

Multi-Frequency Satellite Approaches for Snow on Sea Ice

Polar+ Snow on Sea Ice (PSSI)



Deliverable 4.1:
Experimental Dataset Description (EDD)



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Polar+ Theme 1
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Document History

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Detailed History of Changes

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Contact details: Alice Carret

Alice.Carret@legos.obs-mip.fr

Sara Fleury

sara.fleury@legos.obs-mip.fr

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Acronyms and Abbreviations

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

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



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1 Document objectives

This document aims at making an assessment of the comparisons of snow depth products in the framework of the ESAPolar+ project. All these snow products have been obtained from satellite altimetry measurements using 2 different frequencies: either Ku and Ka from the differences between the satellites CryoSat-2 and Saral, or Ku and Laser from the differences between the satellites CryoSat-2 and IceSat-2. These KaKu and LaKu products have been computed by 3 different institutes: University of Tromsø (UIT), University of Leeds (UoL) and LEGOS.

2 Data

We have compared 6 different snow depth products from UIT, UoL and LEGOS (Table 1). The period they cover, the original gridding and the method used to obtain the products are described in section 3.

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

Table 1: Description of the characteristics of each snow product

Impact of the sampling period (on the UoL data)

In the following sections we have compared these products over a common period of 12 winter months from November 2018 to April 2020. In order to compare the different products this study focuses on their common period (11/2018 - 04/2020). However two of these products cover a larger period (2013 - 2021). In order to check for the representativity of the 2 years sampling, this section first compares it to the full period of UoL.

We have computed and represented the mean and the standard deviation (STD) for the short and long periods (Figure 1 and Figure 2). We observe that we have the same means and STD for the 2 periods. However we can notice a more pronounced difference for the STD along the coasts (Figure 2) whereas it is stronger within the Beaufort Gyre for the mean (Figure 1).

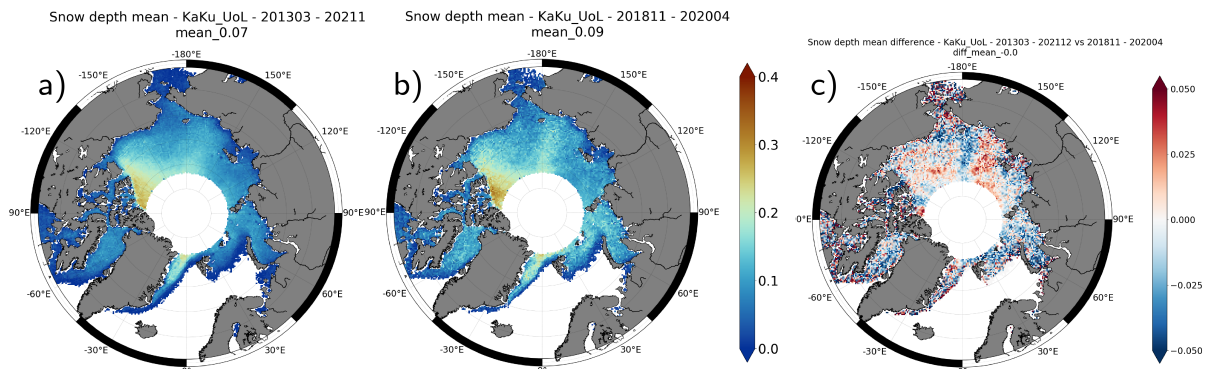


Figure 1: Snow depth mean for the UoL KaKu product over a) 03/2013-12/2021 and b) 11/2018-04/2020. c) Difference between the 2 periods

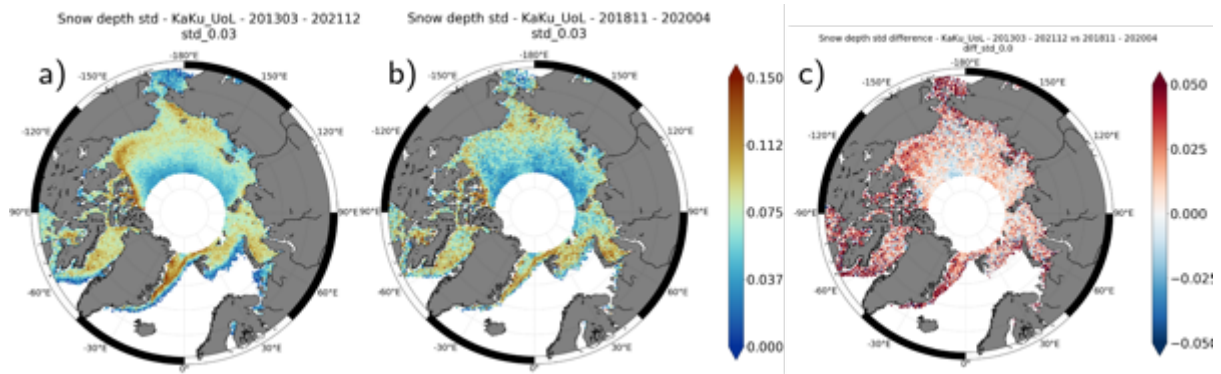


Figure 3: Snow depth STD for the UoL KaKu product over a) 03/2013-12/2021 and b) 11/2018-04/2020. c) Difference between the 2 periods

The mean and STD show similar patterns for both periods with however more variability for the longer period as shown by Figure 2a and b. There is no difference between the global mean and STD between both periods. Thus the use of a short period over 2 winters does not bias too much the results.



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3 Analysis of the products

Figure 3 and Figure 4 show the mean and STD over the common 11/2018-04/2020 period for each product. The median and Median Absolute Deviation (MAD) are shown in Appendices A and B.

We can note differences in the spatial coverage as the products from UoL present gaps near the coasts, probably because of the sea ice concentration (SIC) used. Indeed the auxiliary SIC datasets are often used to focus the processings over sea ice covered regions. A mask combining all products is then applied for each month and used to compute statistics.

Concerning the MAD all products present higher values in the Canadian Archipelago and along the Greenland coast. It is however less pronounced for the KaKu product from UoL (Appendix Bb). There are also high values at the Bering Strait which are more visible in the LaKu products (Appendix Ba, c and e). The regional MAD is smaller for the KaKu product from UIT.

The mean of all products is shown on Figure 3. The spatial patterns are quite similar between all products except in the Hudson Bay where the KaKu products differ from the LaKu products. For the LaKu products the values are higher northern Greenland for the UIT and LEGOS products compared to the UoL product. The mean of the ASD product is quite smaller compared to the 5 others.

Figure 4 shows the STD for all products. The strong patterns are localized over multi-year ice, along the Greenland coasts and north of the bering strait. The variability of the ASD product is weaker than the other product everywhere but the global STD is almost the same for all products.

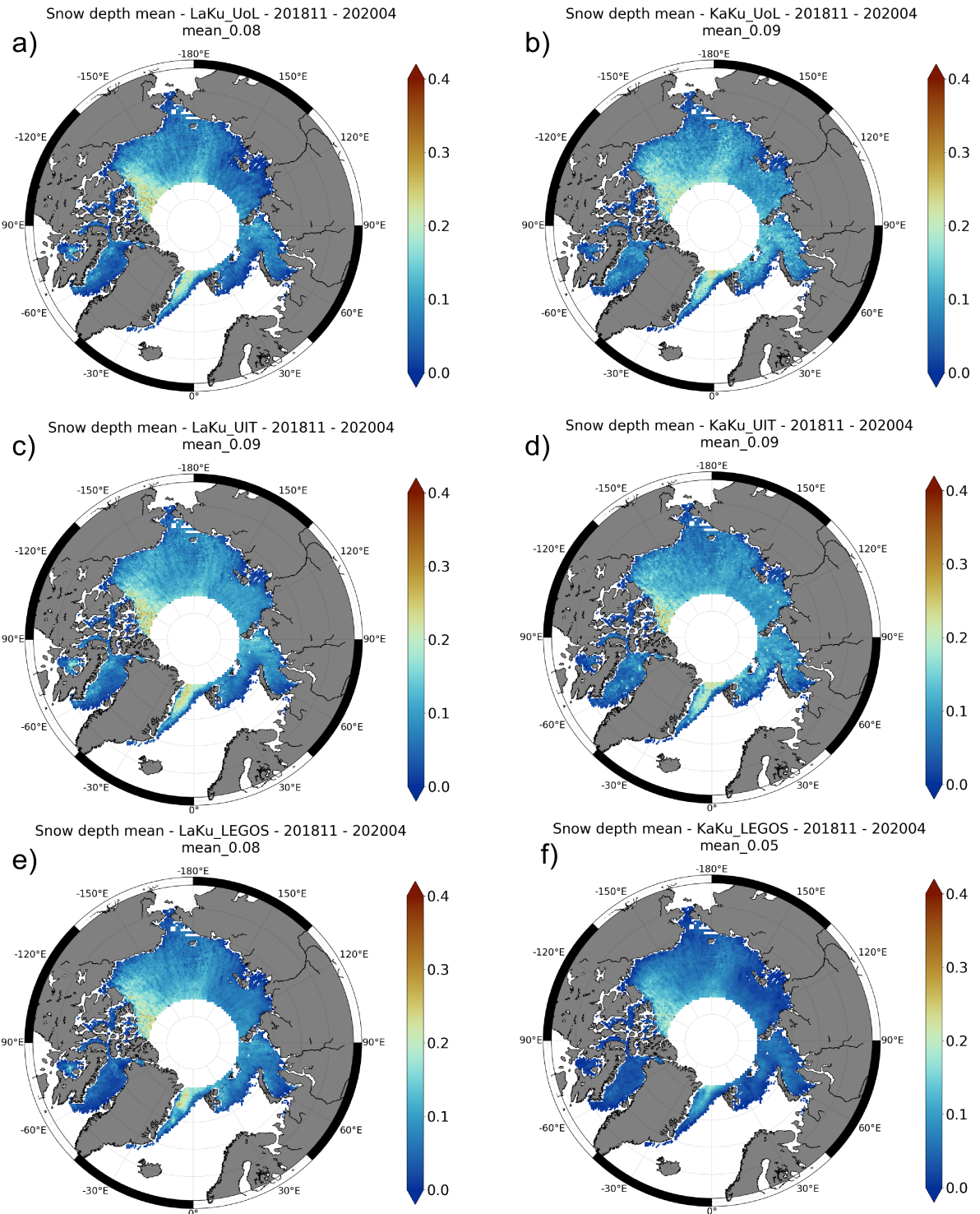


Figure 4: Maps of snow depth mean over the period 11/2018 - 04/2020 for a) LaKu from UoL; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS

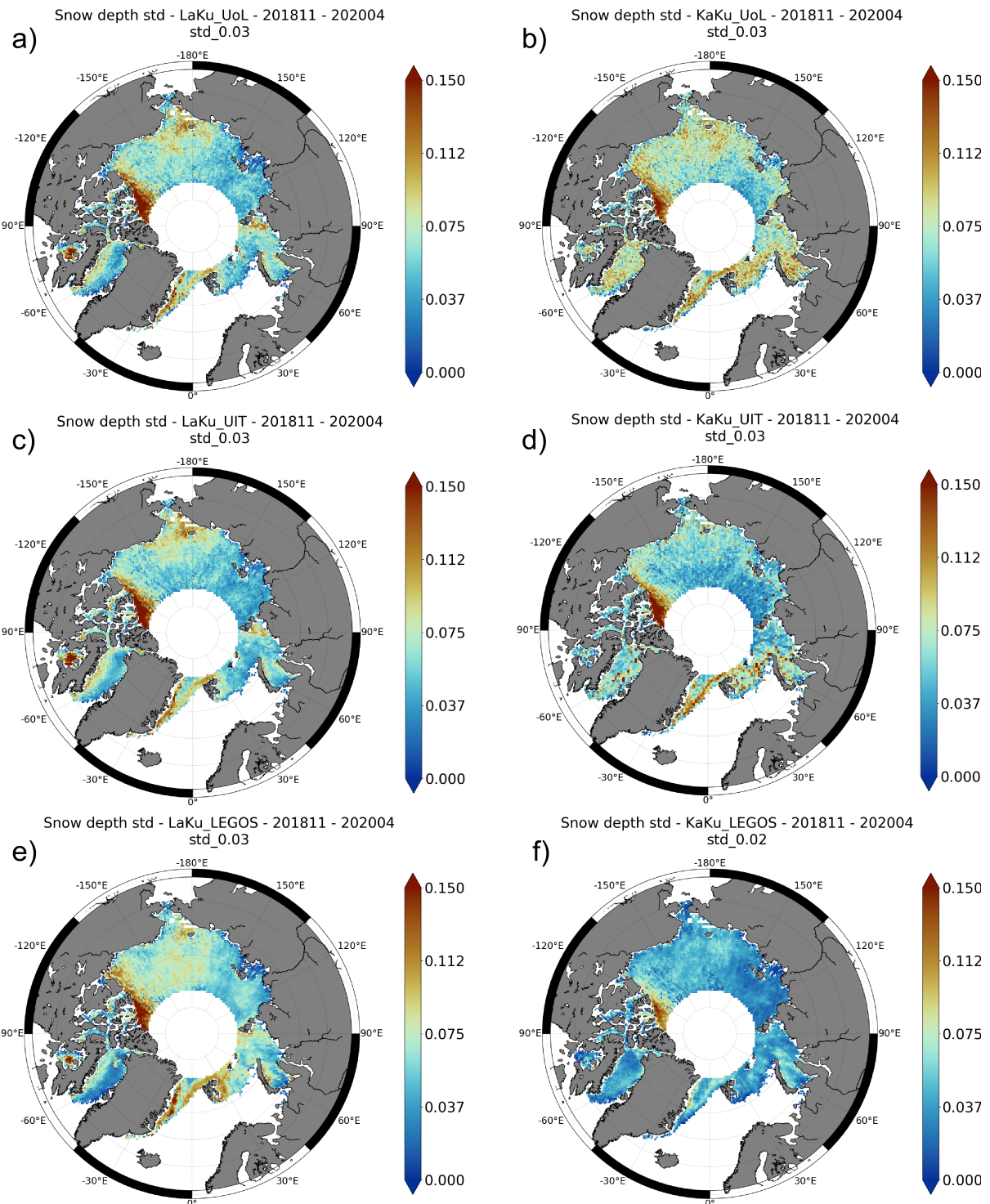


Figure 6: Maps of snow depth STD over the period 11/2018 - 04/2020 for a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS



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	Product	Mean	Median	STD	MAD
LaKu	UoL	0.076	0.055	0.029	0.021
	UIT	0.090	0.093	0.029	0.018
	LEGOS	0.077	0.063	0.027	0.024
KaKu	UoL	0.093	0.090	0.026	0.025
	UIT	0.086	0.094	0.035	0.020
	LEGOS	0.052	0.037	0.020	0.015

Table 2: Mean, Median, STD and MAD for each product over the common period

We also investigated the temporal variations over one winter (from November 2018 to April 2019) for each product (Figure 5 for the KaKu products and Figure 6 for the LaKu products). Table 3 shows the statistics for each month and each product. The mean is increasing monotonically with the months for the LaKu products and increasing in stages for the KaKu products. The amplitude between the smallest and the highest mean is also quite different between products. It is higher for the LaKu products (0.08, 0.09 and 0.11 for the UoL, UIT and LEGOS products respectively) than for the KaKu products (0.05 and 0.03 for the UoL and UIT products). Otherwise the snow is extending through the Arctic with the winter for all products.

Figure 7 shows the time series of the snow volume over the common period for each product. The KaKu LEGOS product shows quite weaker snow volume than the other products for all months. As for the snow depth mean, the amplitude over one winter is larger in the LaKu product.

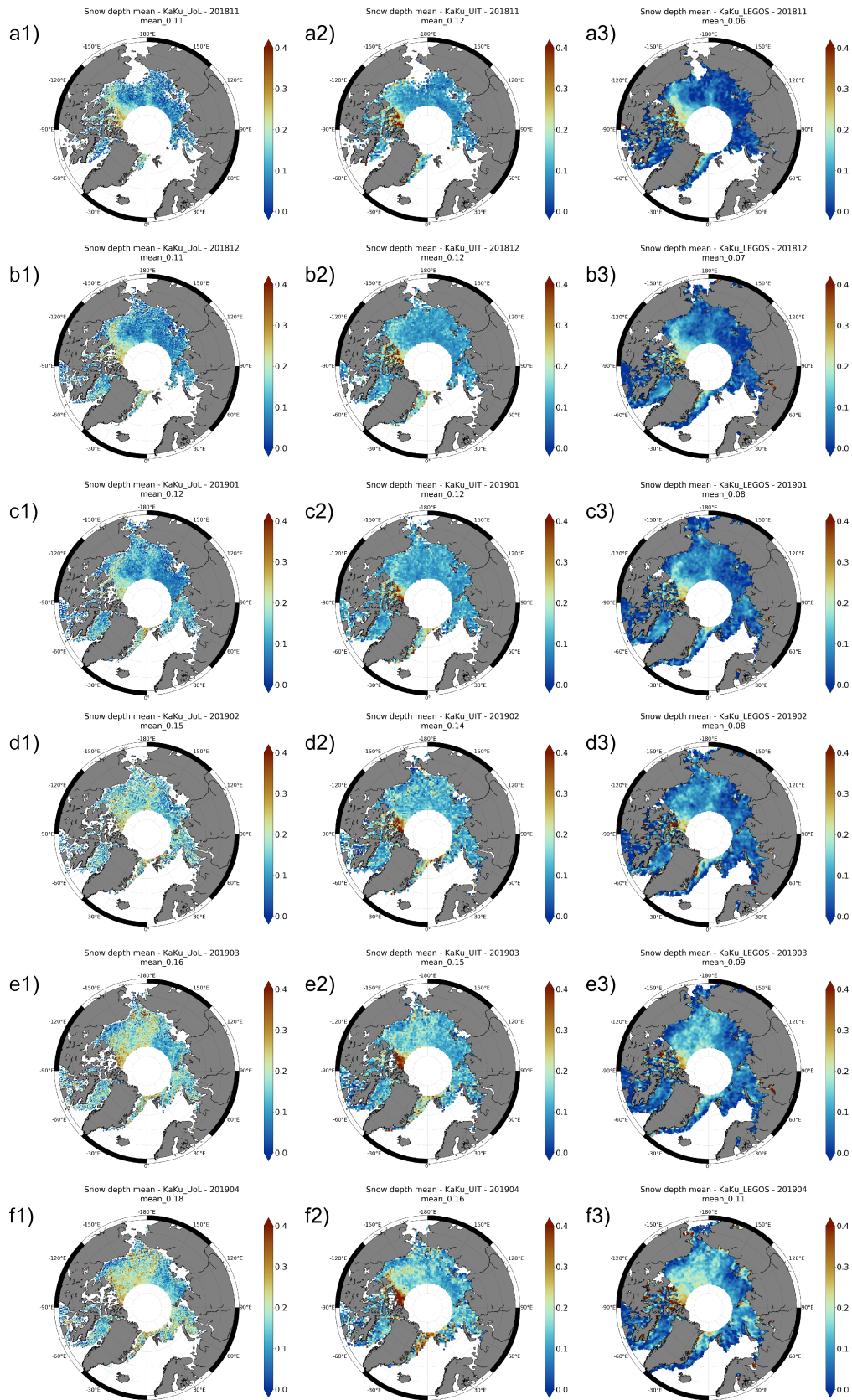


Figure 8: Maps of the monthly snow depth mean over a) 11/2018 ; b) 12/2018 ; c) 01/2019 ; d) 02/2019 ; e) 03/2019 ; f) 04/2019 for 1) KaKu from UoL ; 2) KaKu from UIT ; 3) KaKu from LEGOS

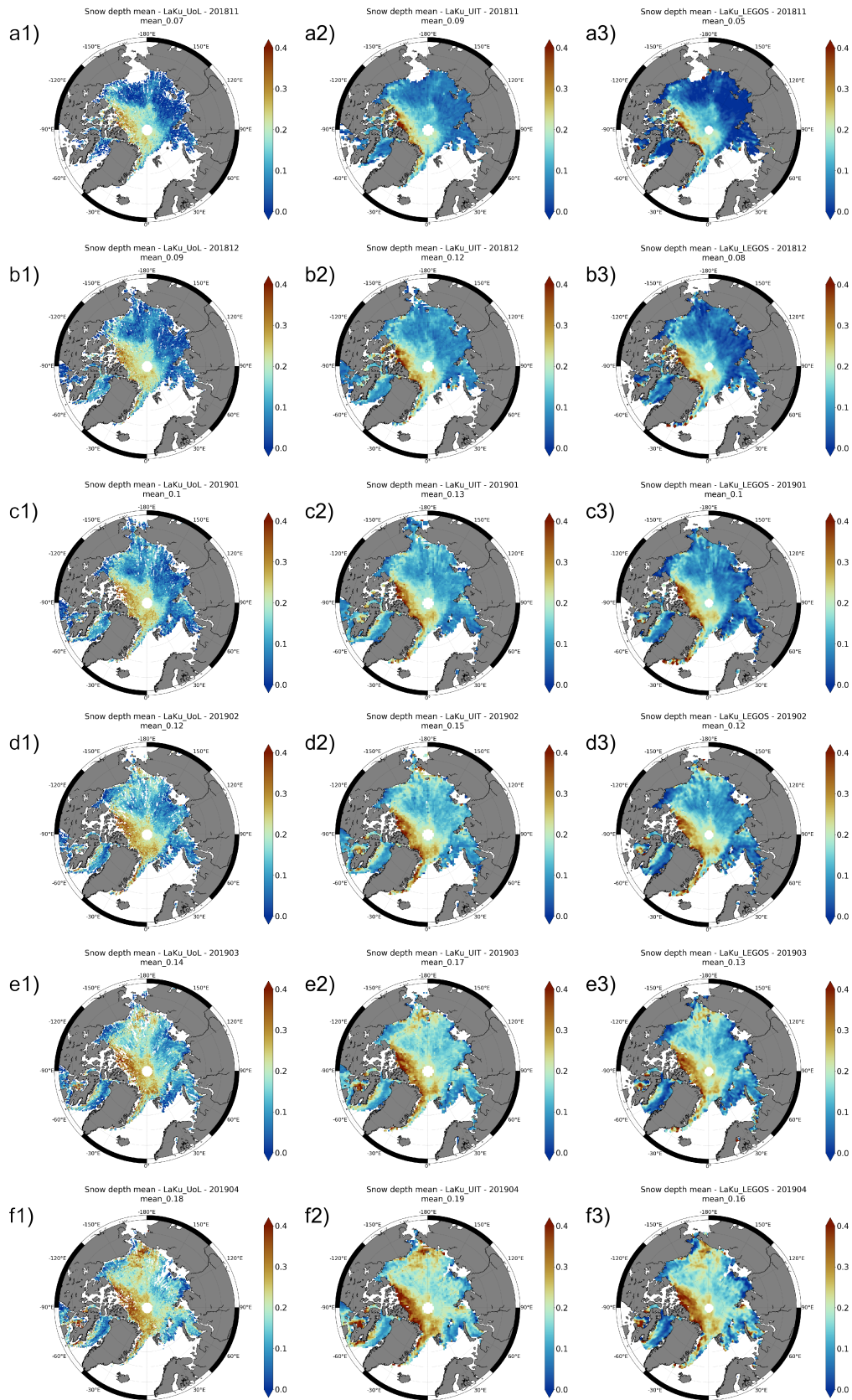


Figure 10: Maps of the monthly snow depth mean over a) 11/2018 ; b) 12/2018 ; c) 01/2019 ; d) 02/2019 ; e) 03/2019 ; f) 04/2019 for 1) LaKu from UoL ; 2) LaKu from UIT ; 3) LaKu from LEGOS

	LaKu			KaKu		
	UoL	UIT	LEGOS	UoL	UIT	LEGOS
11/2018	0.069	0.095	0.049	0.115	0.115	0.064
12/2018	0.090	0.115	0.081	0.115	0.118	0.071
01/2019	0.103	0.128	0.097	0.119	0.119	0.076
02/2019	0.123	0.148	0.117	0.155	0.139	0.078
03/2019	0.143	0.166	0.135	0.165	0.146	0.089
04/2019	0.175	0.190	0.164	0.176	0.161	0.114

Table 3: mean value over the Arctic region per month and per product

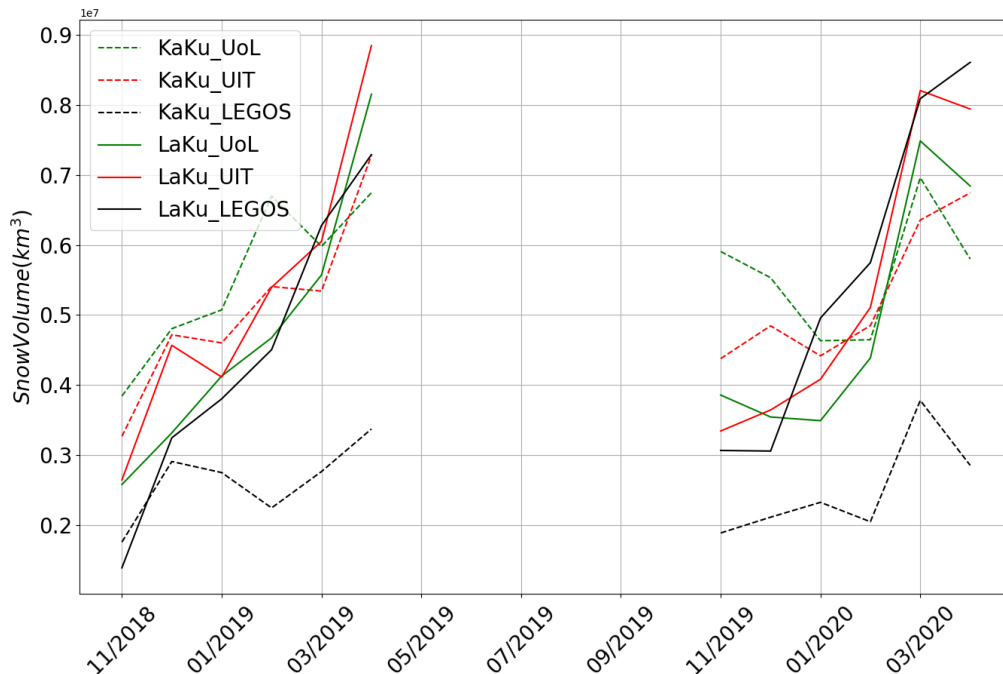


Figure 12: Time serie of the snow volume during the common period of all products

We can observe an important bias of KaKu LEGOS relatively to other solutions.



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4 Quantitative comparison

We also computed 2 to 2 statistics between the products. The resulting scatter plots are shown on Figure 8 and the correlation coefficients are given in Table 4.

The best correlation coefficients are obtained for the LaKu products. This is quite expected as they are computed using laser altimetry data which are identical for every product whereas the KaKu products are computed using different solutions for the Ka-band radar freeboard.

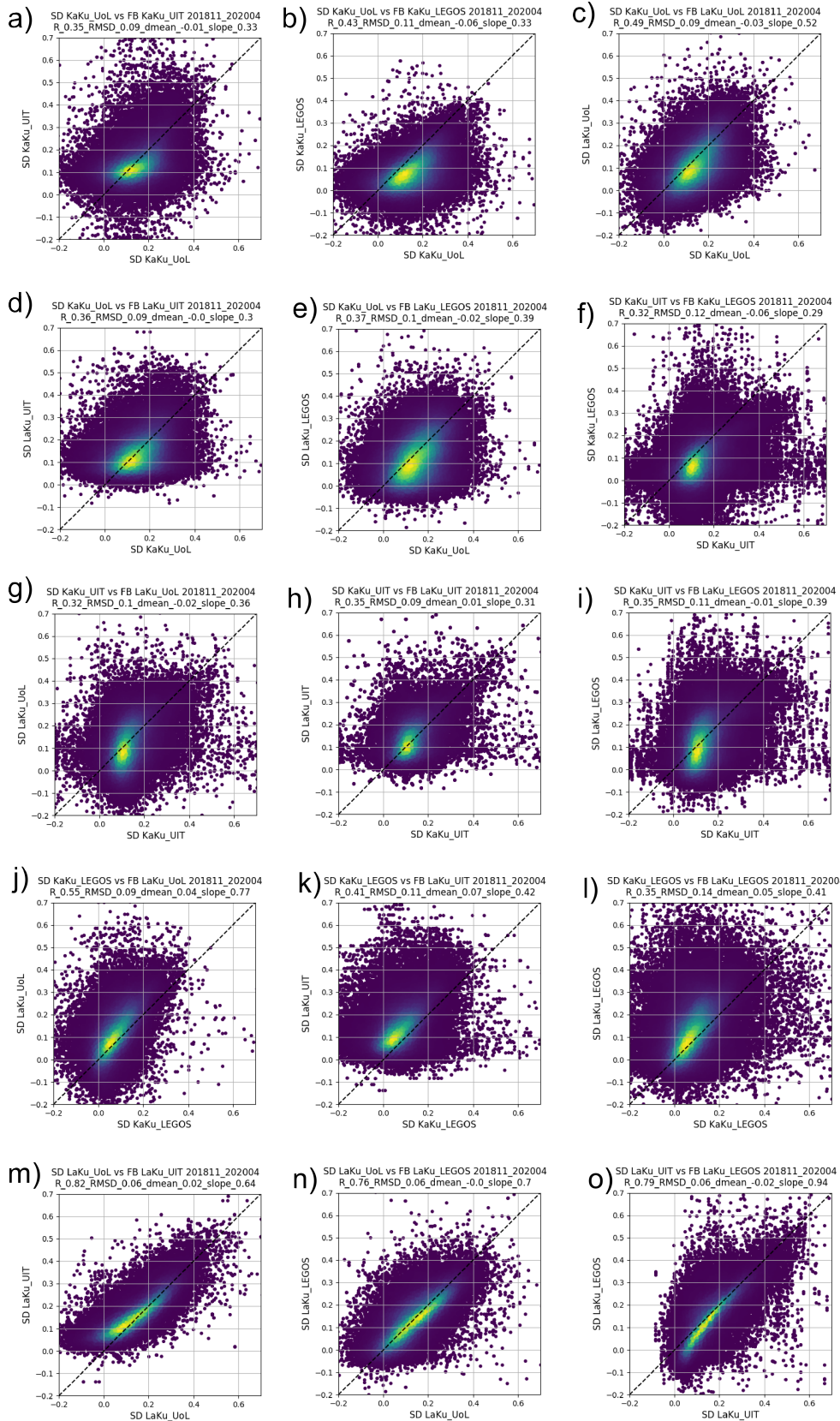


Figure 14: Scatter plots of the snow depth products



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		LaKu			KaKu		
		UoL	UIT	LEGOS	UoL	UIT	LEGOS
LaKu	UoL	X	0.82	0.76	0.50	0.32	0.55
	UIT	X	X	0.79	0.36	0.35	0.41
	LEGOS	X	X	X	0.37	0.35	0.35
KaKu	UoL	X	X	X	X	0.35	0.43
	UIT	X	X	X	X	X	0.38
	LEGOS	X	X	X	X	X	X

Table 4: Correlation coefficients between the snow depth products. In green the best correlations and in red the weakest.

5 Comparison with ATL20 data

ATL20 is a gridded product containing sea ice thickness and ancillary data provided by NSDIC using IS2 data and NESOSIM snow depth/density estimates.

We performed a comparison between the ATL20 gridded snow depth product and the different snow depth products (Figure 9).

Regarding the correlation coefficient the LaKu product perform better (0.71 and 0.74 vs 0.36, 0.32 and 0.49 for KaKu products).

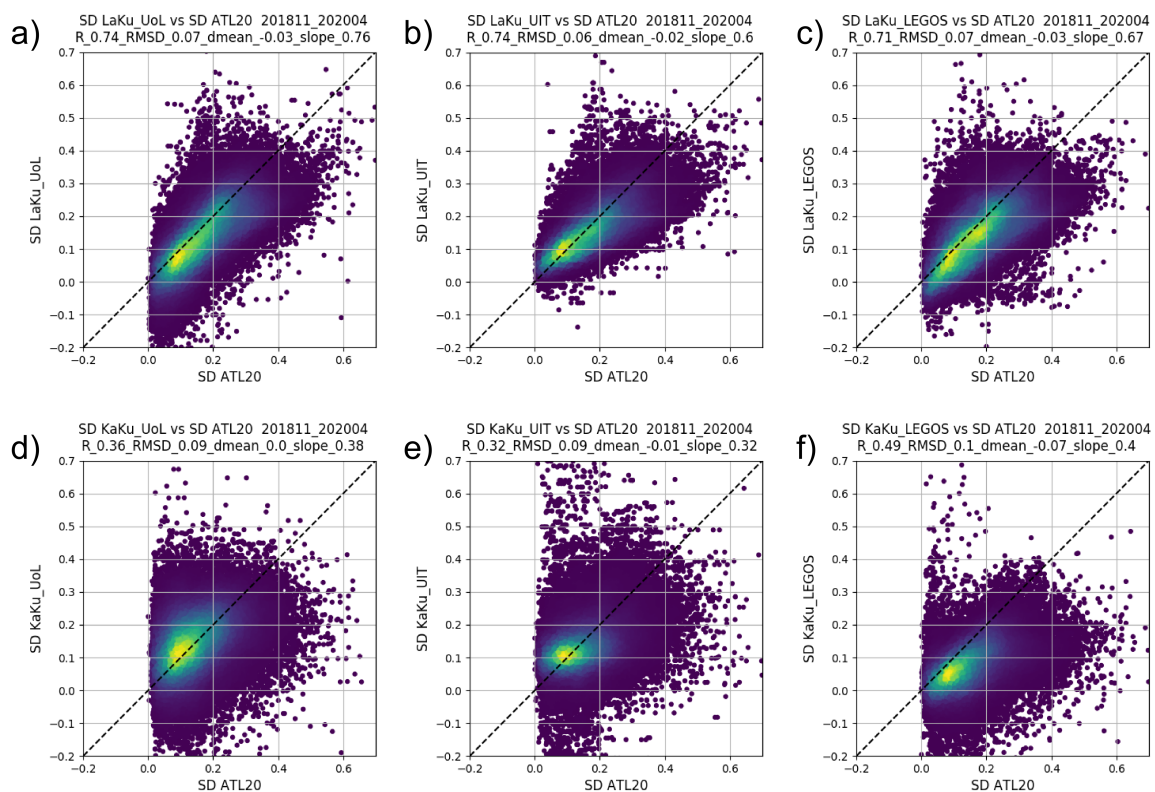


Figure 16: Scatter plots between ATL20 and a) KaKu UoL ; b) KaKu UIT ; c) KaKu LEGOS ; d) LaKu UoL ; e) LaKu UIT ; f) LaKu LEGOS over the common period (11/2018 - 04/2020)

6 Comparison with in situ data

We also performed comparisons with in situ data to get an idea of the performance of each product. There is little in situ data available on the period but we have been able to make comparisons with Operation IceBridge (OIB), ICEBird and BGEP. Figure 10 indicates the location of these in situ datasets.

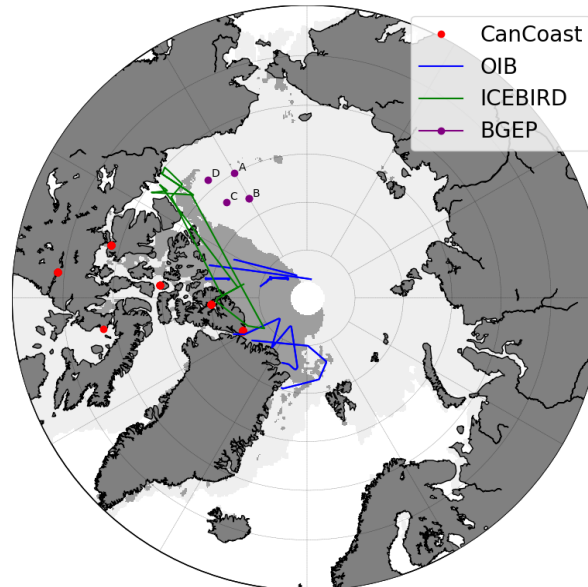


Figure 18: Map of in situ measurements

6.1 Comparisons with Operation Ice Bridge

Operation IceBridge (OIB) is a NASA's mission to collect polar data to fill the gap between the end of the ICESat mission in 2009 and the beginning of the ICESat-2 mission in 2018. It consists of airborne measurements over West Arctic mainly near the Canadian and Greenland coasts and up to the North Pole. The campaigns took place every year mainly in April but with some drifts in March or May.

The airplane has on board a Ku-band radar altimeter, a laser altimeter and a snow radar to characterize the sea ice thickness and the snow depth. It flies between 1000 and 2000 feet above the ground. The spatial resolution is about 43 m between each measurement. For comparison purposes, we grid the data with a 25 km resolution.

The common period to all 6 datasets covers only the OIB month of April 2019. There are 62 points of comparison. The statistics are provided Table 5 and the scatter plots on Figure 11. The RMSE are between 8 and 12 cm. Although the LEGOS KaKu and LaKu products differ significantly in Figure 7, they still provide the best correlations and MADs in their respective categories.



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For 2 products (ASD and KaKu UoL) we have a longer time series of data. The computation of statistics (not shown) induces an improvement of the RMSE (-3 cm for ASD and -2 cm for UoL). The correlation coefficient for the UoL KaKu product is also increasing.

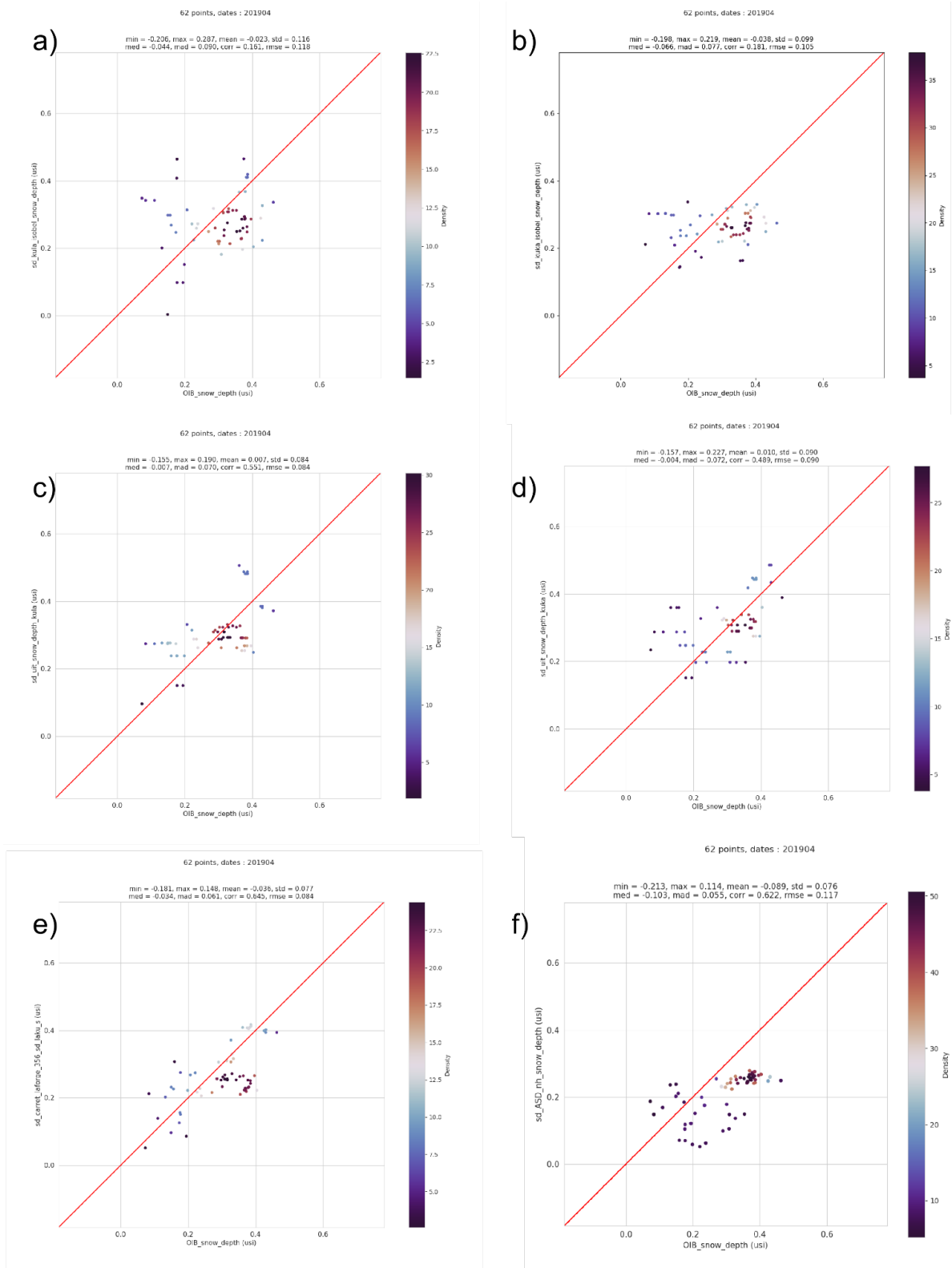


Figure 20: Scatter plots of OIB data vs a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS

	04/2019 62 points	med	MAD	corr	rmse
LaKu	UoL	-0.044	0.090	0.161	0.118
	UIT	-0.007	0.070	0.551	0.084
	LEGOS	-0.034	0.061	0.645	0.084
KaKu	UoL	-0.066	0.077	0.181	0.105
	UIT	-0.004	0.072	0.489	0.090
	LEGOS	-0.103	0.055	0.622	0.117

Table 5: statistics between OIB and the 6 products

6.2 Comparisons with Icebird

The IceBird program is led by the Alfred Wegener Institute (AWI). It consists of airborne surveys which took place once in summer and once in winter (March/April) per year since 2009. We represented the trajectory of aircraft for winter 2019 in green on Figure 10.

The aircraft carry a sensor ElectroMagnetic (EM) induction, used to measure sea ice thickness, a laser scanner, a camera providing photos of the sea ice surface and a snow radar. The plane is flying at about 100 m from the surface and the towed EM takes measures at 20 m height. The mean spatial resolution along the tracks is 350 m.

The best results are obtained for the LEGOS product which shows the highest correlation coefficient and the smallest RMSE, median and MAD (Figure 12 and Table 6).

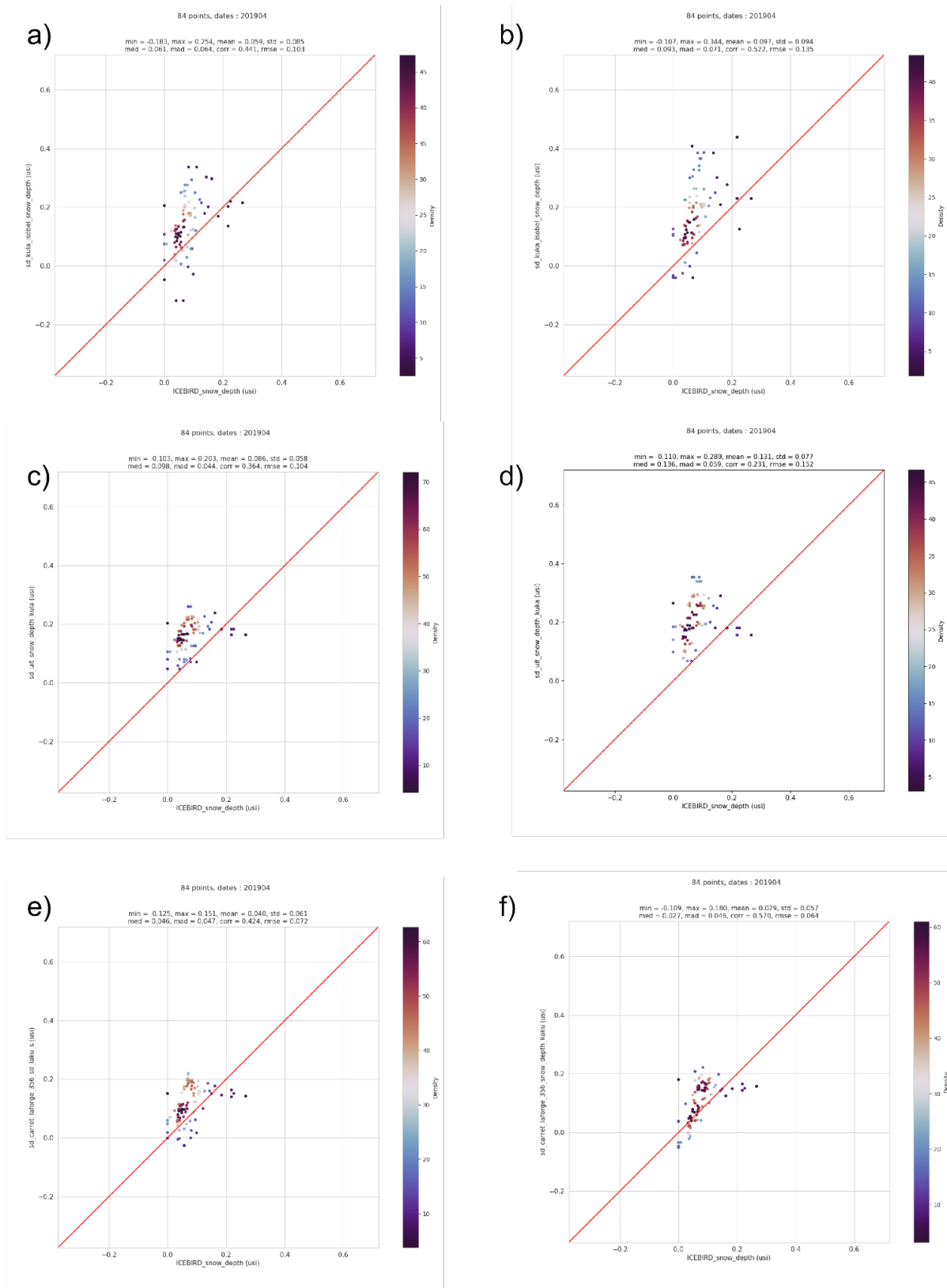


Figure 22: Scatter plots of ICEBird data vs a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS



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	04/2019 62 points	med	MAD	corr	rmse
KaKu	UIT	0.136	0.059	0.231	0.152
	UoL	0.093	0.071	0.522	0.135
	LEGOS	0.027	0.046	0.570	0.064
LaKu	UIT	0.098	0.044	0.364	0.104
	UoL	0.061	0.064	0.441	0.103
	LEGOS	0.046	0.047	0.424	0.072

Table 6: statistics between ICEBird and the 6 products

6.3 Comparisons with BGEP

The Beaufort Gyre Exploration Project (BGEP) has for purpose to monitor the Canadian basin to study fresh water and its variability especially in the Beaufort Gyre. It started in summer 2003. In this study we interested in the moorings deployed in the framework of this program. There are 4 moorings at representative locations. They provide daily time series of temperature, salinity, currents, sea ice draft and bottom pressure. We used monthly-averaged data. Sea ice draft is measured thanks to an upward-looking sonar mounted in the mooring flotation at 50 m depth which sends a pulse reflected by the surface water or the sea ice.



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Here we first convert the snow depth of each product to a draft, using the hydrostatic equation and 3 different freeboard products from LEGOS (samosa+, c2esaD1RN) and UIT. We based our work on the Sea Ice Thickness equations:

$$SIT = draft + FB_{ice} \quad (1)$$

$$SIT = \frac{\rho_w}{\rho_w - \rho_i} \times FB_{ice} + \frac{\rho_s}{\rho_w - \rho_i} \times SD \quad (2)$$

$$FB_{ice} = FB_{ku} - SD \quad (3)$$

$$FB_{ice} = FB_{ku} + \delta R_{snowKu} \quad (4)$$

$$\delta R_{snowKu} = SD \times \left(\frac{c}{c_{snow}} - 1 \right) \quad (5)$$

$$\frac{c}{c_{snow}} = \left(1 + 0.00051 \rho_{snow} \right)^{1.5} \quad (6)$$

where SIT is the Sea Ice Thickness, FB is the Freeboard, SD is the Snow Depth.

We tested 3 different freeboards because the final statistics will partly depend on this parameter.

We computed the correlation coefficient, the median which indicates the bias, the MAD which corresponds to the dispersion in relation to the bias and the RMSE which is the error.

First, Figure 13 and Table 7 show the results using a LEGOS freeboard (TFMRA50). Results are better with the LEGOS product.

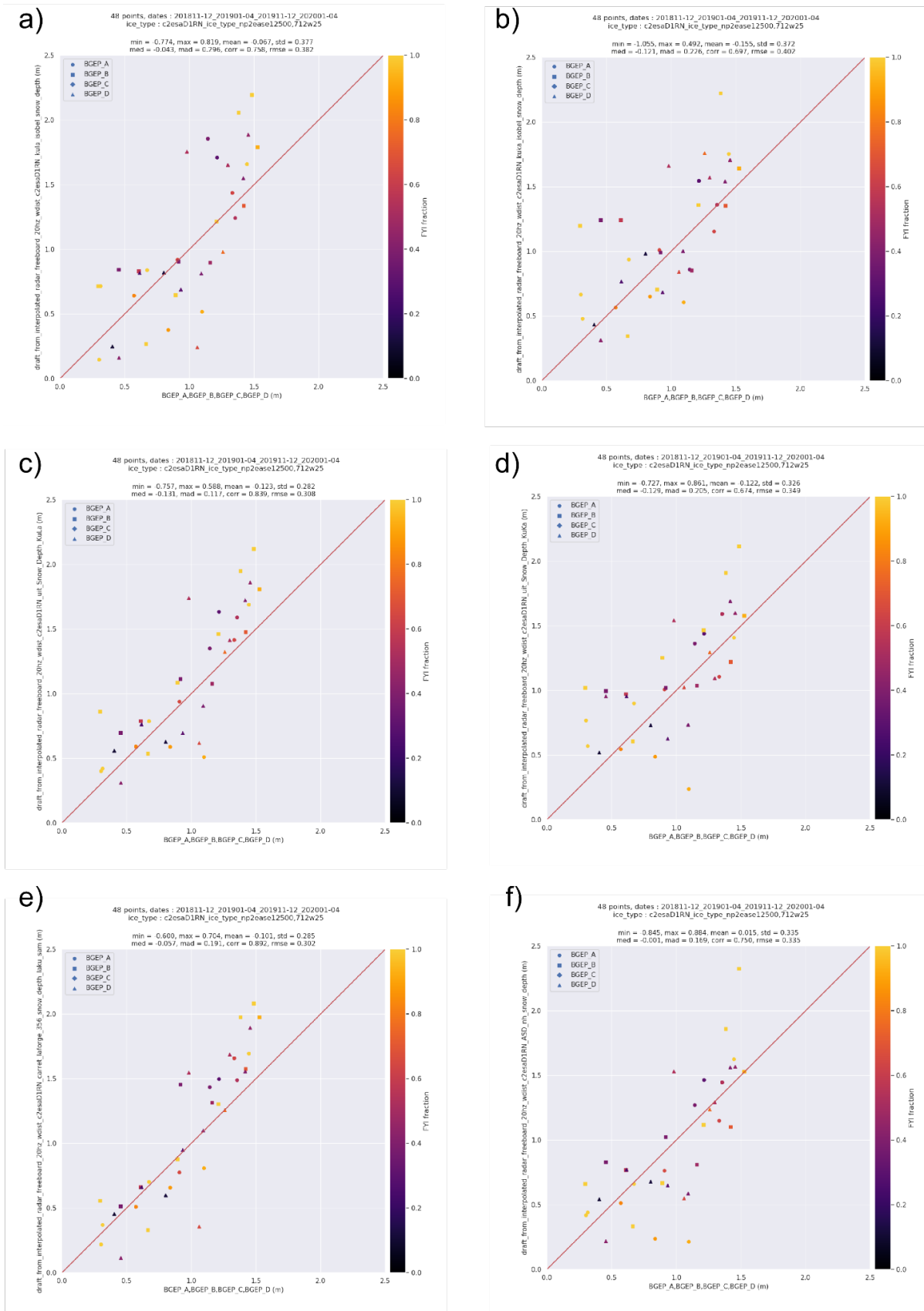


Figure 24: Scatter plots of BGEP draft data from 4 moorings vs the draft obtained from the LEGOS freeboard product and the snow depth from a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from IIT ; d) KaKu from IIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS



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	04/2019	med	MAD	corr	rmse
	62 points				
KaKu	UIT	-0.129	0.205	0.674	0.349
	UoL	-0.121	0.226	0.697	0.402
	LEGOS	-0.001	0.169	0.750	0.335
LaKu	UIT	-0.131	0.117	0.839	0.308
	UoL	-0.043	0.296	0.758	0.382
	LEGOS	-0.057	0.191	0.892	0.302

Table 7: statistics between BGEP draft and the 6 products using a LEGOS TFMRA50 freeboard

We also represented the time series of the draft obtained from daily BGEP measurements and derived from the LEGOS TFMRA50 freeboard and the different snow depth products at the moorings location. Figure 14 shows these time series over the common period for the 3 moorings. There is a good agreement between the different products and BGEP in winter 2018-2019. In winter 2019-2020 the datasets can diverge especially for mooring B. The intra annual variability is more pronounced for this winter which may explain these results. With the daily dataset we are able to understand the variations observed with altimetry data for example in February 2019 at mooring D.

FB LEGOS TFMRA50

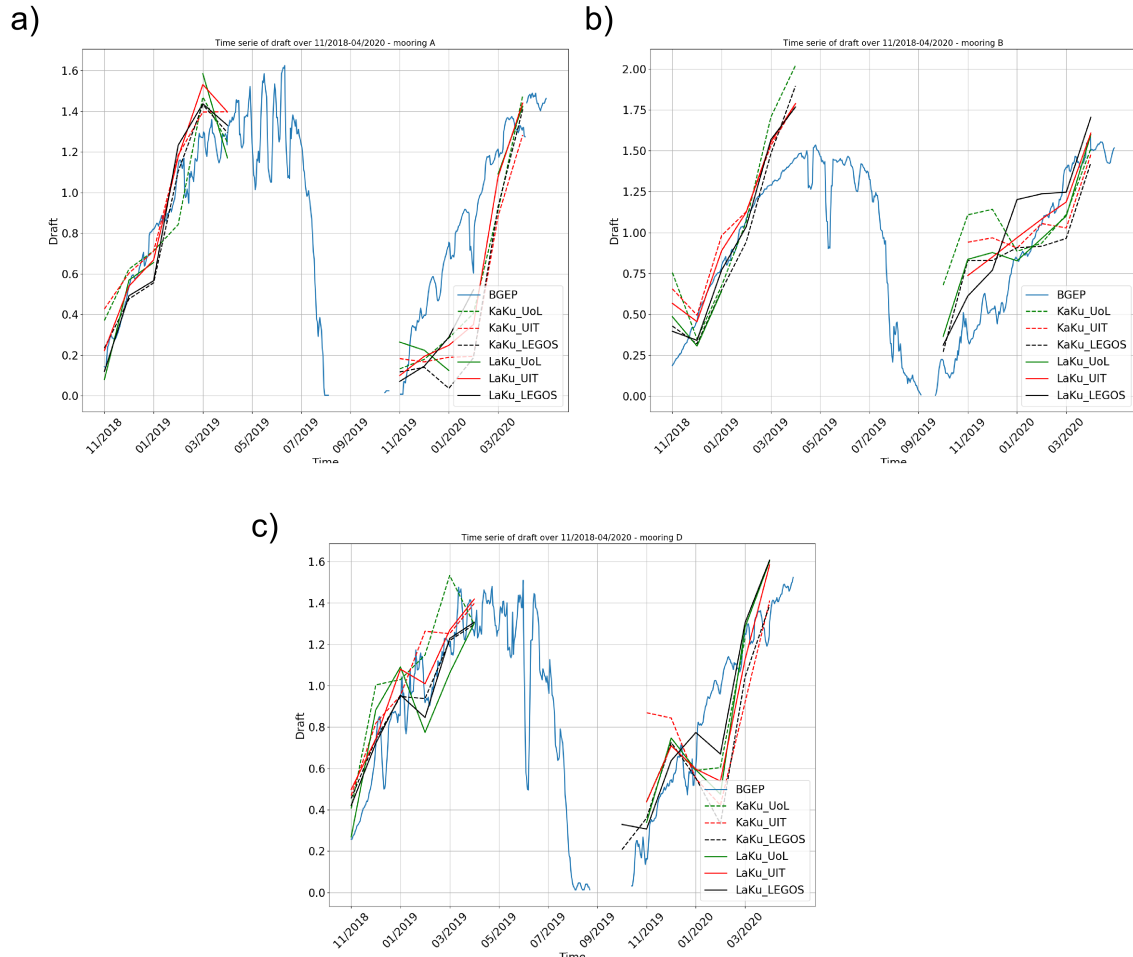


Figure 26: Time series of the draft from daily BGEP measurements (in blue) and from the LEGOS TFMRA50 Freeboard and UoL in green, UIT in red and LEGOS in black snow depth products for a) mooring A ; b) mooring B and c) mooring D. Dashed lines correspond to KaKu products and solid lines to LaKu products

We did the same diagnostics with a freeboard provided by UIT (Figure 15, Figure 16 and Table 8).

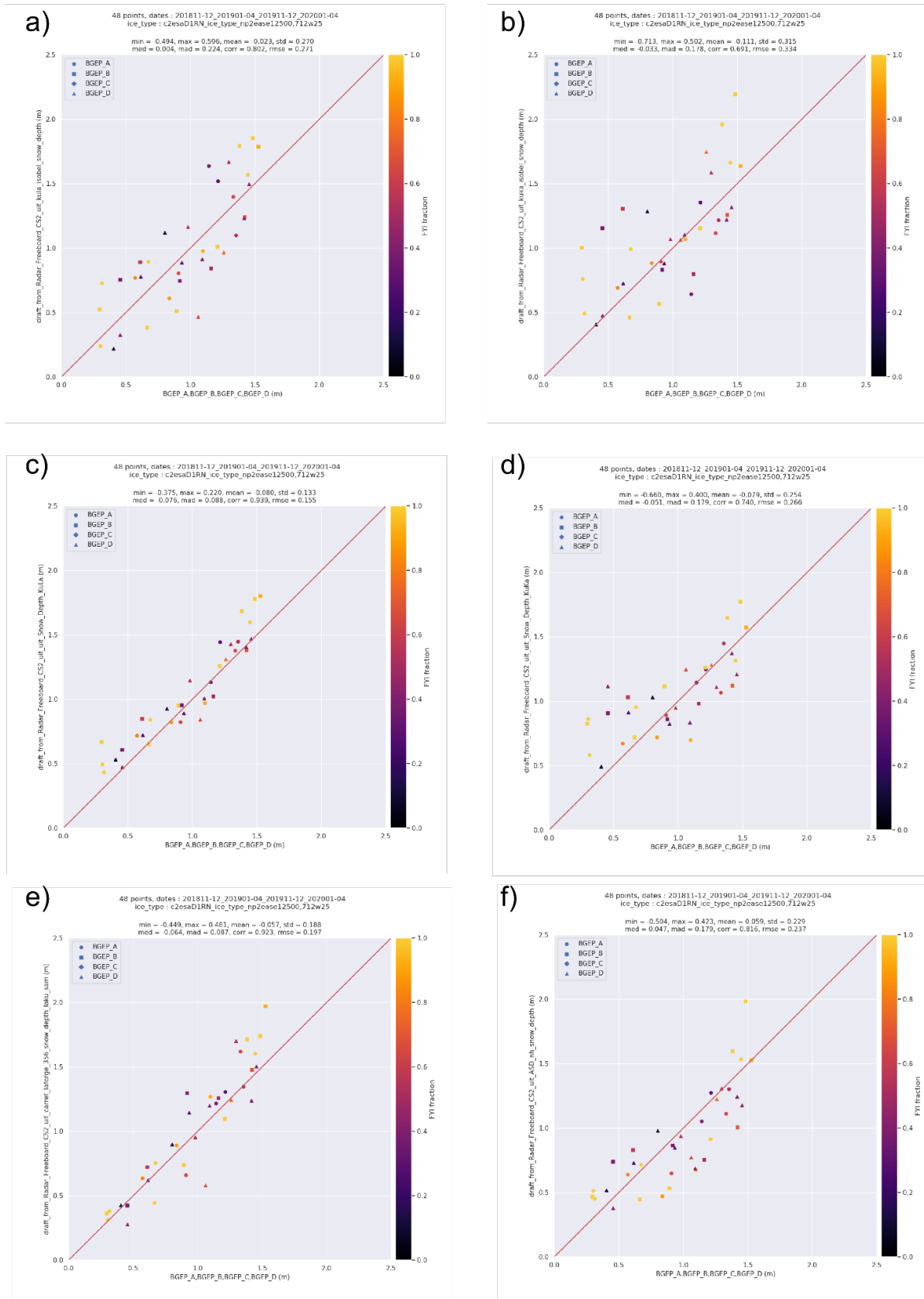


Figure 28: Scatter plots of BGEF draft data from 4 moorings vs the draft obtained from the UIT freeboard product and the snow depth from a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS



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	04/2019 62 points	med	MAD	corr	rmse
KaKu	UIT	-0.051	0.179	0.740	0.226
	UoL	-0.033	0.178	0.691	0.334
	LEGOS	0.047	0.179	0.816	0.237
LaKu	UIT	-0.076	0.088	0.939	0.155
	UoL	0.004	0.224	0.802	0.271
	LEGOS	0.064	0.087	0.923	0.197

Table 8: statistics between BGEP draft and the 6 products using a UIT freeboard

FB UIT

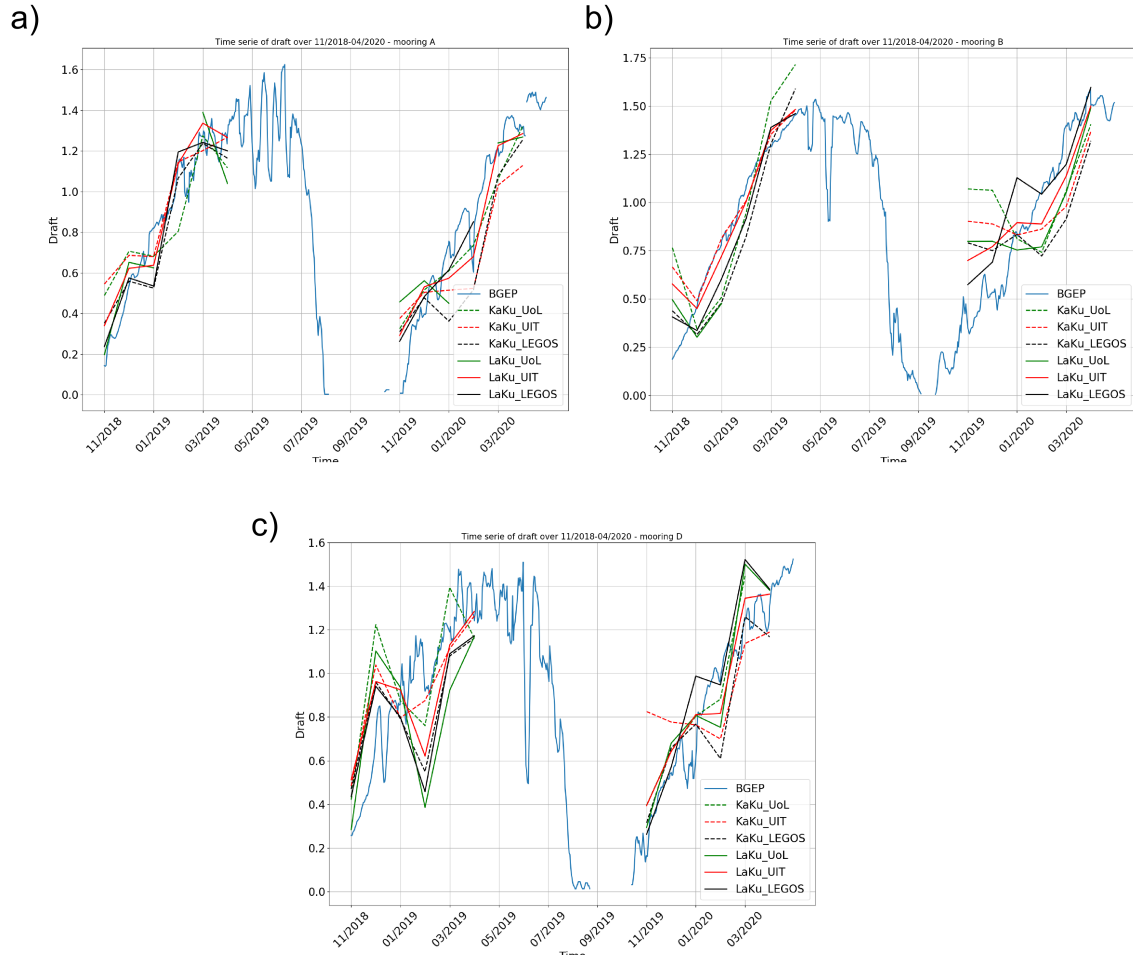


Figure 30: Time series of the draft from daily BGEF measurements (in blue) and from the UIT Freeboard and UoL in green, UIT in red and LEGOS in black snow depth products for a) mooring A ; b) mooring B and c) mooring D. Dashed lines correspond to KaKu products and solid lines to LaKu products

Finally we tested a third freeboard solution provided by LEGOS (Figure 17, Figure 18 and Table 9).

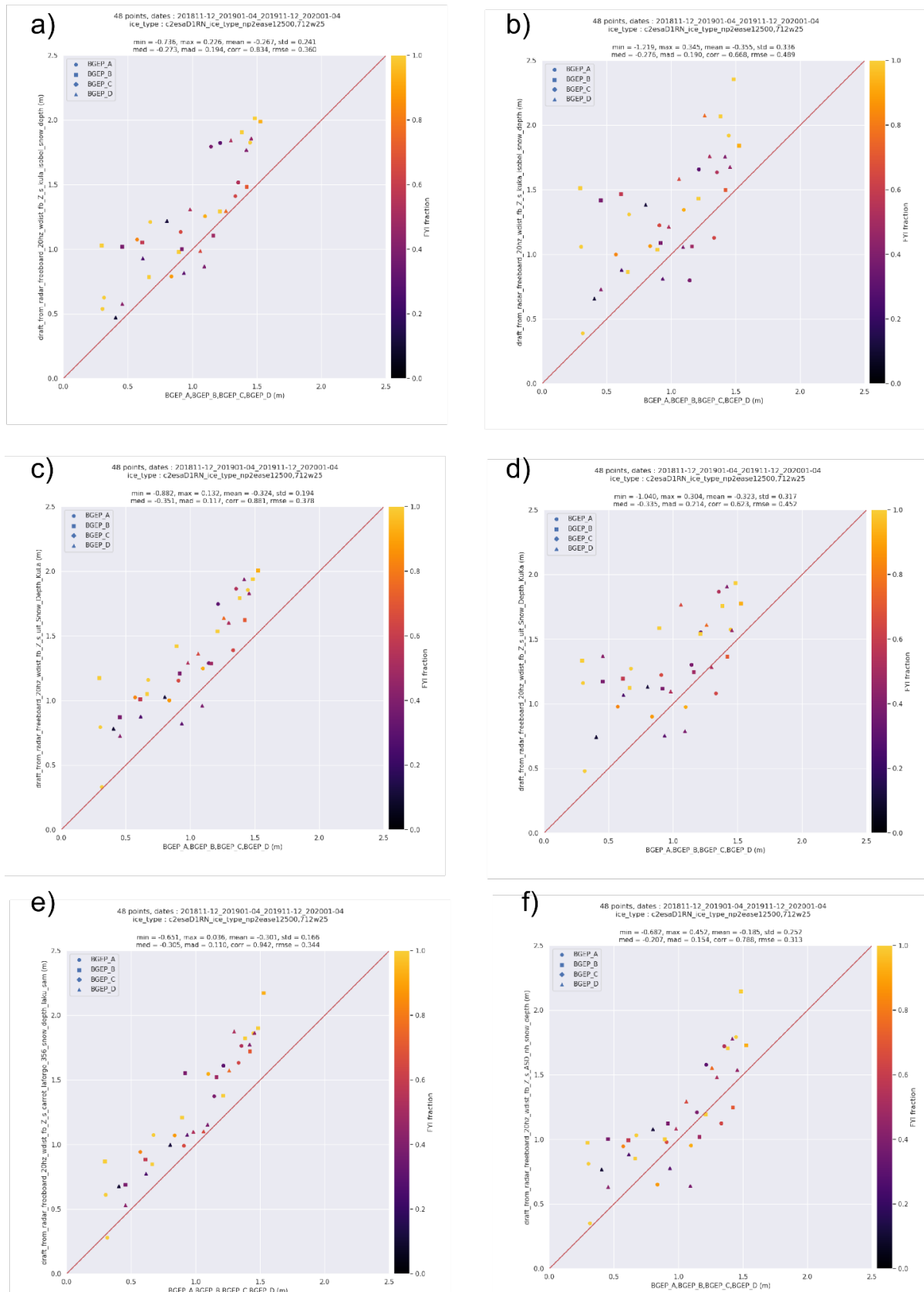


Figure 32: Scatter plots of BGEF draft data from 4 moorings vs the draft obtained from the samosa+ freeboard product and the snow depth from a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS



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	04/2019 62 points	med	MAD	corr	rmse
KaKu	UIT	-0.335	0.214	0.623	0.452
	UoL	-0.276	0.190	0.668	0.489
	LEGOS	-0.207	0.154	0.788	0.313
LaKu	UIT	-0.351	0.117	0.881	0.378
	UoL	-0.273	0.194	0.834	0.360
	LEGOS	-0.305	0.110	0.942	0.344

Table 9: statistics between BGEP and the 6 products using a LEGOS samosa+ freeboard

FB LEGOS SAMOSA+

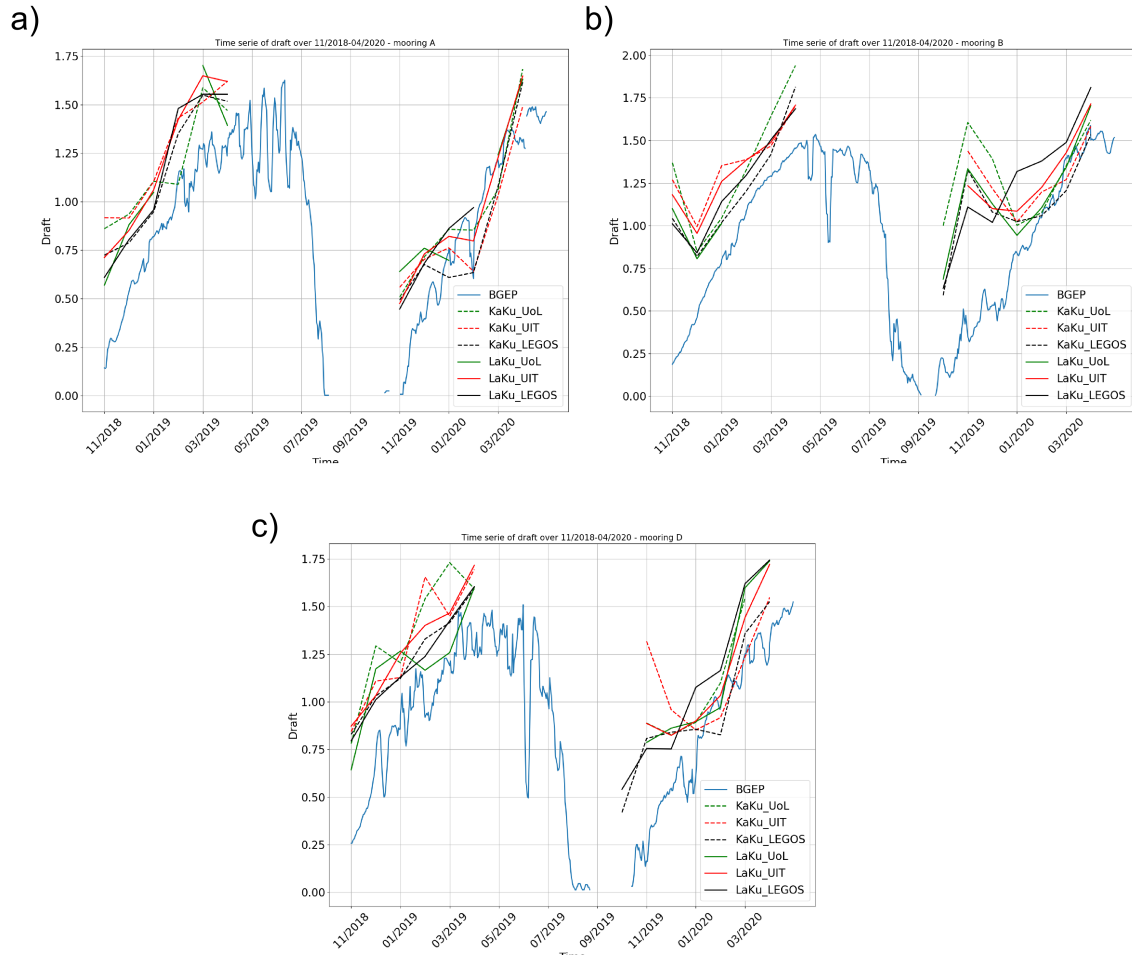


Figure 34: Time series of the draft from daily BGEP measurements (in blue) and from the LEGOS SAMOSA+ Freeboard and UoL in green, UIT in red and LEGOS in black snow depth products for a) mooring A ; b) mooring B and c) mooring D. Dashed lines correspond to KaKu products and solid lines to LaKu products

The different tables indicate that the better statistics are obtained when using the same snow depth and freeboard products.

The correlation coefficients are between 0.62 and 0.94. The smallest median, MAD and RMSE are almost always obtained for the LEGOS product in KaKu or LaKu.



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7 Conclusions

In this analysis we performed comparisons of the 6 products 2 by 2 and also with reference to 3 in situ datasets (OIB, IceBird, BGEP) and the ATL20 snow depth product.

The 6 products show similar patterns with some differences in the coverage of the region and near the coasts. In particular UoL misses some data along the coasts but it is probably due to the Sea Ice Concentration product often used as a computation mask.

The KaKu and LaKu products show differences in the evolution through one winter. The mean is increasing monotonically with the months for the LaKu products and increasing in stages for the KaKu products.

The comparison with BGEP requires a Freeboard product and the results are better when this FB product uses the same source products as for the SD. This is intuitively understandable because the measurements are then consistent and errors can be compensated. For example, an over- or underestimation of the snow penetration will be partially compensated by an over- or underestimation of the ice freeboard, the total freeboard being unchanged. These results are very favorable to the CRISTAL solution which measures both frequencies simultaneously.

Concerning the construction of a snow product based on the different products analyzed, the comparisons with in situ data enables to highlight some interesting criteria in the purpose of merging products:

- the median indicates the bias. Using in situ data would allow to first unbias the products
- the MAD corresponds to the dispersion with reference to the bias. It must be the smallest possible
- the RMSE corresponds to the error and could be used to attribute a weight to each product

Nevertheless, it will be necessary to ensure that these different products will be available over the period considered by the project.

The final product will contain the LEGOS LaKu and KaKu products, the corresponding freeboards used to compute the snow depth and the minimum, maximum and standard deviation values for all products, for the KaKu products and the LaKu products. It is provided in 356x356 EASE2 grids on a monthly basis over the common period.

Appendice A: Maps of snow depth median

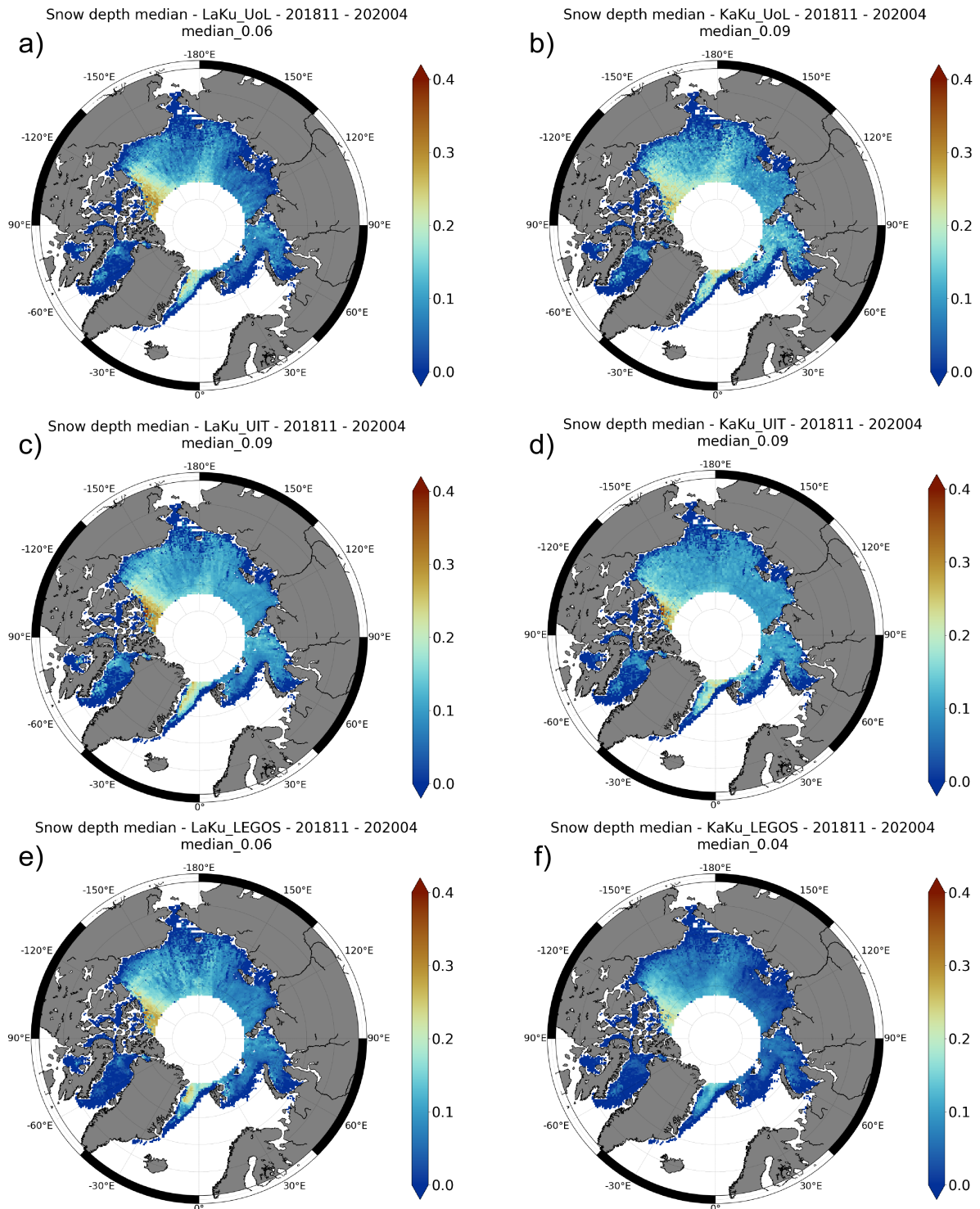


Figure 35: Maps of snow depth median over the period 11/2018 - 04/2020 for a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS

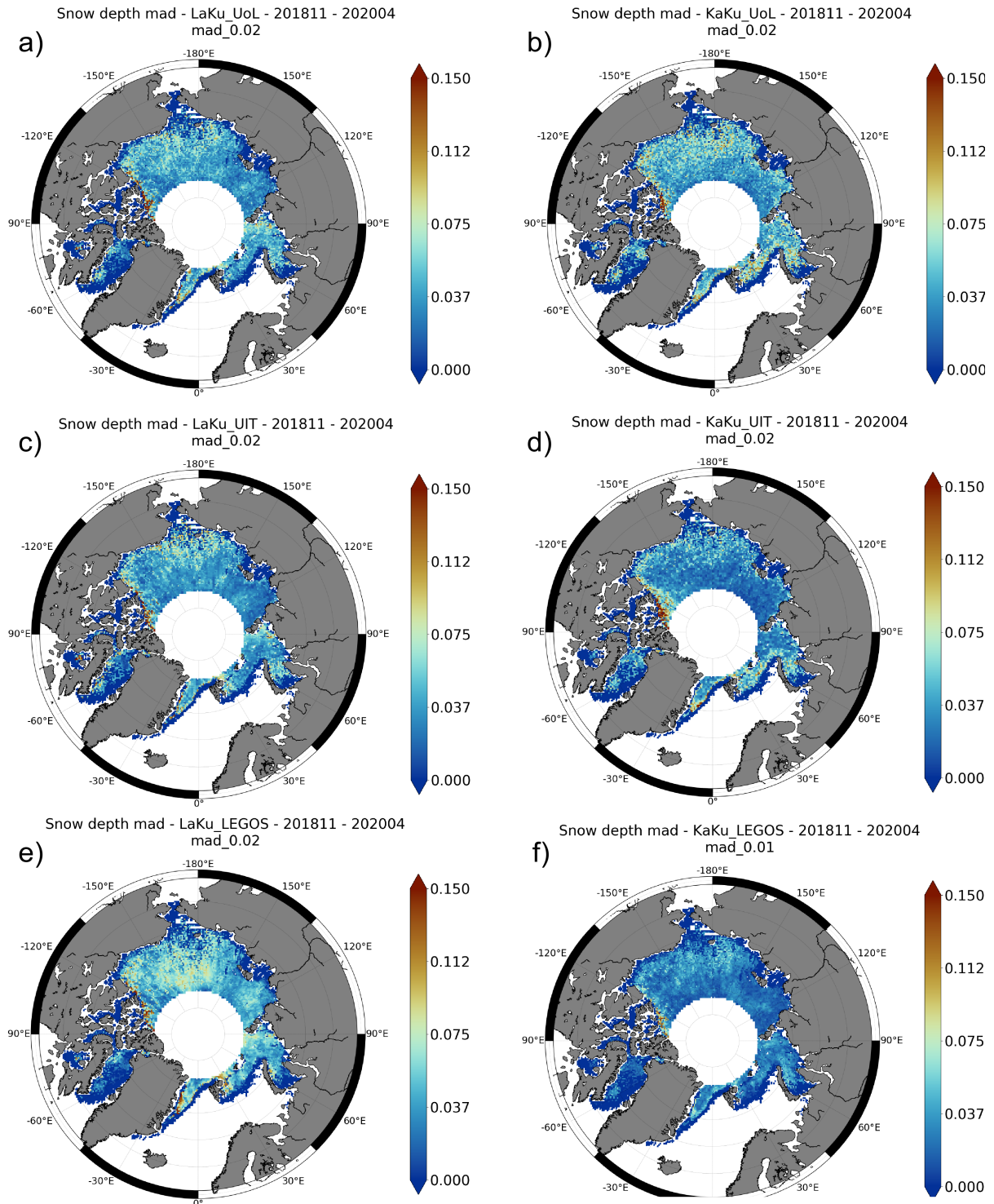


Figure 36: Maps of snow depth MAD over the period 11/2018 - 04/2020 for a) LaKu from UoL ; b) KaKu from UoL ; c) LaKu from UIT ; d) KaKu from UIT ; e) LaKu from LEGOS ; f) KaKu from LEGOS



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Appendix B: Final product description

The final product will contain the LEGOS LaKu and KaKu snow depth products, the corresponding freeboards used to compute the snow depth and the standard deviation values of all products, for the 3 KaKu products and the 3 LaKu products with also a variable containing the number of products used to compute these statistics at each grid point. It is provided in 356x356 EASE2 grids on a monthly basis over the common period.

Here is the netcdf description using the *ncdump* command.

```
netcdf SD_201910 {
dimensions:
    u = 356 ;
    v = 356 ;
    time = UNLIMITED ; // (1 currently)
variables:
    float latitude(u, v) ;
        latitude:units = "degree_north" ;
        latitude:long_name = "latitude" ;
        latitude:description = "ease grid" ;
        latitude:_CoordinateAxisType = "Lat" ;
    float longitude(u, v) ;
        longitude:units = "degree_east" ;
        longitude:long_name = "ease grid" ;
        longitude:_CoordinateAxisType = "Lon" ;
    float time(time) ;
        time:units = "days since 2000-01-01" ;
        time:long_name = "time" ;
    float snow_depth_laku_LEGOS_sam(time, u, v) ;
        snow_depth_laku_LEGOS_sam:units = "m" ;
        snow_depth_laku_LEGOS_sam:long_name =
"snow_depth_laku_samosa_LEGOS" ;
        snow_depth_laku_LEGOS_sam:description = "snow depth from LEGOS
computed from freeboard elevation difference between IS2 ATL10 product and CS2 (GPOD
SAMOSA). The snow delay correction is calculated using Mallett et 2020 formula" ;
        snow_depth_laku_LEGOS_sam:coordinates = "lat lon" ;
    float freeboard_ku_sam(time, u, v) ;
        freeboard_ku_sam:units = "m" ;
        freeboard_ku_sam:long_name = "radar_freeboard_sam_LEGOS" ;
        freeboard_ku_sam:description = "Ku-band SAR radar freeboard from the
CryoSat-2 mission calculated using SAM+ retracker (for more details see laforge et al,
2020)" ;
        freeboard_ku_sam:coordinates = "lat lon" ;
    float freeboard_ku_sam_std(time, u, v) ;
        freeboard_ku_sam_std:units = "m" ;
        freeboard_ku_sam_std:long_name = "radar_freeboard_sam_LEGOS_std" ;
```



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```

freeboard_ku_sam_std:description = "Standard deviation of
radar_freeboard_sam_std parameter" ;
freeboard_ku_sam_std:coordinates = "lat lon" ;
float snow_depth_laku_LEGOS_t50(time, u, v) ;
snow_depth_laku_LEGOS_t50:units = "m" ;
snow_depth_laku_LEGOS_t50:long_name = "snow_depth_laku_t50_LEGOS" ;
snow_depth_laku_LEGOS_t50:description = "snow depth from LEGOS
computed from freeboard elevation difference between IS2 ATL10 product and CS2
(BASELINE-D L1B + LEGOS PROCESSING TFMRA50). The snow delay correction is calculated
using Mallett et 2020 formula" ;
snow_depth_laku_LEGOS_t50:coordinates = "lat lon" ;
float freeboard_ku_t50(time, u, v) ;
freeboard_ku_t50:units = "m" ;
freeboard_ku_t50:long_name = "freeboard_ku_tfmra50_LEGOS" ;
freeboard_ku_t50:description = "Ku-band SAR radar freeboard from the
CryoSat-2 mission calculated using TFMRA50 retracker from baseline-D L1B official
product" ;
freeboard_ku_t50:coordinates = "lat lon" ;
float freeboard_ku_t50_std(time, u, v) ;
freeboard_ku_t50_std:units = "m" ;
freeboard_ku_t50_std:long_name = "freeboard_ku_tfmra50_LEGOS_std" ;
freeboard_ku_t50_std:description = "Standard deviation of
radar_freeboard_t50" ;
freeboard_ku_t50_std:coordinates = "lat lon" ;
float snow_depth_laku_UoL(time, u, v) ;
snow_depth_laku_UoL:units = "m" ;
snow_depth_laku_UoL:long_name = "snow_depth_laku_UoL" ;
snow_depth_laku_UoL:description = "Snow depth derived from (IS2-
Ku_calibrated)*0.781 [m]" ;
snow_depth_laku_UoL:coordinates = "lat lon" ;
float snow_depth_laku_UIT(time, u, v) ;
snow_depth_laku_UIT:units = "m" ;
snow_depth_laku_UIT:long_name = "snow_depth_laku_UIT" ;
snow_depth_laku_UIT:description = "Snow Depth from ICESat-2 ATLAS
freeboard minus CryoSat-2 SIRAL freeboard (multiplied by correction factor 0.781)" ;
snow_depth_laku_UIT:coordinates = "lat lon" ;
float snow_depth_kaku_LEGOS(time, u, v) ;
snow_depth_kaku_LEGOS:units = "m" ;
snow_depth_kaku_LEGOS:long_name = "snow_depth_kaku_LEGOS" ;
snow_depth_kaku_LEGOS:description = "computed as
(saral_radar_freeboard_40hz_median- c2esaOC1_radar_freeboard_20hz_median)/1.238) to
take in account the speed reduction of radar in snow" ;
snow_depth_kaku_LEGOS:coordinates = "lat lon" ;
float freeboard_ka(time, u, v) ;
freeboard_ka:units = "m" ;

```



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```

freeboard_ka:long_name = "radar_freeboard_SRL_LEGOS" ;
freeboard_ka:description = "Radar (ku-band) freeboard computed from
differences between the ila_smooth_40hz (12.5km smoothed) and the sla_smooth_40hz
(12.5km)" ;
freeboard_ka:coordinates = "lat lon" ;
float snow_depth_kaku_UoL(time, u, v) ;
snow_depth_kaku_UoL:units = "m" ;
snow_depth_kaku_UoL:long_name = "snow_depth_kaku_UoL" ;
snow_depth_kaku_UoL:description = "Snow depth derived from
(Ka_calibrated-Ku_calibrated)*0.781 [m]" ;
snow_depth_kaku_UoL:coordinates = "lat lon" ;
float snow_depth_kaku_UIT(time, u, v) ;
snow_depth_kaku_UIT:units = "m" ;
snow_depth_kaku_UIT:long_name = "snow_depth_kaku_UIT" ;
snow_depth_kaku_UIT:description = "Snow Depth from AltiKa SARAL
freeboard minus CryoSat-2 SIRAL freeboard (multiplied by correction factor 0.781)" ;
snow_depth_kaku_UIT:coordinates = "lat lon" ;
float std_sd(time, u, v) ;
std_sd:units = "m" ;
std_sd:long_name = "standard_deviation_snow_depth" ;
std_sd:coordinates = "lat lon" ;
float std_sd_laku(time, u, v) ;
std_sd_laku:units = "m" ;
std_sd_laku:long_name = "standard_deviation_snow_depth_laku" ;
std_sd_laku:coordinates = "lat lon" ;
float std_sd_kaku(time, u, v) ;
std_sd_kaku:units = "m" ;
std_sd_kaku:long_name = "standard_deviation_snow_depth_kaku" ;
std_sd_kaku:coordinates = "lat lon" ;
float nb_data_per_pixel(time, u, v) ;
nb_data_per_pixel:units = "" ;
nb_data_per_pixel:long_name = "number_of_data_per_pixel" ;
nb_data_per_pixel:coordinates = "lat lon" ;
nb_data_per_pixel:description = "Number of products (LaKu and KaKu from
LEGOS and UIT) used to compute the standard deviation for each grid point" ;
float nb_laku_data_per_pixel(time, u, v) ;
nb_laku_data_per_pixel:units = "" ;
nb_laku_data_per_pixel:long_name = "number_of_laku_data_per_pixel" ;
nb_laku_data_per_pixel:coordinates = "lat lon" ;
nb_laku_data_per_pixel:description = "Number of products (LaKu from
LEGOS and UIT) used to compute the standard deviation for each grid point" ;
float nb_kaku_data_per_pixel(time, u, v) ;
nb_kaku_data_per_pixel:units = "" ;
nb_kaku_data_per_pixel:long_name = "number_of_kaku_data_per_pixel" ;
nb_kaku_data_per_pixel:coordinates = "lat lon" ;

```



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nb_kaku_data_per_pixel:description = "Number of products (KaKu from LEGOS and UIT) used to compute the standard deviation for each grid point" ;

// global attributes:

:institution = "LEGOS, UIT, UoL" ;

:contact = "sara.fleury@cnsr.fr, jack.c.landy@uit.no,

i.r.lawrence@leeds.ac.uk" ;

:references = "Technical document available on request" ;

:project = "Polar+ Snow on Sea Ice" ;

:title = "6 altimetry snow depth products from Polar+ Snow on Sea Ice ESA

project" ;

End of the document