4.2 Comparison with in-situ measurements

The in-situ data include Upward-Looking Sonar (ULS) moorings measurements in the Beaufort Sea, from the Beaufort Gyre Exploration Project (BGEP) with moorings A, B and D; and in the Fram Strait, from the Norwegian Polar Institute (NPI) (Sumata et al., 2021) with moorings F11, F12, F13 and F14. We also use airborne laser and radar altimeter measurements in the western Arctic from the Operation Ice Bridge Quick Look product (OiB-QL, Kurtz et al., 2016).

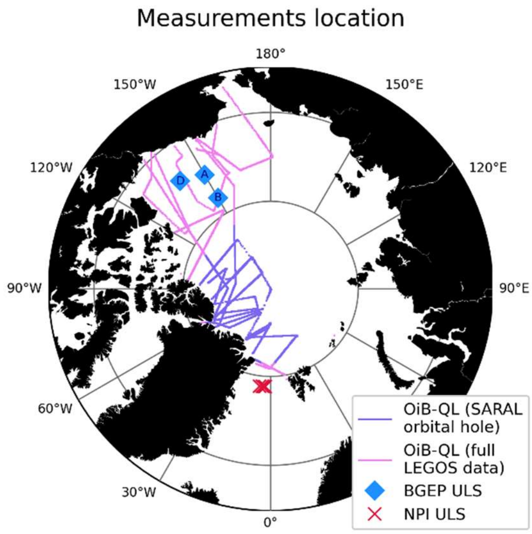

Figure 7: Map of the Arctic and the different in-situ measurements used for validation of the simulations.

The ULS moorings are located in regions where the LEGOS data are fully available (both RFB and SNOW-KaKu). A distinction is made for OiB-QL measurements based on the availability of LEGOS data, highlighting the orbital hole that results from using SARAL-AltiKa measurements.

BGEP ULS measurements, available all year long, are available for the whole duration of the simulations, and the NPI ULS data are available until August 2018. Airborne OiB-QL observations are collected only in spring, but they sample a variety of ice (MYI and FYI) and cover a significant area in the Arctic. OiB-QL measurements campaigns took place during 7 days in March 2017, 3 days in April 2017, 1 day in March 2018 and 6 days in April 2018. The comparison for all measurements is made at monthly frequency. The LEGOS values presented in this section are made from the LEGOS RFB data, the SNOW-KaKu data, and the model fixed densities (LEGOS_mD).

4.2.1 Beaufort Sea: BGEP ULS

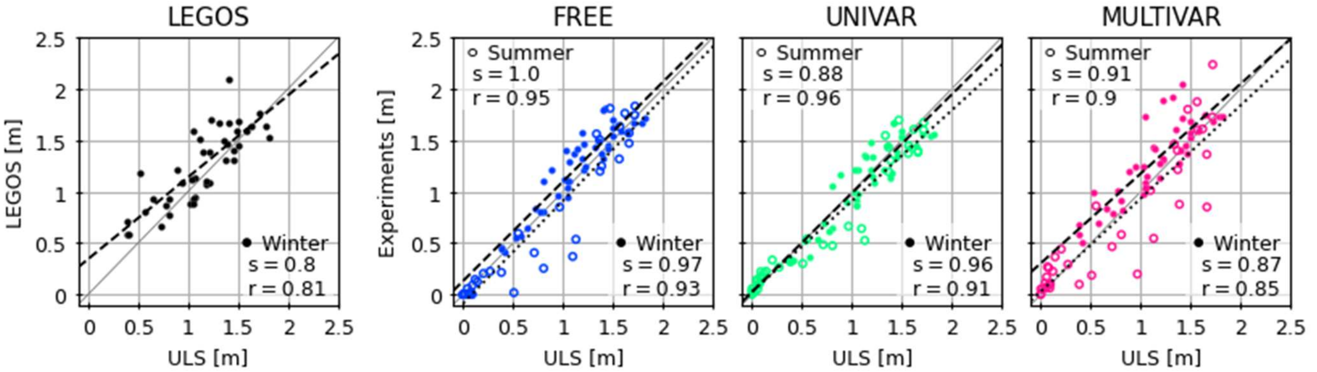

Figure 8: Comparison of monthly average ice draft from LEGOS data, FREE, UNIVAR and MULTIVAR experiments within 200 km of the Beaufort Gyre Experiment Program ULS Moorings for the summer (empty circles) and winter (solid circles). The linear regression (dashed b lack line for winter, dotted black line for summer), slope (s) and r-value (r) are shown for each dataset. Methodology from (Laxon et al., 2013).

The Figure 8 shows a remarkable agreement of ice drafts between BGEP data and all experiments. The LEGOS observations have less coherence with the BGEP ULS measurements than the experiments but still with very high statistics. The values that underestimate the BGEP measurements in all 3 experiments are mostly during summertime (Table 4). The MULTIVAR experiment exhibits less accuracy than the FREE and UNIVAR simulations, with more scattered values and higher RMSE (Table 4), inheriting the behaviour of assimilated LEGOS data. However, MULTIVAR ice drafts have higher correlation than those from LEGOS estimates and, further, the MULTIVAR experiment is able to keep the strong correlation obtained with the FREE ice draft values during summertime (Figure 8).

BGEP ULS DATA	RMSE total	MD total	RMSE winter	MD winter	RMSE summer	MD summer
LEGOS			0.194	0.113		
FREE	0.134	0.011	0.121	0.095	0.150	-0.087
UNIVAR	0.139	-0.038	0.141	-0.020	0.137	-0.058
MULTIVAR	0.191	0.068	0.182	0.160	0.202	-0.039

Table 4: Root mean square error (RMSE) and mean differences (MD) between the BGEP ULS measurements and LEGOS data (only winter months: November to April), FREE, UNIVAR and MULTIVAR experiments, by season (summer: May to October and winter) and over the two seasons as a total.

4.2.2 Fram Strait: NPI ULS

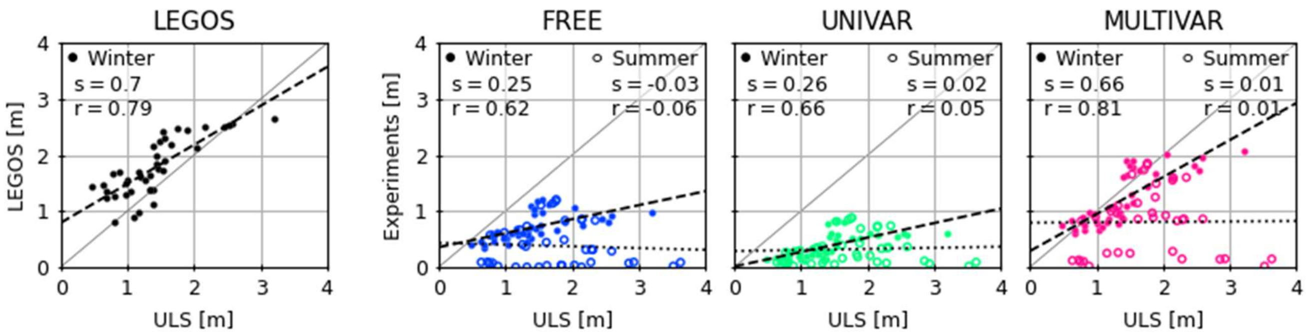

Figure 9: Comparison of monthly average ice draft from LEGOS data, FREE, UNIVAR and MULTIVAR experiments within 200 km of the Norwegian Polar Institut (NPI) Fram Strait ULS Moorings for the summer (empty circles) and winter (solid circles). The linear regression (dashed black line for winter, dotted black line for summer), slope (s) and r-value (r) are given for each dataset.

The ULS ice draft measurements are thicker in the Fram Strait than in the Beaufort Sea. The LEGOS data is in general agreement with the NPI data but presents mostly thicker ice drafts than the ULS measurements. The FREE and UNIVAR ice drafts consistently underestimate the ULS measurements, with very low slopes and r-values (Figure 9). These two experiments have most of the ice drafts at 0 m and show a deficit of up to 1.4 m compared with in-situ measurements (Table 5). Assimilating LEGOS RFB and SNOW-KaKu results in higher ice drafts, especially in winter when the assimilation is effective, and drastically reduces errors. Large errors in the MULTIVAR experiment's summer ice drafts values still remain in this region of the Fram Strait where the ice front is highly variable.

NPI ULS DATA	RMSE total	MD total	RMSE winter	MD winter	RMSE summer	MD summer
LEGOS			0.427	0.366		
FREE	1.040	-1.040	0.696	-0.696	1.402	-1.402
UNIVAR	1.238	-1.238	1.029	-1.029	1.458	-1.458
MULTIVAR	0.645	-0.571	0.316	-0.189	0.991	-0.972

Table 5: Same as Table 4 with the NPI ULS measurements.

4.2.3 Operation IceBridge QuickLook sea ice thickness

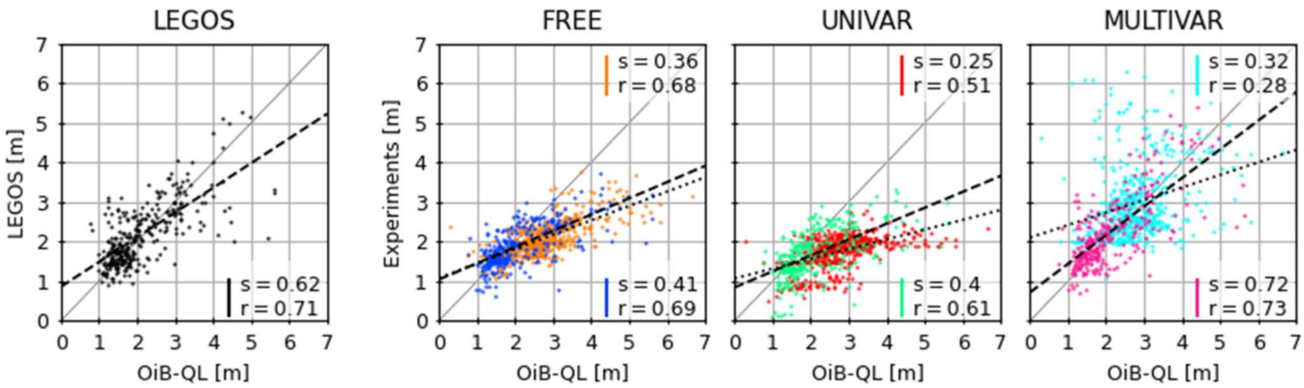

Figure 10: Comparison of monthly average ice thickness from LEGOS data, FREE, UNIVAR and MULTIVAR experiments collocated with OiB-QL airborne measurements in the Arctic. Areas where LEGOS SNOW-KaKu and RFB measurements are available are respectively in black, blue (FREE), green (UNIVAR) and pink (MULTIVAR) with linear regression in dashed black line; otherwise, orange (FREE), red (UNIVAR) and cyan (MULTIVAR) with linear regression in dotted black line refer to regions where SNOW-KaKu data are not available. All ice thickness values are gridded onto a 0.4° latitude by 4° longitude Arctic grid, following the methodology of (Tilling et al., 2018). The slope (s) and r-value (r) are given for each dataset.

The LEGOS data and the OiB-QL ice thickness measurements are in general good agreement (Figure 10). The OiB-QL data presents a cluster of measurements between 1 and 2 m that is well reproduced by all experiments and by the LEGOS data. Thicker measurements from the OiB-QL 2017 and 2018 campaigns are underestimated by the FREE and UNIVAR experiments (Table 6). These two experiments do not show ice thickness values higher than 4 m, whereas the OiB-QL measurements signal ice up to 6.6 m thick. The MULTIVAR simulation is able to reproduce thicker ice, resulting in a general reduction of errors, especially bias, with the OiB-SL measurements, in regions where all the assimilated data is available, and also where some or all of the assimilated data are missing (Table 6). However, the MULTIVAR experiment's ice thickness values are very scattered, especially in the region where the LEGOS data is not entirely available (no SNOW-KaKu poleward of 81.5°N; and no RFB LEGOS poleward of 88°N).

OiB AIRBORNE DATA	RMSE total	MD total	RMSE lat<81.5°N	MD lat<81.5°N	RMSE lat>81.5°N	MD lat>81.5°N
LEGOS			0.449	0.068		
FREE	0.639	-0.503	0.459	-0.200	0.744	-0.681
UNIVAR	0.869	-0.794	0.574	-0.416	1.042	-1.016
MULTIVAR	0.652	0.182	0.486	0.135	0.750	0.209

Table 6: Same as Table 4 with the OiB Airborne data and, according to the areas where SNOW-KaKu data is present (<81,5°N) or not (> 81,5°N) and for all OiB Airborne data.