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Ice thickness and water level estimation for ice-covered lakes with satellite altimetry waveforms and backscattering coefficients

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Supplementary Figure:

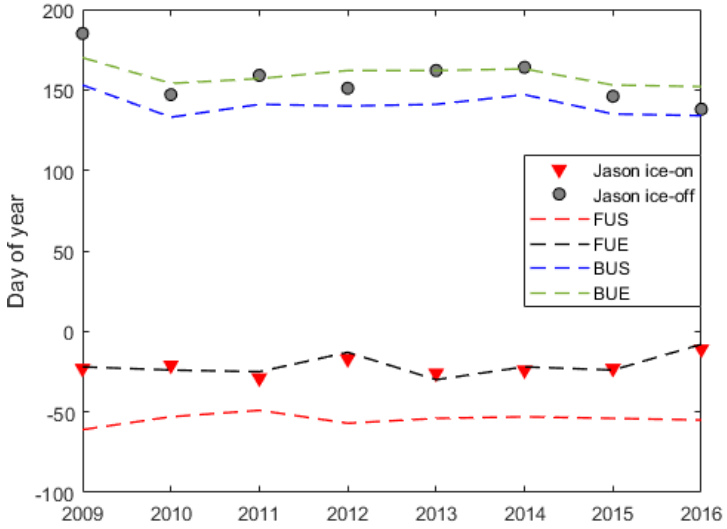

Figure S1 Comparison between the backscatter-based and the MODIS-based lake ice phenology in GSL from 2009 to 2016. FUS, FUE, BUS, and BUE denote freeze-up start, freeze-up end, break-up start, and break-up end of lake ice manually identified from MODIS images, respectively. The Jason-based ice-on dates are very close to the FUE, with an RMSE of 3 days, while the backscattered ice-off dates are close to the BUE, with an RMSE of 9 days.

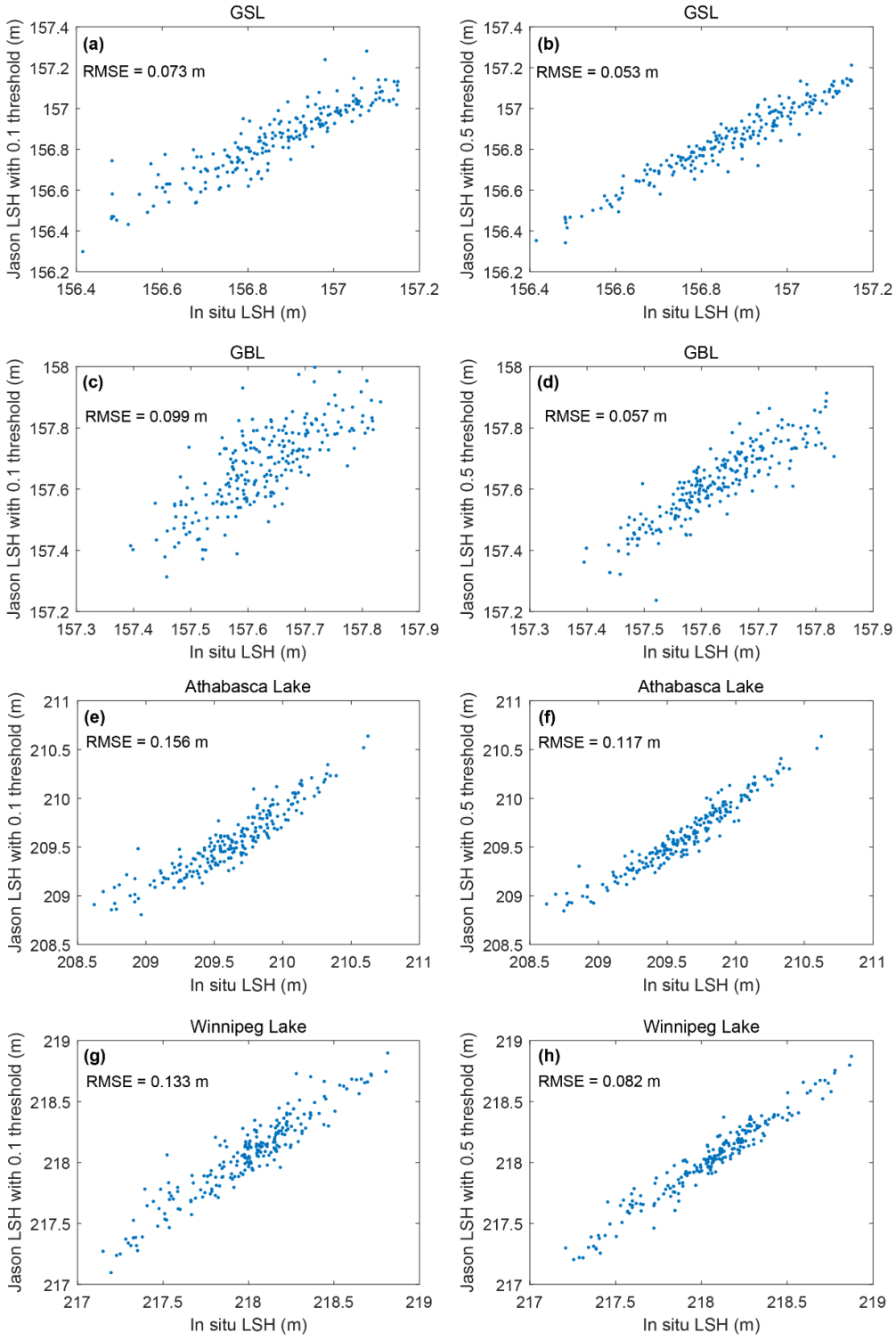

Figure S2 Comparison between LSH derived from the 0.1 threshold and the 0.5 threshold during open water periods. (a) Scatterplots of the 0.1-threshold-based LSH against in situ water levels for GSL. (b) Scatterplots of the 0.5-threshold-based LSH against in situ water level for GSL. (c–d), (e–f), and (g–h) are the same as (a–b) but for GBL, Athabasca Lake, and Winnipeg Lake.

Supplementary Table:

Table S1 Calibrated parameters and metrics for the logarithmic model in four study lakes

Lake name	Ice season	-1/K	A	C	R^2	RMSE (m)
Great Slave Lake	2002/11─2003/5	-0.50	1.62	21.11	0.14	0.38
	2003/11─2004/5	-0.57	1.84	17.67	0.92	0.08
	2004/11─2005/5	-1.76	6.41	0.19	0.64	0.16
	2005/11─2006/5	-1.34	4.91	0.545	0.64	0.09
	2006/11─2007/5	-1.29	5.00	0.535	0.87	0.11
	2007/11─2008/5	-1.32	4.66	3.62	0.86	0.11
	2008/11─2009/5	-1.42	5.48	0.45	0.94	0.07
	2009/11─2010/5	-1.46	5.48	0.94	0.86	0.08
	2010/11─2011/5	-1.20	4.41	5.68	0.96	0.07
	2011/11─2012/5	-1.62	6.16	0.18	0.78	0.14
	2012/11─2013/5	-1.89	6.84	0.81	0.19	0.26
	2013/11─2014/5	-1.30	4.95	0.69	0.17	0.36
	2014/11─2015/5	-1.30	4.67	0.275	0.09	0.20
	2015/11─2016/5	-1.58	5.76	0.89	0.79	0.10
	2016/11─2017/5	-1.61	6.03	0.72	0.79	0.15
	2017/11─2018/5	-0.57	1.89	14.43	0.79	0.09
	2018/11─2019/5	-1.64	6.09	0.04	0.90	0.07
Hulun Lake	2013/11─2014/5	-2.72	9.96	0.87	0.81	0.12
	2014/11─2015/5	-2.44	9.48	0.55	0.67	0.09
	2015/11─2016/5	-1.91	7.45	0.085	0.85	0.10
	2016/11─2017/5	-2.31	8.86	0.42	0.58	0.19
	2017/11─2018/5	-2.55	9.55	0.995	0.60	0.16
	2018/11─2019/5	-2.72	10.48	0.92	0.38	0.16

Lake name	Ice season	-1/K	A	C	R^2	RMSE (m)
Baker Lake	2002/11–2003/5	-1.53	5.67	5.69	0.90	0.12
	2003/11–2004/5	-0.75	2.32	12.75	0.98	0.05
	2004/11–2005/5	-2.04	7.75	0.69	0.98	0.09
	2005/11–2006/5	-1.73	6.67	2.83	0.93	0.10
	2006/11–2007/5	-0.23	1.00	18.72	0.94	0.05
	2007/11–2008/5	-4.21	14.89	0.23	0.26	0.40
	2008/11–2009/5	-2.18	8.18	0.27	0.96	0.12
	2009/11–2010/5	-1.30	4.23	7.05	0.96	0.07
	2010/11–2011/5	-2.27	7.80	0.6	0.85	0.18
	2011/11–2012/5	-1.80	6.78	0.33	0.48	0.31
	2012/11–2013/5	-2.13	7.54	0.045	0.87	0.15
	2013/11–2014/5	-3.62	13.01	0.2	0.75	0.21
	2014/11–2015/5	-1.66	5.46	7.56	0.69	0.24
	2015/11–2016/5	-1.30	4.57	8.39	0.91	0.15
	2016/11–2017/5	-0.66	2.17	12.46	0.96	0.06
	2017/11–2018/5	-2.16	7.97	0.97	0.96	0.10
	2018/11–2019/5	-2.53	9.12	0.3	0.97	0.08
Har Lake	2005/11–2006/5	-6.31	23.93	0.81	0.65	0.10
	2006/11–2007/5	-5.28	20.23	0.48	0.52	0.11
	2007/11–2008/5	-2.76	10.38	14.28	0.69	0.08
	2008/11–2009/5	-0.51	1.59	33.78	0.96	0.04
	2009/11–2010/5	-1.04	3.55	19.92	0.89	0.09
	2010/11–2011/5	-0.59	1.73	34.21	0.77	0.16
	2011/11–2012/5	-0.47	1.19	31.45	0.84	0.09
	2012/11–2013/5	-6.35	24.59	0.87	0.90	0.08
	2013/11–2014/5	-0.37	1.09	34.26	0.77	0.09
	2014/11–2015/5	-2.19	8.50	6.84	0.98	0.03
	2015/11–2016/5	-1.38	4.36	21.84	0.94	0.03
	2016/11–2017/5	-4.97	18.82	0.48	0.1	0.14
	2017/11–2018/5	-3.38	13.43	0.11	0.92	0.06
	2018/11–2019/5	-2.98	11.91	0.64	0.92	0.08

Supplementary Text:

Quantification of remaining systematic biases in altimetric water levels

Here we provide a brief analysis of the source and magnitude of possible remaining systematic biases based on Jason-2 and Jason-3. The analysis for Jason-1 and Jason-2 would be similar but with a slightly different length of the overlapping period. As illustrated in the main context, the systematic bias is calculated as the difference between the mean LSH from Jason-2 and Jason-3 during the overlapping periods. Water level fluctuations during the time lag between Jason-2 and the Jason-3 observations could result in some remaining biases. Such a remaining bias caused by water level fluctuations can be largely reduced if the length of the overlapping period is long enough. However, the overlapping period is fixed for Jason-1/2/3. Another important source of the remaining bias is outliers during overlapping periods, especially when mean values are used to calculate the bias instead of median values.

We estimated the remaining systematic bias between Jason-2 and Jason-3 in GSL with the standard deviation (STD) of the LSH difference between the two satellites obtained on the same day. The overlapping period between the J2 and J3 in GSL is ~ 210 days, providing 21 data pairs. The STD of the LSH differences is 6.7 cm, which is not negligible when comparing the merged LSH against in situ data. As for Jason-1 and Jason-2, the STD of the LSH differences is 5.3 cm calculated from 17 data pairs.