Multi-Frequency Satellite Approaches for Snow on Sea Ice

Polar+ Snow on Sea Ice (PSSI)

Deliverable 3.2:

Product Validation Report (PVR)

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Document History

Version	Date	Updated by	Reason
1.a	*01/05/2023*	*All*	
1.b	*12/06/2023*	*All*	Validation of merged snow product Change of linear regression to orthogonal distance regression

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 of Contents

List of Figures

List of Tables

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

1 Introduction

1.1 Document objectives

This document describes the results of the validation exercise with independent reference data for snow depth on sea ice. Section 2 describes the validation data sources, Section 3 the validation methodology, Section 4 the validation results with subsection for KuKa, KuLa and Merged snow depth products and Section 5 closes with a discussion of the validation results.

2 Validation Datasets

This section contains a brief description of the validation data for snow depth on sea ice.

2.1 NASA Operation IceBridge (OIB)

Snow depth from airborne radar data of the NASA Operation IceBridge (OIB) project is based on the IceBridge Sea Ice Freeboard, Snow Depth, and Thickness Quick Look, Version 1 (NSIDC-0708) data set (Kurtz et al, 2016).

The data set includes surveys from 2012 to 2019 in the period between March and April.

2.2 AWI IceBird

Snow depth from airborne radar of the AWI IceBird project is based on the multi-sensor airborne data release described in Jutila et al, 2022 and available from the PANGAEA data base (Jutila et al, 2021a, Jutila et al, 2021b).

Data is available for April 2017 and April 2019.

2.3 MOSAiC Transect Data

Snow depth data from MOSAiC transect is described in Itkin et al., 2023 and the data can be downloaded from PANGAEA (Itkin et al., 2021). Temporal coverage of the data ranges from October 2019 to May 2020. Due to the location of the MOSAiC expedition, there is no collocated data with AltiKa Ka-Band radar altimeter data.

2.4 Ice Mass Balance Buoys

Snow depth measurements from drifting ice mass balance buoys of CRREL-Dartmouth Mass Balance Buoy Program[1] (Perovich et al, 2023) are available from 2011 to 2016. The buoys measures snow depth only locally, but for several month.

2.5 Snow Buoys

Similar to snow depth measurements from ice mass balance buoys, snow buoy measure changes of the snow height but with 4 instead of 1 sensor. The methodology is described in Nicolaus et al, 2021 and the processed snow depth data is available from PANGAEA (Nicolaus et al., 2017).

[1] http://imb-crrel-dartmouth.org/results/ (Last accessed May 2023)

3 Validation Methodology

This section describes the validation methodology

3.1 Data Colocation

All Polar+ snow data sets use their own grid, defined by the projection, the extent and the grid resolution. All validation data sets are therefore gridded to the three different grids for the monthly periods of the Polar+ snow products using a python script.

The grids are created using the pyproj python package with the known resolution and dimensions of the grid. This is done by computing (x, y) coordinates of the grid cell center in projection coordinates assuming a constant grid resolution and then projecting the (x, y) coordinated to (lon, lat) positions.

But the location of individual grid cells may still depend on the specific method of the grid setup e.g., by varying distance between grid cell center positions. Therefore, parameters such as extend and grid resolution used for the pyproj grid creation are slightly modified to create an optimal agreement with the longitude/latitude parameters in the delivered product files.

An overview of the grid parameters are shown in Table 1 and quality control figures (Figure 1 through Figure 3) show the grids can be recreated with an acceptable level of accuracy (< 0.1 degrees in latitude: < 15 km). Differences, mostly in the latitude, arise when the grid spacing is not strictly equidistant as assumed by the grid creation method for the validation data.

The merged solution is not included in this analysis. Its grid definition was specified directly.

Table 1: Grid parameters for pyproj to recreate grids of Polar+ Snow Products from CPOM, LEGOS and UIT and the merged solution.

Product	**Parameter**	**Value**
CPOM	Projection	+proj=stere +a=6378273 +b=6356889.44891 +lat_0=90 +lat_ts=70 +lon_0=-45
	Grid Size (m)	x: 6_646_132, x_off: 12_377 y: 6_646_132, y_off: 12_377
	Grid Resolution (m)	dx: 24_892 dy: 24_892
	Dimension	(267, 267)
Merged	Projection	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=90.0
	Grid Size (m)	x: 8_750_000

		y: 8_750_000
	Grid Resolution (m)	dx: 25_000 dy: 25_000
	Dimension	(350, 350)

Table 1 (continued): Grid parameters for pyproj to recreate grids of Polar+ Snow Products from CPOM, LEGOS and UIT and the merged solution.

Product	**Parameter**	**Value**
LEGOS	Projection	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=90.0
	Grid Size (m)	x: 8_913_973 y: 8_913_973
	Grid Resolution (m)	dx: 12_500 dy: 12_500
	Dimension	(712, 712)
UIT	Projection	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=90.0
	Grid Size (m)	x: 9_050_526 y: 9_050_526
	Grid Resolution (m)	dx: 50_200 dy: 50_200
	Dimension	(181, 181)
Merged	Projection	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=90.0
	Grid Size (m)	x: 8_750_000 y: 8_750_000
	Grid Resolution (m)	dx: 25_000 dy: 25_000
	Dimension	(350, 350)

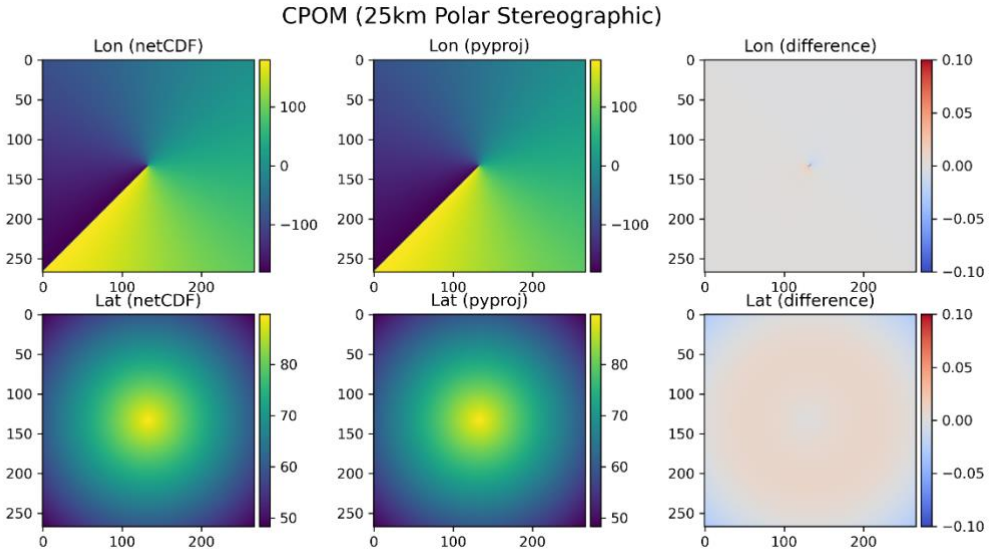


Figure 1: Longitude, latitude from the CPOM Polar+ snow product (left columm), created by pyproj (center column) and the difference in decimal degrees (right column).

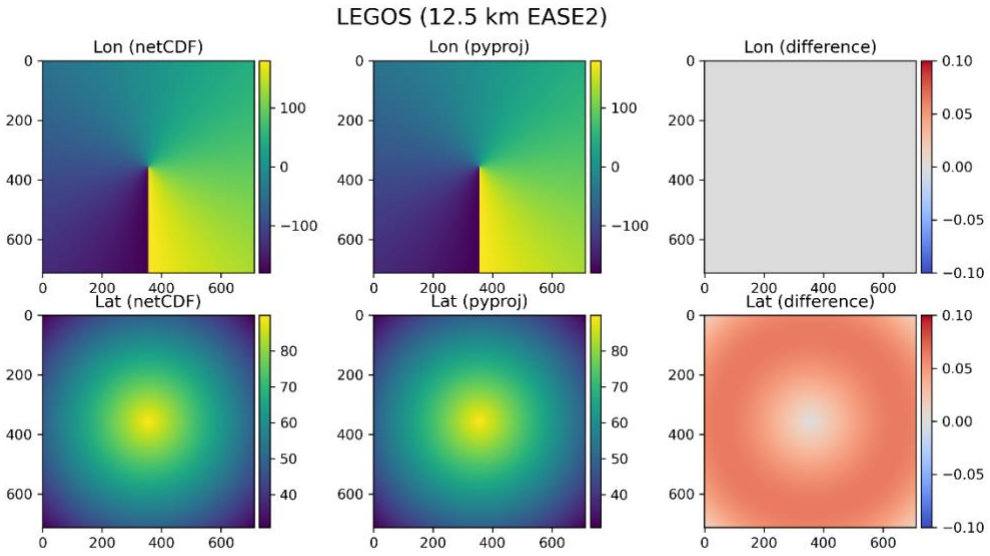


Figure 2: Longitude, latitude from the LEGOS Polar+ snow product (left columm), created by pyproj (center column) and the difference in decimal degrees (right column).

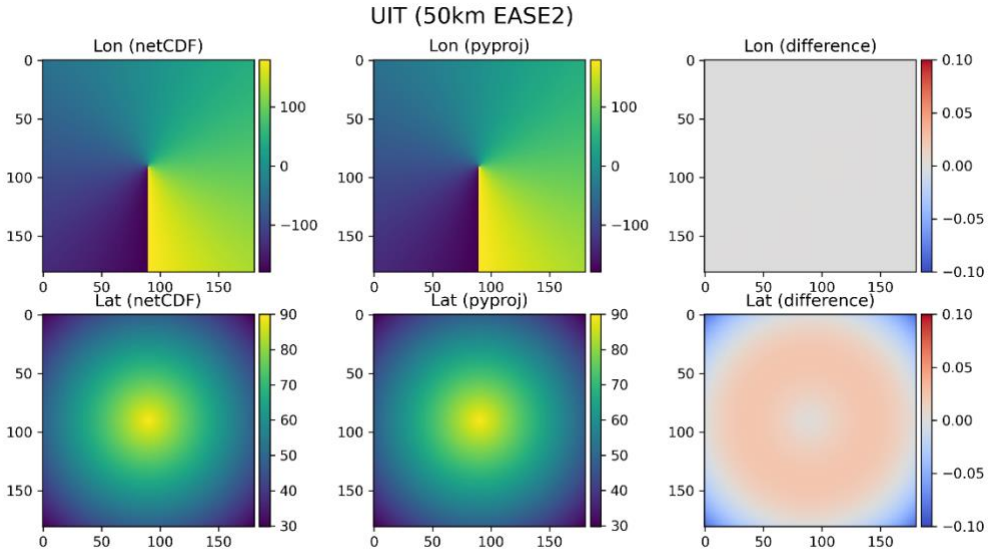


Figure 3: Longitude, latitude from the UIT Polar+ snow product (left columm), created by pyproj (center column) and the difference in decimal degrees (right column).

The validation dataset are gridded for each projection and the result is saved as a netCDF file.

3.2 Validation Metrics

Metrics of the sea ice thickness error based on a data comparison for km grid cells are:

1. Number of grid cell pairs (Num);
2. Mean difference between satellite and reference snow depth data computed as satellite minus reference (Bias) [target: 0.0m];
3. The Root Mean Square Error (RMSE) between satellite and validation data (all grid cells) [target: 0.0m];
4. The Pearson correlation coefficient (R) [target: 1.0];
5. The Slope [target: 1.0] and Intercept [target: 0.0] of a linear regression of the satellite and reference difference.

These are computed for combination of KuKa or KuLa data set where there is data overlap. In addition, the airborne and MOSAiC data sets are grouped (see discussion on quality of buoy data in section 5.1).

The validation metrics for each permutation of Polar+ Snow Product and Validation data source are saved as a csv file.

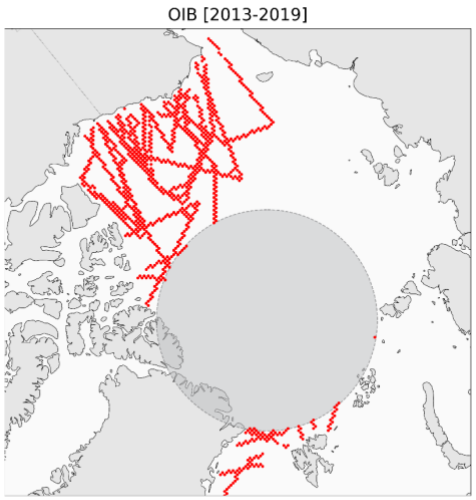
4 Validation Results

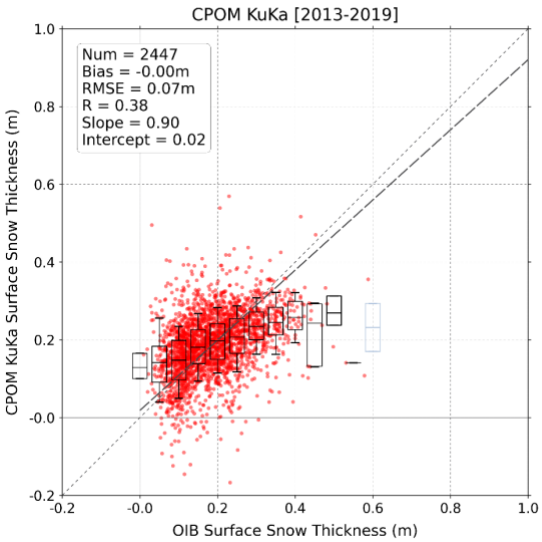
4.1 Radar-Radar (KuKa)

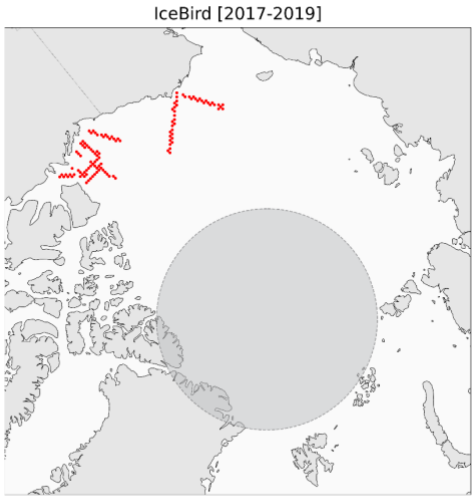
All validation metrics for Polar+ KuKa data sets. Cells marked in green show the best values per metric and validation data source.

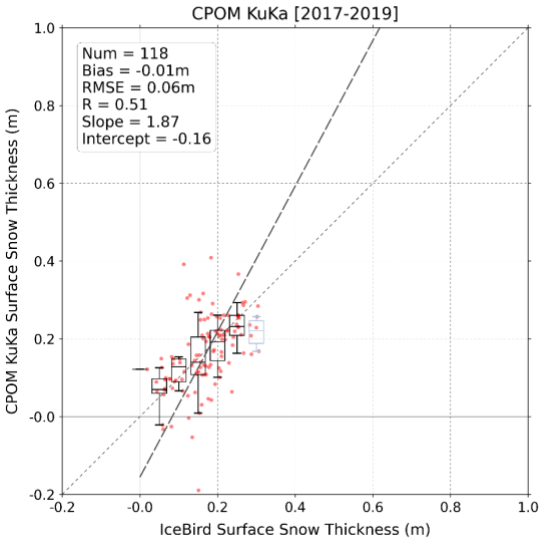
Validation Source	Metric	CPOM	LEGOS	UIT
OIB	Coverage	2013-2019	2013-2019	2019
	num	2447	5701	20
	bias	0.00	-0.04	0.01
	rmse	0.07	0.06	0.06
	pearson	0.38	0.53	0.70
	slope	0.90	0.49	1.21
	intercept	0.02	0.06	-0.06
IceBird	Coverage	2017-2019	2017-2019	2019
	num	118	242	30
	bias	-0.01	-0.05	0.06
	rmse	0.06	0.07	0.09
	pearson	0.51	0.69	0.35
	slope	1.87	0.92	1.07
	intercept	-0.16	-0.04	0.05
Airborne (OIB+IceBird)	Coverage	2013-2019	2013-2019	2019
	num	2565	5943	50
	bias	0.00	-0.04	0.04
	rmse	0.07	0.06	0.08
	pearson	0.39	0.54	0.65
	slope	0.94	0.51	0.88
	intercept	0.01	0.05	0.07
Ice Mass Balance	Coverage	2013-2016	2013-2016	
	num	576	1389	
	bias	-0.07	-0.18	
	rmse	0.12	0.20	
	pearson	0.22	-0.35	
	slope	0.11	-0.08	
	intercept	0.16	0.16	
Snow Buoy	Coverage	2015-2019	2013-2019	2018-2019
	num	41	164	28
	bias	-0.18	-0.35	-0.23
	rmse	0.20	0.35	0.23
	pearson	-0.02	-0.37	0.34
	slope	-0.01	-0.21	0.11
	intercept	0.23	0.20	0.17

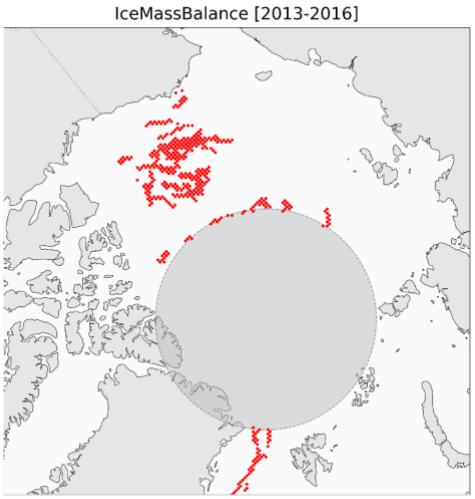
4.1.1 CPOM

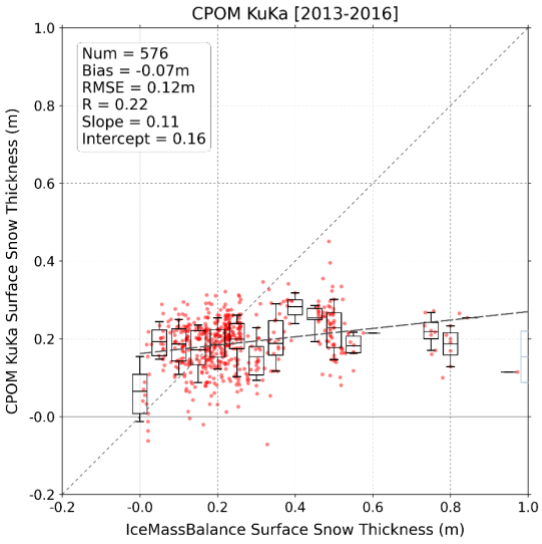

OIB [2013-2019]

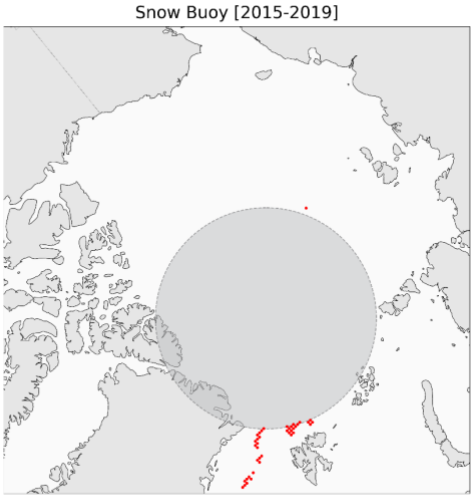

CPOM KuKa [2013-2019]
Num = 2447
Bias = -0.00m
RMSE = 0.07m
R = 0.38
Slope = 0.90
Intercept = 0.02
CPOM KuKa Surface Snow Thickness (m)
OIB Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

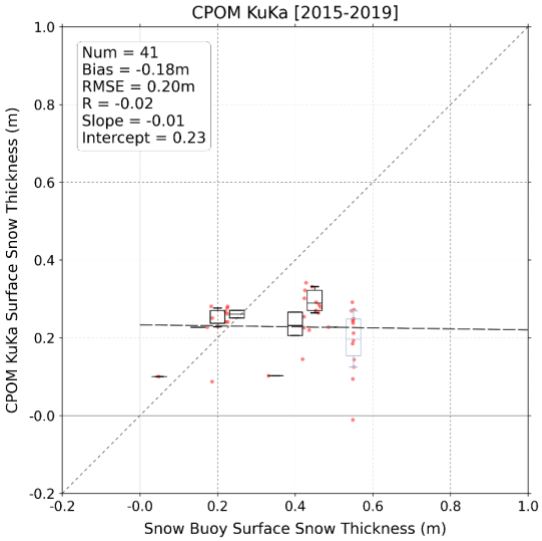

IceBird [2017-2019]


CPOM KuKa [2017-2019]
Num = 118
Bias = -0.01m
RMSE = 0.06m
R = 0.51
Slope = 1.87
Intercept = -0.16
CPOM KuKa Surface Snow Thickness (m)
IceBird Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

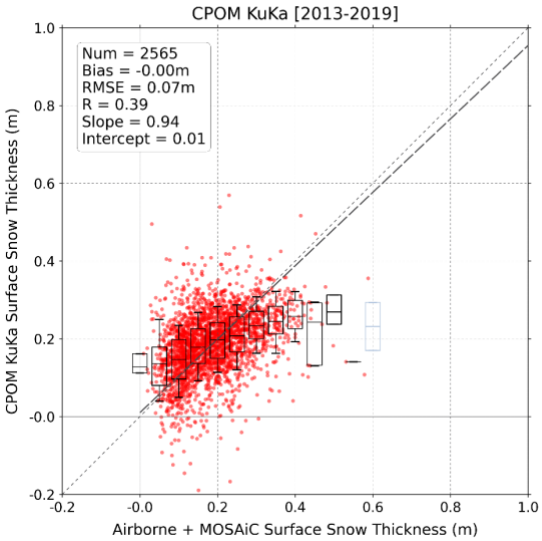

IceMassBalance [2013-2016]


CPOM KuKa [2013-2016]
Num = 576
Bias = -0.07m
RMSE = 0.12m
R = 0.22
Slope = 0.11
Intercept = 0.16
CPOM KuKa Surface Snow Thickness (m)
IceMassBalance Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

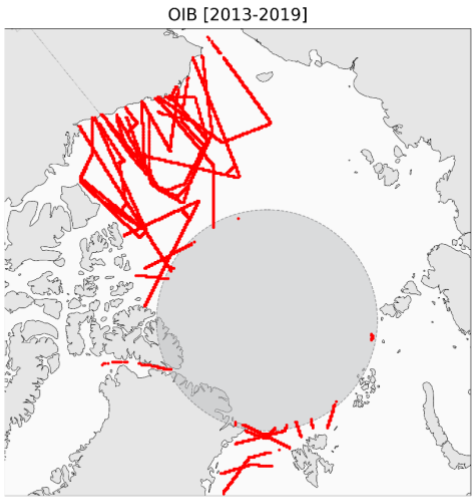

Snow Buoy [2015-2019]

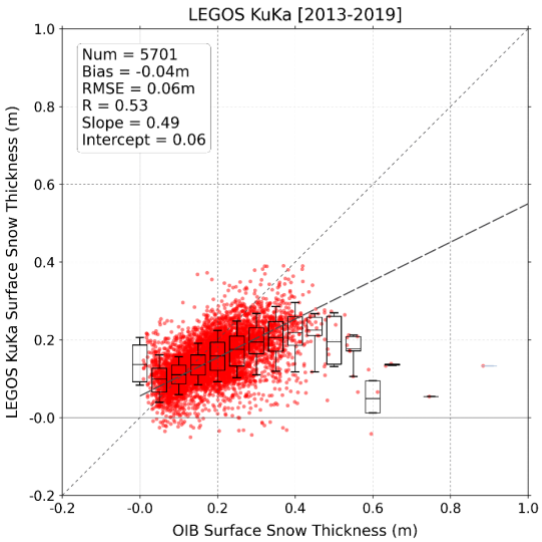

CPOM KuKa [2015-2019]
Num = 41
Bias = -0.18m
RMSE = 0.20m
R = -0.02
Slope = -0.01
Intercept = 0.23
CPOM KuKa Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

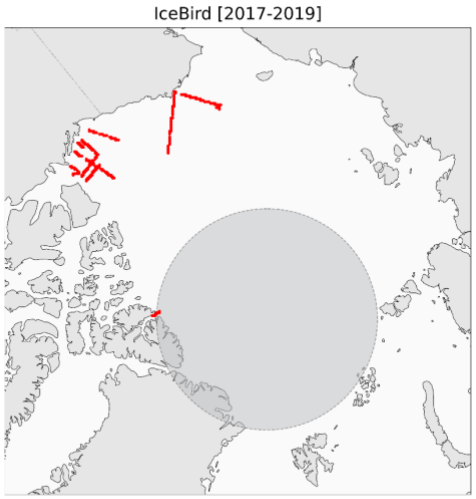

Airborne + MOSAiC [2013-2019]

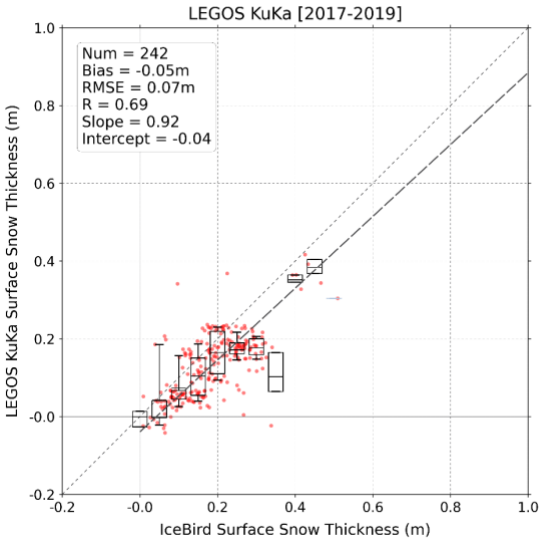

CPOM KuKa [2013-2019]
Num = 2565
Bias = -0.00m
RMSE = 0.07m
R = 0.39
Slope = 0.94
Intercept = 0.01
CPOM KuKa Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

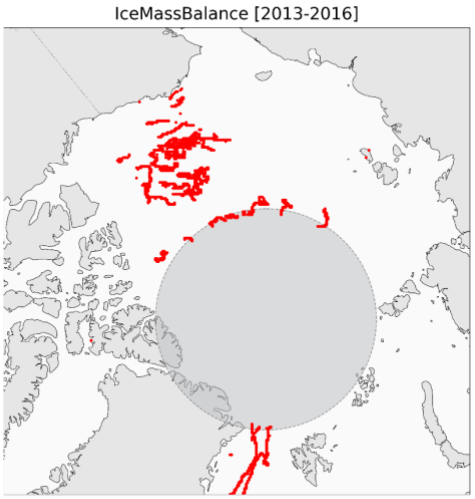
4.1.2 LEGOS

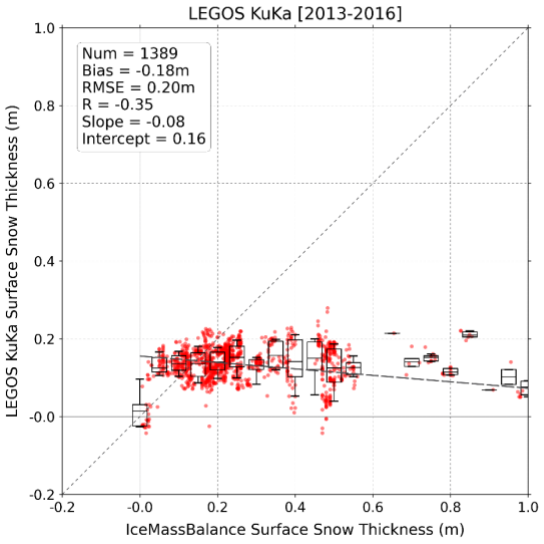

OIB [2013-2019]

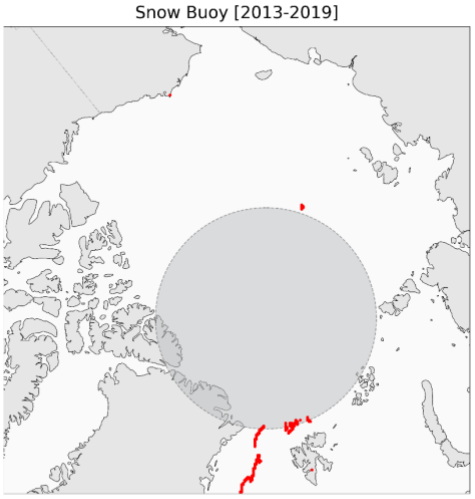

LEGOS KuKa [2013-2019]
Num = 5701
Bias = -0.04m
RMSE = 0.06m
R = 0.53
Slope = 0.49
Intercept = 0.06
LEGOS KuKa Surface Snow Thickness (m)
OIB Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

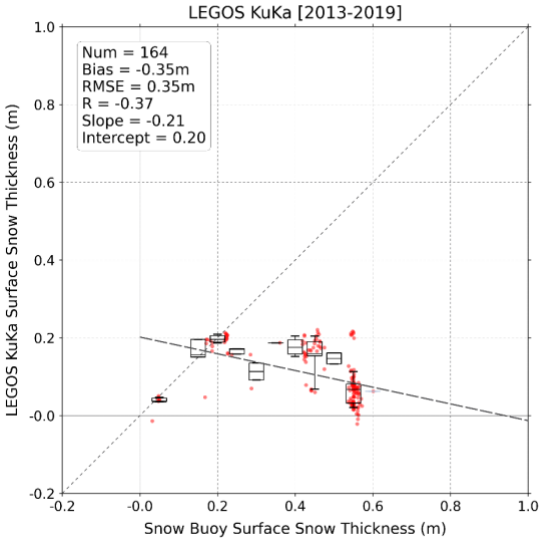

IceBird [2017-2019]


LEGOS KuKa [2017-2019]
Num = 242
Bias = -0.05m
RMSE = 0.07m
R = 0.69
Slope = 0.92
Intercept = -0.04
LEGOS KuKa Surface Snow Thickness (m)
IceBird Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

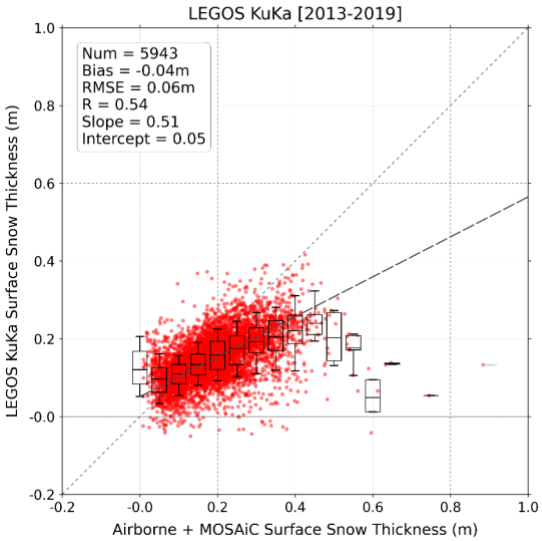

IceMassBalance [2013-2016]


LEGOS KuKa [2013-2016]
Num = 1389
Bias = -0.18m
RMSE = 0.20m
R = -0.35
Slope = -0.08
Intercept = 0.16
LEGOS KuKa Surface Snow Thickness (m)
IceMassBalance Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

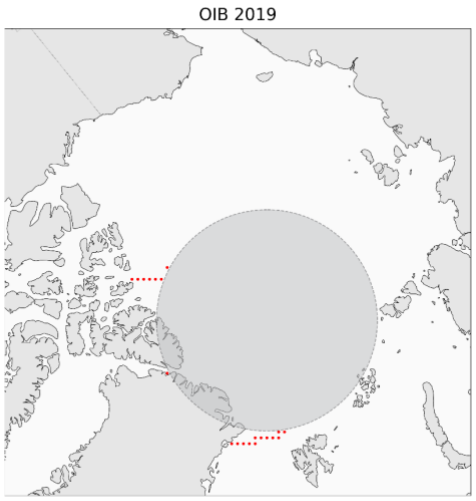

Snow Buoy [2013-2019]

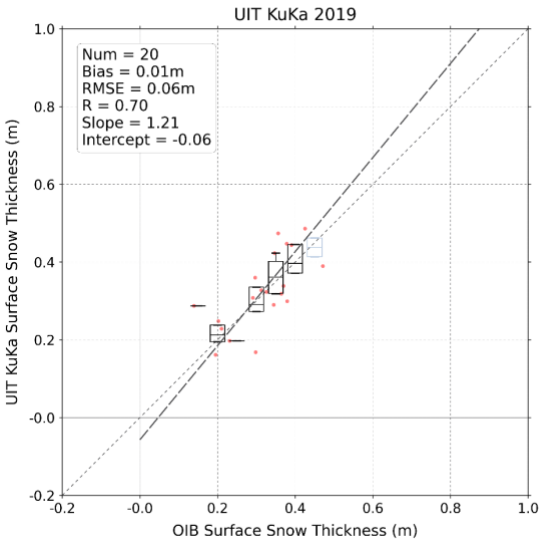

LEGOS KuKa [2013-2019]
Num = 164
Bias = -0.35m
RMSE = 0.35m
R = -0.37
Slope = -0.21
Intercept = 0.20
LEGOS KuKa Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

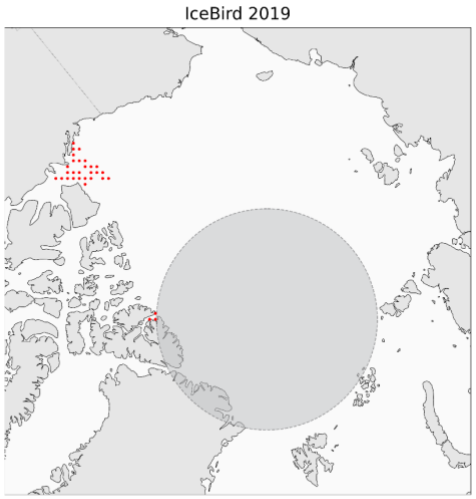

Airborne + MOSAiC [2013-2019]

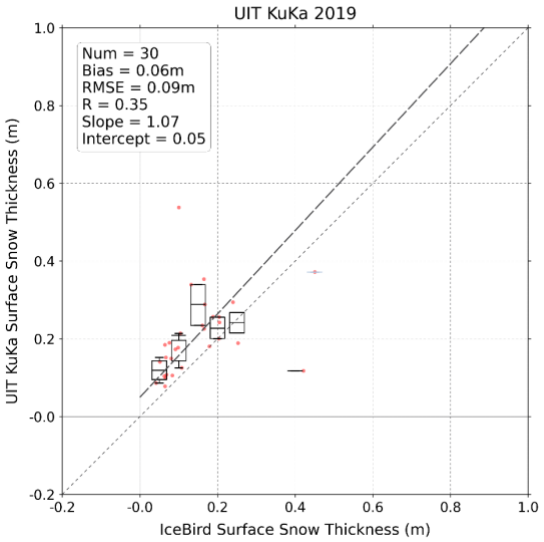

LEGOS KuKa [2013-2019]
Num = 5943
Bias = -0.04m
RMSE = 0.06m
R = 0.54
Slope = 0.51
Intercept = 0.05
LEGOS KuKa Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

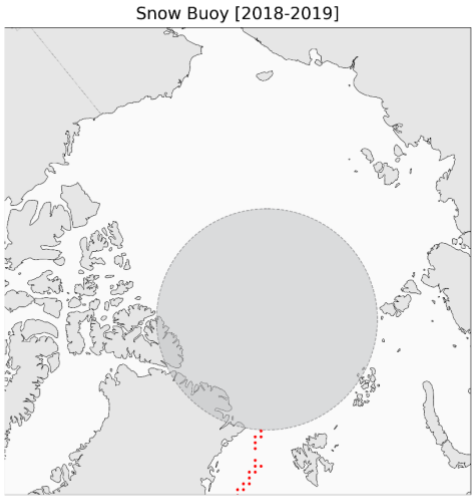
4.1.3 UIT

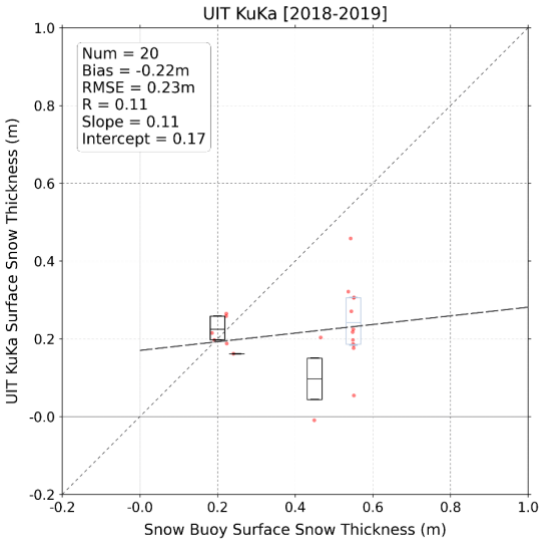

OIB 2019

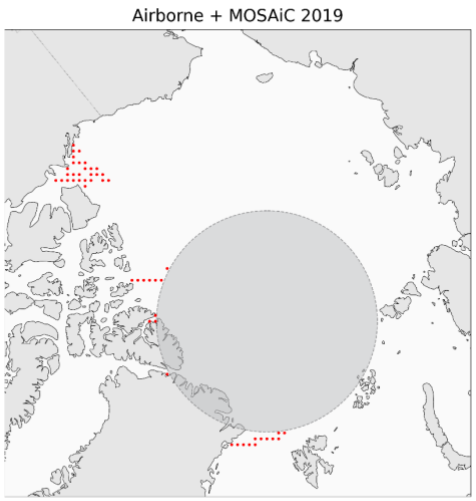

UIT KuKa 2019
Num = 20
Bias = 0.01m
RMSE = 0.06m
R = 0.70
Slope = 1.21
Intercept = -0.06
UIT KuKa Surface Snow Thickness (m)
OIB Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

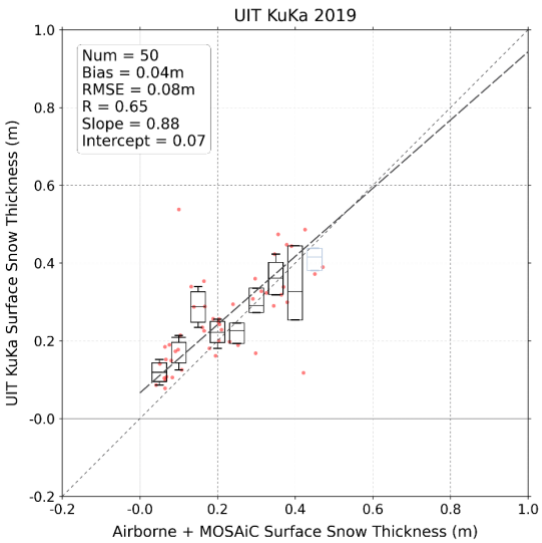

IceBird 2019


UIT KuKa 2019
Num = 30
Bias = 0.06m
RMSE = 0.09m
R = 0.35
Slope = 1.07
Intercept = 0.05
UIT KuKa Surface Snow Thickness (m)
IceBird Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0


Snow Buoy [2018-2019]


UIT KuKa [2018-2019]
Num = 20
Bias = -0.22m
RMSE = 0.23m
R = 0.11
Slope = 0.11
Intercept = 0.17
UIT KuKa Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2


Airborne + MOSAiC 2019

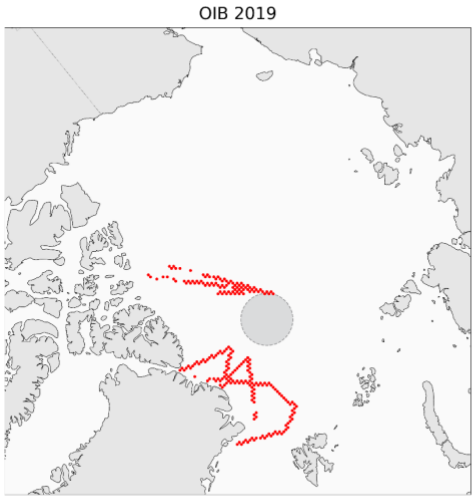

UIT KuKa 2019
Num = 50
Bias = 0.04m
RMSE = 0.08m
R = 0.65
Slope = 0.88
Intercept = 0.07
UIT KuKa Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

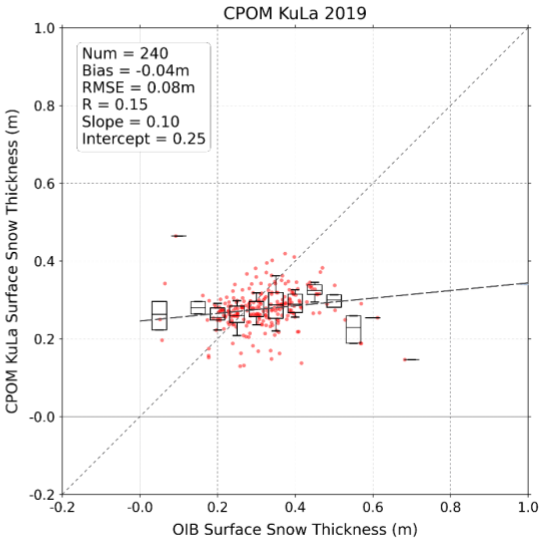
4.2 Radar-Laser (KuLa)

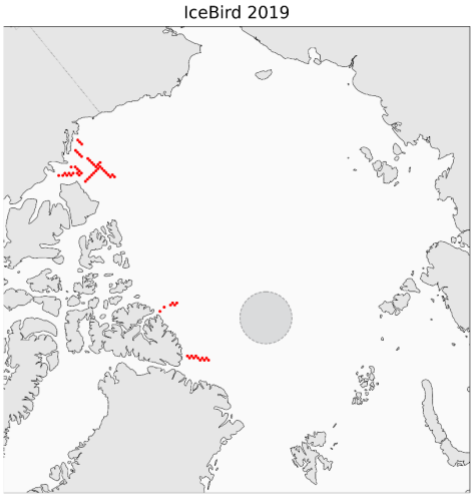
All validation metrics for Polar+ KuLa data sets. Cells marked in green show the best values per metric and validation data source.

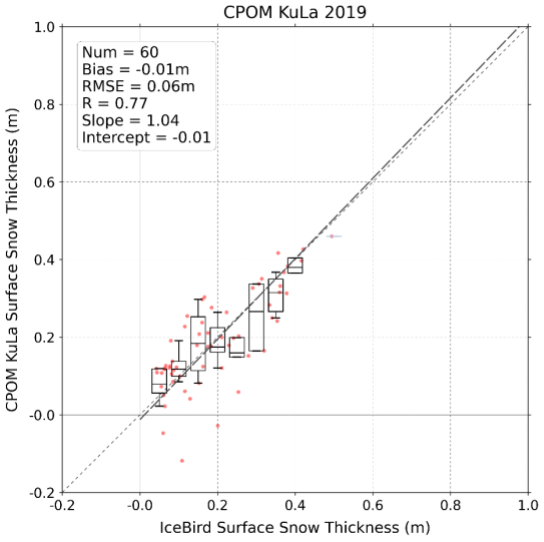
Validation Source	Metric	CPOM	LEGOS (SAM)	LEGOS (T50)	UIT
OIB	Coverage	2019	2019	2019	2019
	num	240	500	500	118
	bias	-0.04	-0.03	-0.08	-0.01
	rmse	0.08	0.06	0.10	0.04
	pearson	0.15	0.64	0.38	0.73
	slope	0.10	0.66	0.35	0.93
	intercept	0.25	0.08	0.13	0.01
IceBird	Coverage	2019	2019	2019	2019
	num	60	125	126	39
	bias	-0.01	-0.02	-0.03	0.04
	rmse	0.06	0.06	0.08	0.06
	pearson	0.77	0.75	0.58	0.85
	slope	0.791.04	1.02	0.41	1.04
	intercept	-0.01	-0.02	0.09	0.03
MOSAiC Transect	Coverage	2019-2020	2019-2020	2019-2020	2019-2020
	num	32	36	36	31
	bias	-0.10	-0.08	-0.05	-0.05
	rmse	0.10	0.08	0.06	0.06
	pearson	0.67	0.74	0.73	0.66
	slope	0.94	0.92	0.61	0.80
	intercept	-0.08	-0.06	0.04	-0.01
Airborne + MOSAiC	Coverage	2019-2020	2019-2020	2019-2020	2019
	num	332	661	662	188
	bias	-0.04	-0.03	-0.07	-0.01
	rmse	0.08	0.06	0.09	0.05
	pearson	0.52	0.74	0.54	0.80
	slope	0.59	0.84	0.42	0.95
	intercept	0.08	0.01	0.10	0.00
Snow Buoy	Coverage	2018-2019	2018-2019	2018-2019	2018-2019
	num	53	159	159	28
	bias	-0.16	-0.25	-0.25	-0.23
	rmse	0.17	0.25	0.26	0.23
	pearson	-0.32	0.19	0.28	0.34
	slope	-0.13	0.06	0.13	0.10
	intercept	0.21	0.12	0.09	0.13

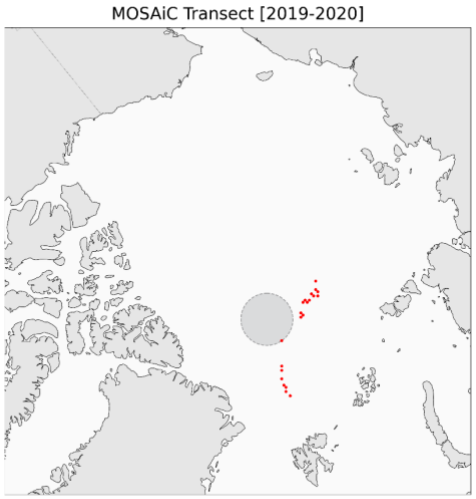
4.2.1 CPOM

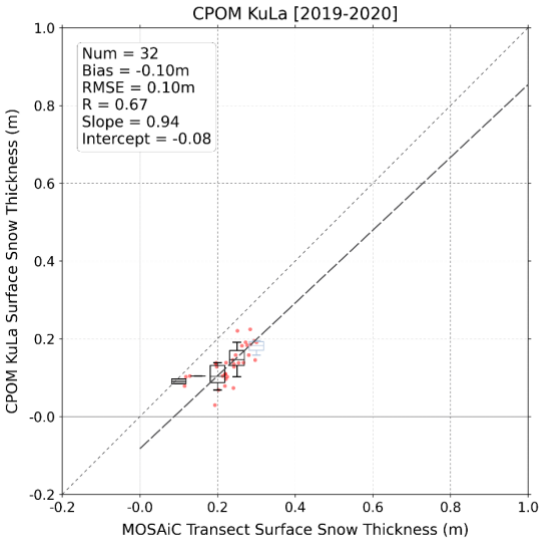

OIB 2019

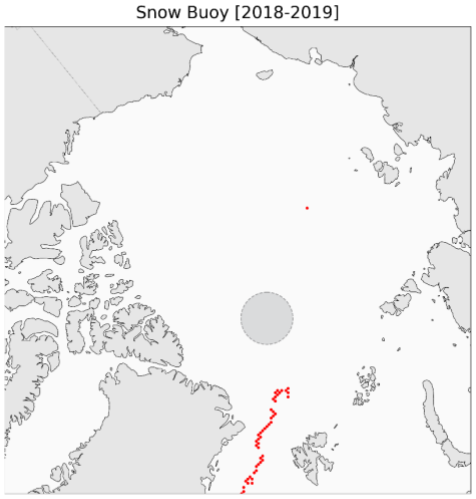

CPOM KuLa 2019
Num = 240
Bias = -0.04m
RMSE = 0.08m
R = 0.15
Slope = 0.10
Intercept = 0.25
CPOM KuLa Surface Snow Thickness (m)
OIB Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

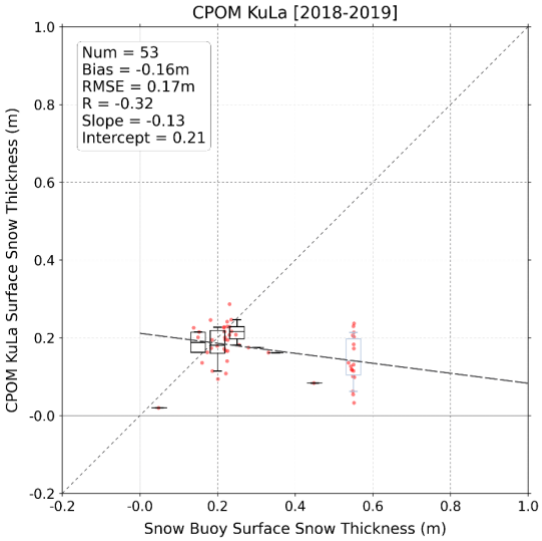

IceBird 2019

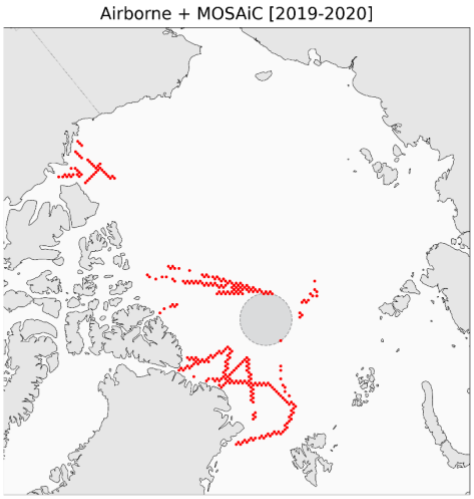

CPOM KuLa 2019
Num = 60
Bias = -0.01m
RMSE = 0.06m
R = 0.77
Slope = 1.04
Intercept = -0.01
CPOM KuLa Surface Snow Thickness (m)
IceBird Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

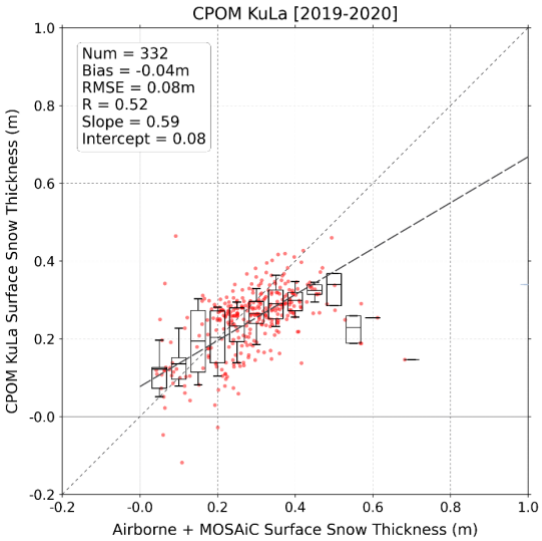

MOSAiC Transect [2019-2020]


CPOM KuLa [2019-2020]
Num = 32
Bias = -0.10m
RMSE = 0.10m
R = 0.67
Slope = 0.94
Intercept = -0.08
CPOM KuLa Surface Snow Thickness (m)
MOSAiC Transect Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

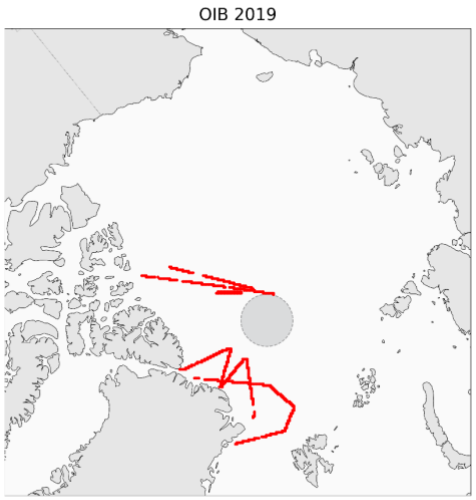

Snow Buoy [2018-2019]

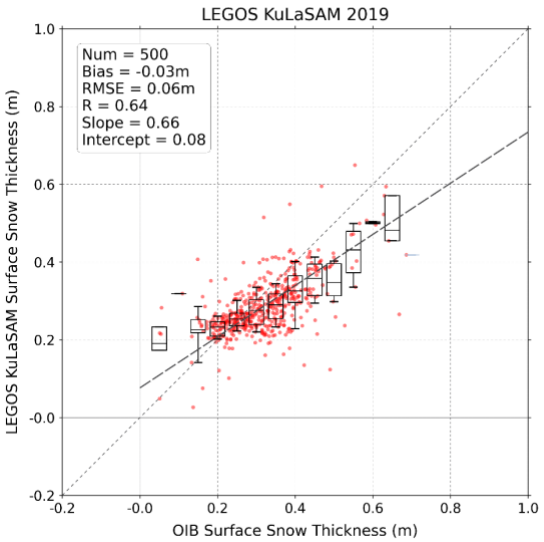

CPOM KuLa [2018-2019]
Num = 53
Bias = -0.16m
RMSE = 0.17m
R = -0.32
Slope = -0.13
Intercept = 0.21
CPOM KuLa Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

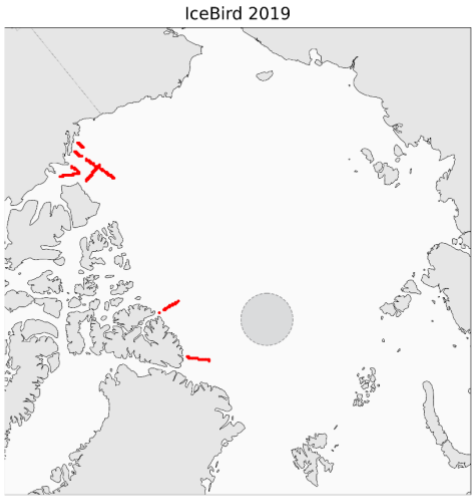

Airborne + MOSAiC [2019-2020]

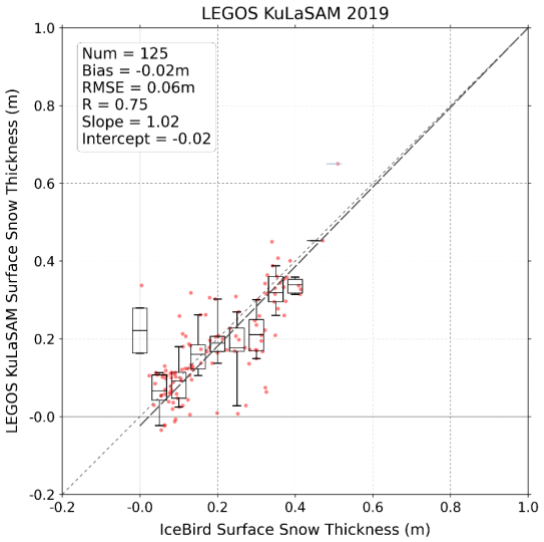

CPOM KuLa [2019-2020]
Num = 332
Bias = -0.04m
RMSE = 0.08m
R = 0.52
Slope = 0.59
Intercept = 0.08
CPOM KuLa Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

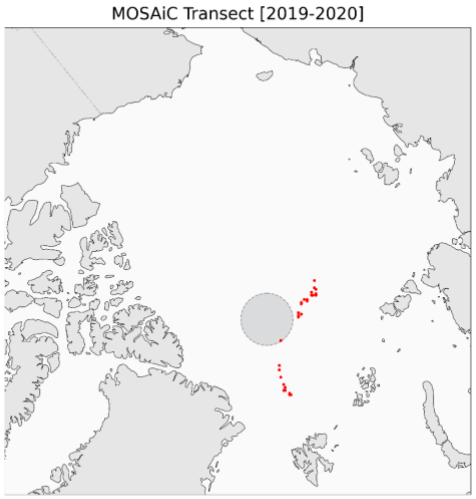
4.2.2 LEGOS (SAMOSA+)

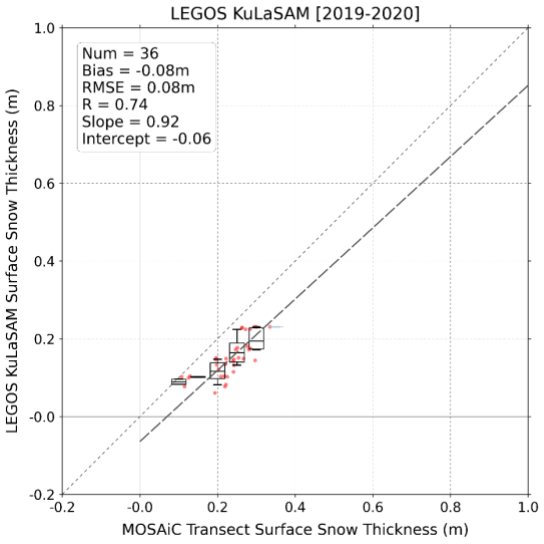


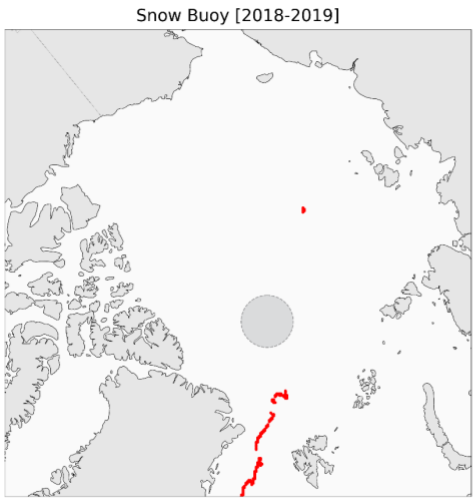


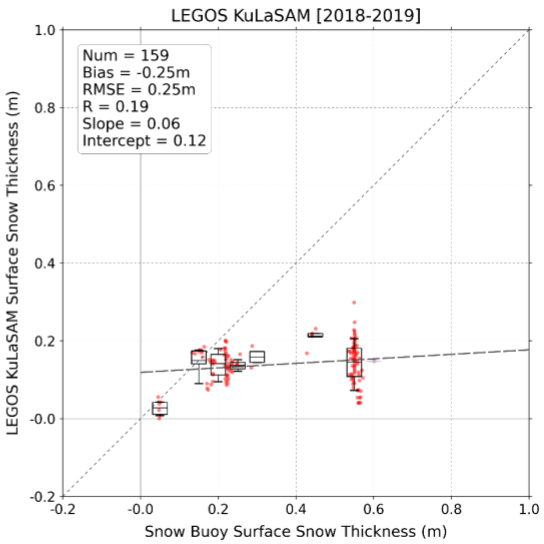


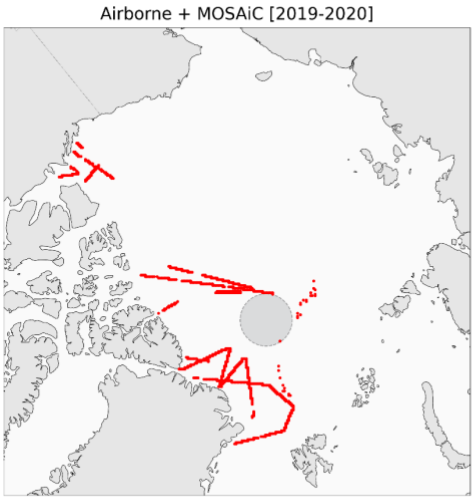


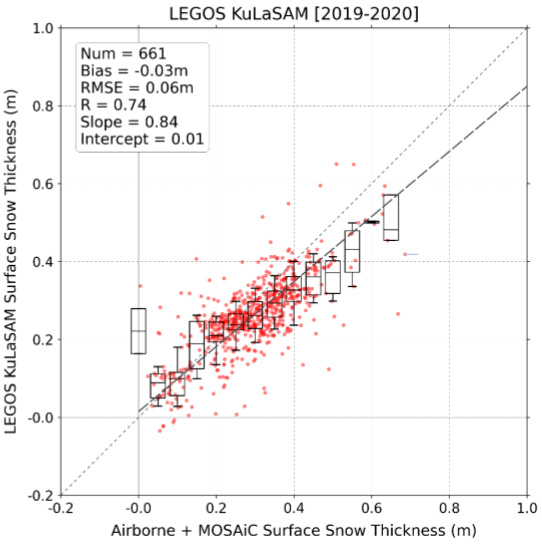

MOSAiC Transect [2019-2020]


LEGOS KuLaSAM [2019-2020]
Num = 36
Bias = -0.08m
RMSE = 0.08m
R = 0.74
Slope = 0.92
Intercept = -0.06
LEGOS KuLaSAM Surface Snow Thickness (m)
MOSAiC Transect Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

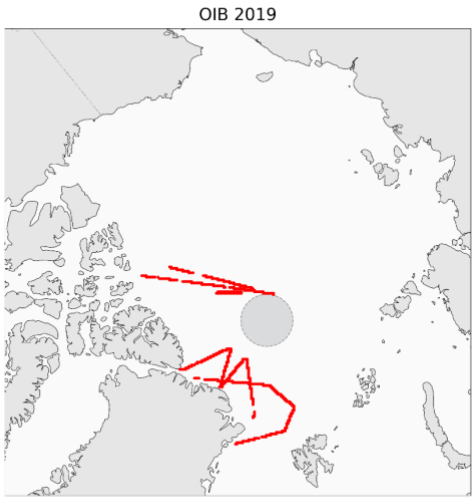

Snow Buoy [2018-2019]

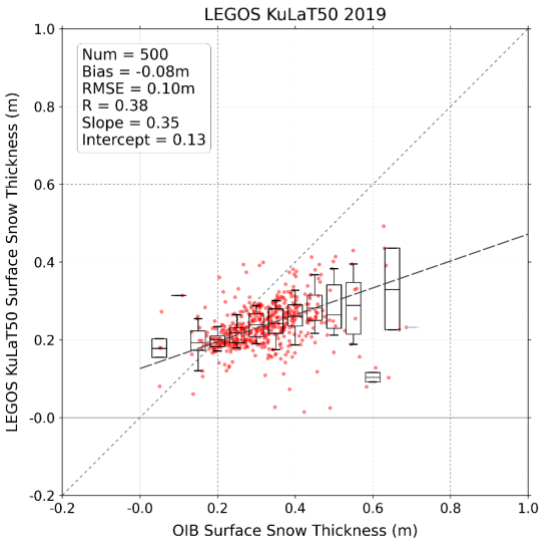

LEGOS KuLaSAM [2018-2019]
Num = 159
Bias = -0.25m
RMSE = 0.25m
R = 0.19
Slope = 0.06
Intercept = 0.12
LEGOS KuLaSAM Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

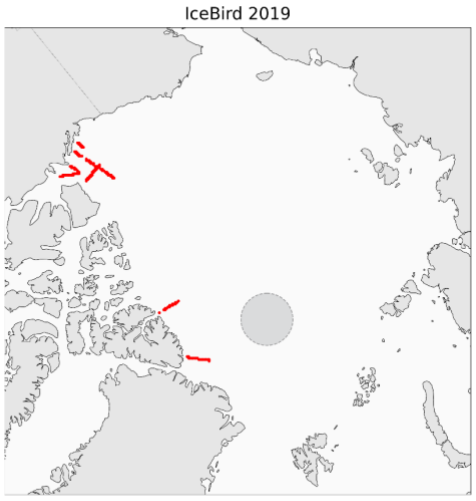

Airborne + MOSAiC [2019-2020]

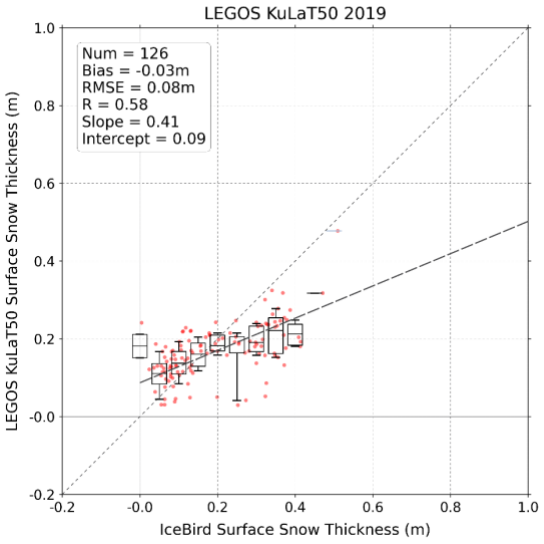

LEGOS KuLaSAM [2019-2020]
Num = 661
Bias = -0.03m
RMSE = 0.06m
R = 0.74
Slope = 0.84
Intercept = 0.01
LEGOS KuLaSAM Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

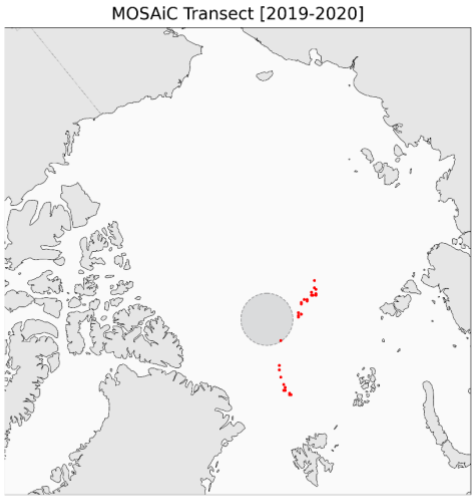
4.2.3 LEGOS (TFMRA50)

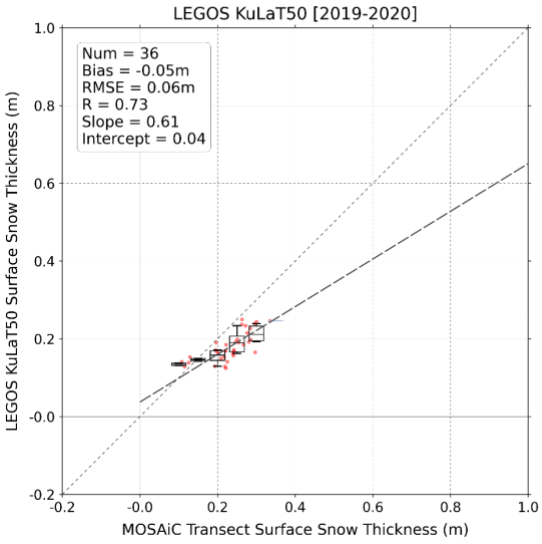


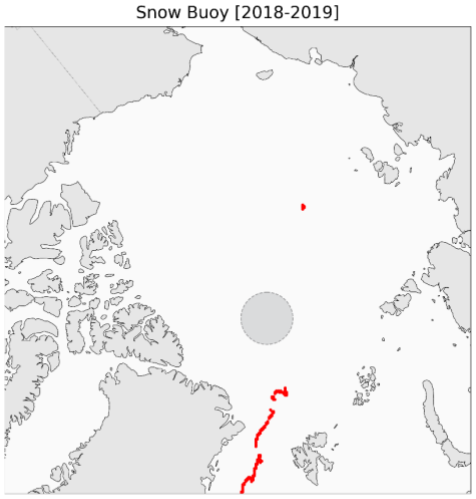


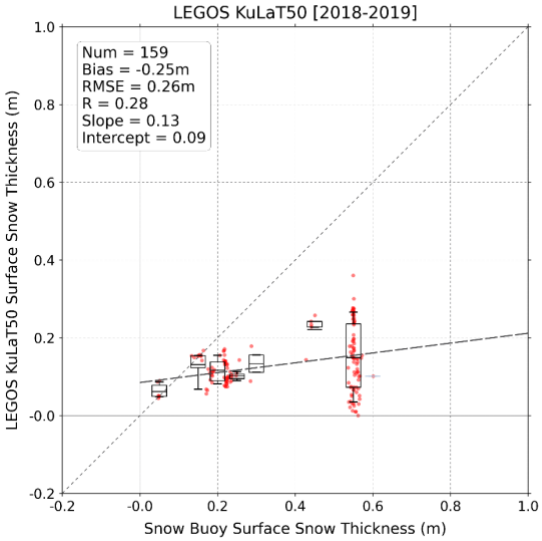


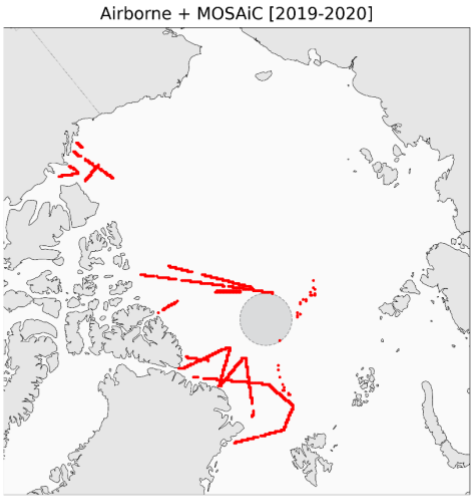


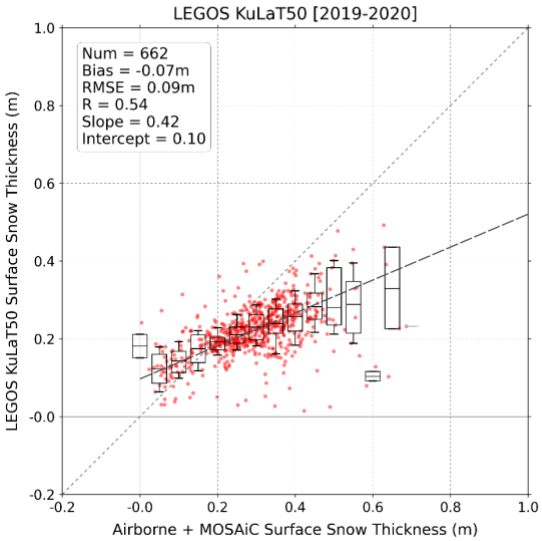

MOSAiC Transect [2019-2020]


LEGOS KuLaT50 [2019-2020]
Num = 36
Bias = -0.05m
RMSE = 0.06m
R = 0.73
Slope = 0.61
Intercept = 0.04
LEGOS KuLaT50 Surface Snow Thickness (m)
MOSAiC Transect Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

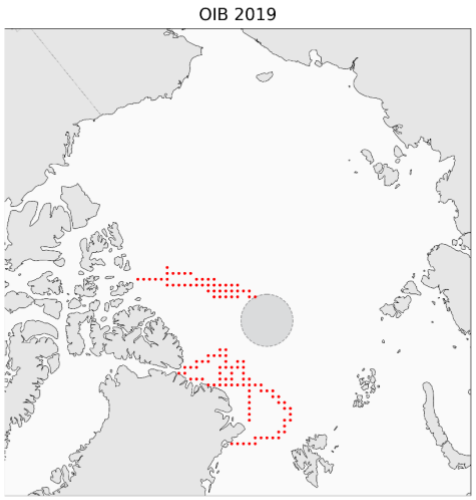

Snow Buoy [2018-2019]

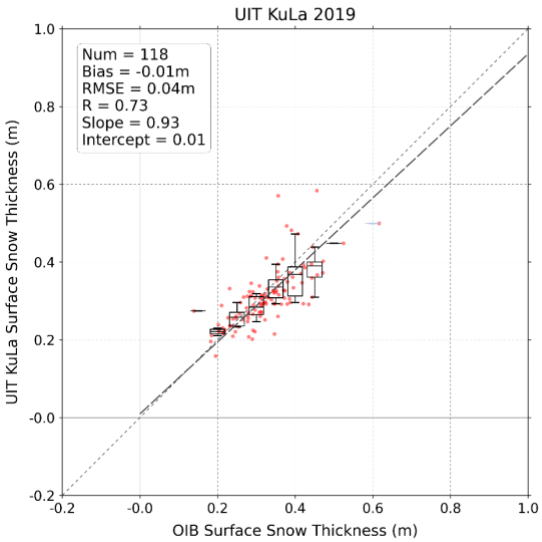

LEGOS KuLaT50 [2018-2019]
Num = 159
Bias = -0.25m
RMSE = 0.26m
R = 0.28
Slope = 0.13
Intercept = 0.09
LEGOS KuLaT50 Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

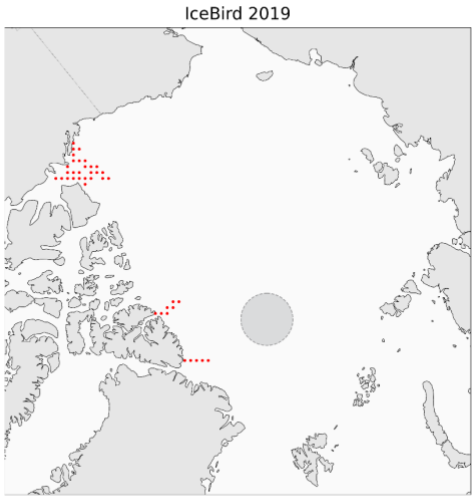

Airborne + MOSAiC [2019-2020]

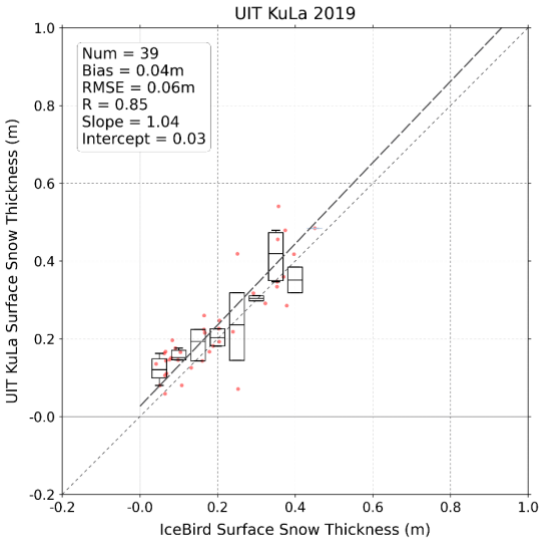

LEGOS KuLaT50 [2019-2020]
Num = 662
Bias = -0.07m
RMSE = 0.09m
R = 0.54
Slope = 0.42
Intercept = 0.10
LEGOS KuLaT50 Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

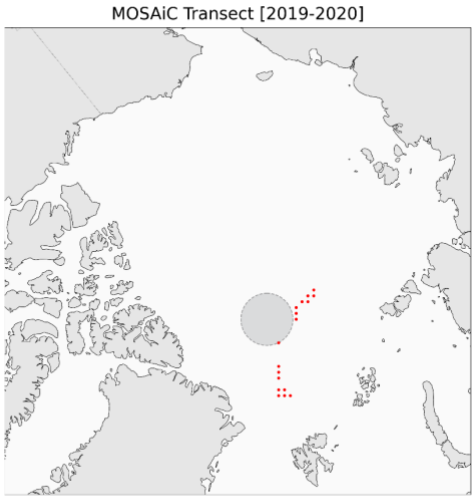
4.2.4 UIT

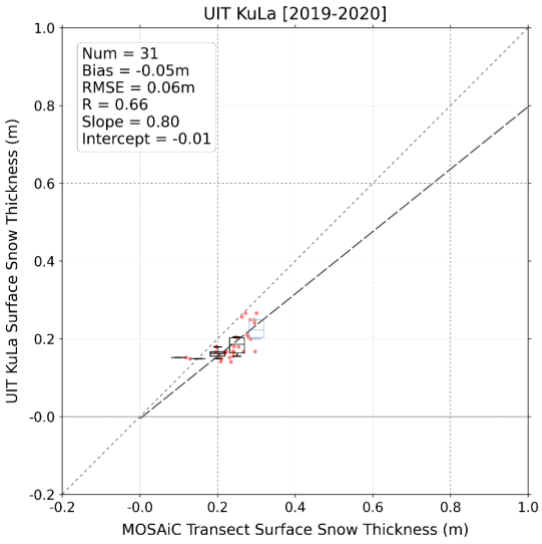

OIB 2019

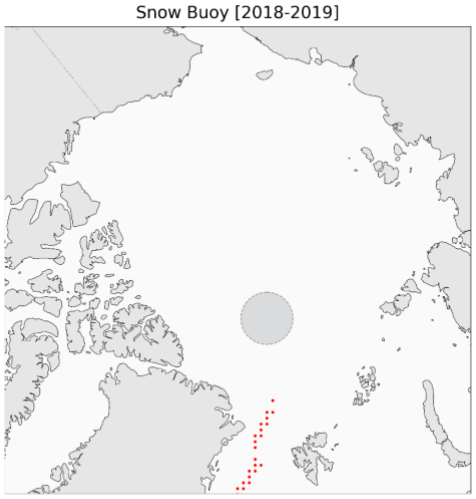

UIT KuLa 2019
Num = 118
Bias = -0.01m
RMSE = 0.04m
R = 0.73
Slope = 0.93
Intercept = 0.01
UIT KuLa Surface Snow Thickness (m)
OIB Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

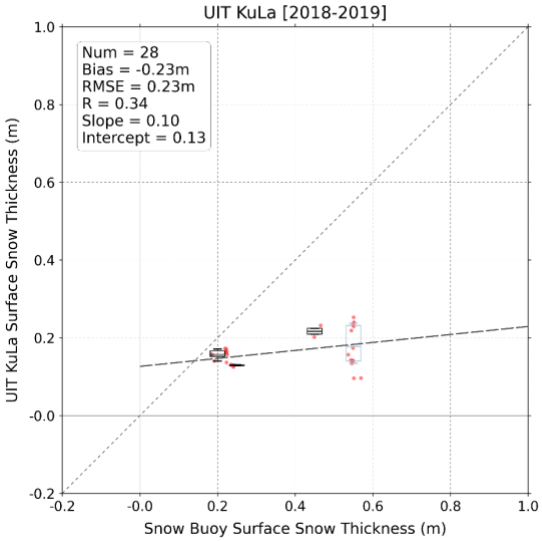

IceBird 2019

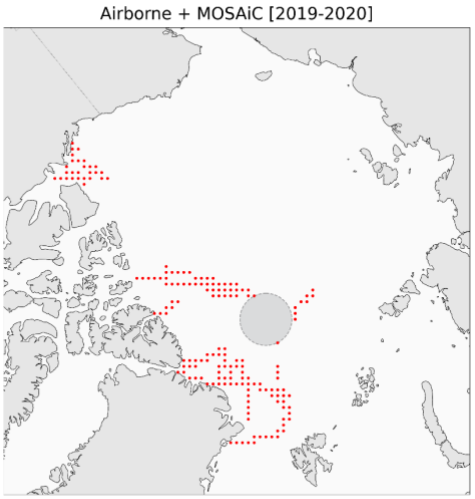

UIT KuLa 2019
Num = 39
Bias = 0.04m
RMSE = 0.06m
R = 0.85
Slope = 1.04
Intercept = 0.03
UIT KuLa Surface Snow Thickness (m)
IceBird Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

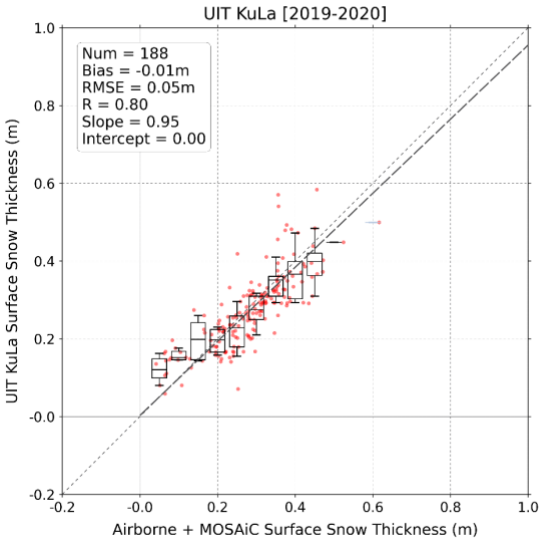

MOSAiC Transect [2019-2020]


UIT KuLa [2019-2020]
Num = 31
Bias = -0.05m
RMSE = 0.06m
R = 0.66
Slope = 0.80
Intercept = -0.01
UIT KuLa Surface Snow Thickness (m)
MOSAiC Transect Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2


Snow Buoy [2018-2019]


UIT KuLa [2018-2019]
Num = 28
Bias = -0.23m
RMSE = 0.23m
R = 0.34
Slope = 0.10
Intercept = 0.13
UIT KuLa Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

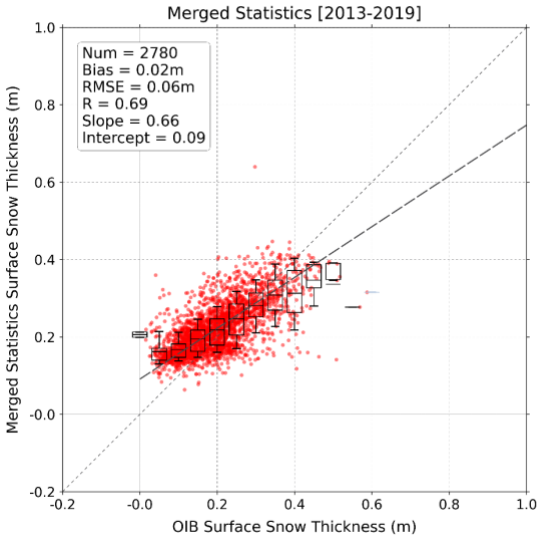

Airborne + MOSAiC [2019-2020]

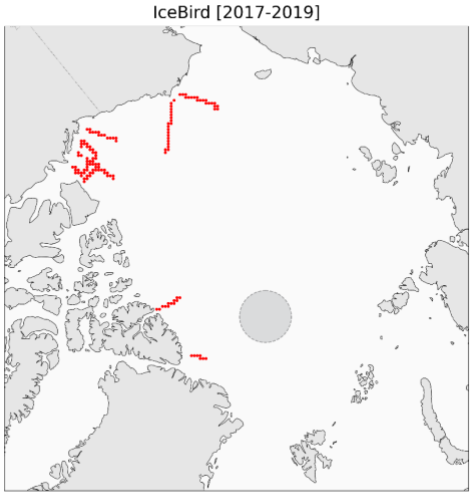

UIT KuLa [2019-2020]
Num = 188
Bias = -0.01m
RMSE = 0.05m
R = 0.80
Slope = 0.95
Intercept = 0.00
UIT KuLa Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

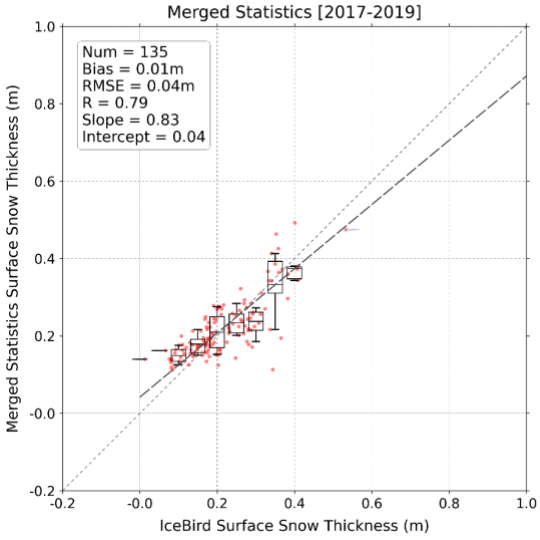
4.3 Merged Product

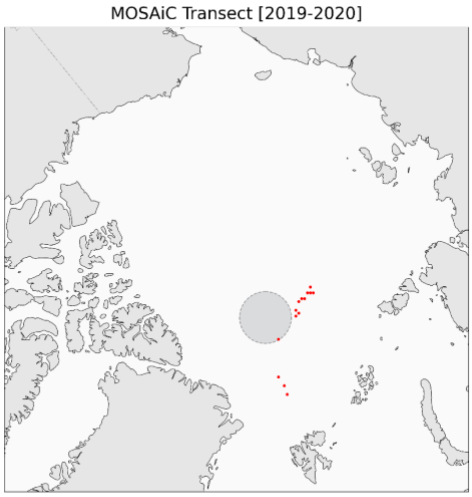
Validation Source	Metric	Merged Product
OIB	Coverage	2013-2019
	num	2780
	bias	0.02
	rmse	0.06
	pearson	0.69
	slope	0.66
	intercept	0.09
IceBird	Coverage	2017-2019
	num	135
	bias	< 0.01
	rmse	0.04
	pearson	0.79
	slope	0.83
	intercept	0.04
Airborne + MOSAIC (OIB+IceBird + MOSAIC)	Coverage	2013-2020
	num	2929
	bias	0.02
	rmse	0.06
	pearson	0.69
	slope	0.66
	intercept	0.09
Ice Mass Balance	Coverage	2013-2016
	num	635
	bias	-0.14
	rmse	0.17
	pearson	-0.25
	slope	-0.05
	intercept	0.19
Snow Buoy	Coverage	2015-2019
	num	91
	bias	-0.24
	rmse	0.25
	pearson	-0.17
	slope	-0.06
	intercept	0.18

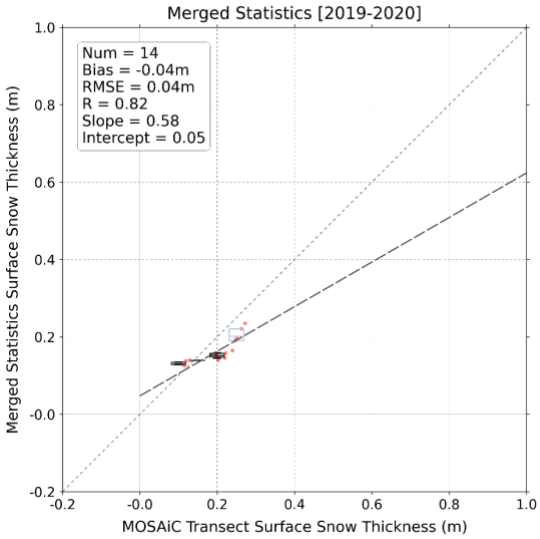

OIB [2013-2019]

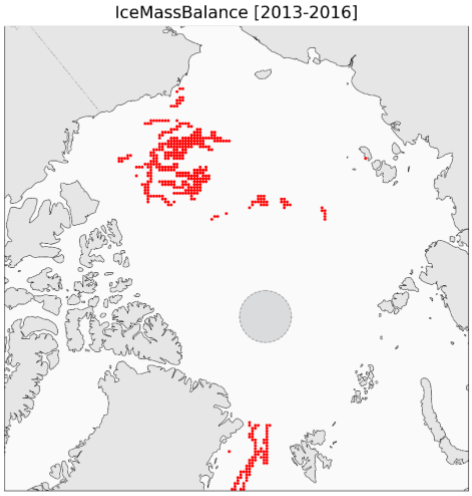

Merged Statistics [2013-2019]
Num = 2780
Bias = 0.02m
RMSE = 0.06m
R = 0.69
Slope = 0.66
Intercept = 0.09
Merged Statistics Surface Snow Thickness (m)
OIB Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

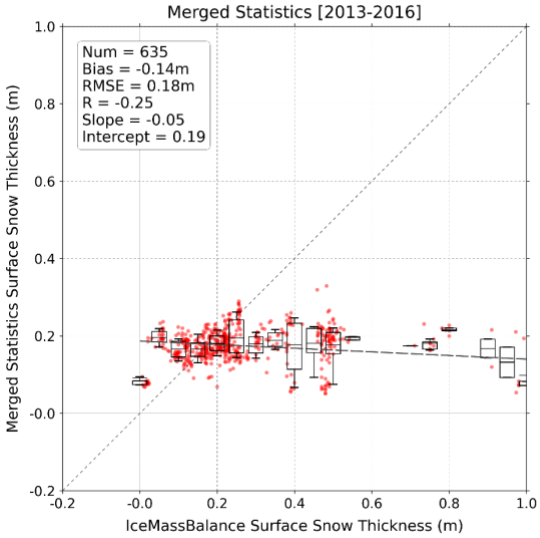

IceBird [2017-2019]

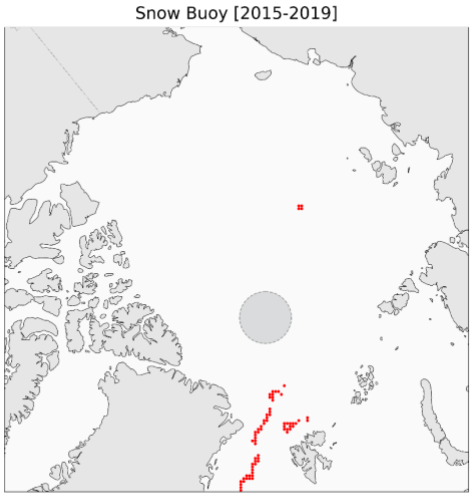

Merged Statistics [2017-2019]
Num = 135
Bias = 0.01m
RMSE = 0.04m
R = 0.79
Slope = 0.83
Intercept = 0.04
Merged Statistics Surface Snow Thickness (m)
IceBird Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

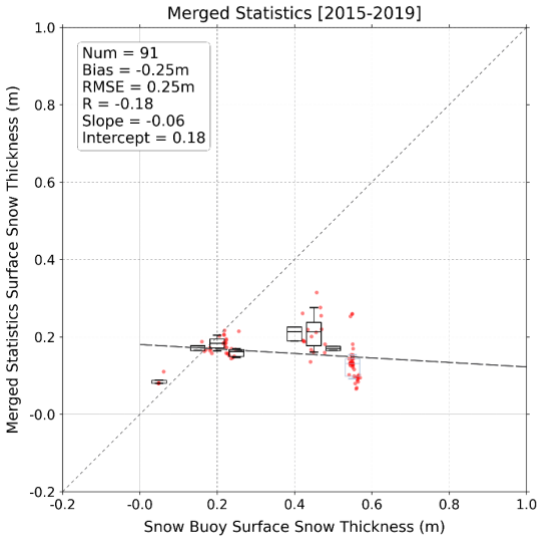

MOSAiC Transect [2019-2020]


Merged Statistics [2019-2020]
Num = 14
Bias = -0.04m
RMSE = 0.04m
R = 0.82
Slope = 0.58
Intercept = 0.05
Merged Statistics Surface Snow Thickness (m)
MOSAiC Transect Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

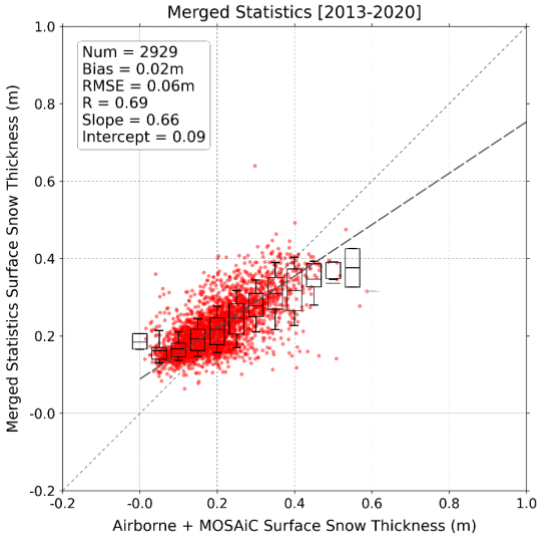

IceMassBalance [2013-2016]


Merged Statistics [2013-2016]
Num = 635
Bias = -0.14m
RMSE = 0.18m
R = -0.25
Slope = -0.05
Intercept = 0.19
Merged Statistics Surface Snow Thickness (m)
IceMassBalance Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2


Snow Buoy [2015-2019]


Merged Statistics [2015-2019]
Num = 91
Bias = -0.25m
RMSE = 0.25m
R = -0.18
Slope = -0.06
Intercept = 0.18
Merged Statistics Surface Snow Thickness (m)
Snow Buoy Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2


Airborne + MOSAiC [2013-2020]


Merged Statistics [2013-2020]
Num = 2929
Bias = 0.02m
RMSE = 0.06m
R = 0.69
Slope = 0.66
Intercept = 0.09
Merged Statistics Surface Snow Thickness (m)
Airborne + MOSAiC Surface Snow Thickness (m)
1.0
0.8
0.6
0.4
0.2
-0.0
-0.2

5 Discussion

5.1 Quality of snow depth from drifting buoys

Snow depth data from ice mass balance and snow buoy frequently contains thick snow (< 0.5 m) that is not poorly, if at all, represented by the Polar+ snow products. It is likely that this mismatch is caused by localized thick snow at the location of the buoy, which is not representative for average conditions at grid cell scale since most of the Polar+ snow products are able to represent the thicker snow categories of airborne data.

5.2 CPOM data not independent from OIB data

OIB data is part of CPOM KuKa algorithm, therefore OIB data is not an independent validation dataset in this case. The negligible bias (< 1 cm) is therefore expected and serves for quality control of the validation methodology.

5.3 Comparison of Merged and Individual Solutions

The comparability of the validation metrics derived from the individual KuKa and KuLa snow solutions and the ones derived from the merged products is very limited, due to differences in both temporal and geographical data coverage as well as varying grid resolutions.

To allow a balanced comparison, the period from October 2018 to April 2020 has been chosen as a reference period to compare products due to the availability of all KuKa and KuLa products. All airborne (OIB + IceBird) and MOSAiC data sets have been chosen as reference data sets. KuKa products are only compared against the airborne data in this period, since the MOSAiC measurements are mostly within the KuKa pole hole. The quality metrics are based on all airborne and MOSAiC reference data. For the KuKa products this means only airborne data, since MOSAiC transect data does not overlap with KuKa snow depths. The results for the KuKa/Merged snow depth intercomparison are summarized in Table 2 and for KuLa/Merged in Table 3 respectively.

Table 2: Validation metrics intercomparison between individual products and merged solution for KuKa data (<81.5N) between October 2018 and April 2020 derived from Airborne and MOSAiC reference datasets: Green highlighted cells indicate best metrics and number in brackets indicates the rank determined by the metric.

Metric	CPOM	LEGOS	UIT	Merged
Bias (m)	0.00 (1)	0.04 (3)	0.04 (3)	-0.01 (2)
RMSE (m)	0.08 (2)	0.08 (2)	0.08 (2)	0.07 (1)
Pearson	0.59 (3)	0.65 (2)	0.65 (2)	0.73 (1)

Slope	0.55 (3)	0.88 (1)	0.88 (1)	0.72 (2)
Intercept	0.10 (3)	0.07 (2)	0.07 (2)	0.06 (1)

Table 3: Validation metrics intercomparison between individual products and merged solution for KuLa data (<88.0N) between October 2018 and April 2020 derived from Airborne and MOSAiC reference datasets Green highlighted cells indicate best metrics and number in brackets indicates the rank determined by the metric.

Metric	CPOM	LEGOS (SAM)	LEGOS (T50)	UIT	Merged
Bias (m)	-0.04 (4)	-0.03 (3)	-0.07 (5)	-0.01 (1)	-0.02 (2)
RMSE (m)	0.08 (2)	0.06 (3)	0.09 (4)	0.05 (1)	0.05 (1)
Pearson	0.52 (5)	0.74 (2)	0.54 (4)	0.80 (1)	0.73 (3)
Slope	0.59 ($)	0.84 (2)	0.42 (5)	0.95 (1)	0.72 (3)
Intercept	0.08 (4)	0.01 (2)	0.10 (5)	0.00 (1)	0.06 (3)

The merged snow depth product ranks high in the quality metrics among the other KuKa products, while for the KuLa product, the UIT KuLa product shows the best results. In the key metrics, bias and RMSE, the difference between the UIT and merged products is small. -

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