Year Ice NASA – National Aeronautics and Space Administration NCEP – National Centers for Environmental Prediction NSIDC – National Snow and Ice Data Centre OIB - Operation IceBridge PP – Project Partner RA2 – Radar Altimeter 2 RB – Requirement Baseline SAR – Synthetic Aperture Radar SARAL – Satellite for Argos and AltiKa SHEBA - Surface Heat Budget of the Arctic Ocean SIPN – Sea Ice Prediction Network SMOS - Soil Moisture and Ocean Salinity satellite SnoDSI – SNOw on Drifting Sea Ice SOW – Statement Of Work SR – Scientific Roadmap SSM/I - Special Sensor Microwave Imager SSMIS – SSM/I Sounder STSE – Support To Science Element SWE – Snow Water Equivalent TP – Technical Proposal UiT – Arctic University of Norway UCL – University College London W99 – Warren et al. (1999) snow climatology WP – Work Package YOPP – Year of Polar Prediction </p>
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1 Introduction

In this document we perform the following tasks.

- Section 2: In this work package we assess the impact of our novel snow product on the total sea ice volume calculation and on the ocean characteristics (WP5.1)
- Section 3: In this work package we assess the impact of our novel snow product on sea-ice ocean model simulations and (with our partners) on data assimilation frameworks as well as on sea ice forecast skill (WP5.2)

2 Impact of Snow on Sea Ice - Altimetry

2.1 Sea Ice Thickness Processing

To study the impact of using the Polar+ experimental data set in satellite sea ice thicknesses, we have processed ESA CryoSat-2 Baseline-D and Baseline-E Level-1B SAR and SARIn files for the winter seasons (October to April), based on Polar+ snow product availabilities (Table 1). For dates prior to October 2021 Baseline-D files have been used, whereas starting from October 2021, Baseline-E files have been used. This is due to ESA switching the baseline processing, and at the time of this work, the Baseline-E processed files do not cover the full study period. The processing from the ESA Level-1 files was made with Pysiral version 0.9.2.6 (Hendricks et al., 2017), which is a Python sea ice radar altimetry processing library that follows the preliminary work of Peacock and Laxon (2004). For auxiliary data the newest mean dynamic topography product of Danish Technical University (DTU22MDT) was used (the product acquired straight from the author at DTU, Per Knudsen). For sea-ice concentration and sea-ice type the products from OSI-SAF (401-b and 403-d, respectively) were used [available at: <https://osi-saf.eumetsat.int/products>]. For snow densities, those from Warren (1999) have been used.

The Polar+ experimental data set snow depths were applied to preprocessed Level-1 files, along with other auxiliary data, and the processor was run to produce both Level-2 (along-track) and Level-3 (monthly gridded) files. The characteristics of each snow product are presented in table 1.

Product	Period	Original gridding	Method
University of Tromsø (UIT)	11/2018 - 04/2020 (November to April)	50 km (181X181)	LaKu - Waveform methodology
	11/2018 - 04/2020 (November to April)	50 km (181X181)	KaKu - Waveform methodology
University of Leeds (UoL)	10/2018 - 12/2021 (October to April)	25,67 km (267x267)	LaKu - Calibration methodology
	03/2013 - 12/2021 (October to April)	25,67 km (267x267)	KaKu - Calibration methodology
LEGOS	10/2018 - 04/2021 (October to April)	25 km (356x356)	LaKu - Bias correction
	10/2013 - 04/2021	25 km (712x712)	KaKu - pLRM/LRM -

	(October to April)	Bias correction
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Table 1: Description of the characteristics of each snow product.

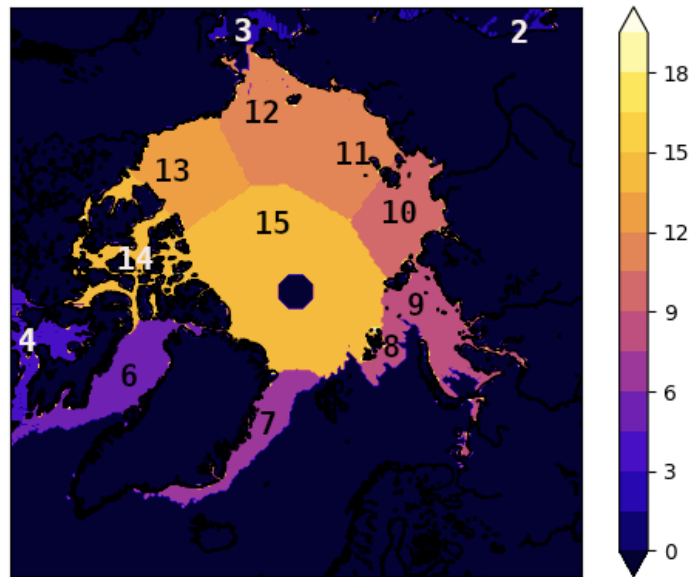


Figure 1 - The region codes used in the analysis.

The sea ice products have been divided to 15 regions to take into account the regional differences and properties of the products, mainly the variable sized polar hole between KaKu and LaKu snow products. The division is shown in Figure 1.

To assess the performance of the sea ice thickness retrieval using each snow product, sea ice thicknesses calculated from upward looking sonar (ULS) draft measurements by the Beaufort Gyre Exploration Project (Krishfield et al, 2014). The ULS draft measurements were averaged to monthly means, and converted to sea ice thickness by multiplying with 1.1 (Percival and Wensnahan, 2008). Resulting correlation, root mean squared error and bias are presented in table 2. The observation here is limited between 2018 and 2020 to minimize the effects of yearly variation in environmental conditions. Ice thickness calculated using the Warren 99 snow depth has been included as a baseline for retrieval performance.

In general the LaKu methodologies perform better than the KaKu methodologies concerning both R^2 and RMSE. However, they do not offer a major improvement over the Warren climatology, and KaKu products perform worse in terms of R^2 and RMSE. All products have lower bias than the on using Warren climatology.

Snow product	R ²	RMSE	Bias
LEGOS KaKu	0.679	0.352	-0.019
LEGOS LaKu	0.82	0.255	0.07
UoL KaKu	0.552	0.334	0.001
UoL LaKu	0.748	0.298	-0.08
UIT KaKu	0.60	0.309	-0.04
UIT LaKu	0.79	0.226	-0.03
Warren	0.79	0.227	0.21

Table 2 - Comparison of sea ice thickness calculated using different snow products and from BGEP ULS draft (11/2018 – 04/2020).

2.2 Sea Ice Thickness

Figures 2. and 3. show the mean SIT calculated with KaKu and LaKu snow products, respectively, from UoL, LEGOS and UIT in relation to SIT calculated using the Warren climatology.



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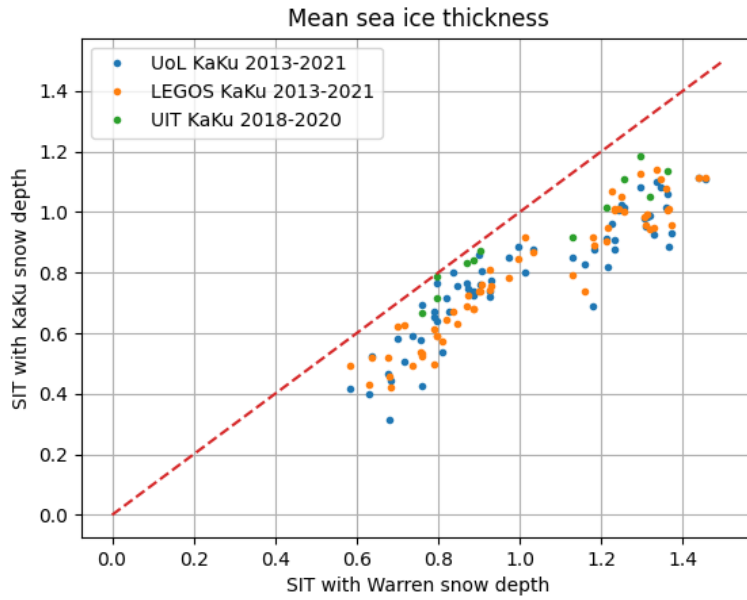


Figure 2 - Mean SIT calculated using KaKu snow products.

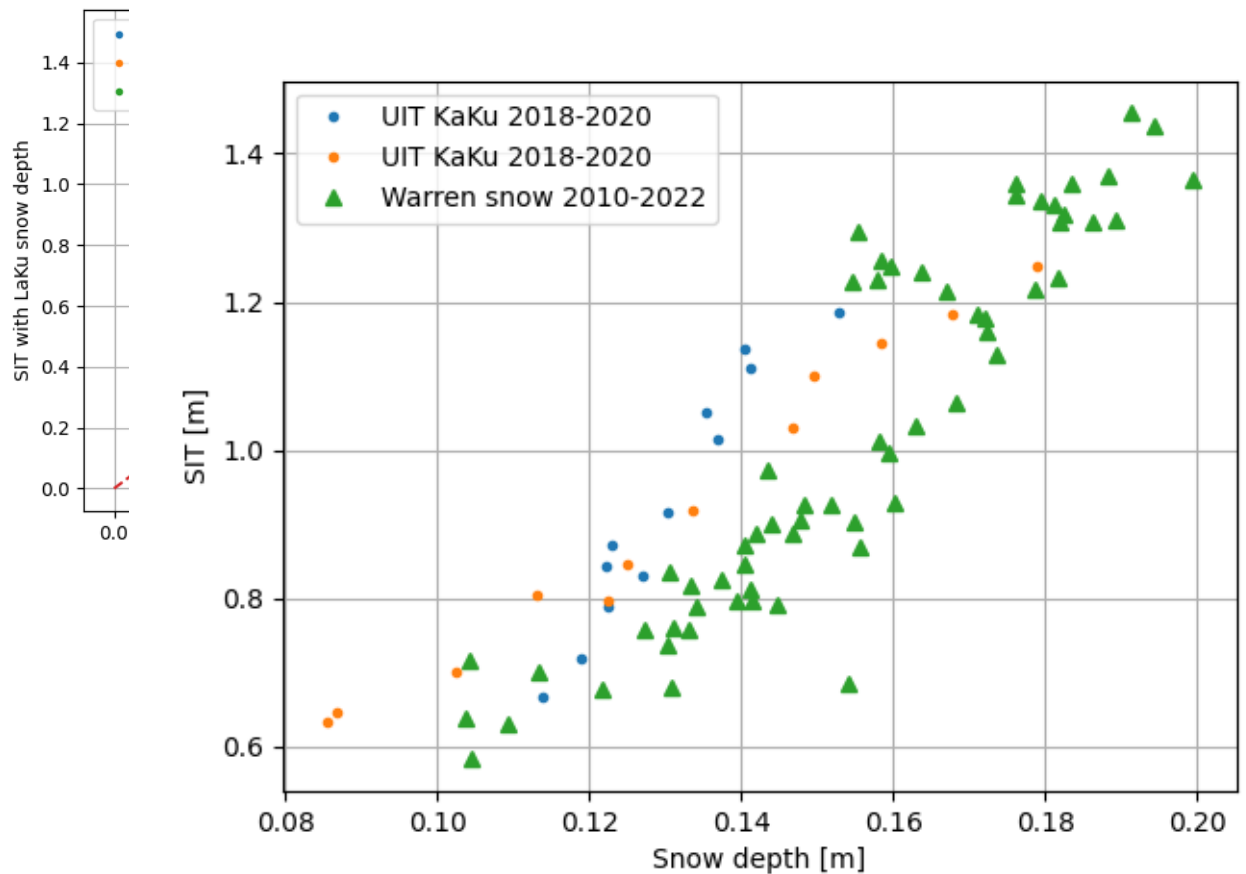


Figure 3. Mean SIT calculated with LaKu snow products.

In Figures 4.-6. the averaged monthly SIT is shown as a function of the average monthly snow depth. The range of both snow depth and SIT varies greatly between the snow products

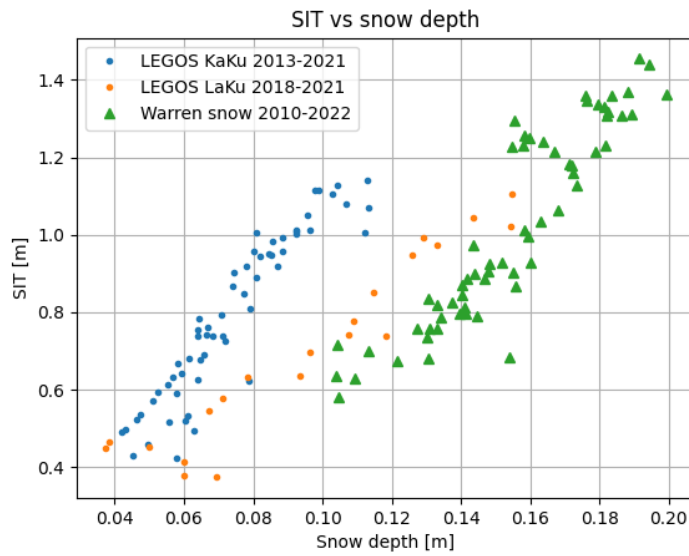


Figure 4 - Averaged monthly SIT using LEGOS snow products and Warren climatology as a function of the average monthly snow depth.

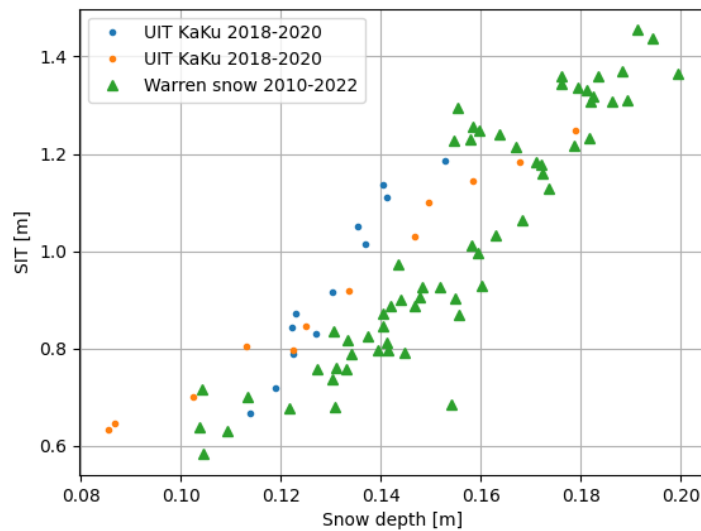


Figure 5 - Averaged monthly SIT using UIT snow products and Warren climatology as a function of the average monthly snow depth.

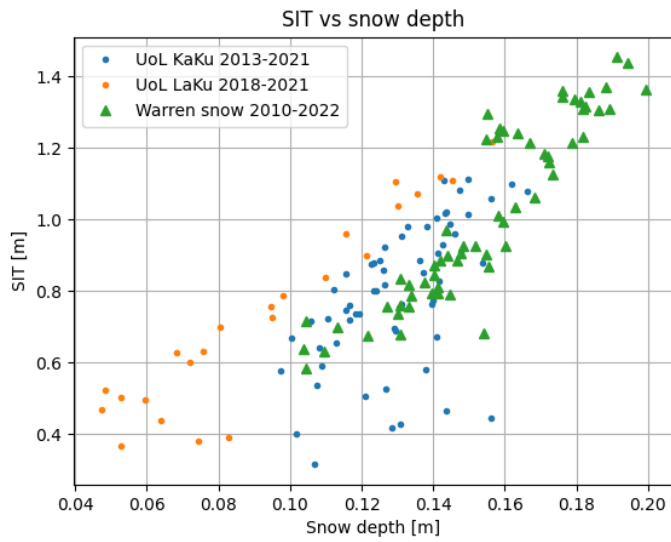
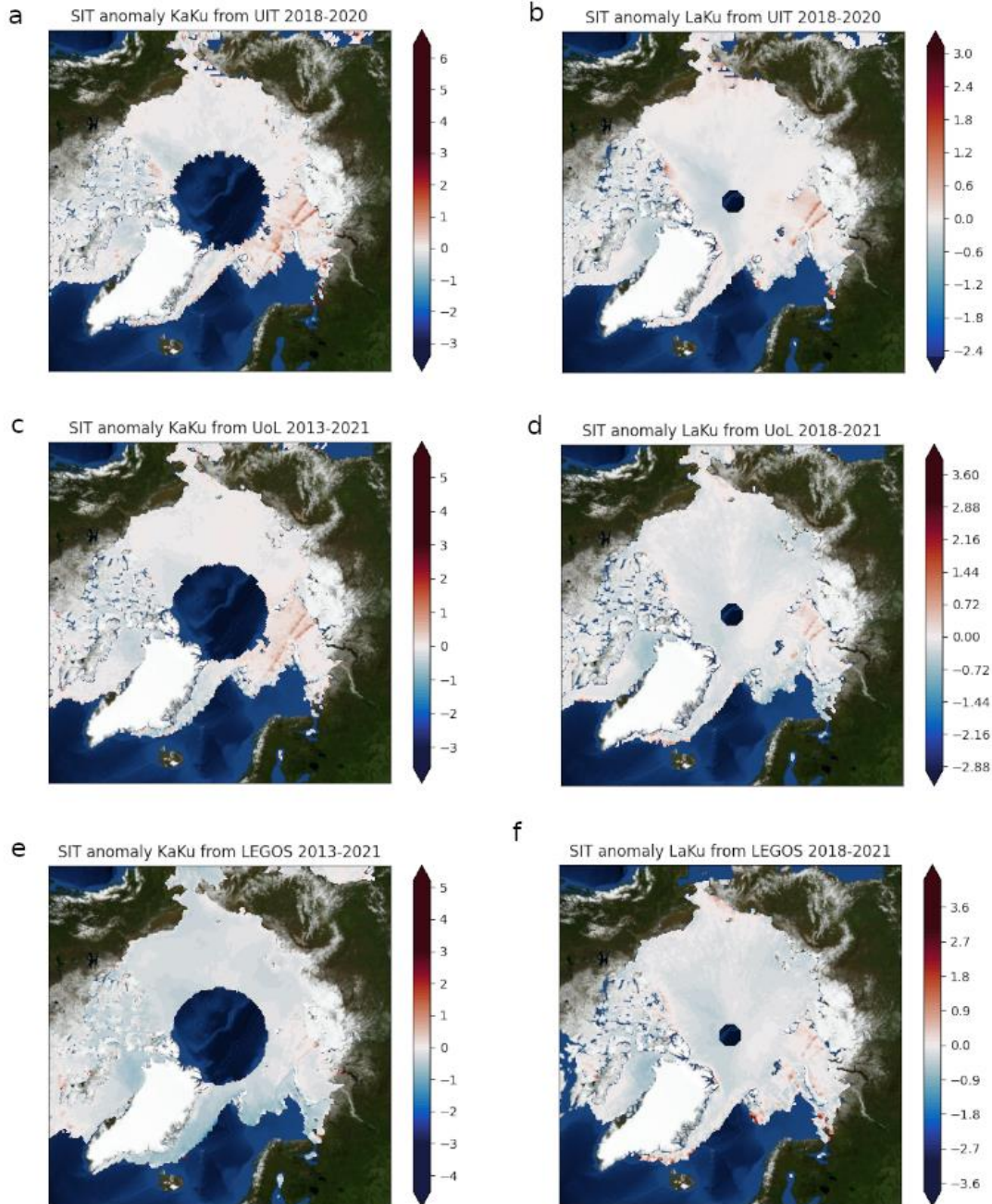


Figure 6 - Averaged monthly SIT using UoL snow products and Warren climatology as a function of the average monthly snow depth.



Figures 7. a)-f) show the mean anomaly of SIT using each snow product compared to the SIT using Warren climatology. In general the SIT is slightly lower, with most positive anomalies in Barents and Kara seas. The most prominent positive anomalies in the Kara sea can be related to processing rather than geophysical features.

2.3 Impact of snow on total sea ice volume trends and growth

Products have different sized polar hole dependent on the snow product method, which has to be accounted for in the analysis. Also, the climatology causes anomalies in marginal areas, such as the Barents Sea and Baffin Bay, therefore the analysis is split between processing zones. In general, the volumes calculated with Warren climatology appear higher than those calculated with the satellite derived snow depths. SIT with UIT LaKu snow depth give generally higher values, and SIT with CPOM and LEGOS are less consistent in relation to each other, but in general below those calculated with Warren snow depth.

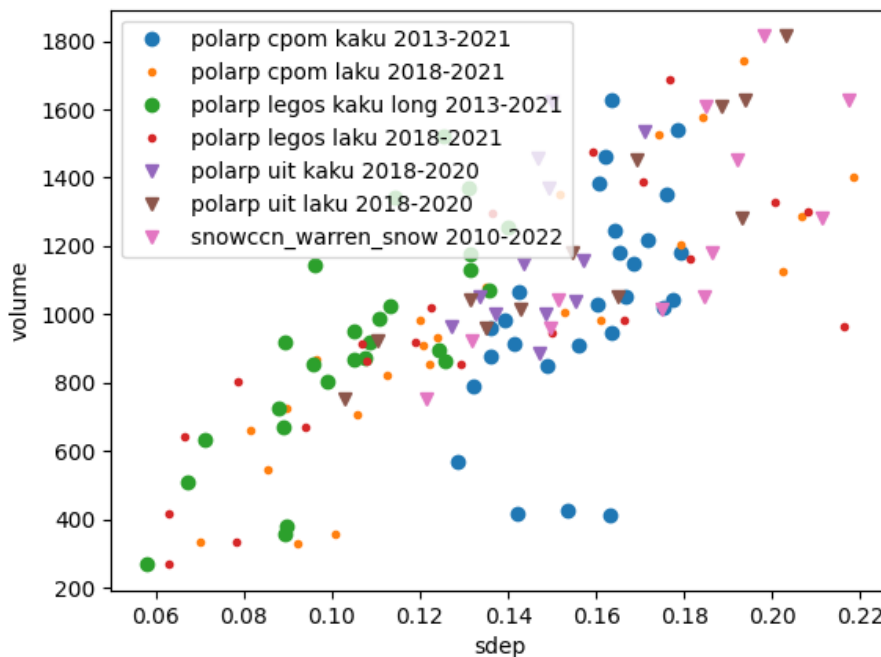


Figure 8 shows the total sea ice volume in region 13, in relation to the average snow depth.

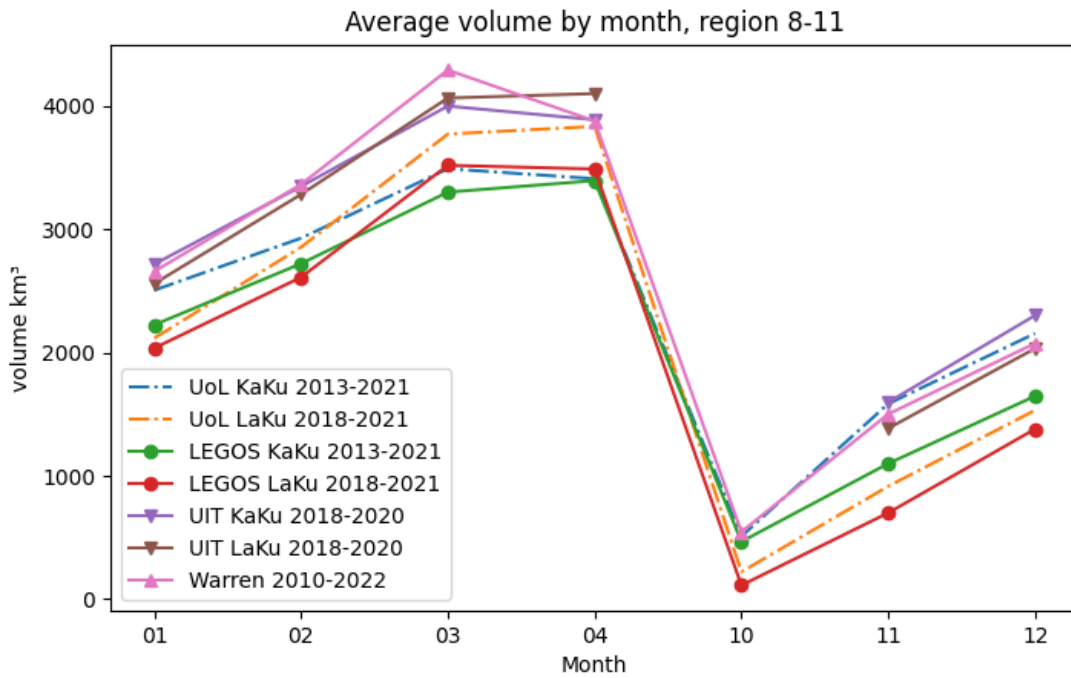
Figures 9.-11. show the average monthly sea ice volume in regions 8-11, 12-13 and 14, respectively. Of these, regions 8-11 cover the Arctic Ocean adjacent to Europe and Asia, 12-13 Arctic Ocean adjacent to North America and 14 covers mainly the Canadian Arctic Archipelago. While the volumes using KaKu and LaKu snow depths show in general lower volumes than volumes using the Warren climatology, this is more pronounced in region 14, probably due to the many coastlines of the



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archipelago affecting the snow depth and the retrieval process.



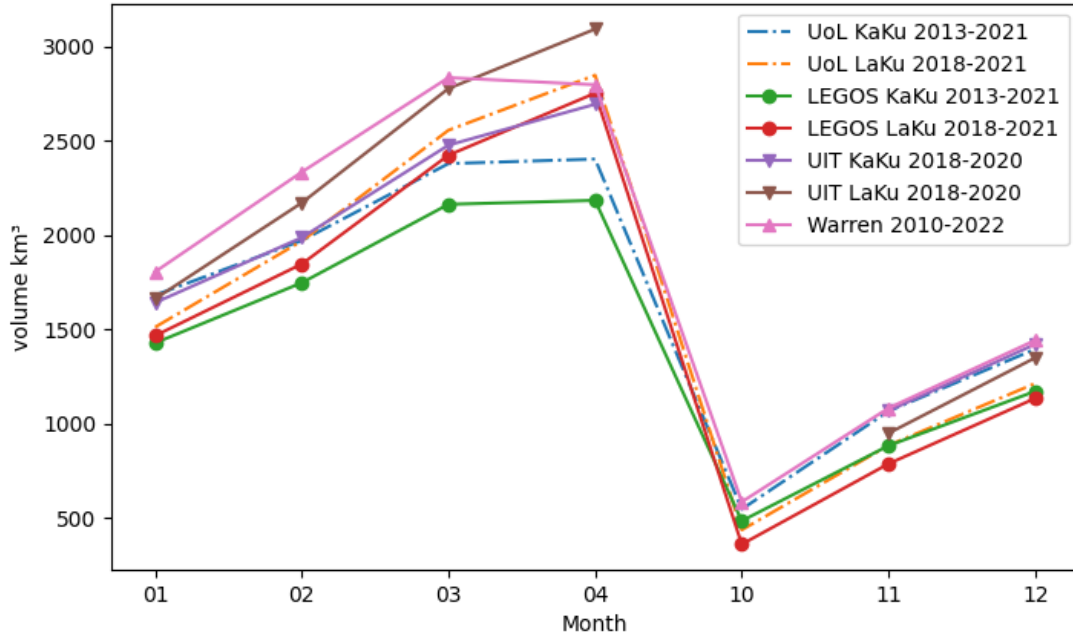
In comparison to ULS SIT, the best result was obtained using UIT LaKu, LEGOS LaKu and Warren datasets. However, when calculating volume, in regions 8-11 their difference is remarkable, with UIT LaKu and Warren showing highest and LEGOS LaKu the lowest volumes.



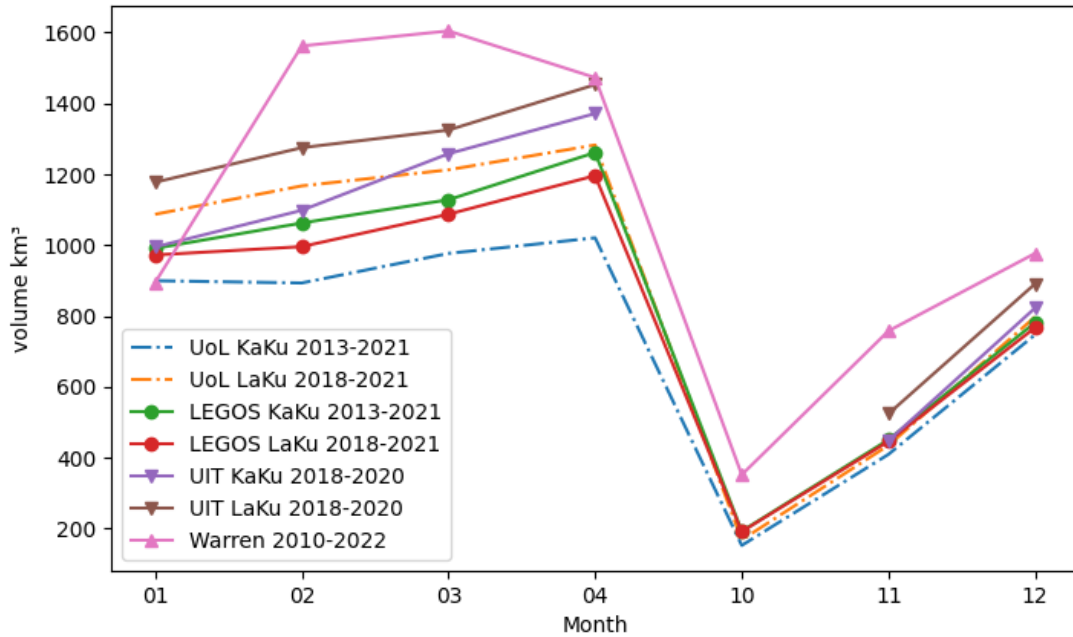
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Average volume by month, region 12-13



Average volume by month, region 6-7



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In regions 6-7, the seas surrounding Greenland, the monthly volumes using Warren snow depth are clearly highest for most months, with exception of January, when the Warren climatology gives the lowest value, and April, when it is nearly tied with the UIT LaKu SIT. From October to December the monthly volumes using experimental snow data are very close to each other, with much larger differences for January-April.

3 Impact of Snow on Sea Ice – Ocean Models

3.1 UK Met Office Forecast Ocean Assimilation Model (FOAM)

This work looked at the impact in a state-of-the-art climate model of our new snow on sea ice product and was undertaken by our project partners at the Met Office Davi Mignac Carneiro, Matthew Martin and UCL PhD student Carmen Nab (who is undertaking a jointly supervised PhD between UCL and the Met Office – Michel Tsamados and Julienne Stroeve are the UCL supervisors). The simulation runs performed are computationally costly and we were able to only perform model runs for the October 2016 to April 2017 period. This ruled out the waveform snow product (Landy) and we only tested the calibration ('CPOM') and bias correction ('LEGOS') snow products developed as part of this ESA project.

As described in Fiedler et al. (2022): "The Forecast Ocean Assimilation Model (FOAM; Blockley et al., 2014) is the Met Office's global, coupled ocean–sea-ice model. It is forced at the surface using output from the Met Office NWP system [...] Analyses and 5 d forecasts of ocean and sea ice variables are produced operationally from the coupled system and are disseminated through the Copernicus Marine Environment Monitoring Service (CMEMS; <https://marine.copernicus.eu/>, last access: 16 December 2021). FOAM analyses are also used operationally to initialise the Met Office's seasonal forecasting system, GloSea [...] Here we focus on the forced ocean and sea ice FOAM system, but the implementation of any developments will also be of benefit to the coupled short-range and seasonal prediction systems.

The ocean model component of FOAM, Nucleus for European Modelling of the Ocean (NEMO), is coupled to the Los Alamos Sea Ice Model, CICE [...] the version of FOAM used herein has a 1/4 ° grid (ORCA025) [...] The data assimilation scheme NEMOVAR is used in FOAM in a 3D-Var First Guess at Appropriate Time (FGAT) configuration to assimilate observations of ocean and sea ice variables."

Here we perform 4 simulation runs as described in Table 1 below. The LEGOS data assimilation (DA) run assimilates for the first time in a coupled model our new snow on sea ice product. In the remaining sections we discuss the impact on the model simulations of this new product.

CTRL: no SIT assimilation
BASE: assimilating CS2 SIT, calculated using FOAM snow depth
LEGOS: assimilating CS2 SIT, calculated using LEGOS snow depth (without FYI corr)
CPOM: assimilating CS2 SIT, calculated using CPOM snow depth

Table 2 - Met Office model runs. For LEGOS and CPOM, FOAM snow depths are used North of 88N (CryoSat-2 'pole hole').

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3.2 FOAM Data Assimilation Results

3.2.1 Sensitivity study

In this section we compare the impact on maps of sea ice thickness of the different snow products developed as part of Polar+ Snow on Sea Ice and available in 2016/2017 to be used in the data assimilation procedure described above.

The leading order effect of the data assimilation comes from the assimilation of sea ice thickness. This is seen when comparing the BASE model run (with sea ice thickness assimilation) with the CTRL run (without data assimilation) that results in total average Winter sea ice thickness that is significantly thinner in the latter (more than 0.5 metre thinner over most of the pack ice).

We now assess the impact of data assimilation our new snow on sea ice products (CPOM and LEGOS, Landy physical product is not available to test in 2016/2017) within the FOAM set up for the Winter 2016/2017. LEGOS underestimates the sea ice thickness over the FYI and overestimates the sea ice thickness over MYI compared to BASE that uses the FOAM model snow thickness in the conversation of radar freeboard to sea ice thickness (Figure 12). In contrast CPOM overestimates sea ice thickness nearly everywhere. Over first year ice, LEGOS can be up to ~0.5 m than the CPOM snow thickness assimilation model runs over the FYI. This demonstrates the importance of snow assimilation as a second order effect (after sea ice thickness assimilation) for future improvements of reanalysis and forecasts.

We next looked at the impact of the snow assimilation on the total sea ice growth (and melt). As expected, we find that on average over the whole Winter the LEGOS model that has a thinner (thicker) sea ice thickness over FYI (MTI) results in more (less) Winter ice growth there as expected from the additional (reduced) insulating effect of the snow layer. The CPOM model run that has a generally thicker ice leads to a reduction in sea ice thickness growth due to the well-known negative growth thickness feedback process. These results are important in the Arctic to understand the sea ice evolution but also from an Arctic Ocean perspective as the total Winter growth has the potential to modulate the amount of salt being released in the Ocean.



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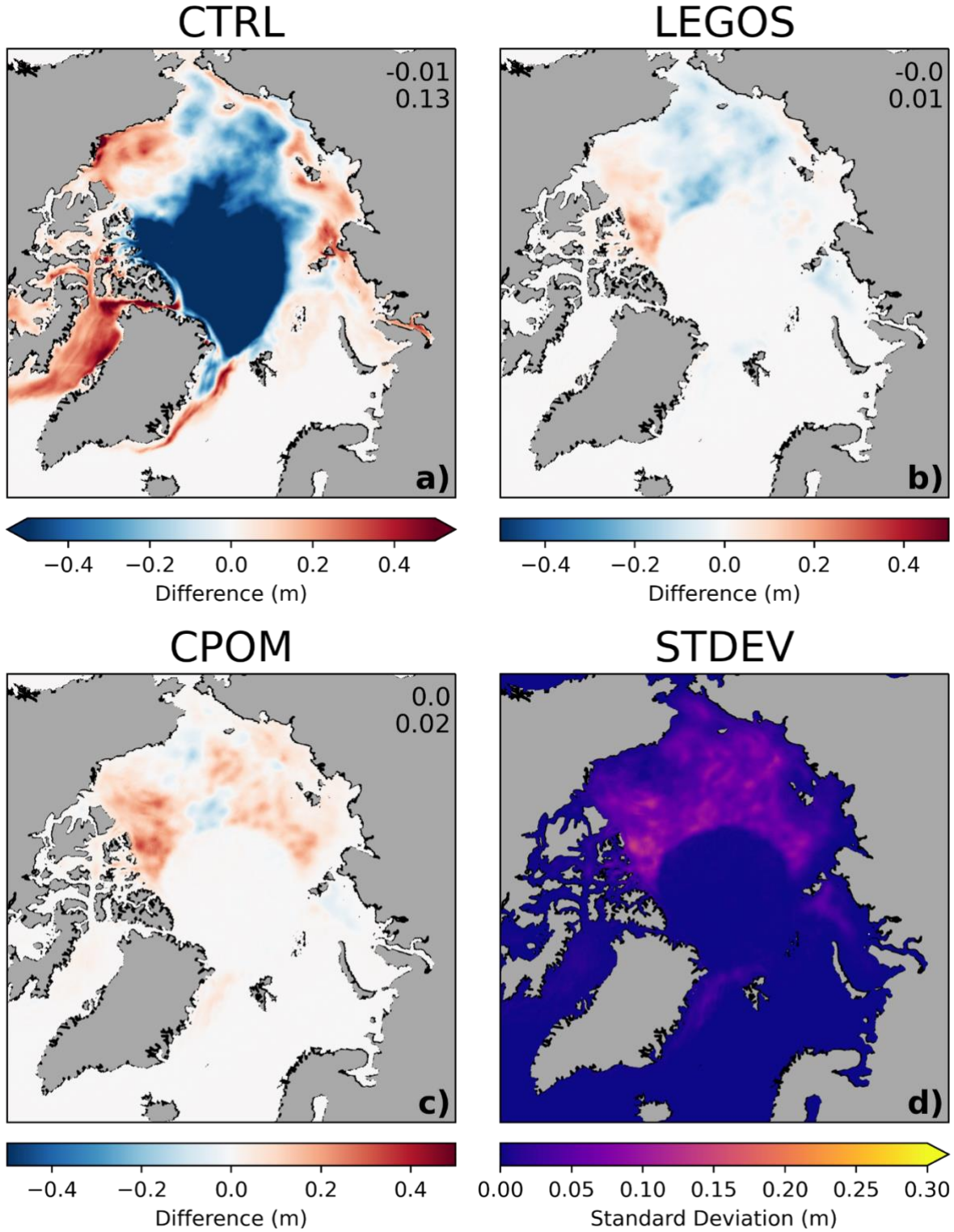


Figure 12 - a-c) Difference between mean daily SIT for each experiment and the BASE experiment. Text shows the pan-arctic mean (top) and standard deviation (bottom). d) Standard deviation between the mean daily SIT for all the assimilation experiments (excluding CTRL). Credit: Carmen Nab (UCL).

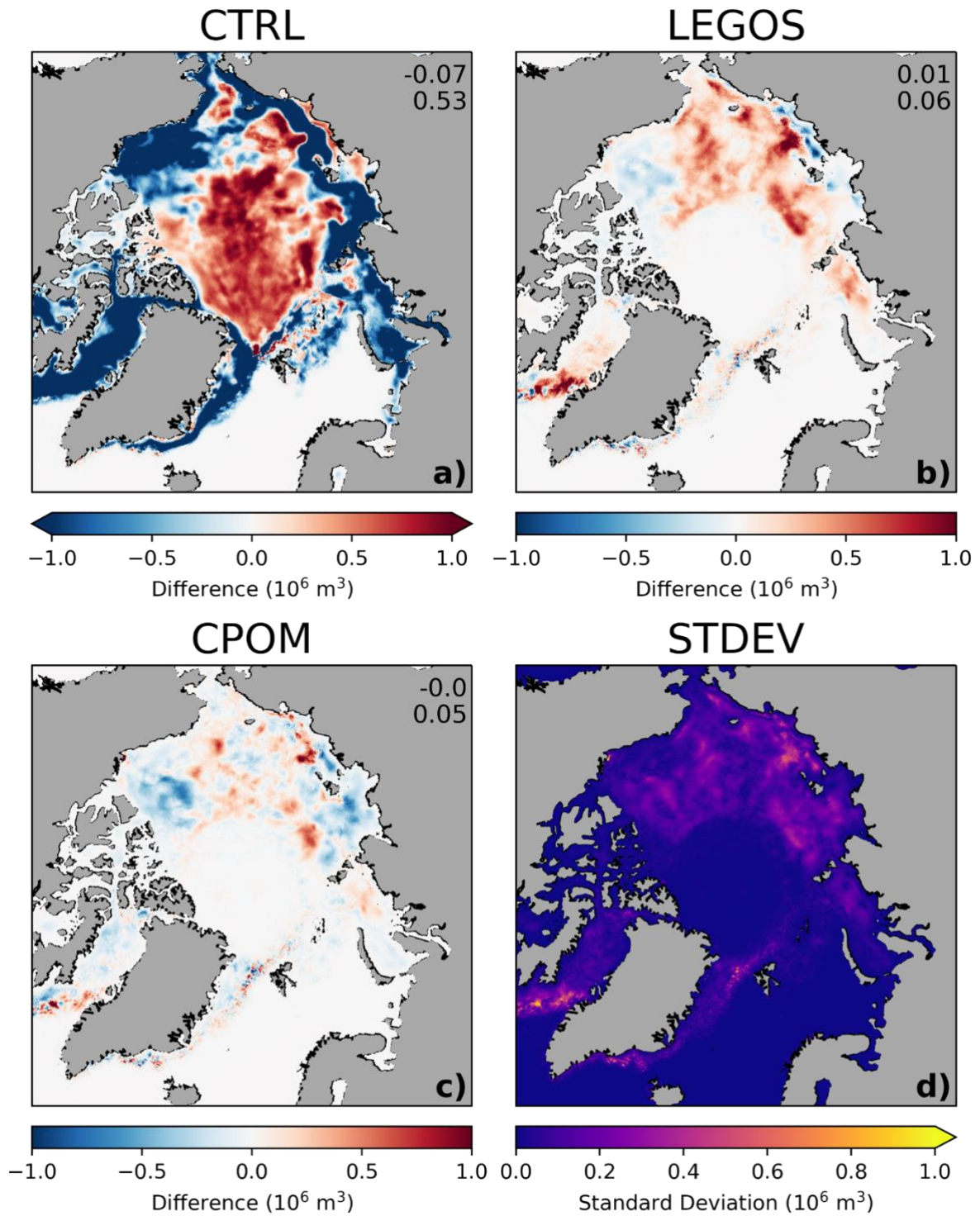


Figure 13 - Difference between mean daily ice volume change due to thermodynamic processes for each experiment and the BASE experiment. Text shows the pan-Arctic mean (top) and standard deviation (bottom). Credit: Carmen Nab (UCL).\

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3.2.2 Comparisons with airborne and in-situ data

In the Figure 14 below we are comparing the various sea ice thickness model results against OIB and IceBird airborne data. This comparison remains preliminary and clear conclusions as to which model run performs best against airborne data is unclear at this stage. For a more thorough validation of our snow products, we are referring back to our validation report.



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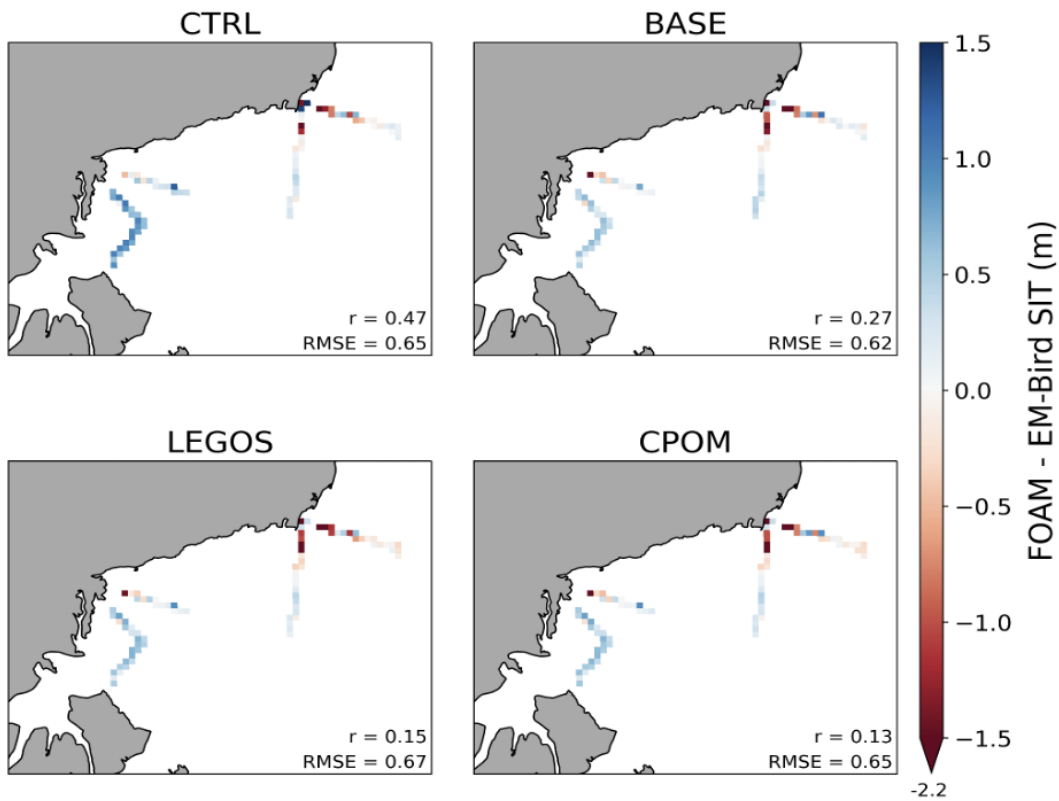
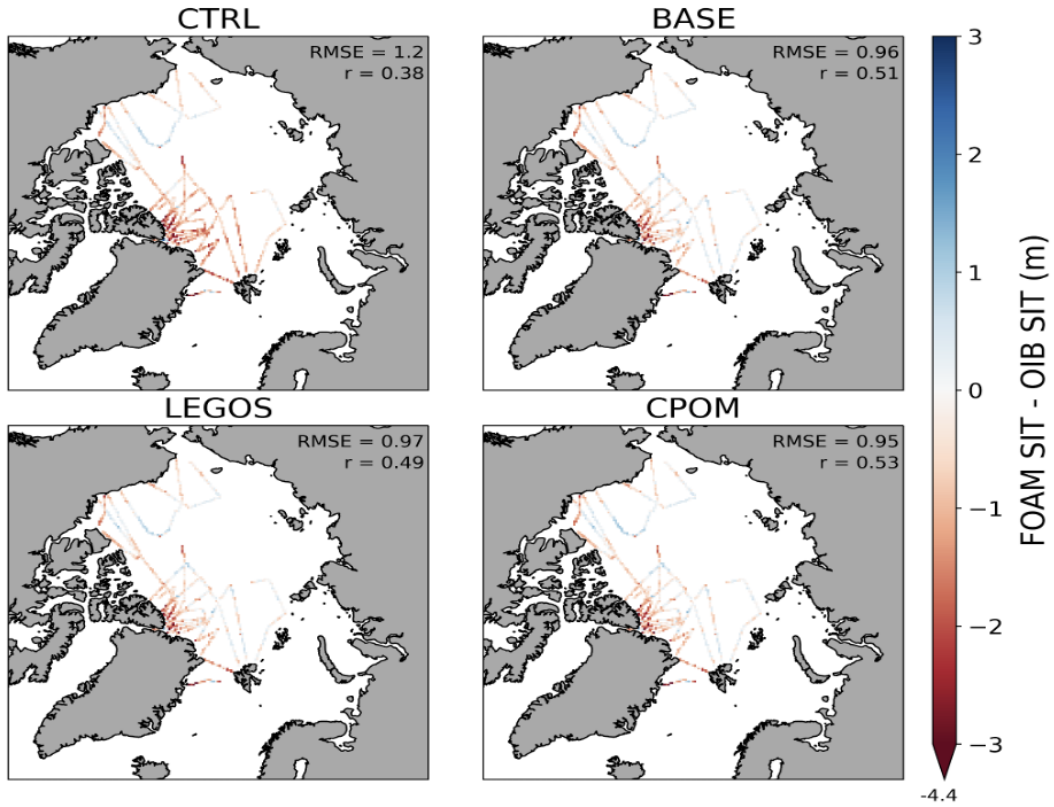
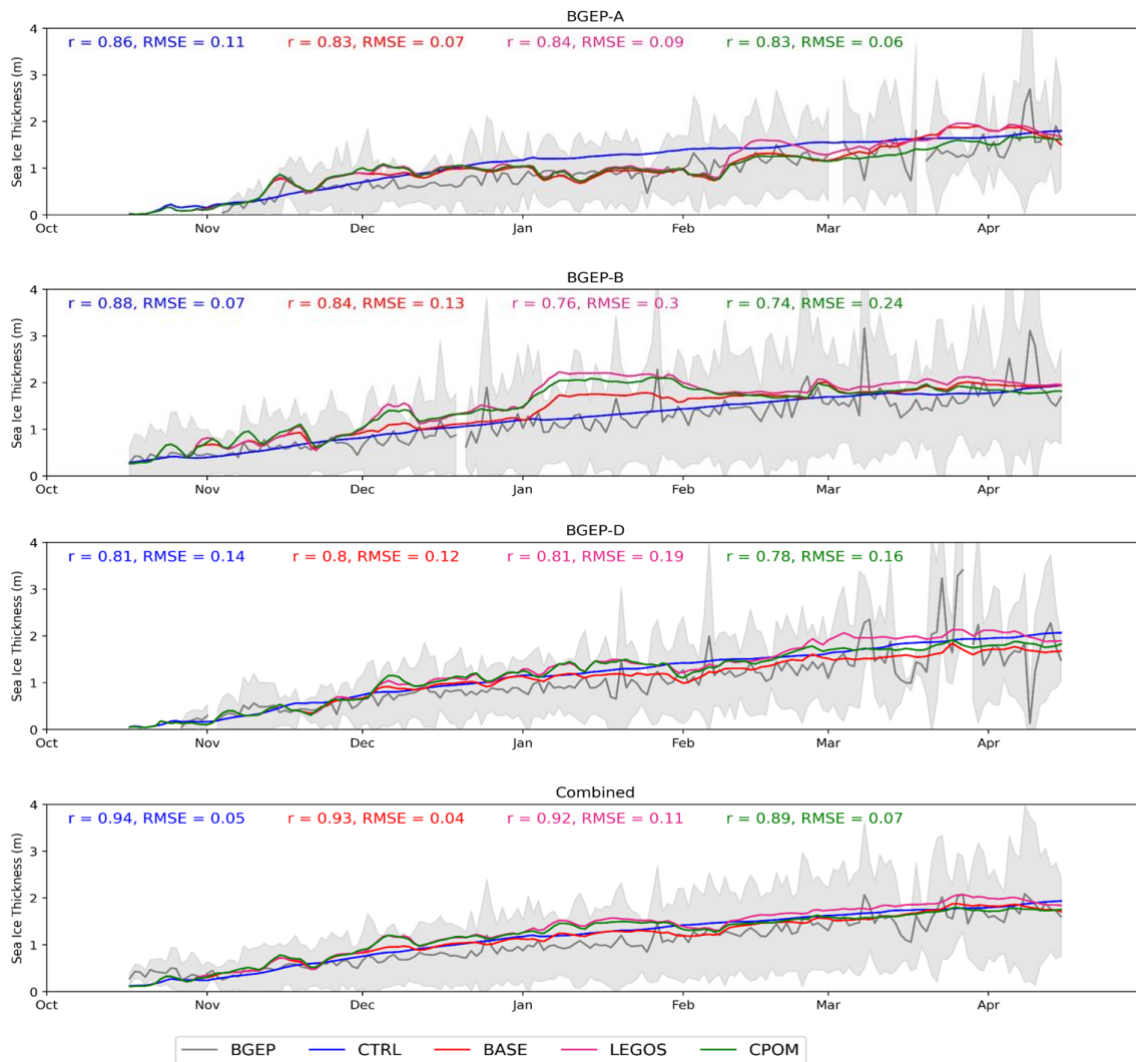


Figure 14 - Comparison of sea ice thickness in the different Met Office model runs against OIB (top panel) and IceBird (bottom panel) sea ice thickness data. Credit: Carmen Nab (UCL).

Finally, to get a sense of the temporal impact of the snow assimilation on the FOAM sea ice thickness we are comparing our model results against the BGEP moorings. For these moorings located in the Beaufort Gyre we find that the impact is significant for extended periods of the Winter 2016/2017 with deviation to the BASE model of more than 0.5 m on regular instances. Overall the LEGOS snow product leads to larger sea ice thickness in this region. This is perhaps surprising when comparing to the results shown in Figure 12. More analysis is being prepared as part of a publication led by Carmen Nab.



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