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Supplement of

A gradient-boosted tree framework to model the ice thickness of the world's glaciers (IceBoost v1.1)

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Supplementary information - ICEBOOST v1.1

S1 Ground truth ice thickness data distribution

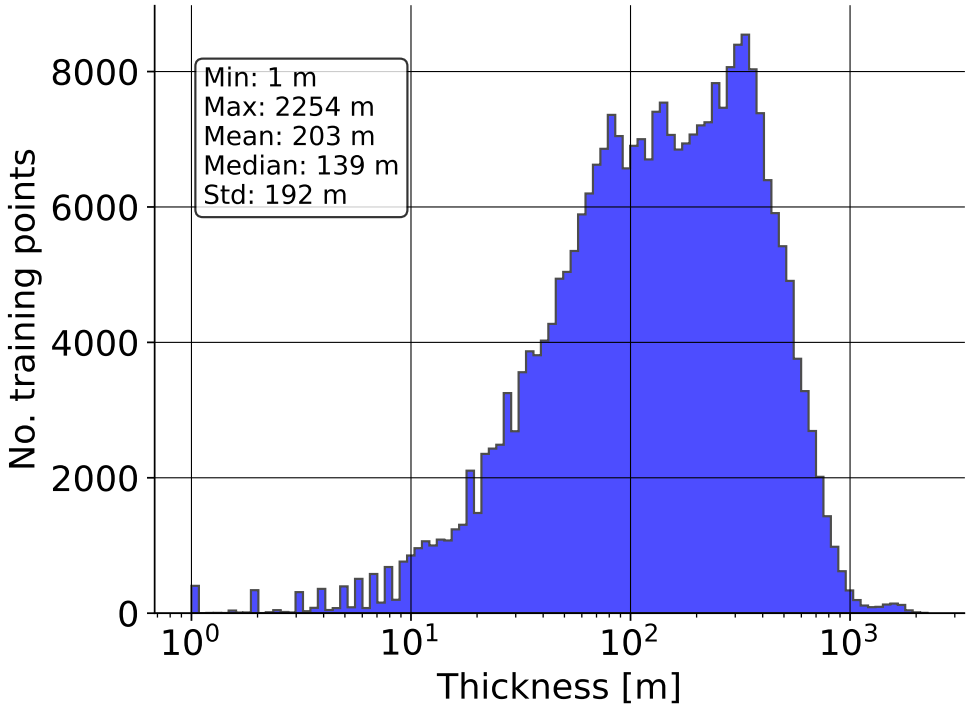


Figure S1: Distribution of ice thickness ground truth data in the training dataset.

S2 Comparison between XGBoost, CatBoost and IceBoost

Table S1: Statistics of the IceBoost (training without supervision) model ensemble, compared to errors of the XGBoost and CatBoost gradient-boosted models taken individually (in bold font the lowest error). The RMSE is evaluated on the 20% of unseen data, selected randomly. The statistics is averaged across n=100 training runs for each region. 1 standard deviation indicated in parentheses.

RGI	Region	RMSE IceBoost [m]	RMSE XGBoost [m]	RMSE CatBoost [m]
1	Alaska	116 (21)	127 (20)	**114 (21)**
2	Western Canada and US	-	-	-
3	Arctic Canada North	83 (7)	**85 (7)**	86 (6)
4	Arctic Canada South	58 (9)	60 (11)	**58 (9)**
5	Greenland Periphery	93 (23)	96 (25)	**94 (21)**
6	Iceland	-	-	-
7	Svalbard	52 (7)	**53 (7)**	54 (8)
8	Scandinavia	42 (6)	44 (8)	44(5)
9	Russian Arctic	-	-	-
10	North Asia	15 (3)	**15 (4)**	18 (4)
11	Central Europe	35 (5)	37 (6)	**36 (5)**
12	Caucasus and Middle East	56 (1)	**55 (1)**	57 (1)
13	Central Asia	36 (12)	39 (14)	**35 (10)**
14	South Asia West	-	-	-
15	South Asia East	-	-	-
16	Low Latitudes	-	-	-
17	Southern Andes	43 (8)	54 (20)	**37 (11)**
18	New Zealand	-	-	-
19	Antarctic and Subantarctic	109 (20)	113 (22)	**111 (19)**

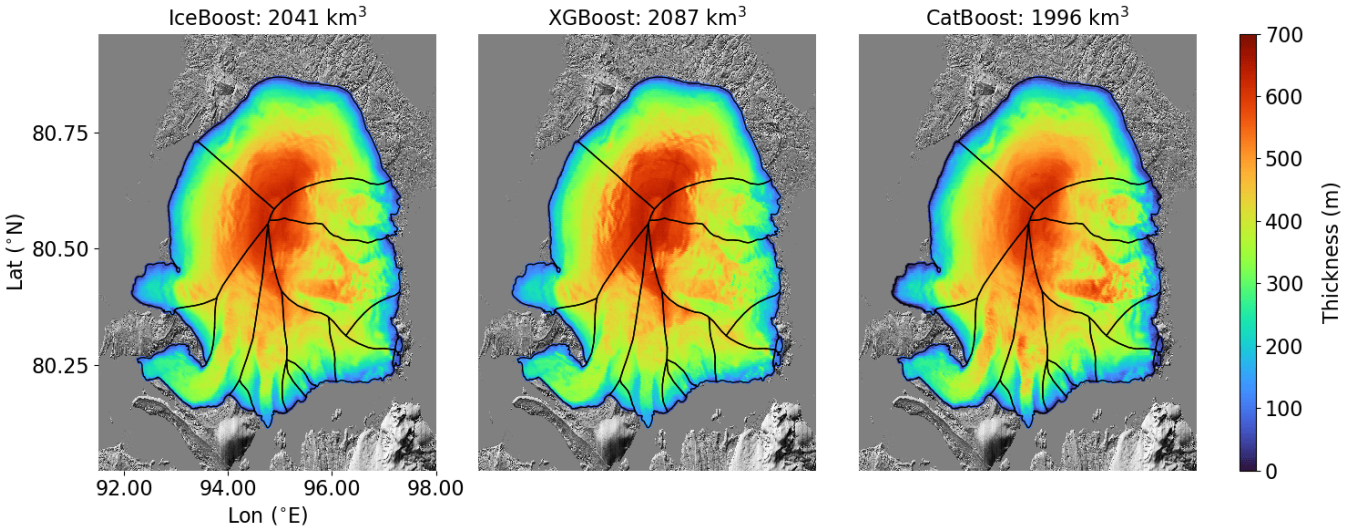


Figure S2: Academy of Sciences ice cap (Russian Arctic, RGI60-09.00917) modeled using XGBoost, CatBoost, and IceBoost (ensemble). The TandemX-EDEM hillshade is shown in transparency.

S3 Training without supervision, validation on Arctic Canada North (few selected glacier examples)

Figure S3 displays the results from one individual validation run on few glaciers randomly selected from Region 3 (Arctic Canada North). In this case, IceBoost is trained "without supervision", i.e. the data from these glaciers is removed from the training dataset before training.

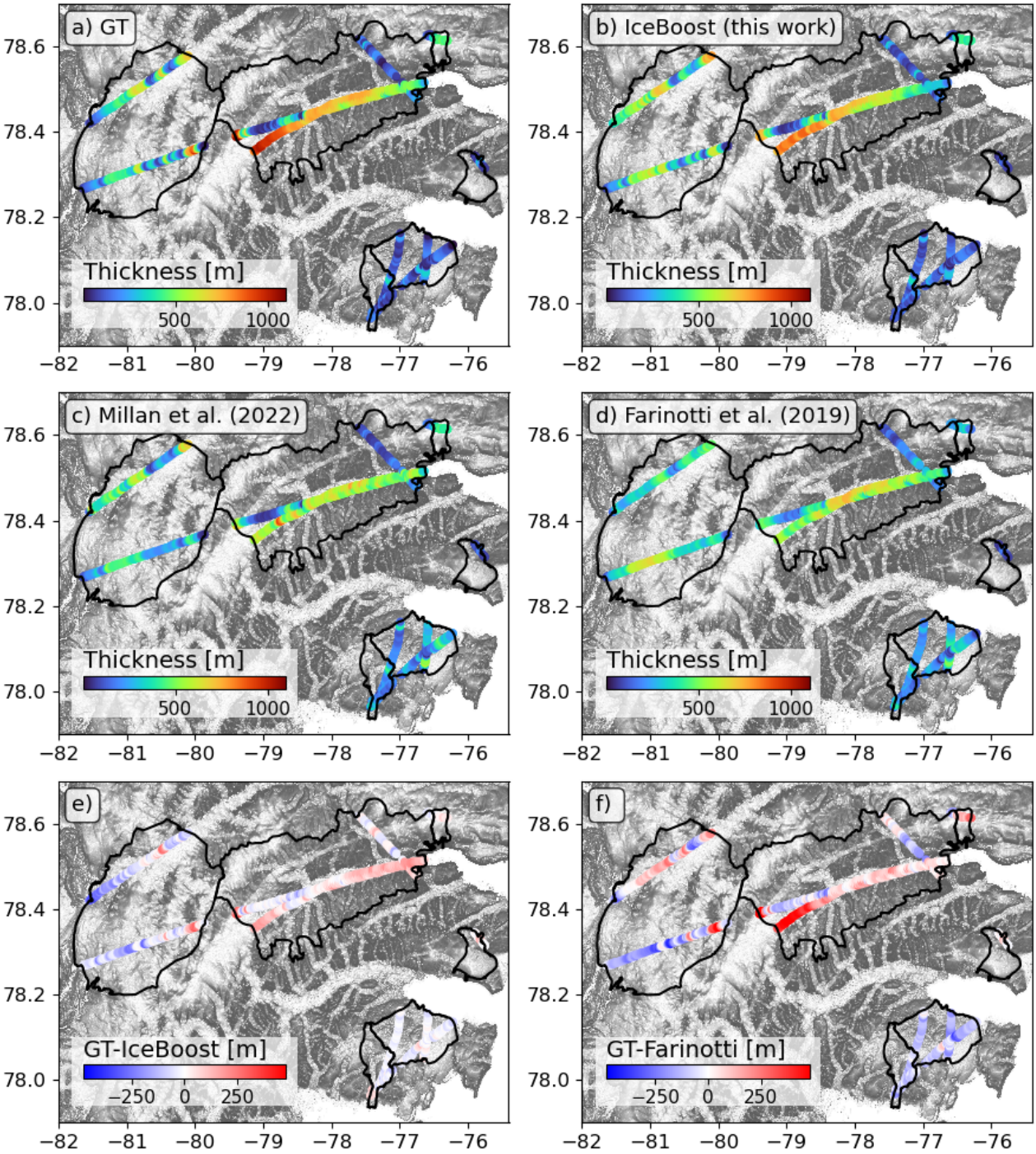


Figure S3: Validation run after training IceBoost "without supervision". a) ground truth data (from the GlaThiDa dataset). b), c), and d) reflect the output respectively from IceBoost (this work), Millan et al. (2022), and Farinotti et al. (2019). e) and f) show respectively the difference between the ground truth and either IceBoost or Farinotti et al. (2019). The TandemX-EDEM hillshade is shown in transparency.

S4 Training without supervision, validation on Arctic Canada North (regional statistics)

Figure S4 displays the results from one individual validation run from Region 3 (Arctic Canada North). In this case, IceBoost is trained "without supervision" on 80% of the regional data (plus all data from all other regions), and evaluated on all the remaining 20% fraction, corresponding to 13,731 points (from 87 glaciers). "Without supervision" means that no data from the 87 glaciers used for evaluation can be used for training. The regional model performance (Table 2 of main text) is considers the averaged statistics from an ensemble of n=100 individual runs. The statistics obtained for this individual run is shown in the colored insets in the top left panel. Across the n=100 runs, randomization of glaciers is applied.

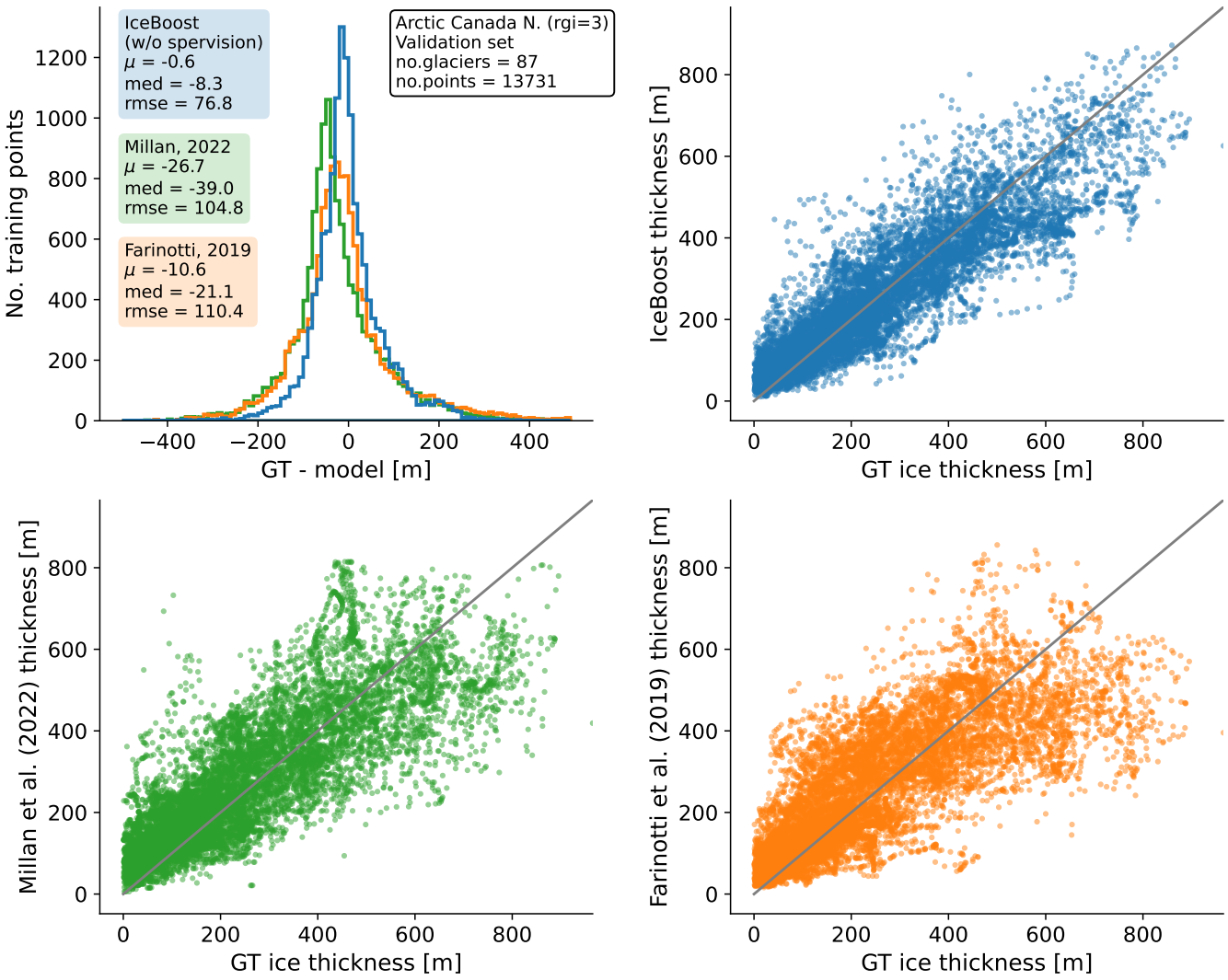


Figure S4: Validation run after training IceBoost "without supervision". The top-left panel shows the misfit between the three models and the ground truth. The three colored scatter plots shows the predicted ice thickness for each data point, compared to ground truth. The grey lines refer to 1:1 lines (they are not fits).

S5 Comparison with existing global models

In the following Figures 5-194, we compare the solutions of IceBoost (this work), with those by Millan et al. (2022), and the ensemble by Farinotti et al. (2019) for n=190 glaciers, 10 glacier per region, in increasing order from region 1 (Figures 5-14) to region 19 (Figures 185-194). See Table S2 for figure numbering. The longitude, latitude coordinates are only shown for the left panel for simplicity. The captions indicate the glacier name, taken from the Randolph Glacier Inventory, version 6. The TandemX-EDEM hillshade is shown in transparency.

In region 5 (Greenland) and region 19 (Antarctica), if the solution from Millan et al. (2022) is not available, the second column shows the output from BedMachine v5 (Greenland, Morlighem 2022b), and BedMachine v3 (Antarctica, Morlighem 2022a). Wherever ground truth data is available, it is displayed with large circles in all three panels. The colorbar range is tied to the IceBoost values, therefore the other 2 solutions may appear with saturated colors. The total glacier ice volumes are indicated above the respective models. A missing plot indicates that the model has no solution for that specific glacier. IceBoost has no missing plots.

In general, similar ice thickness maps are predicted by all models. However, significant differences are also observed. The same applies to glacier-integrated ice volumes.

RGI	Region	Figures	RGI	Region	Figures
1	Alaska	S5-S14	11	Central Europe	S105-S114
2	Western Canada and US	S15-S24	12	Caucasus and Middle East	S115-S124
3	Arctic Canada North	S25-S34	13	Central Asia	S125-S134
4	Arctic Canada South	S35-S44	14	South Asia West	S135-S144
5	Greenland Periphery	S45-S54	15	South Asia East	S145-S154
6	Iceland	S55-S64	16	Low Latitudes	S155-S164
7	Svalbard	S65-S74	17	Southern Andes	S165-S174
8	Scandinavia	S75-S84	18	New Zealand	S175-S184
9	Russian Arctic	S85-S94	19	Antarctic and Subantarctic	S185-S194
10	North Asia	S95-S104			

Table S2: Figure numbers related to the 19 regions in the following pages of the Supplementary Information.

References

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., and Pandit, A.: A consensus estimate for the ice thickness distribution of all glaciers on Earth, Nature Geoscience, 12, 168–173, 2019.

Millan, R., Mouginot, J., Rabatel, A., and Morlighem, M.: Ice velocity and thickness of the world's glaciers, Nature Geoscience, 15, 124–129, 2022.

Morlighem, M.: MEaSUREs BedMachine Antarctica, Version 3, https://doi.org/10.5067/FPSU0V1MWUB6, 2022a.

Morlighem, M. e. a.: IceBridge BedMachine Greenland, Version 5, https://doi.org/10.5067/GMEVBWFLWA7X, 2022b.

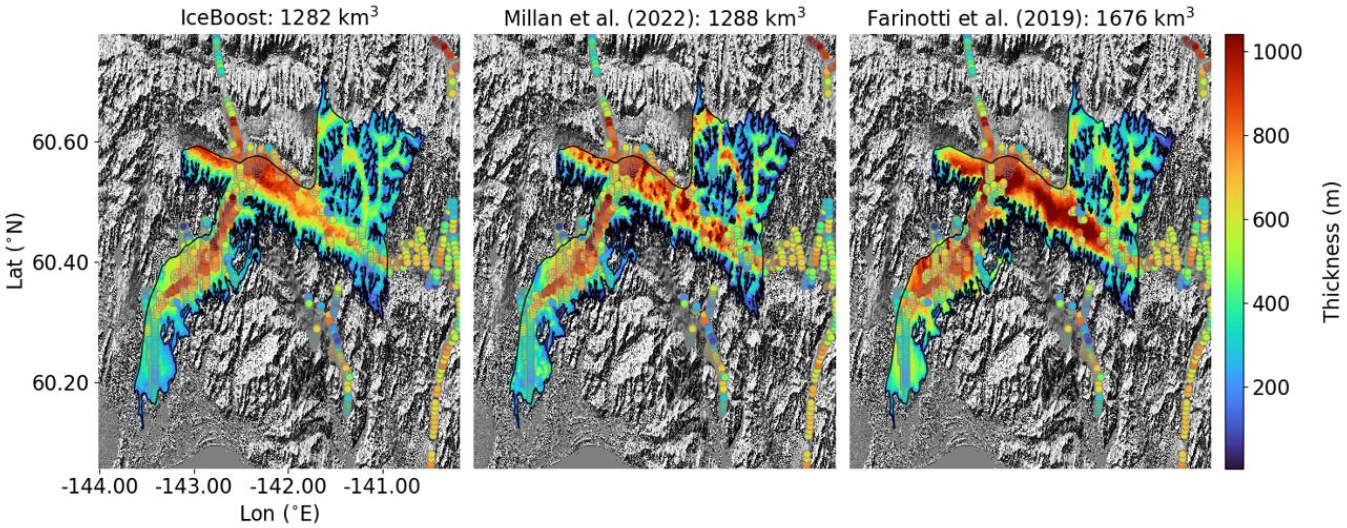
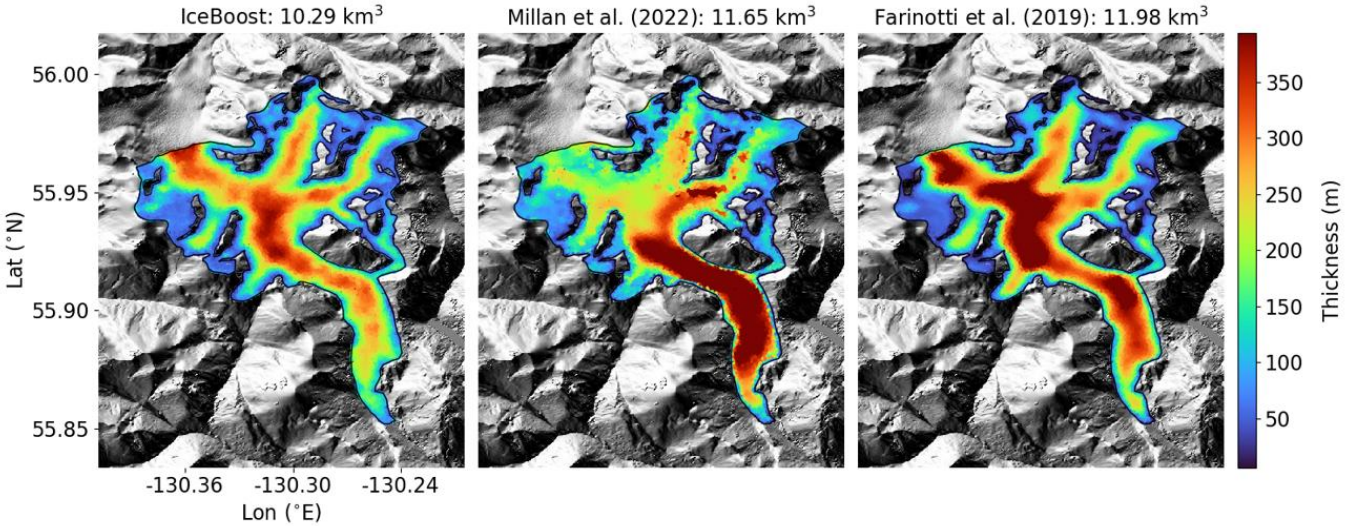


Figure S5: Glacier RGI60-01.13635. Back to Table S2.



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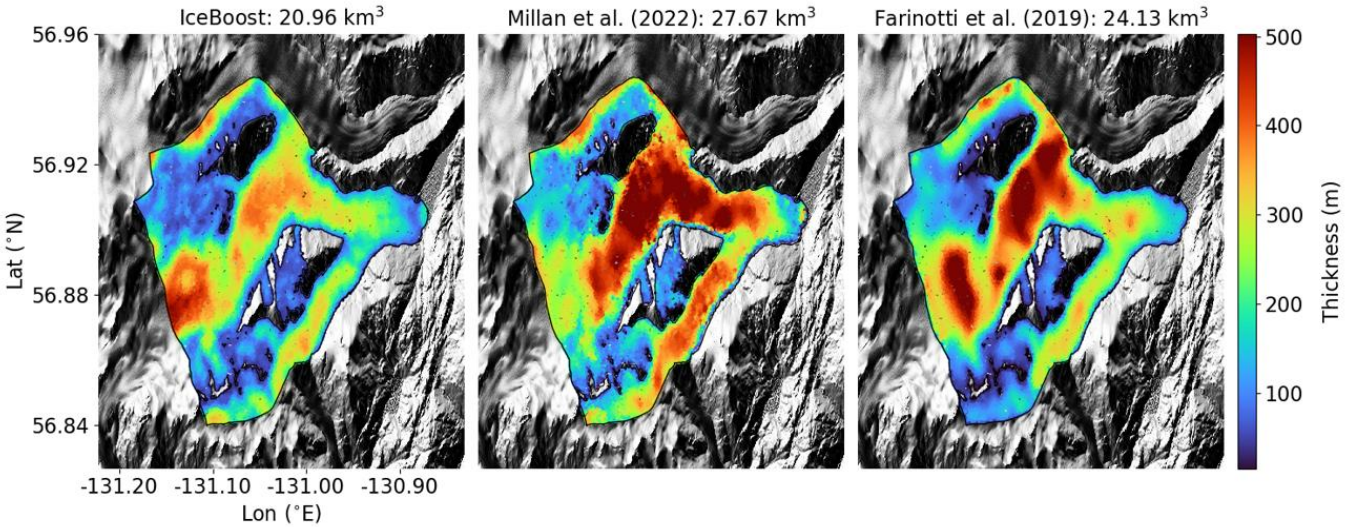

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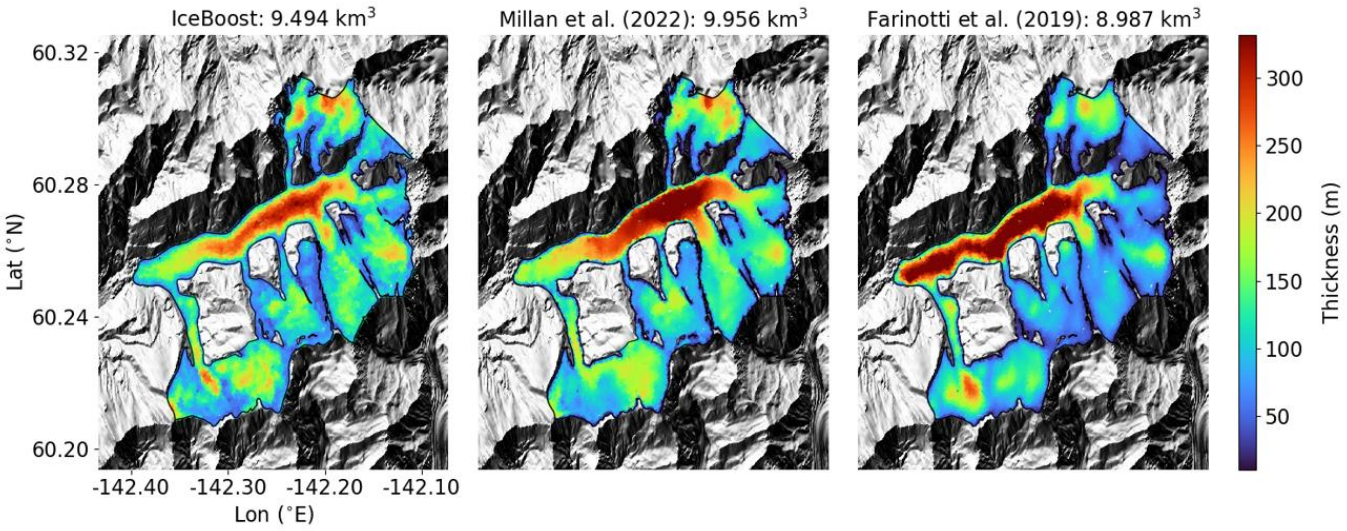

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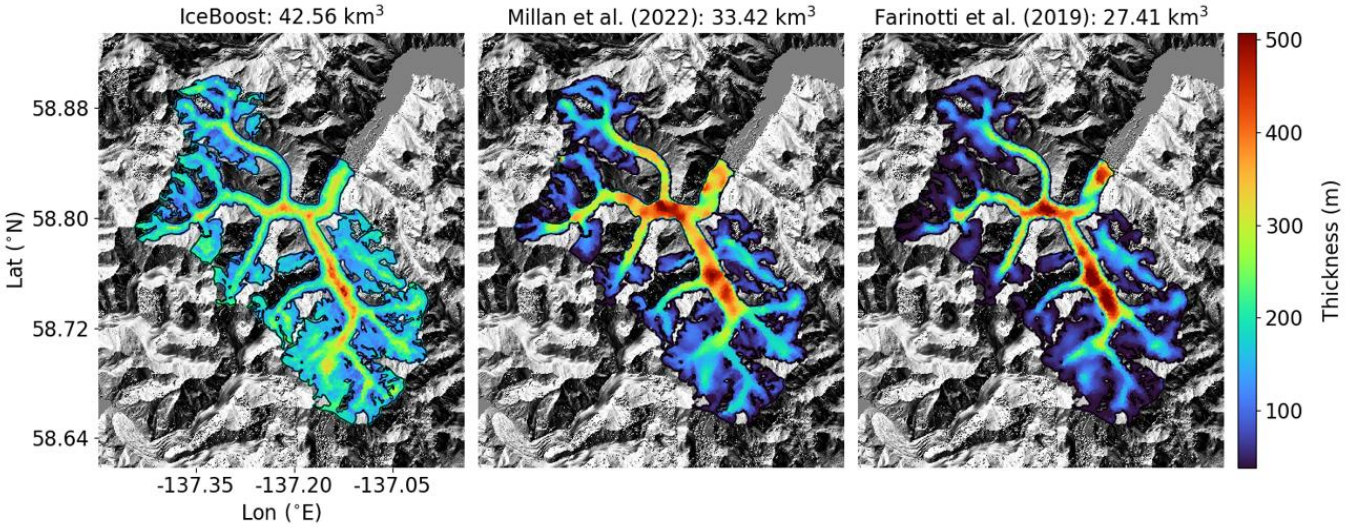

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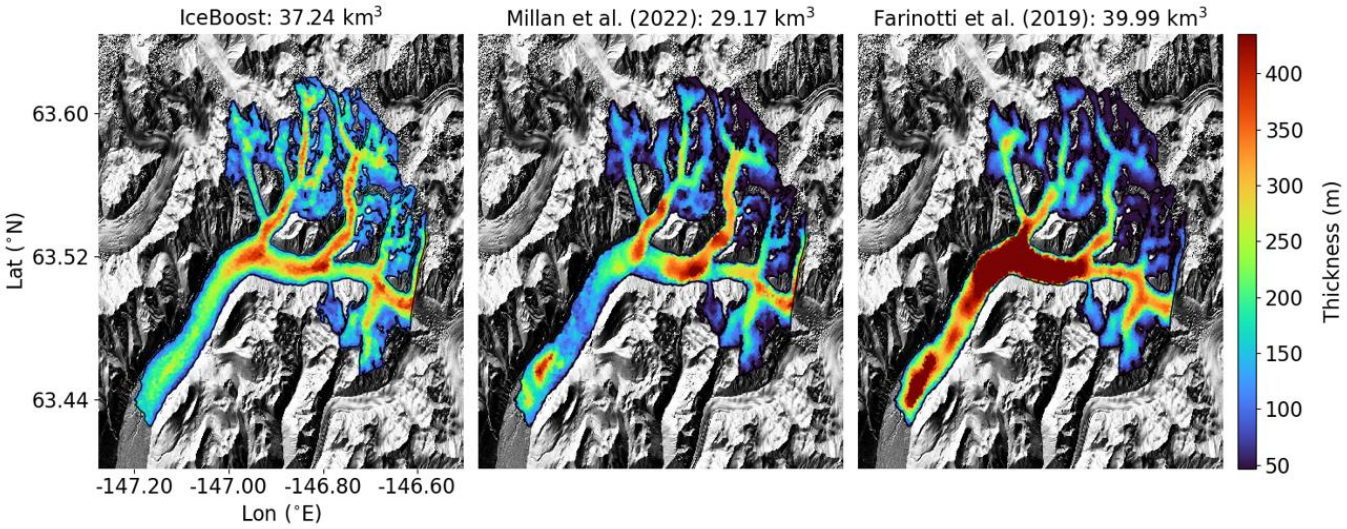

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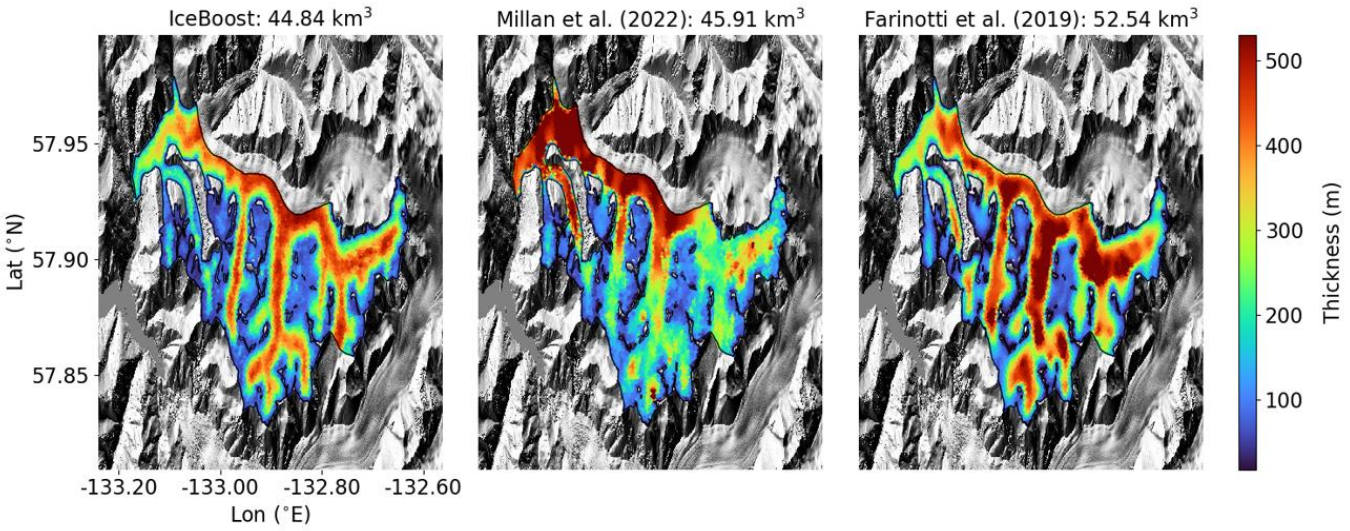

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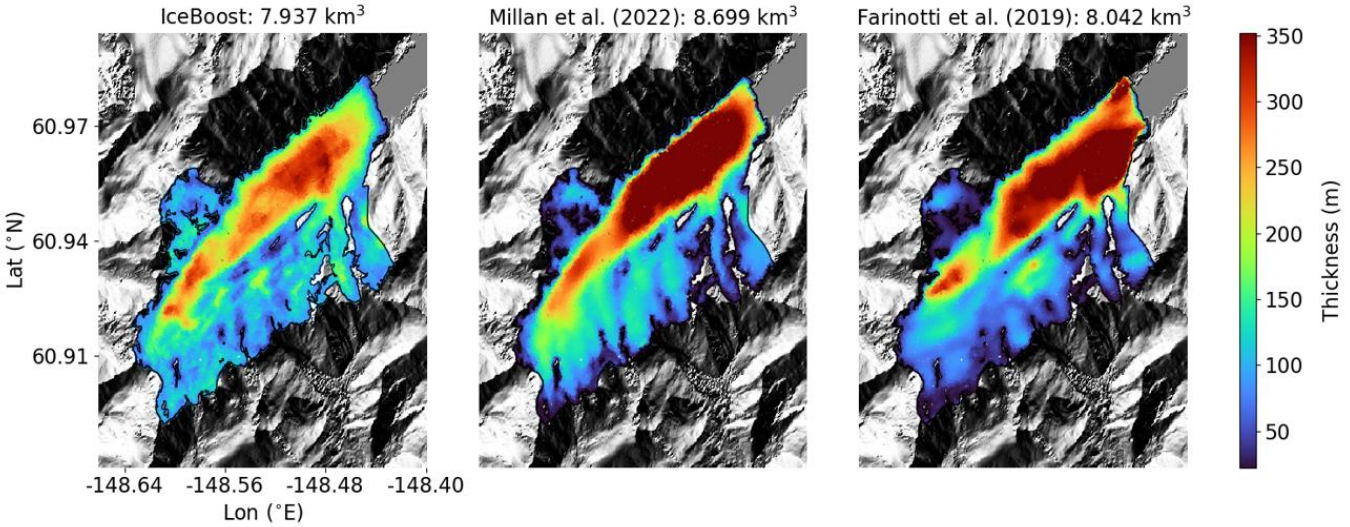

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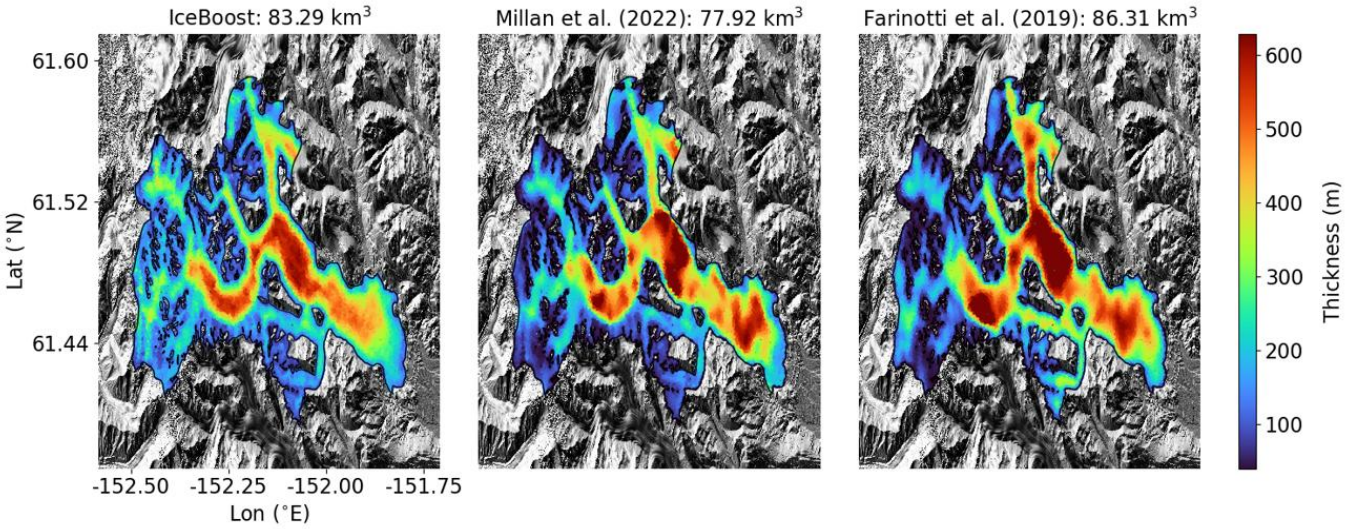

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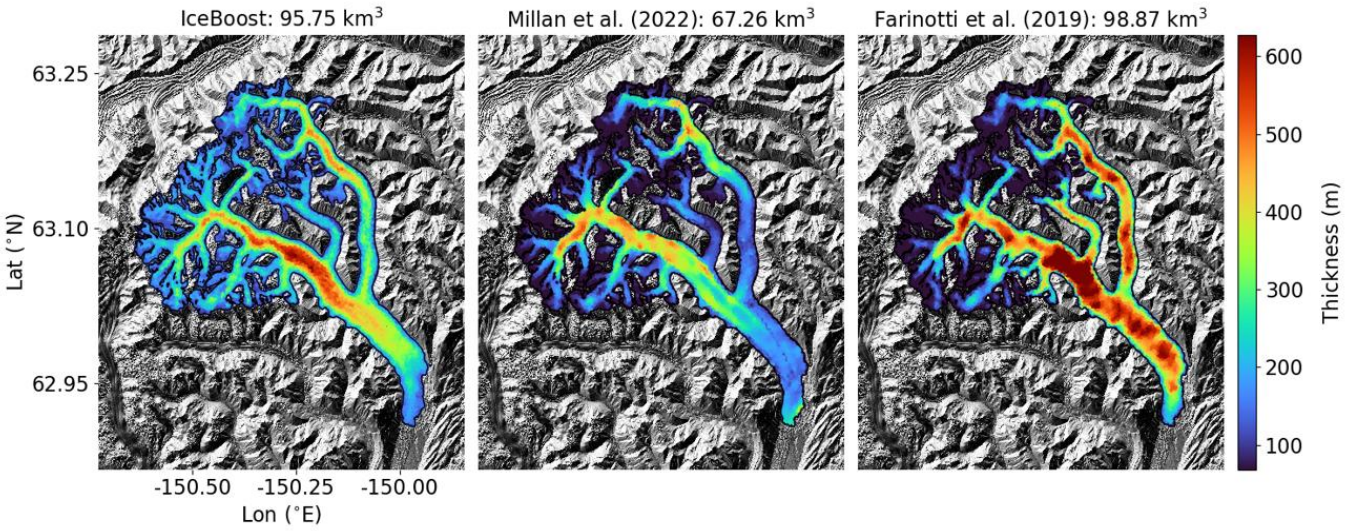

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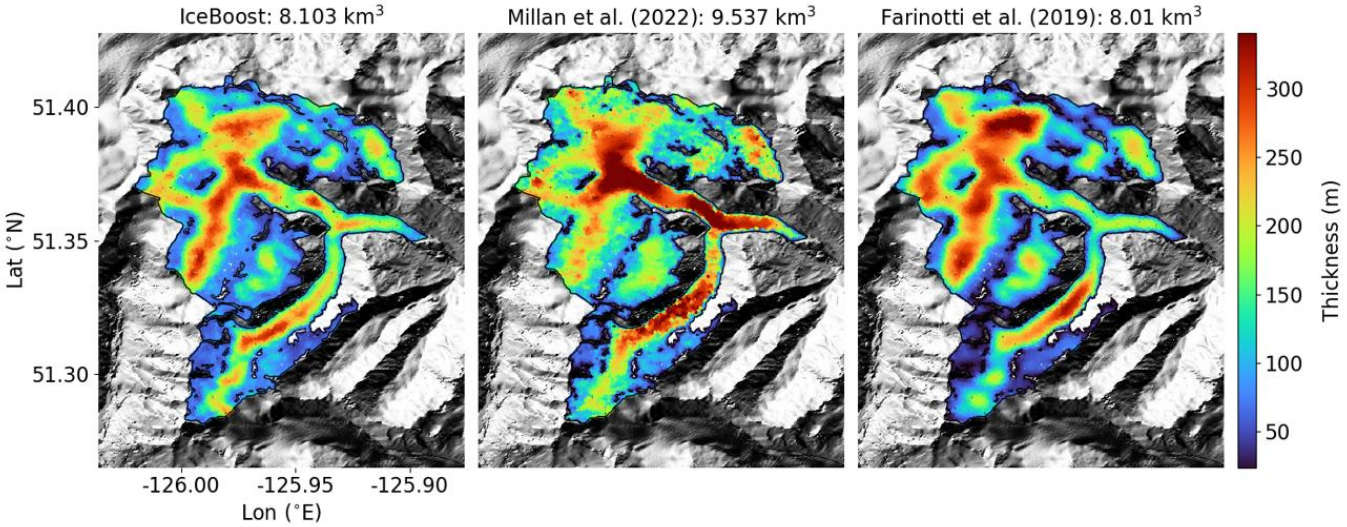

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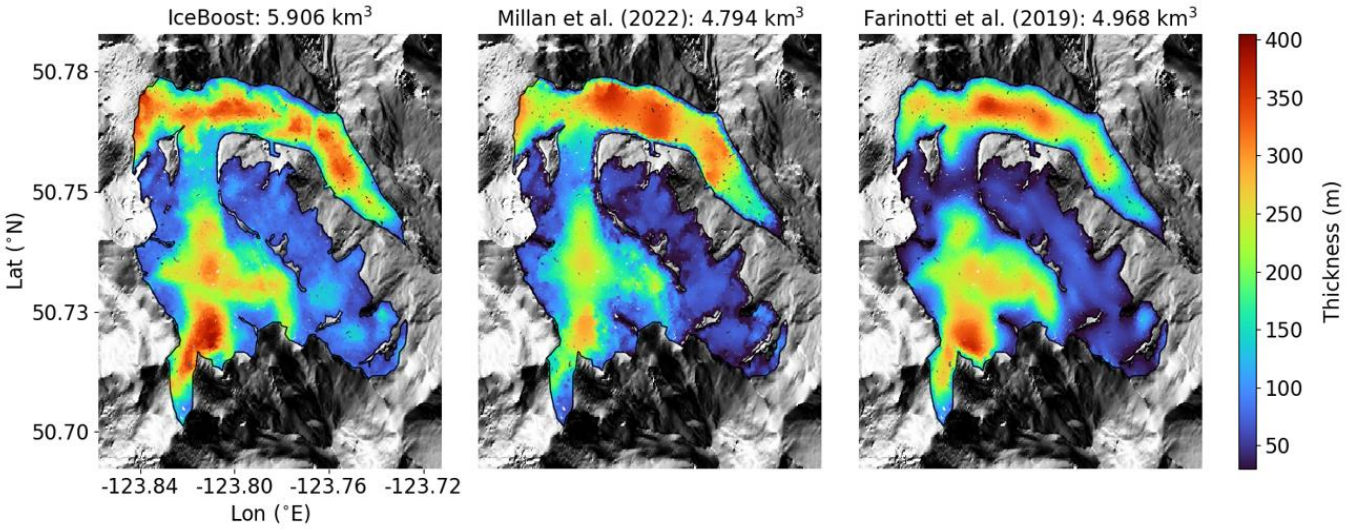

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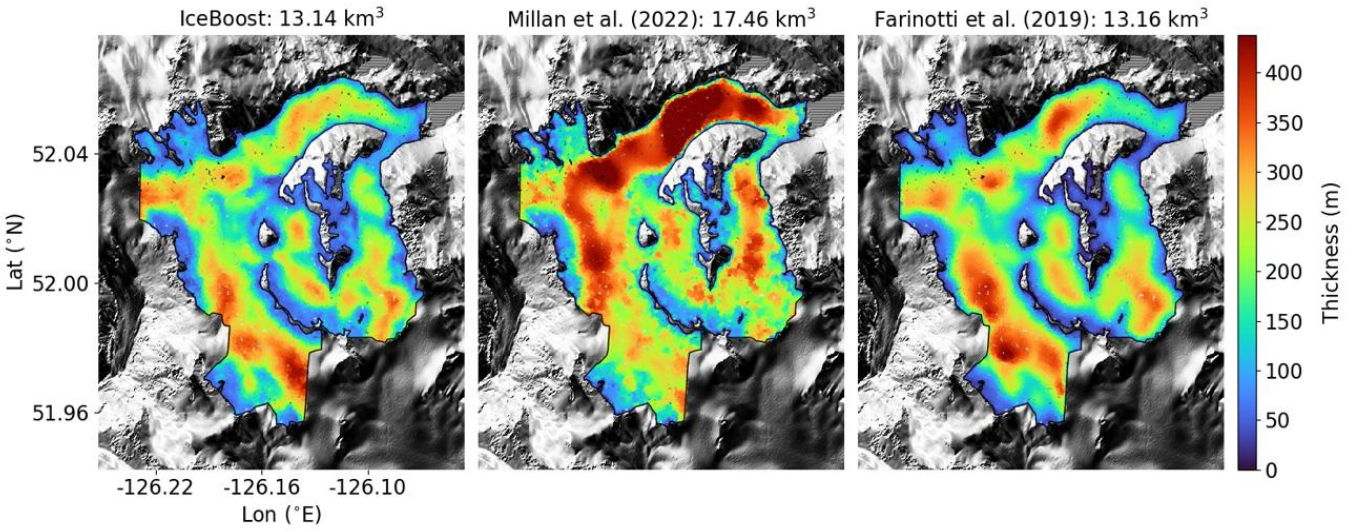

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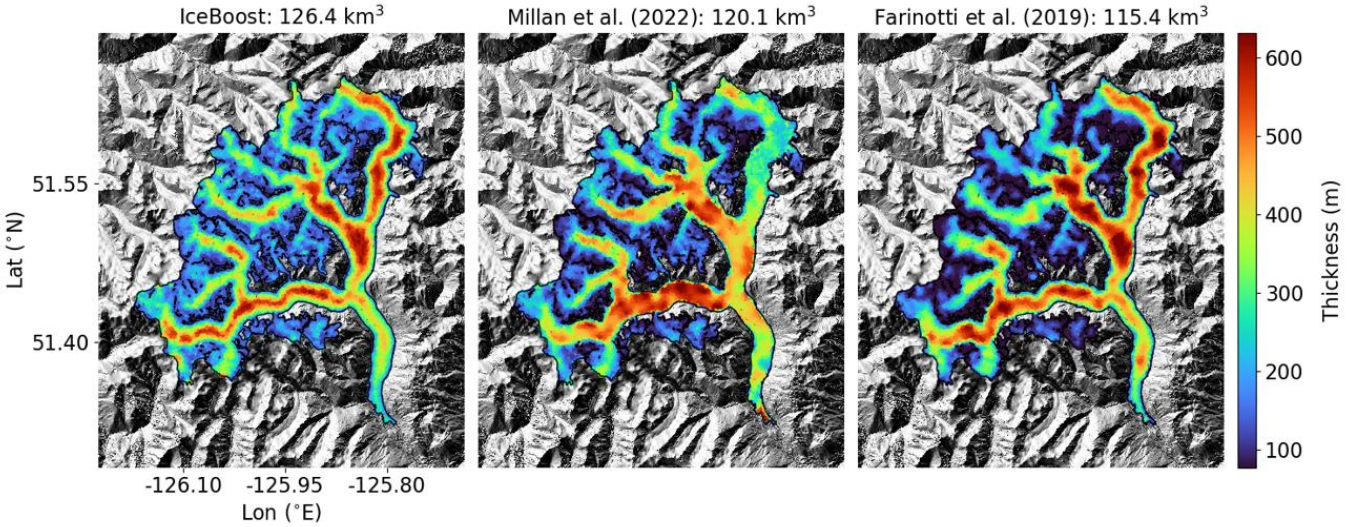

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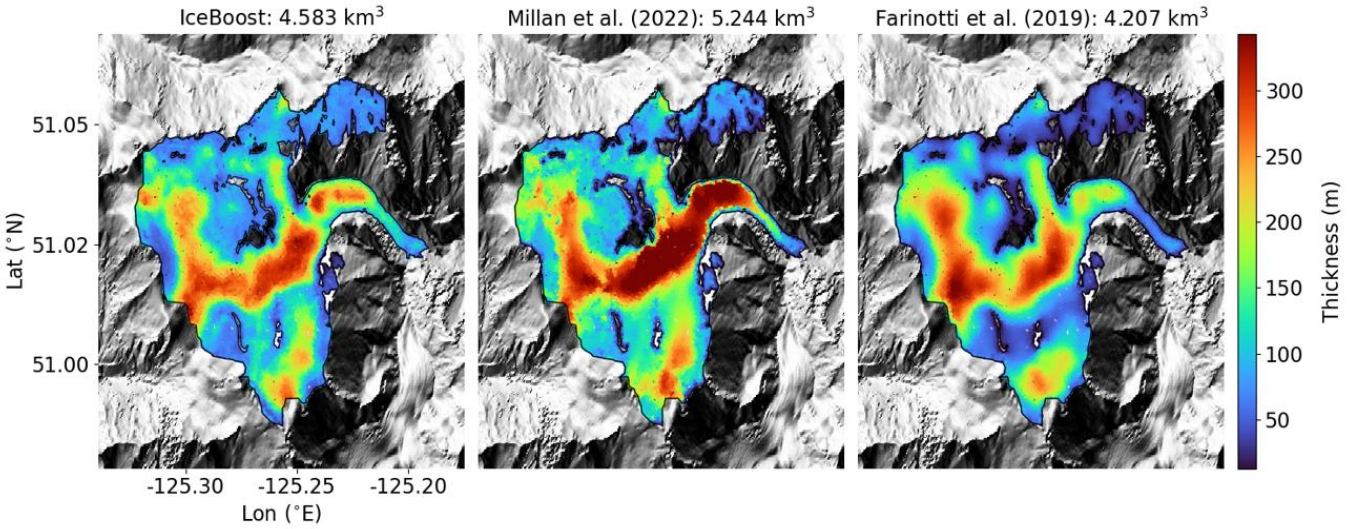

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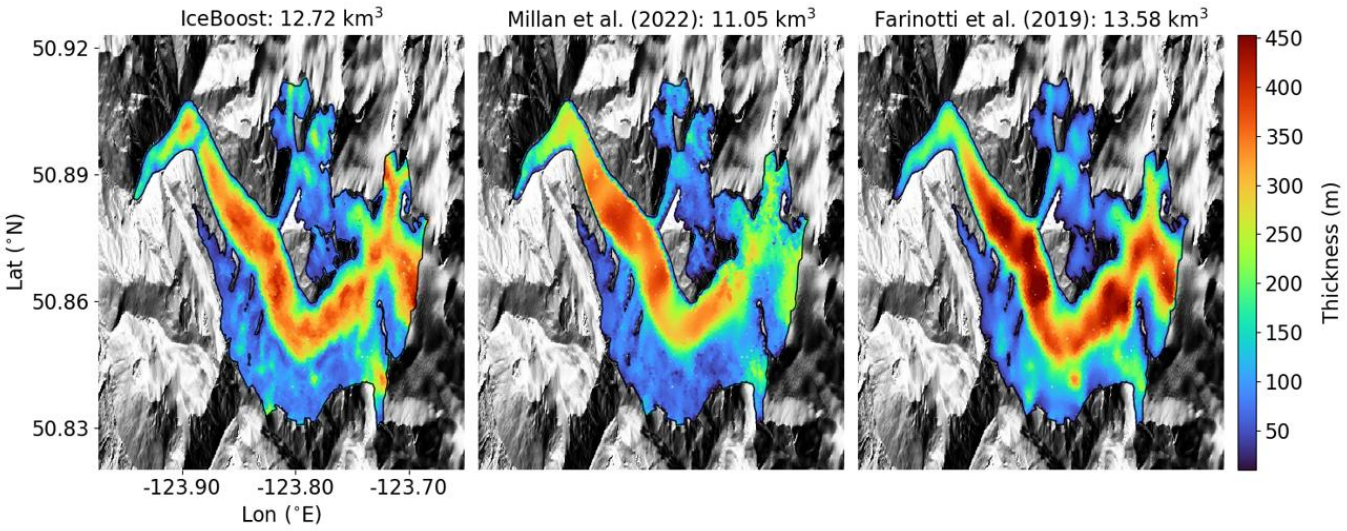

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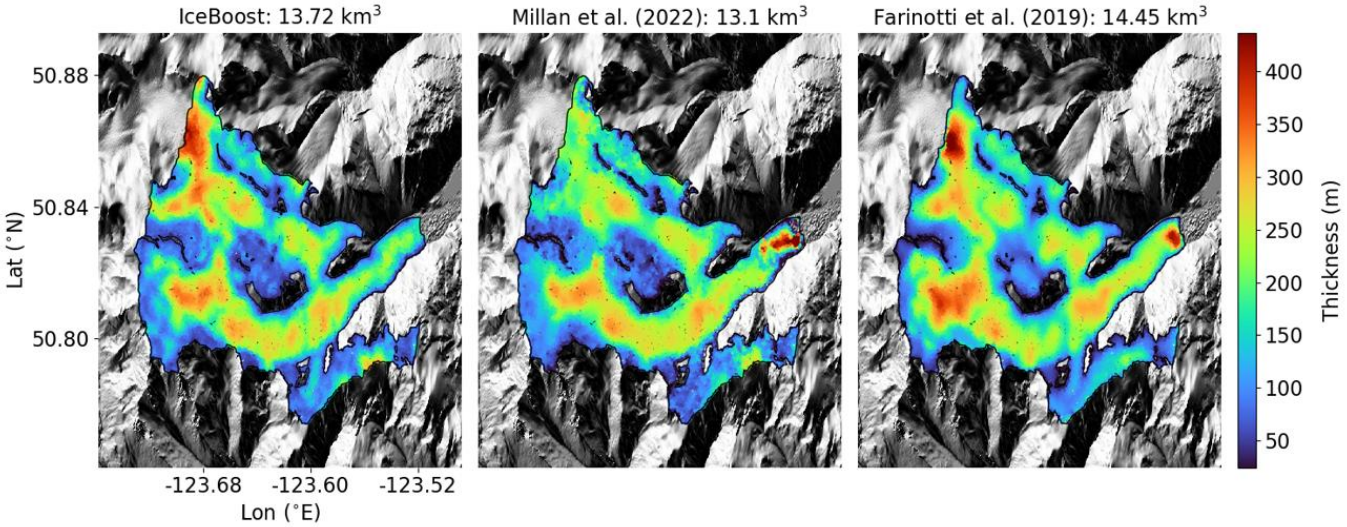

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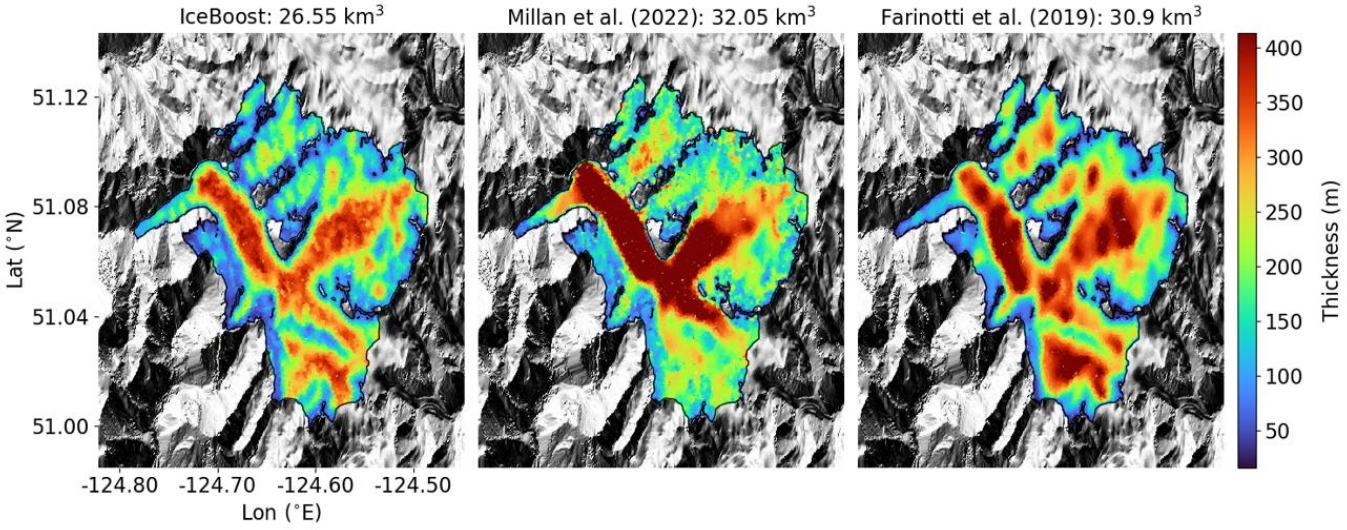

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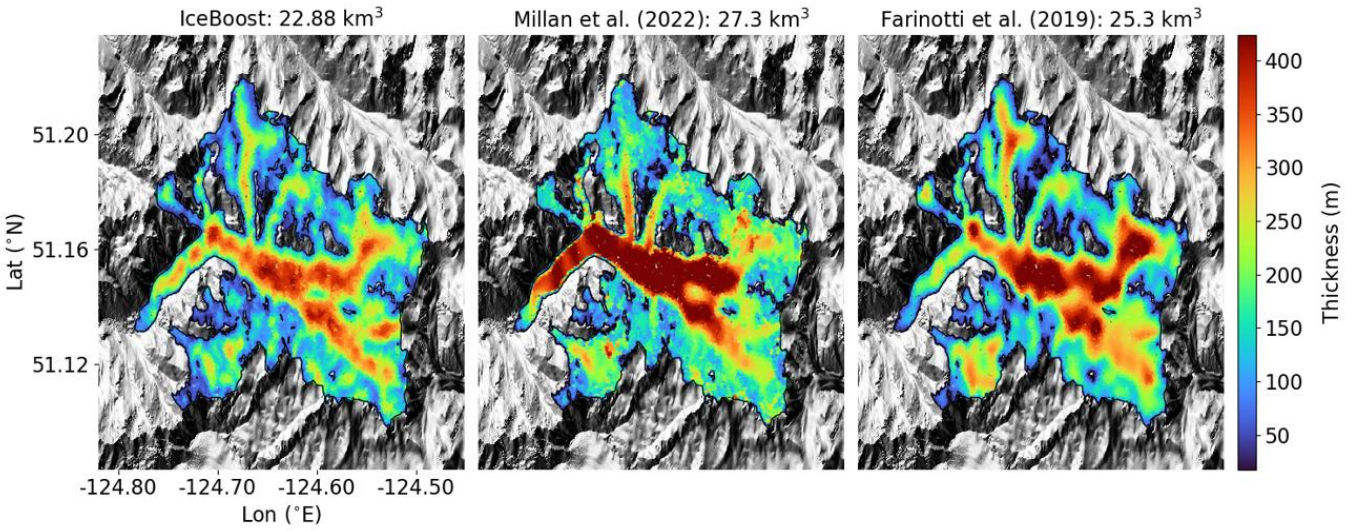

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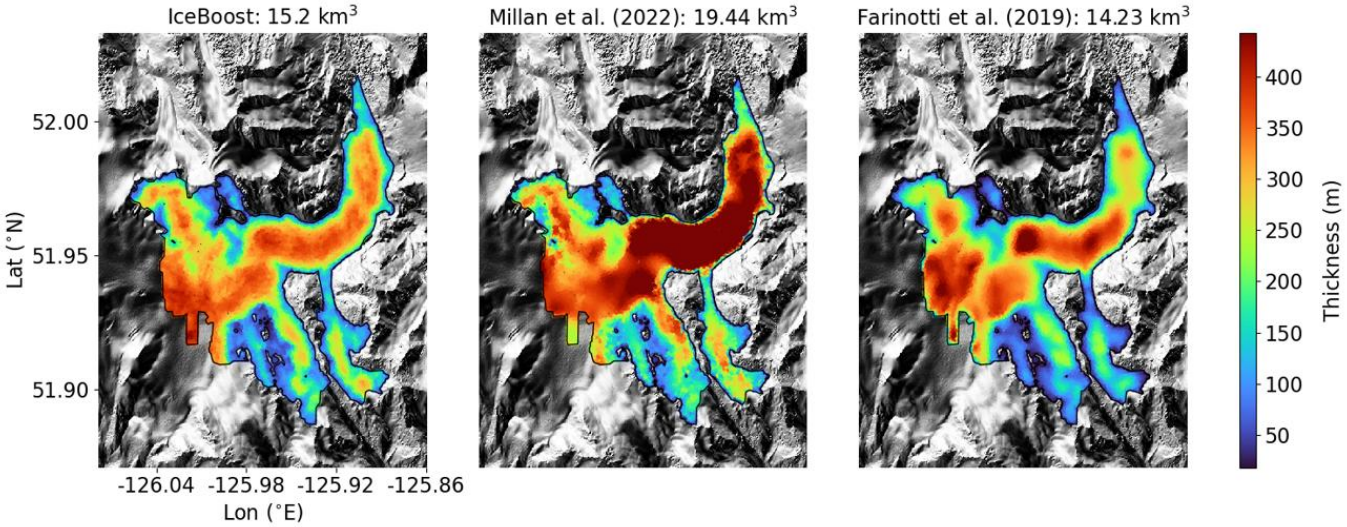

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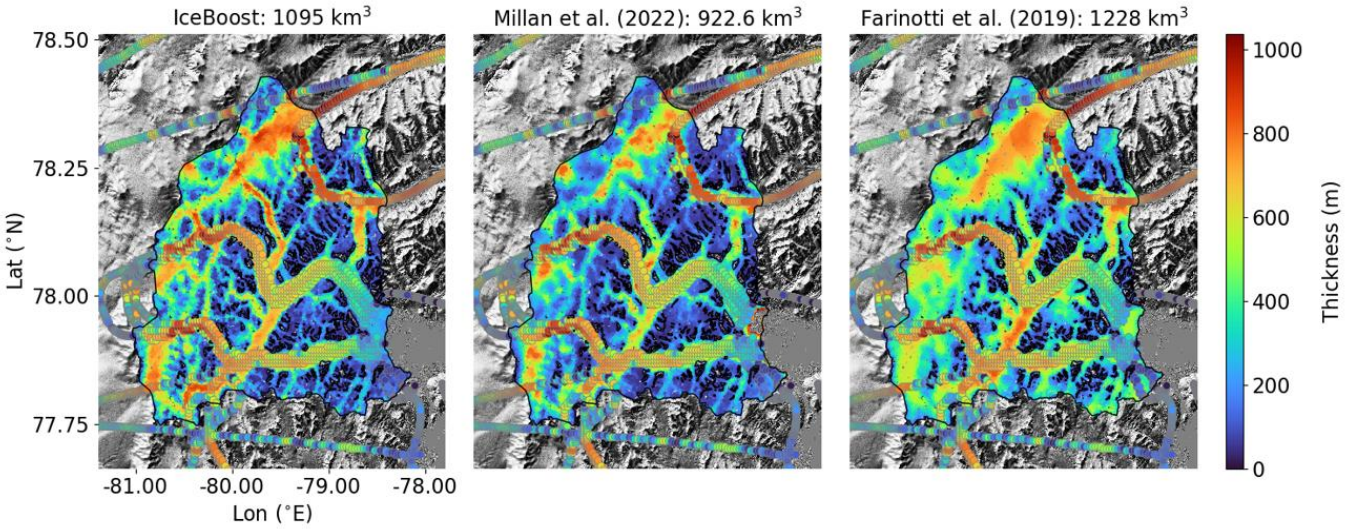

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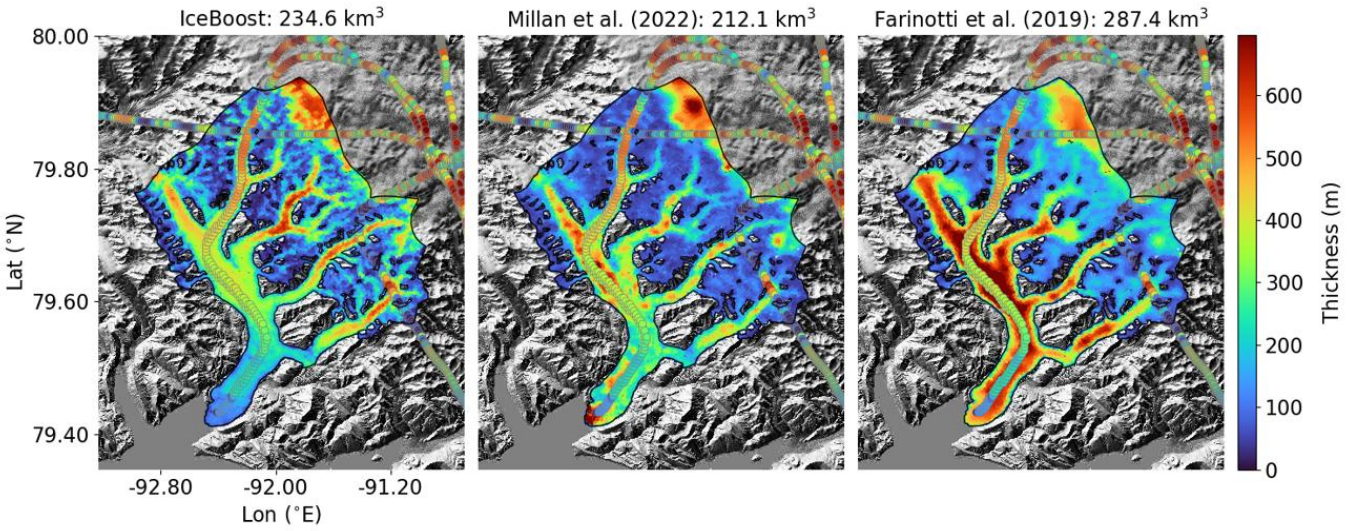

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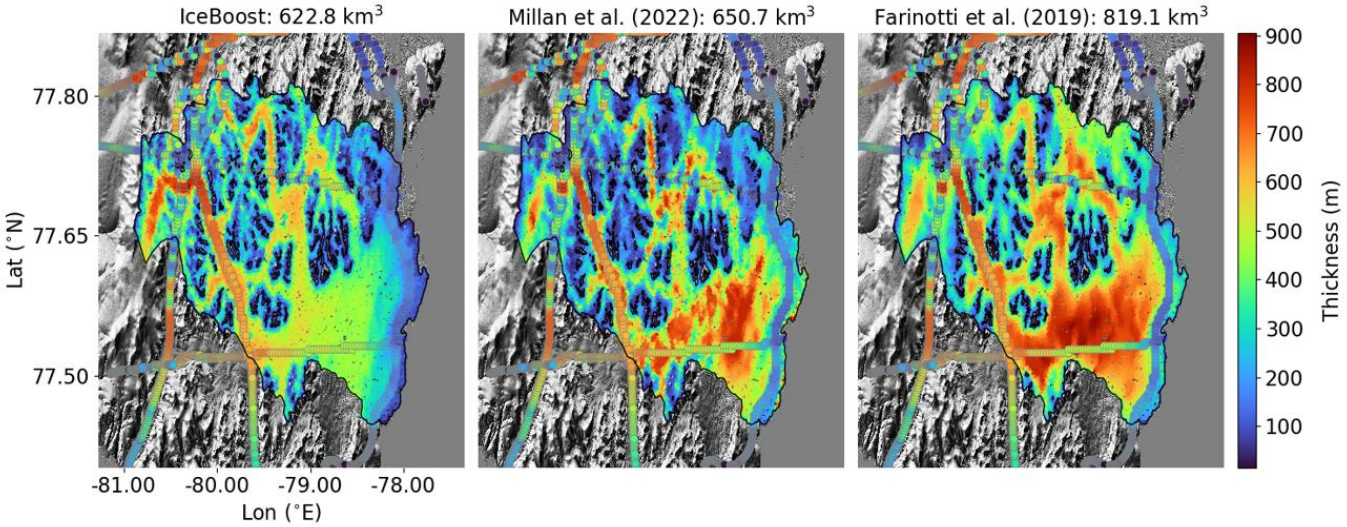

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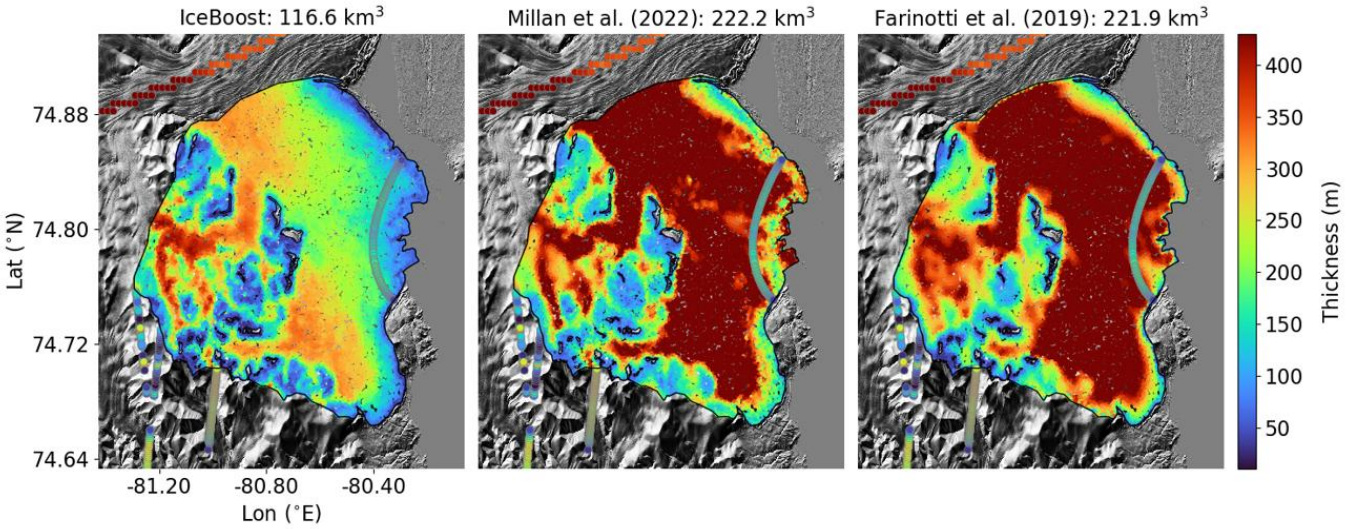

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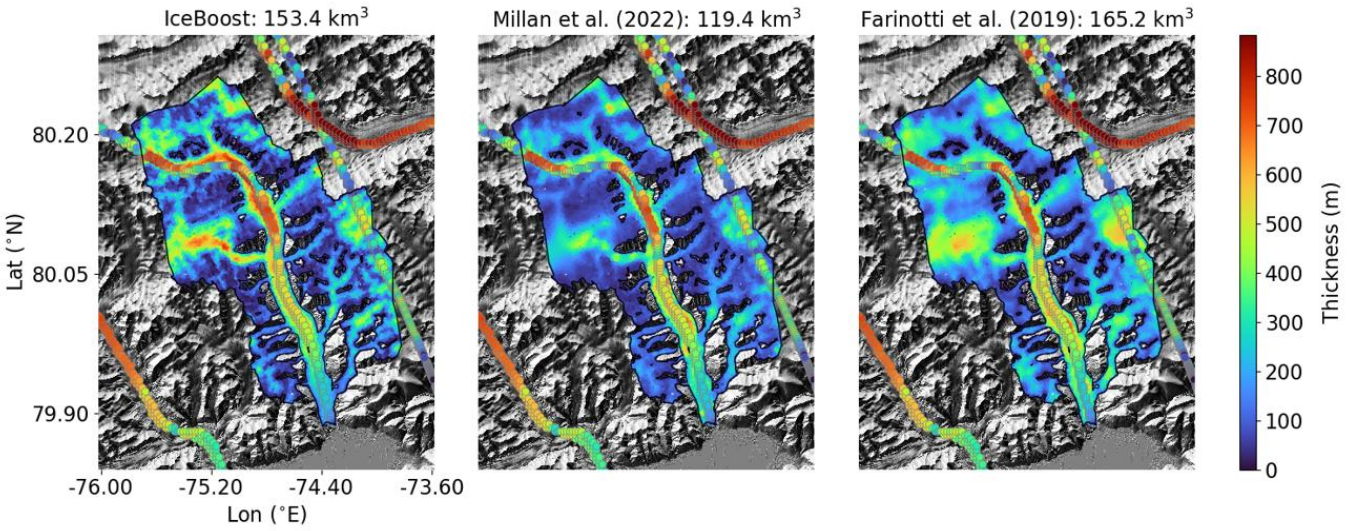

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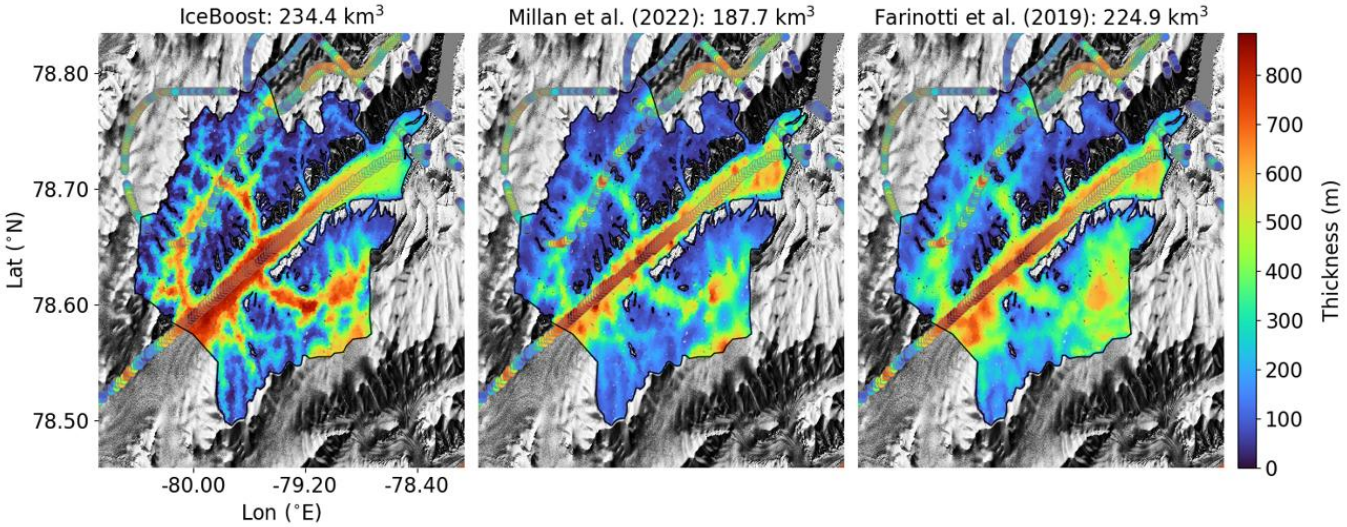

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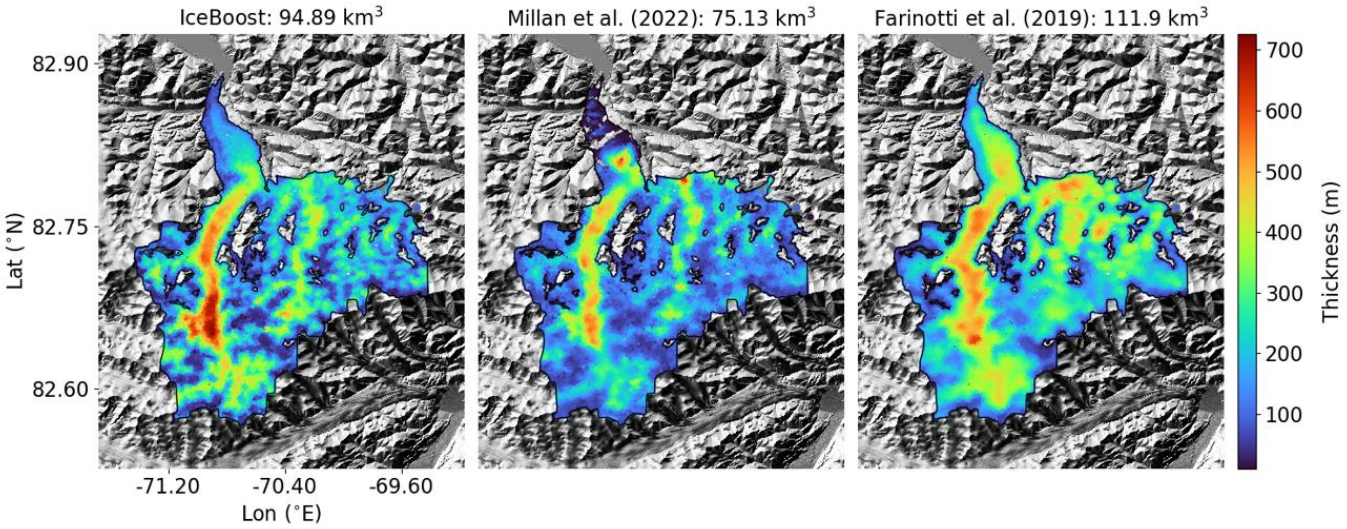

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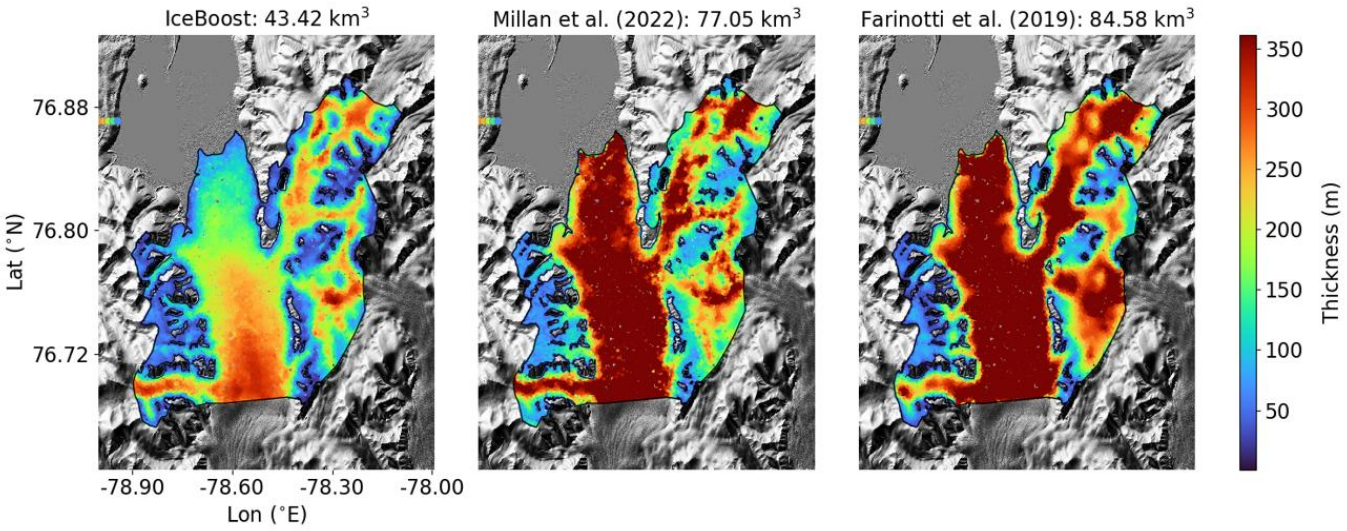

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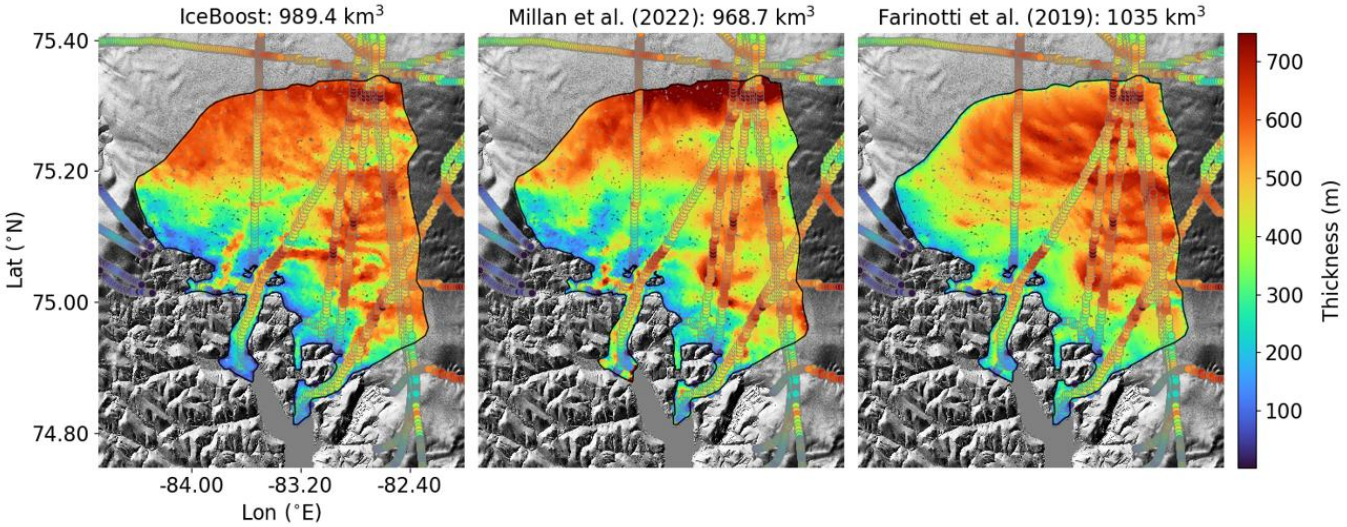

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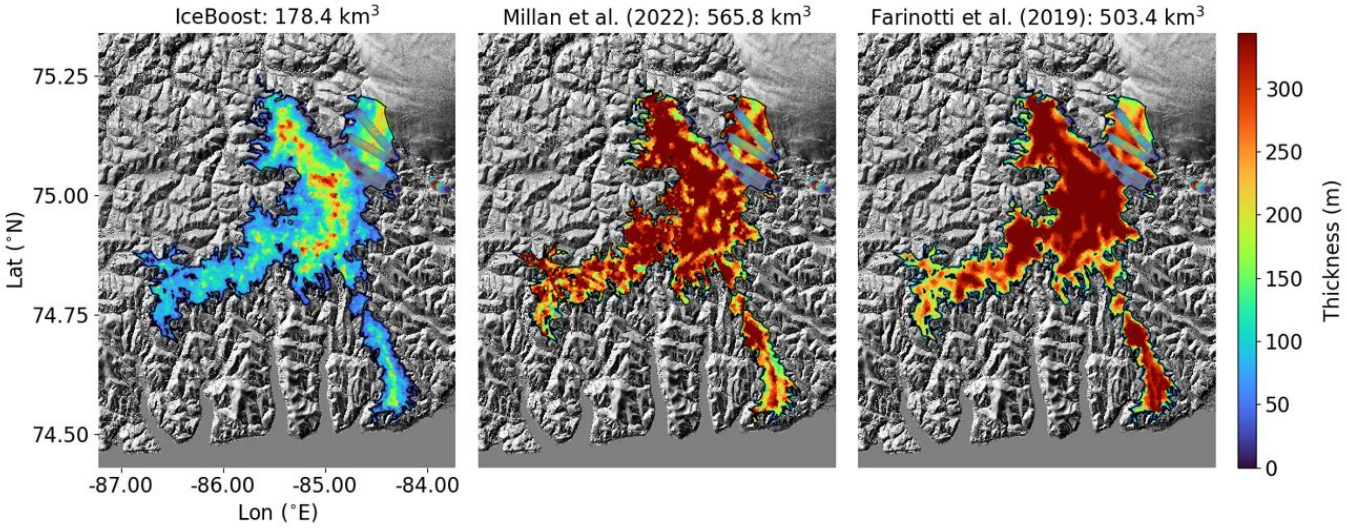

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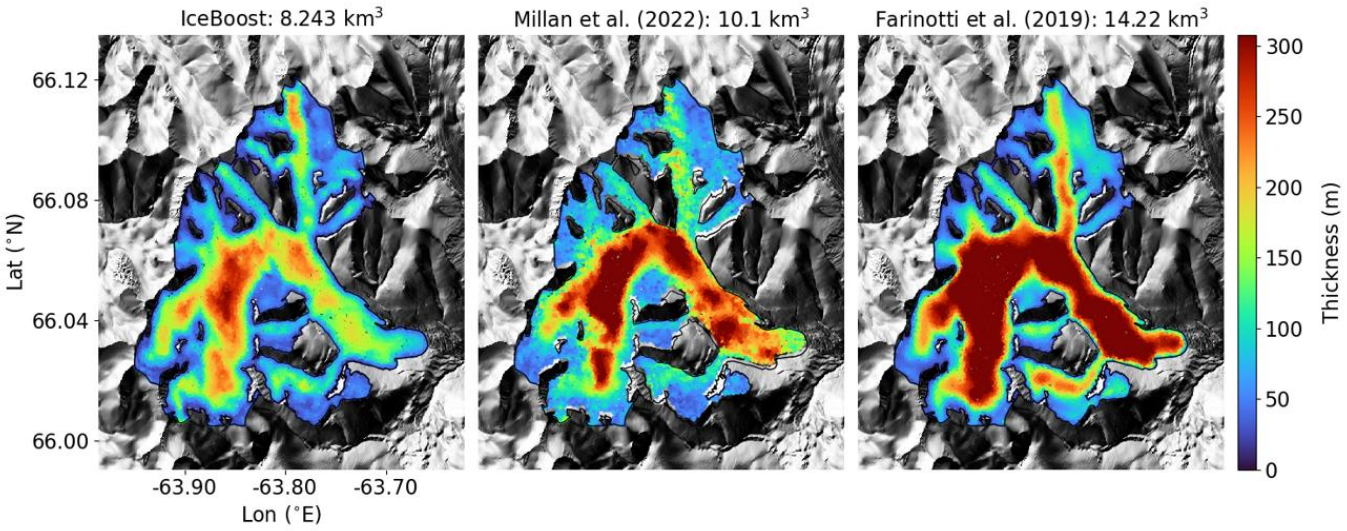

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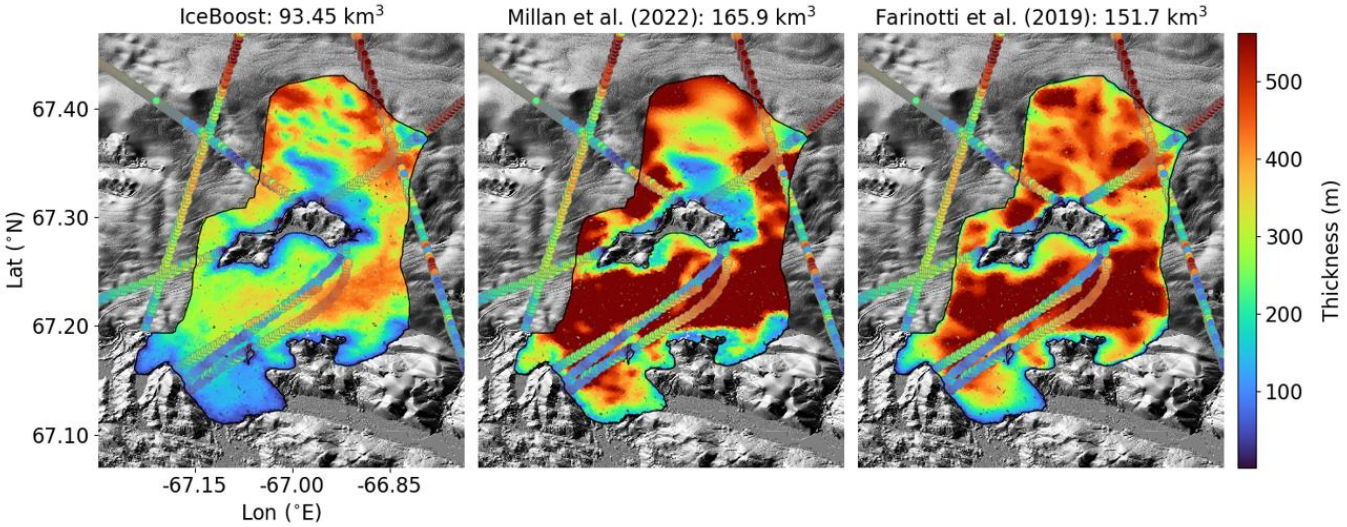

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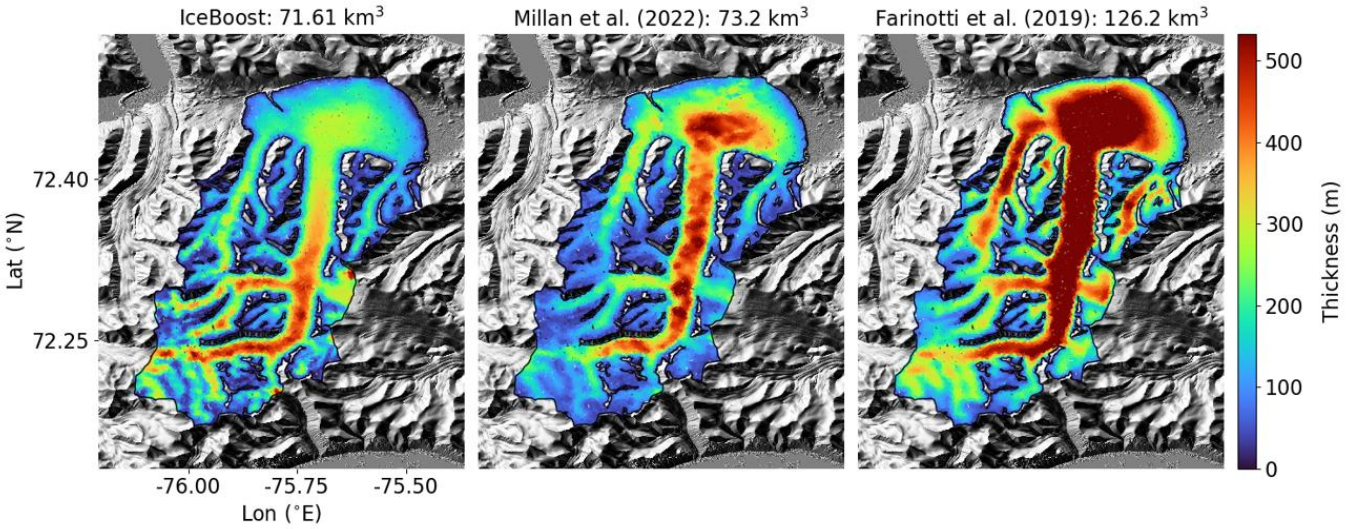

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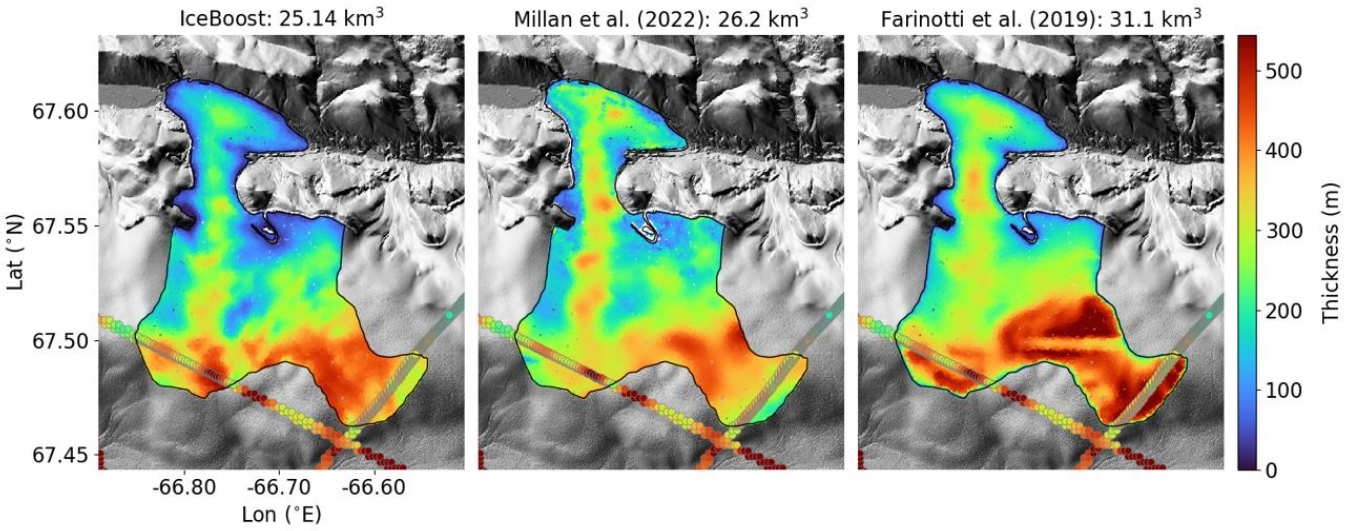

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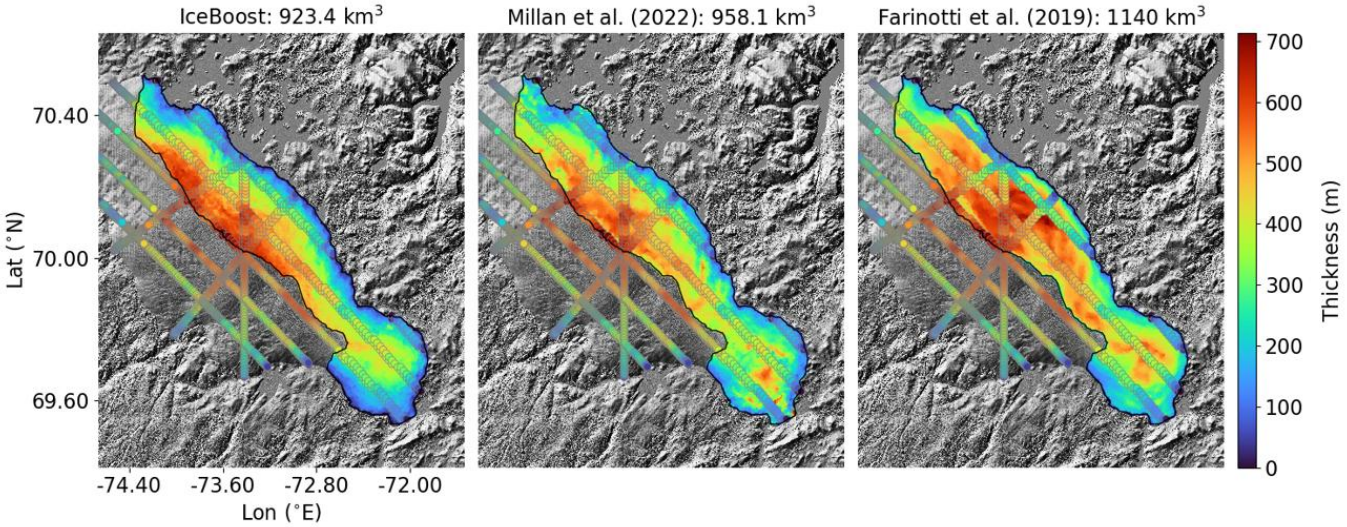

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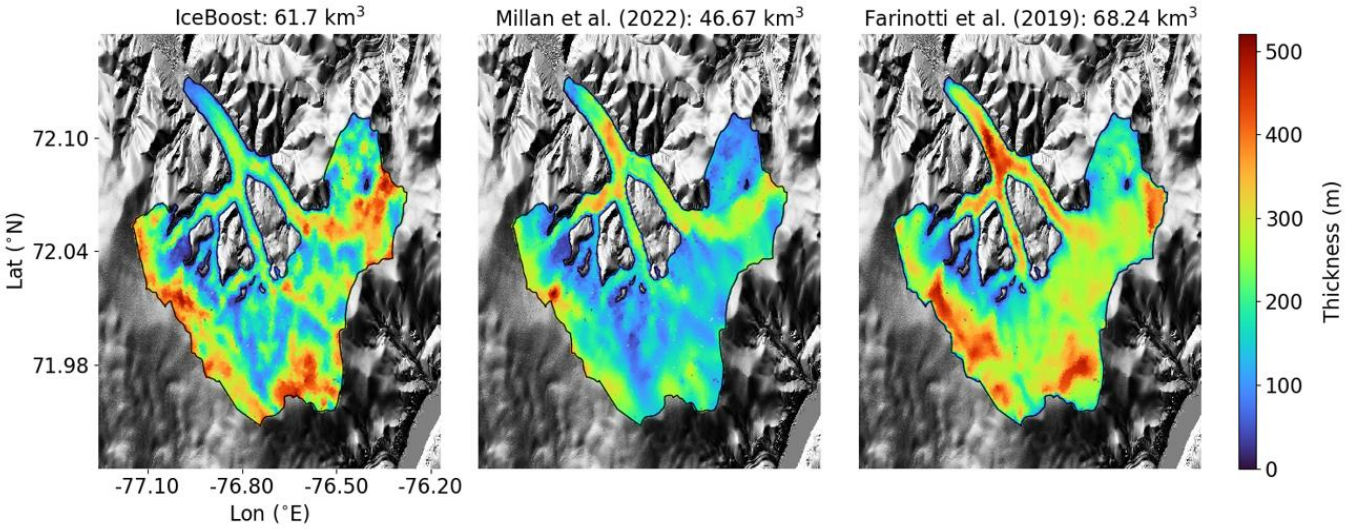

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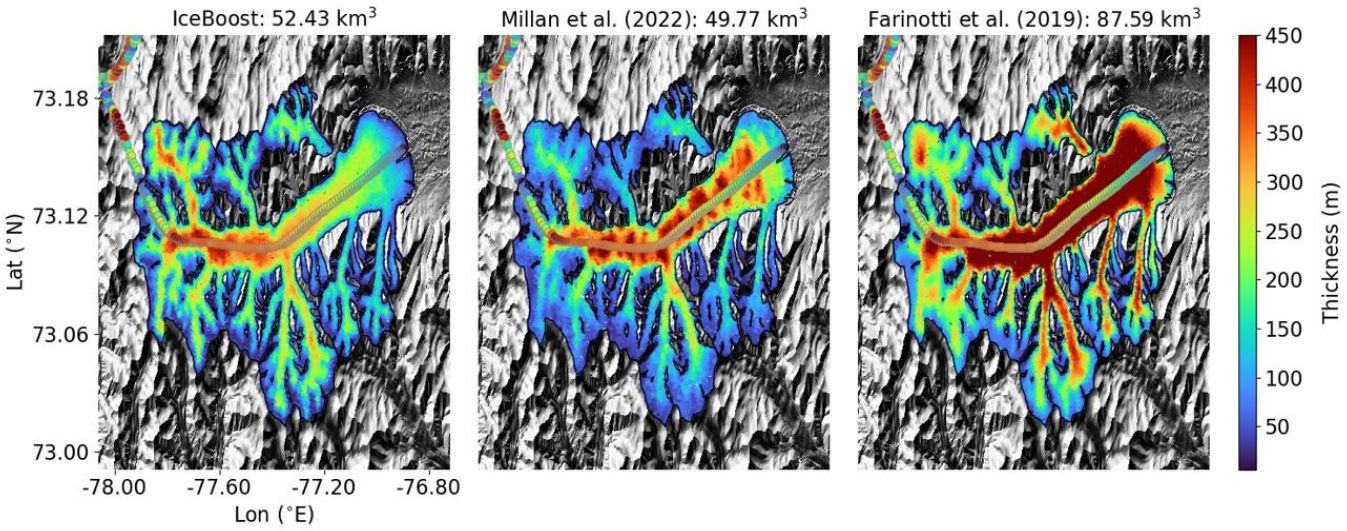

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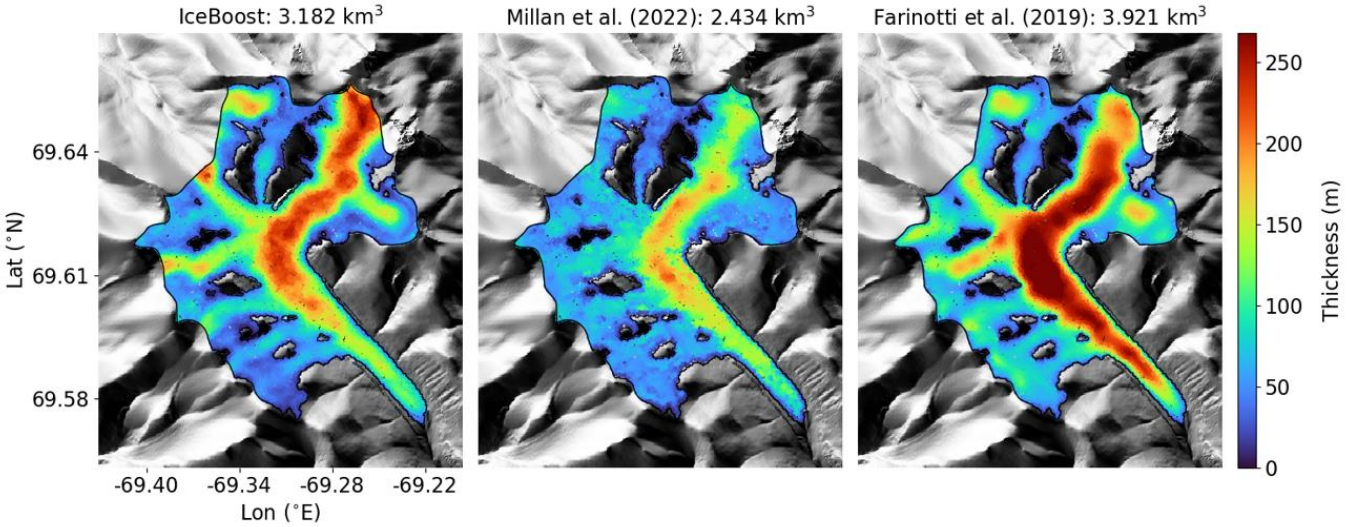

Figure S42: Glacier RGI60-04.02899. Back to Table S2.

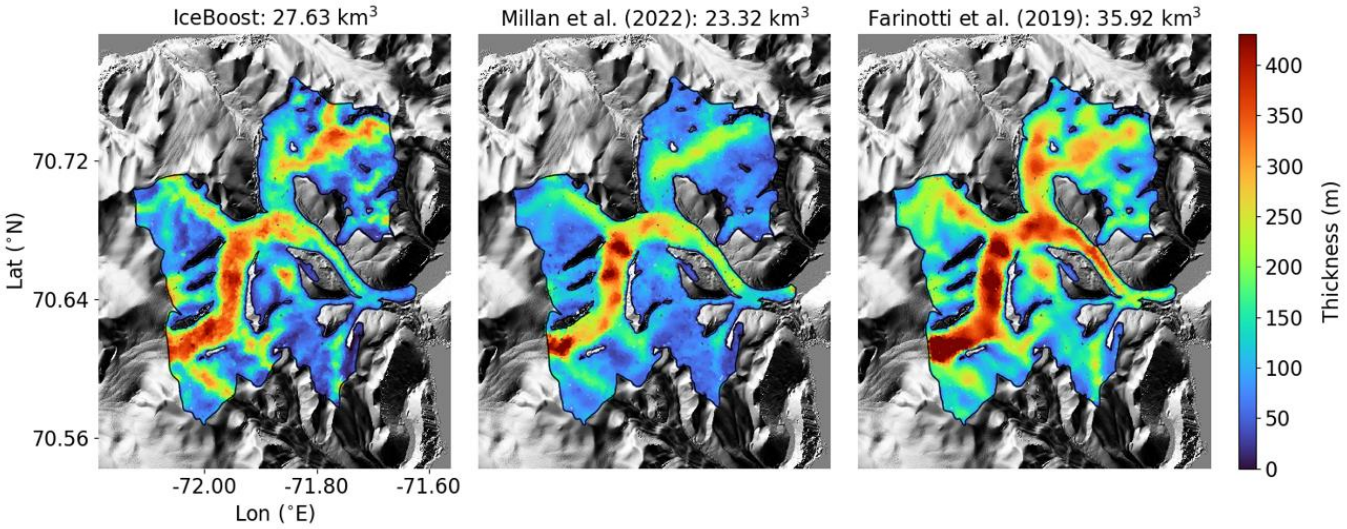

Figure S43: Glacier RGI60-04.03263. Back to Table S2.

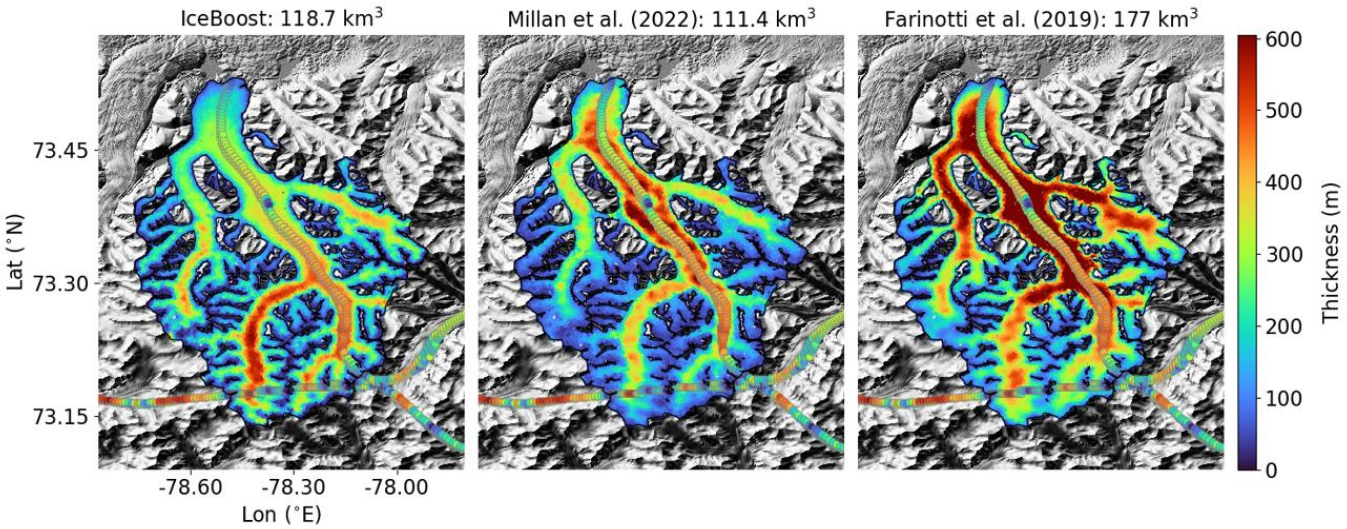

Figure S44: Glacier RGI60-04.07131. Back to Table S2.

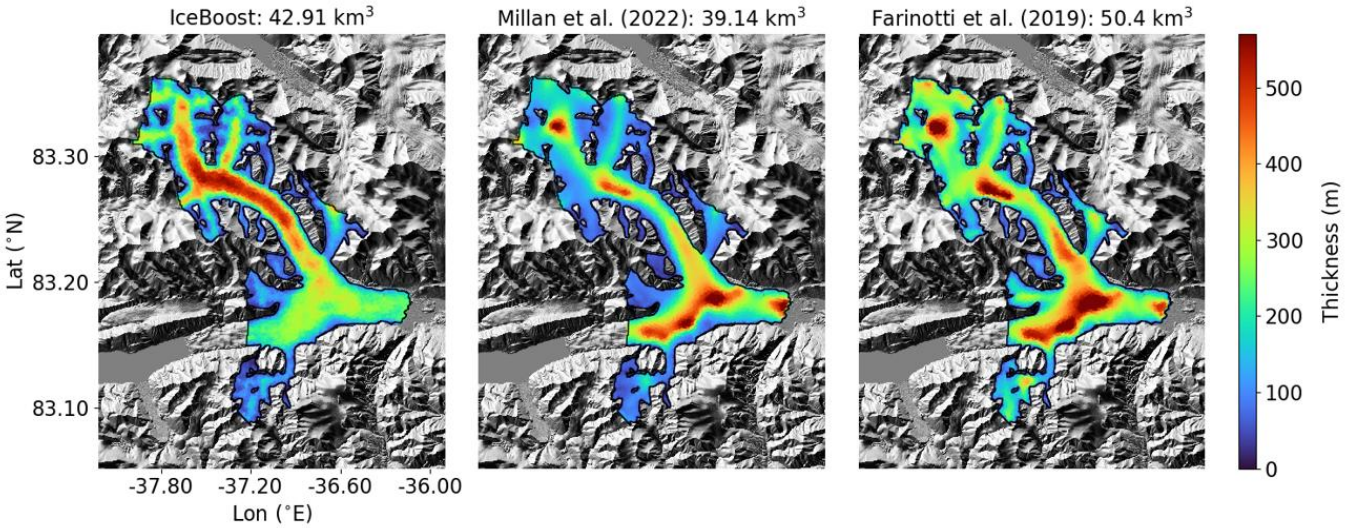

Figure S45: Glacier RGI60-05.10988. Back to Table S2.

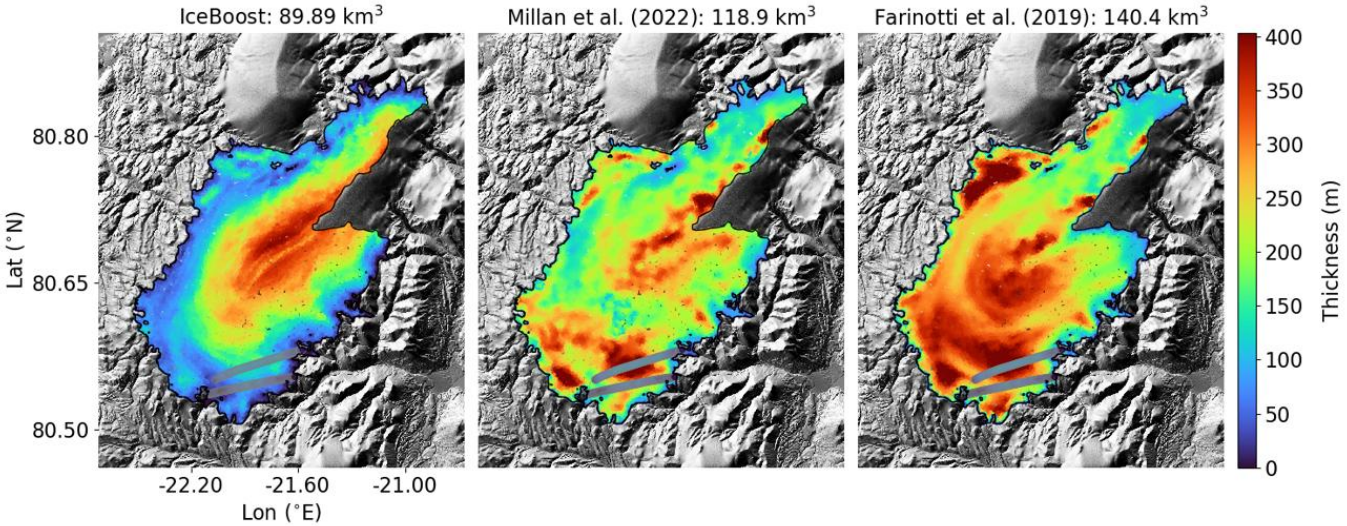

Figure S46: Glacier RGI60-05.10148. Back to Table S2.

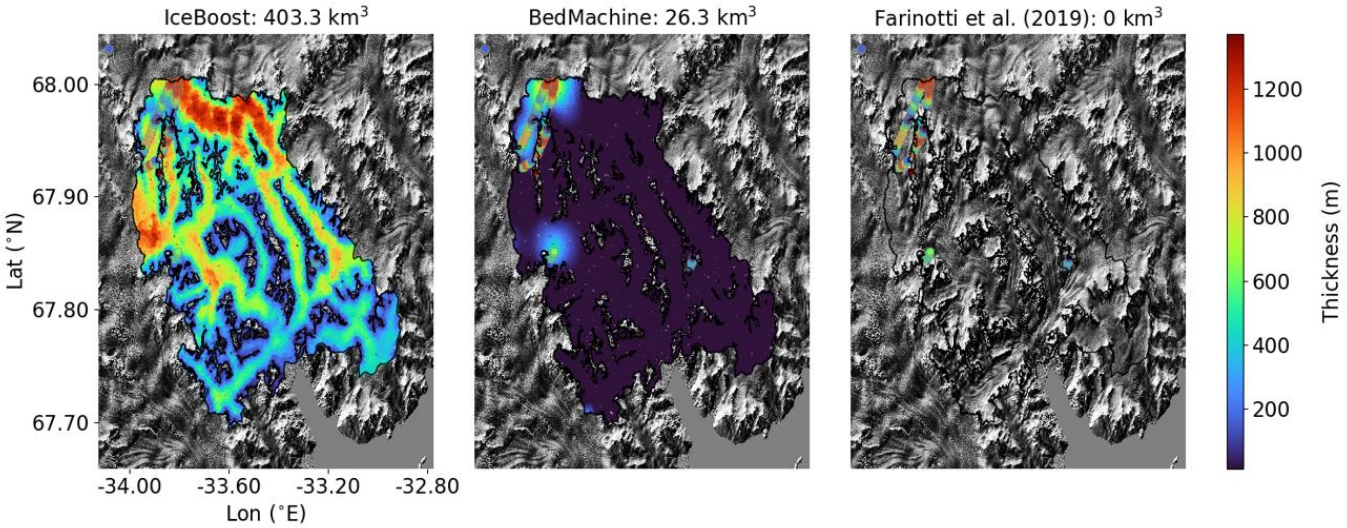

Figure S47: Glacier RGI60-05.12680. Back to Table S2.

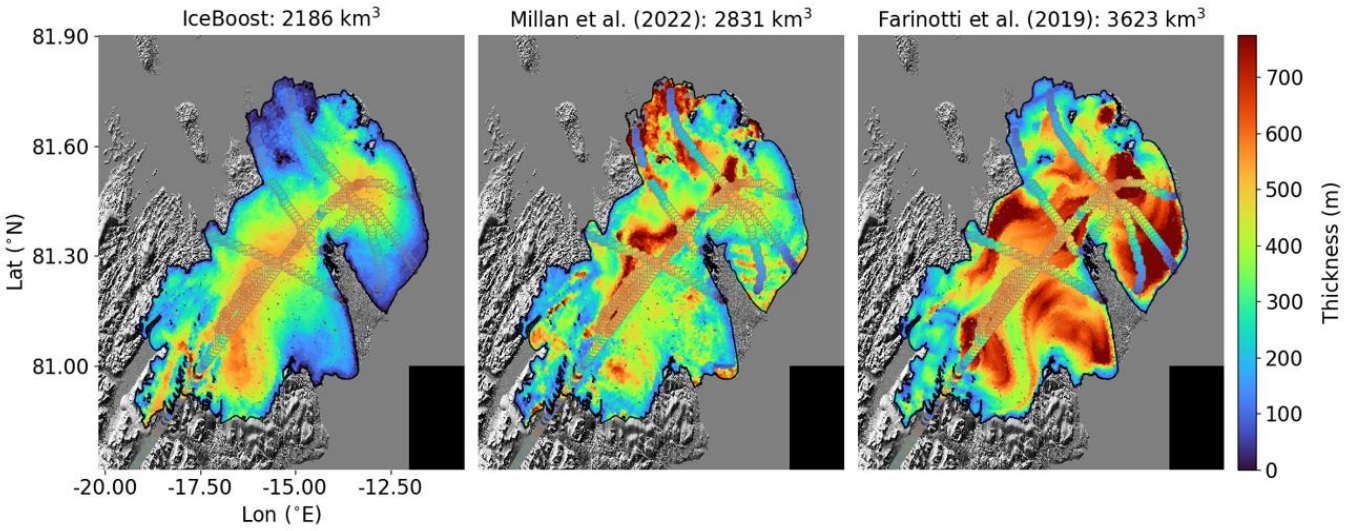

Figure S48: Glacier RGI60-05.10315. Back to Table S2.

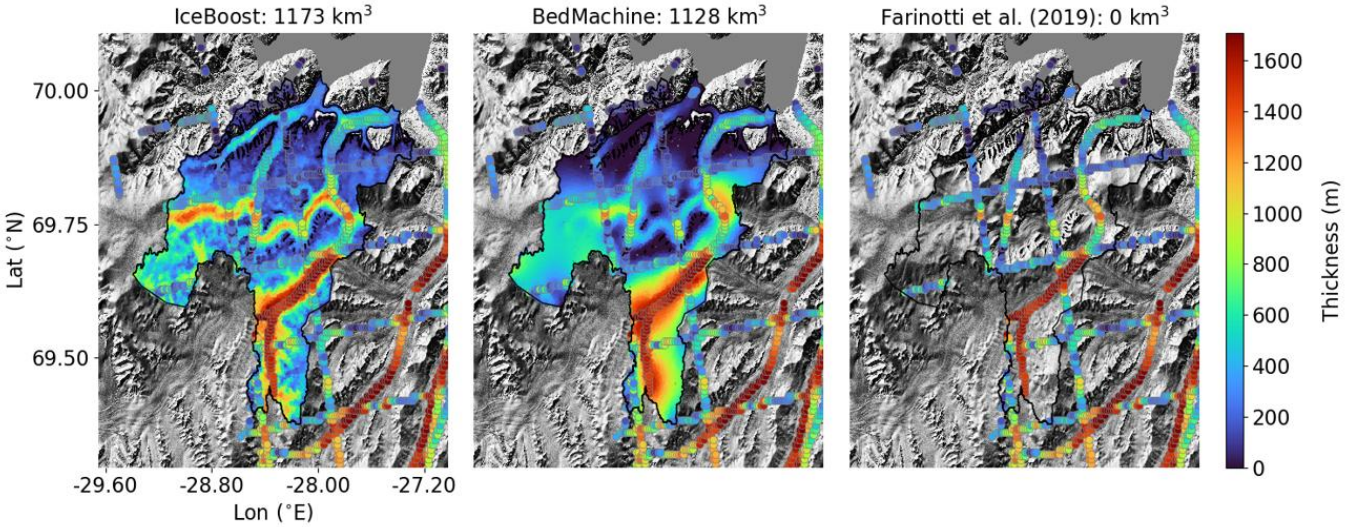

Figure S49: Glacier RGI60-05.13567. Back to Table S2.

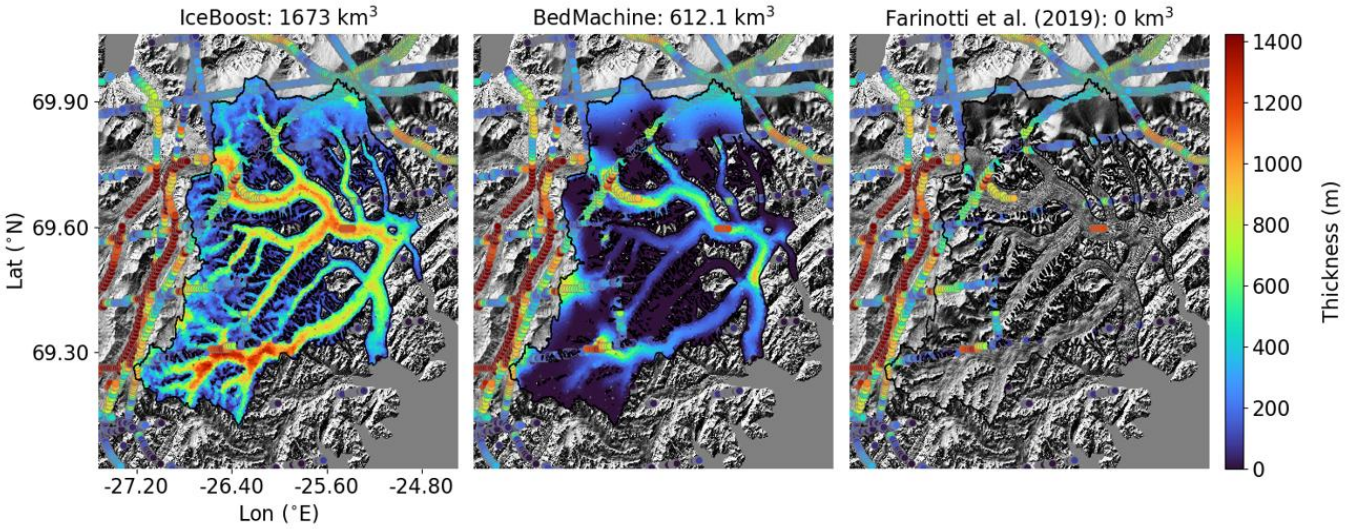

Figure S50: Glacier RGI60-05.13575. Back to Table S2.

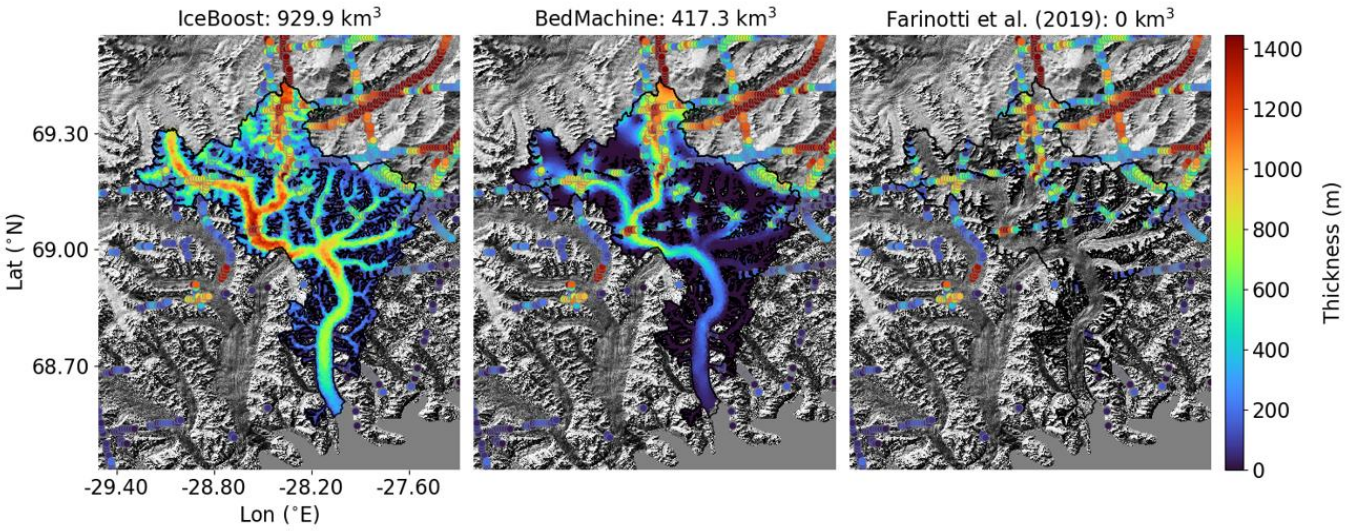

Figure S51: Glacier RGI60-05.13536. Back to Table S2.

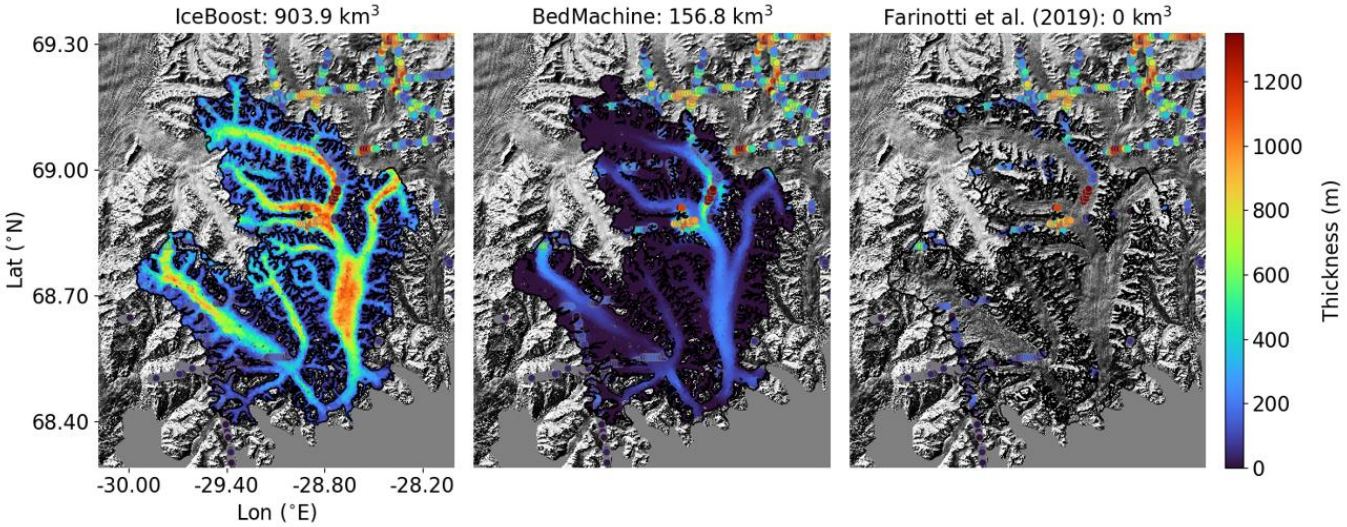

Figure S52: Glacier RGI60-05.13667. Back to Table S2.

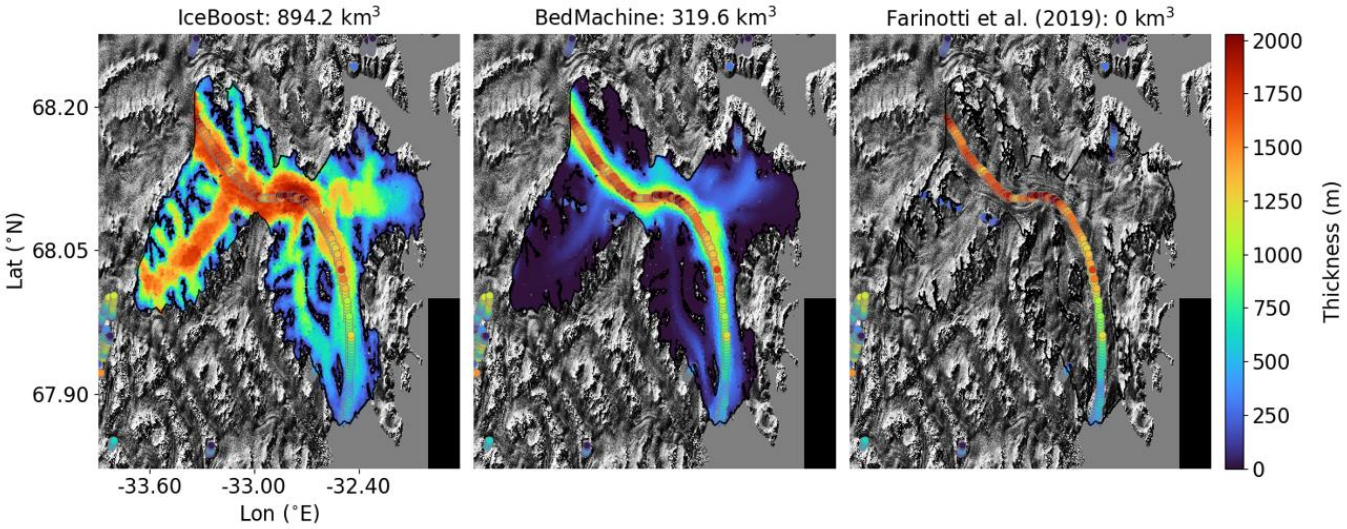

Figure S53: Glacier RGI60-05.12685. Back to Table S2.

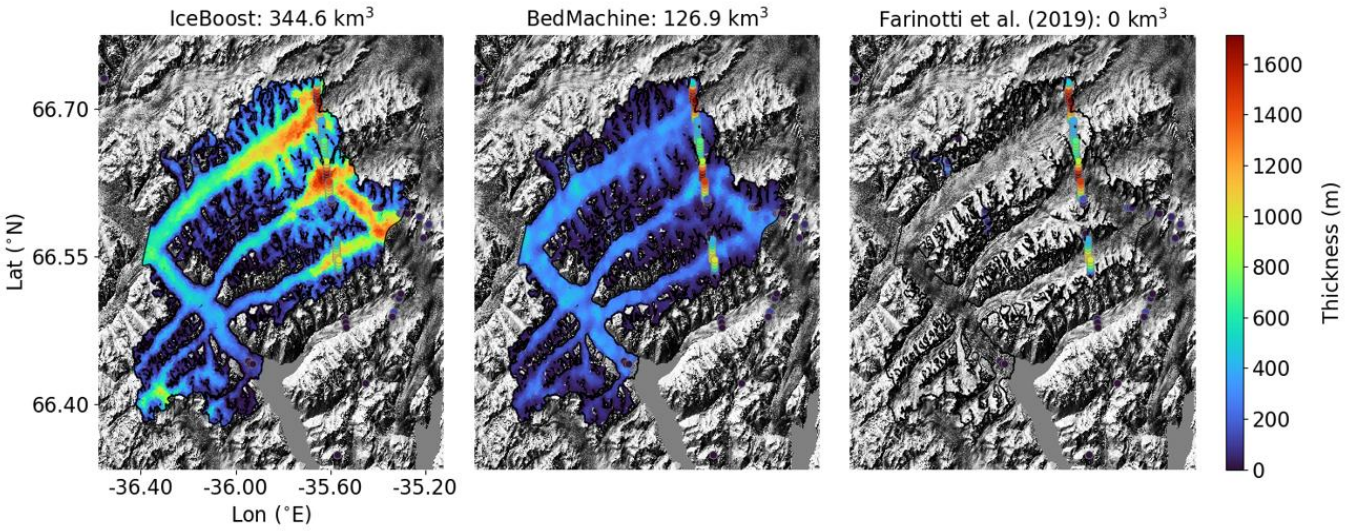

Figure S54: Glacier RGI60-05.13983. Back to Table S2.

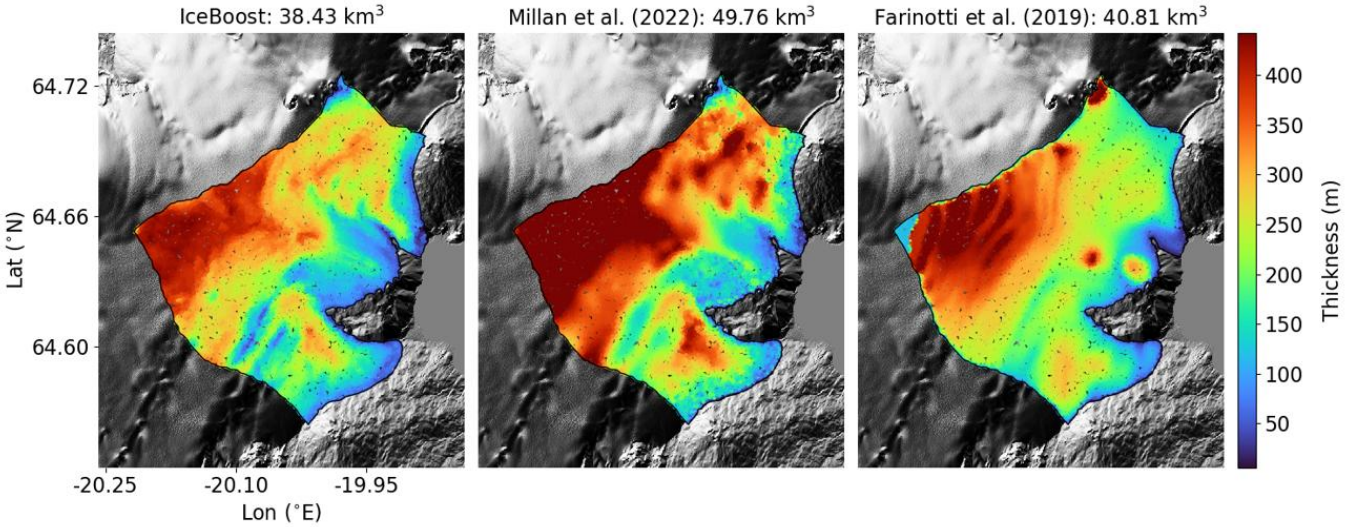

Figure S55: Glacier RGI60-06.00310. Back to Table S2.

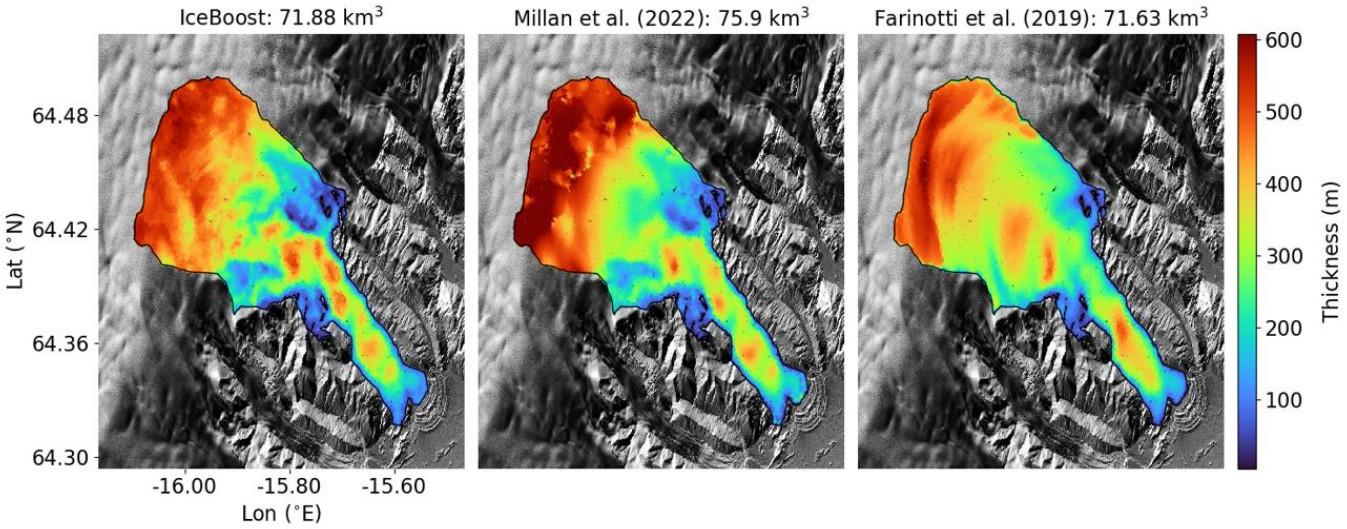

Figure S56: Glacier RGI60-06.00465. Back to Table S2.

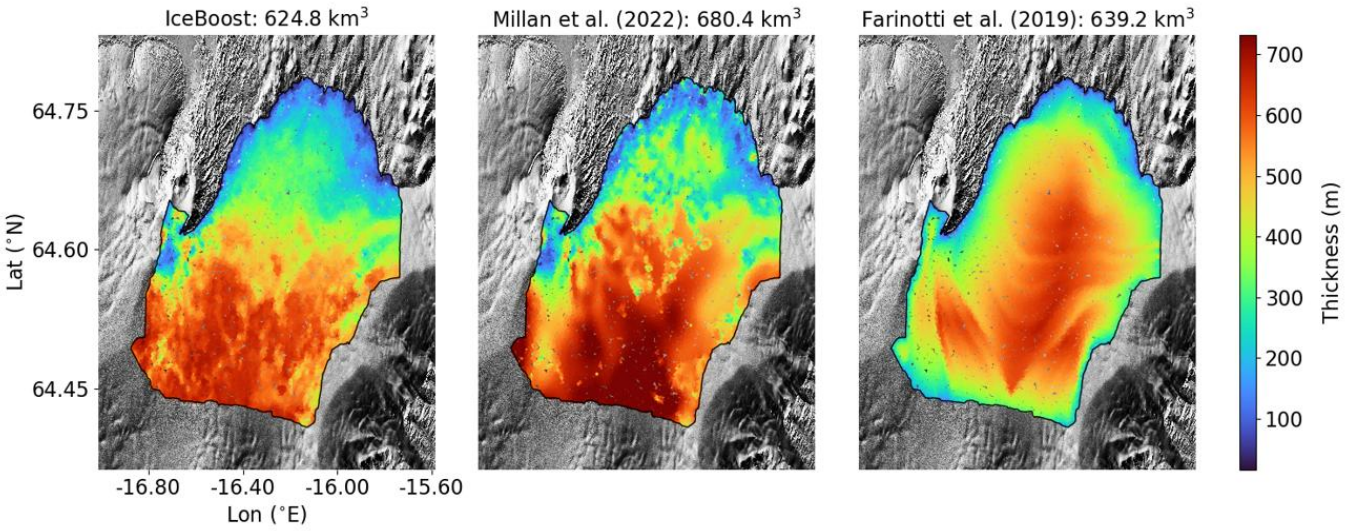

Figure S57: Glacier RGI60-06.00377. Back to Table S2.

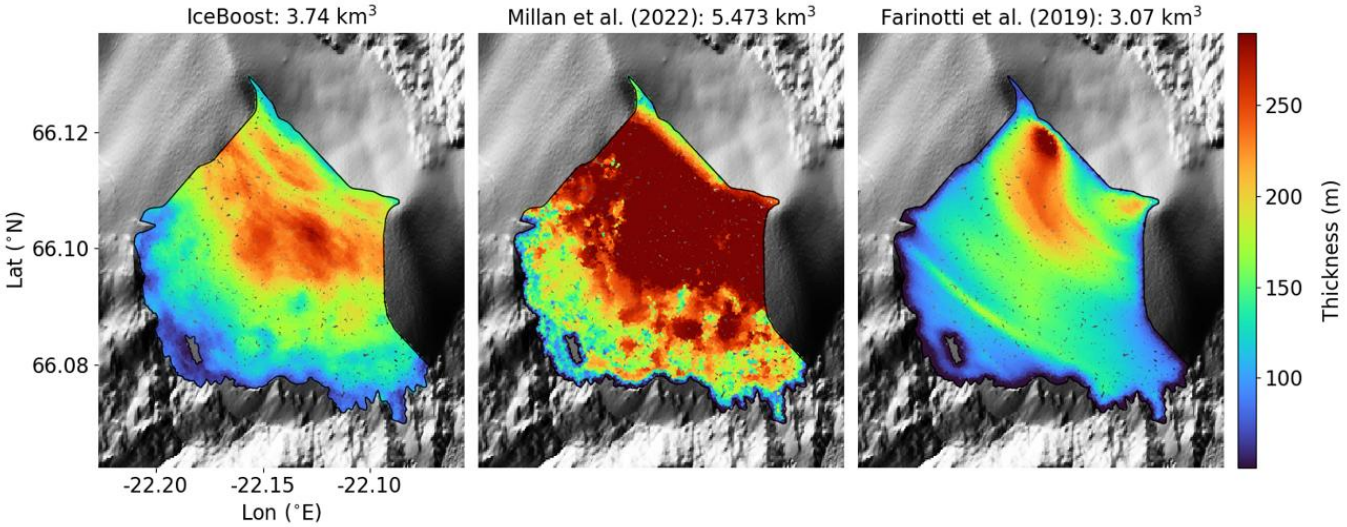

Figure S58: Glacier RGI60-06.00541. Back to Table S2.

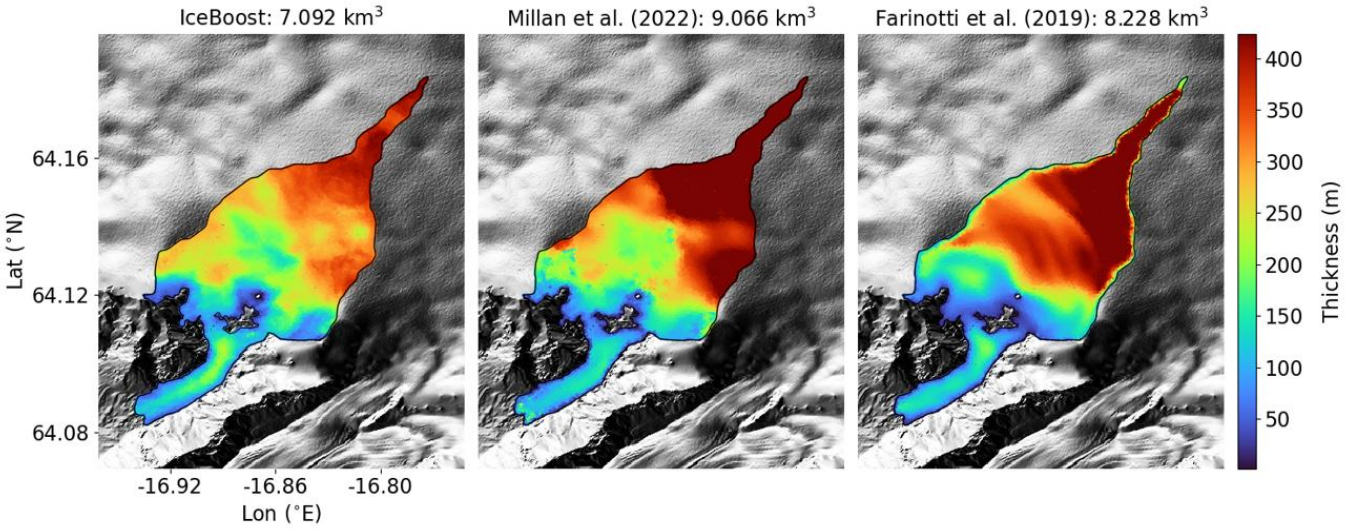

Figure S59: Glacier RGI60-06.00481. Back to Table S2.

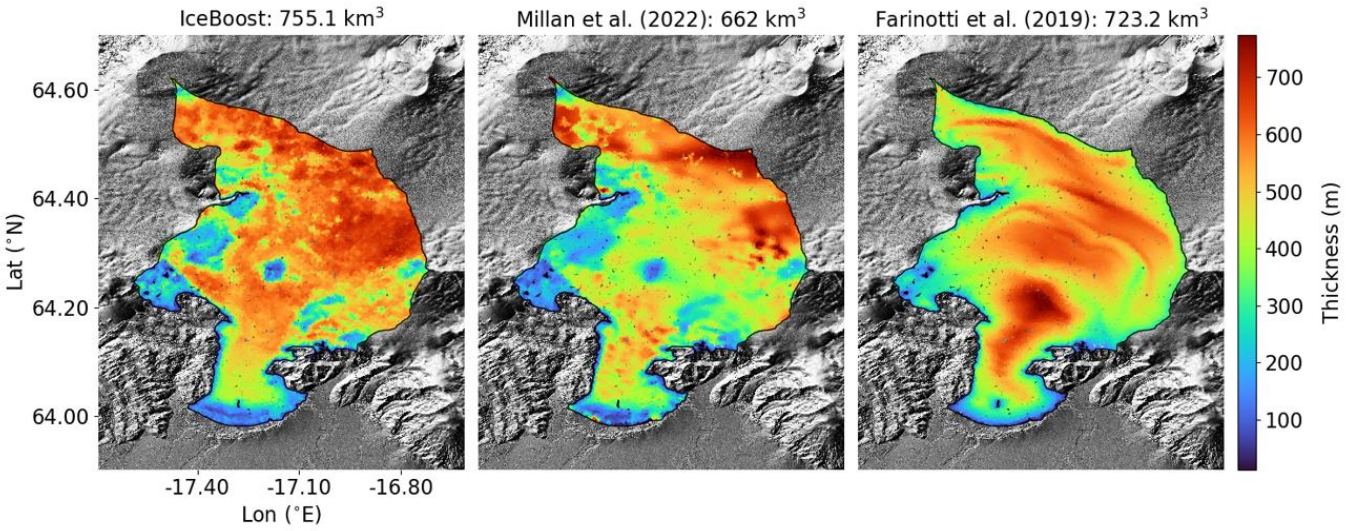

Figure S60: Glacier RGI60-06.00475. Back to Table S2.

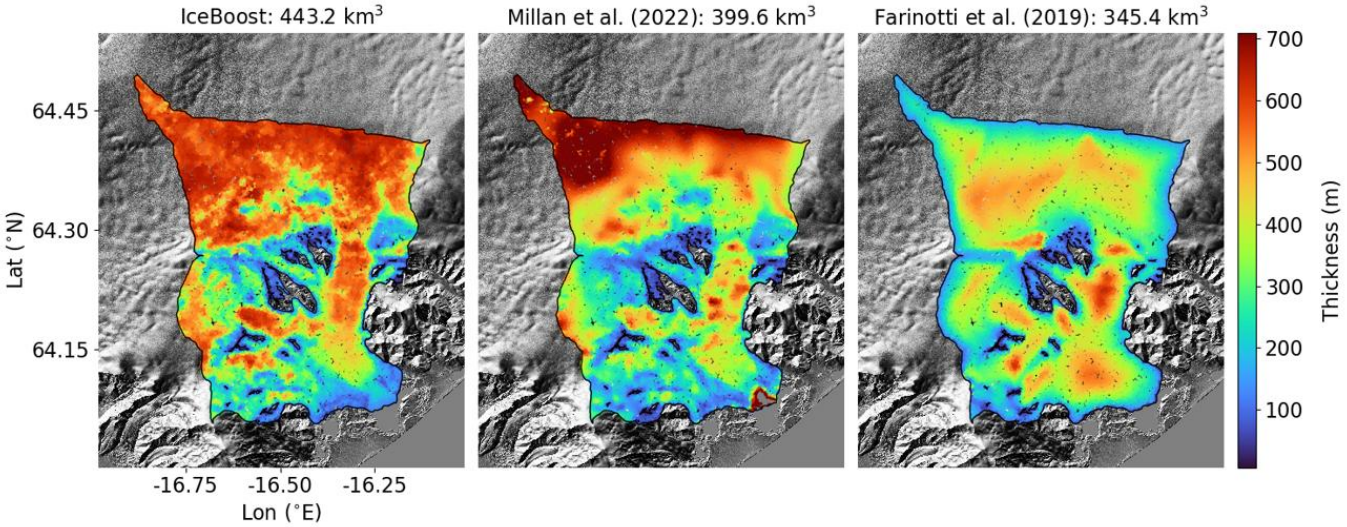

Figure S61: Glacier RGI60-06.00483. Back to Table S2.

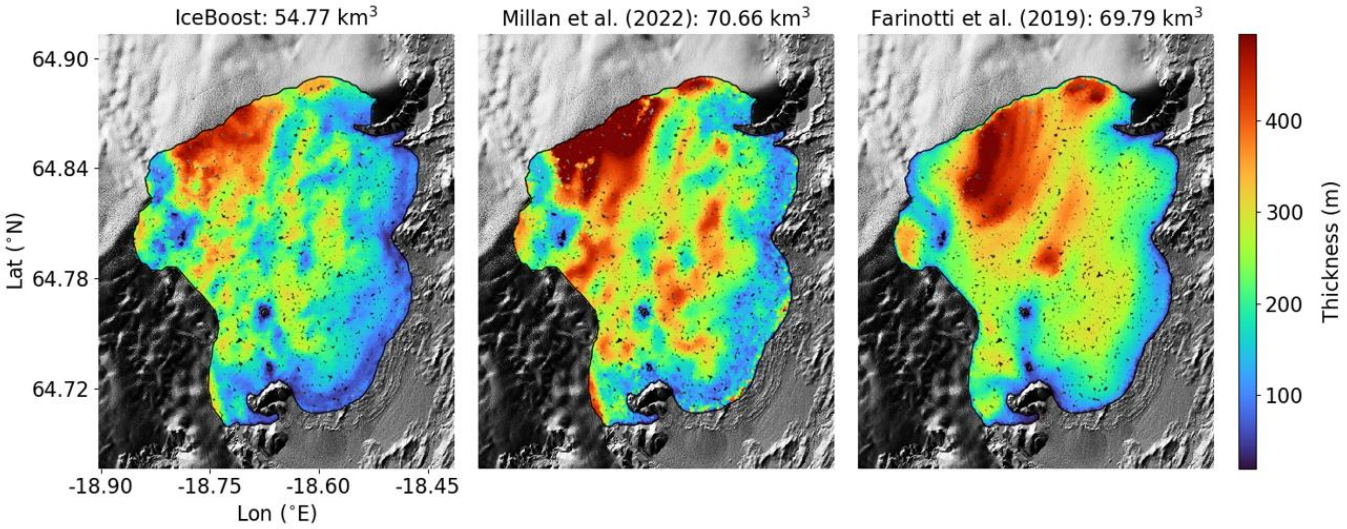

Figure S62: Glacier RGI60-06.00234. Back to Table S2.

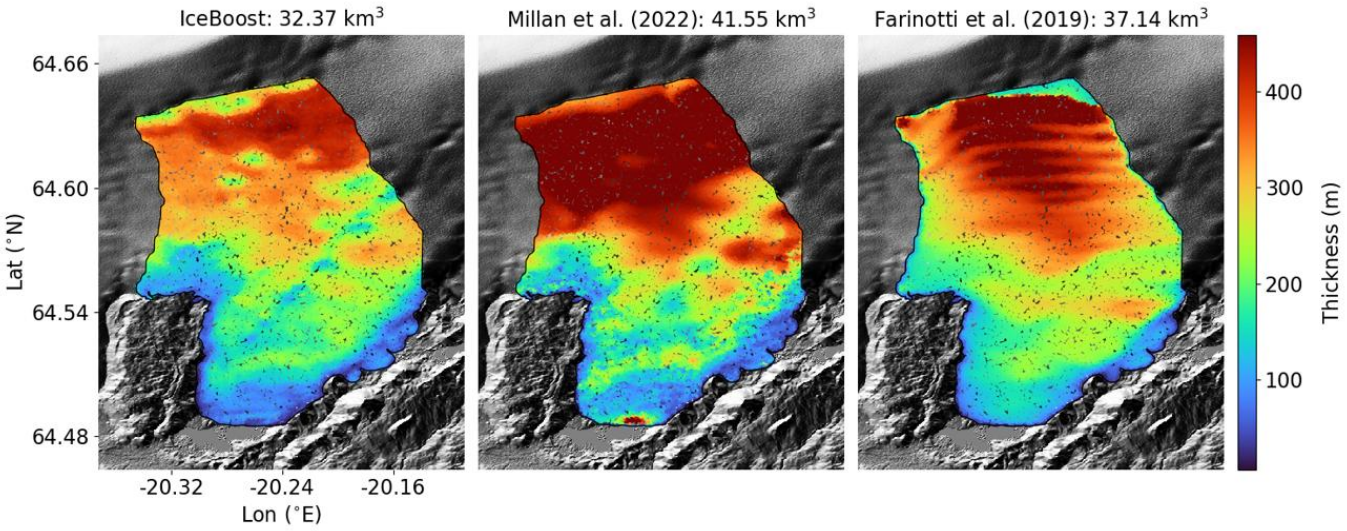

Figure S63: Glacier RGI60-06.00309. Back to Table S2.

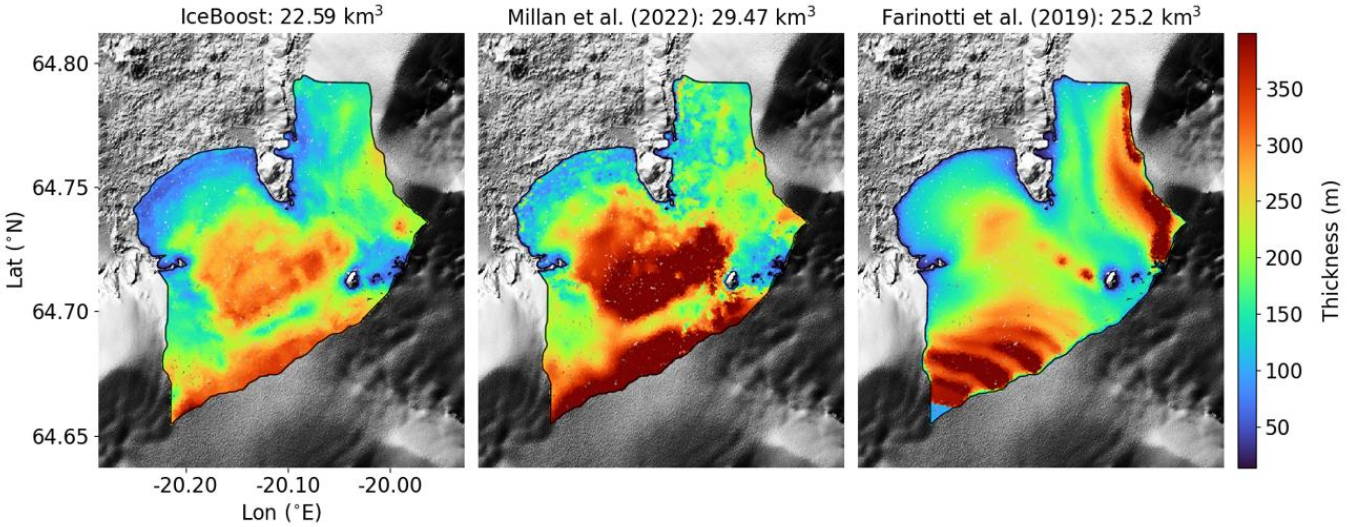

Figure S64: Glacier RGI60-06.00303. Back to Table S2.

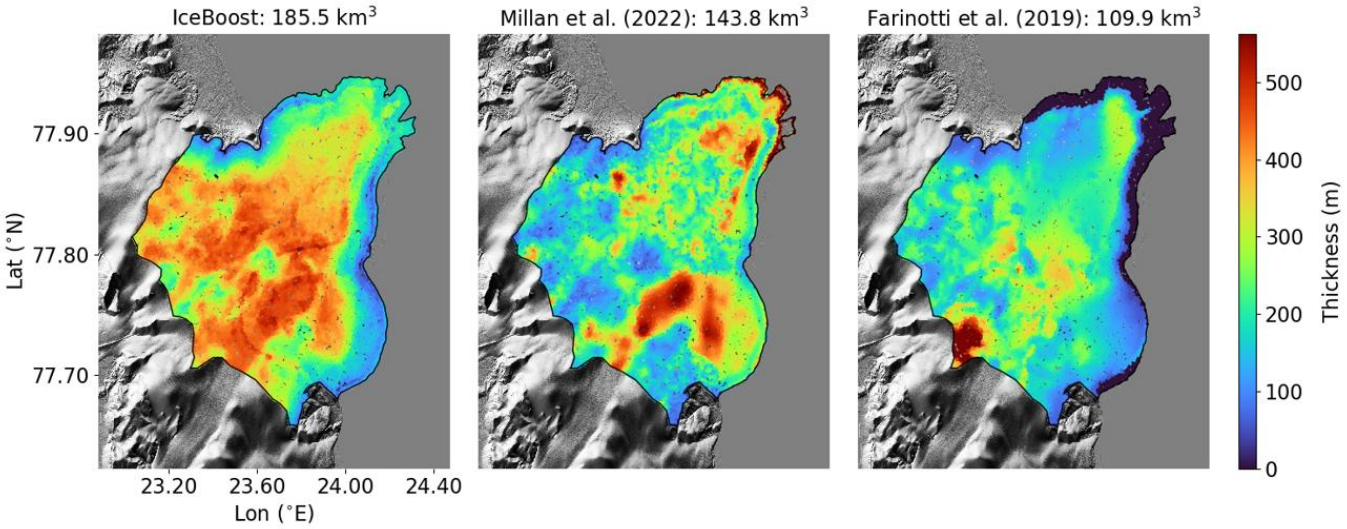

Figure S65: Glacier RGI60-07.01554. Back to Table S2.

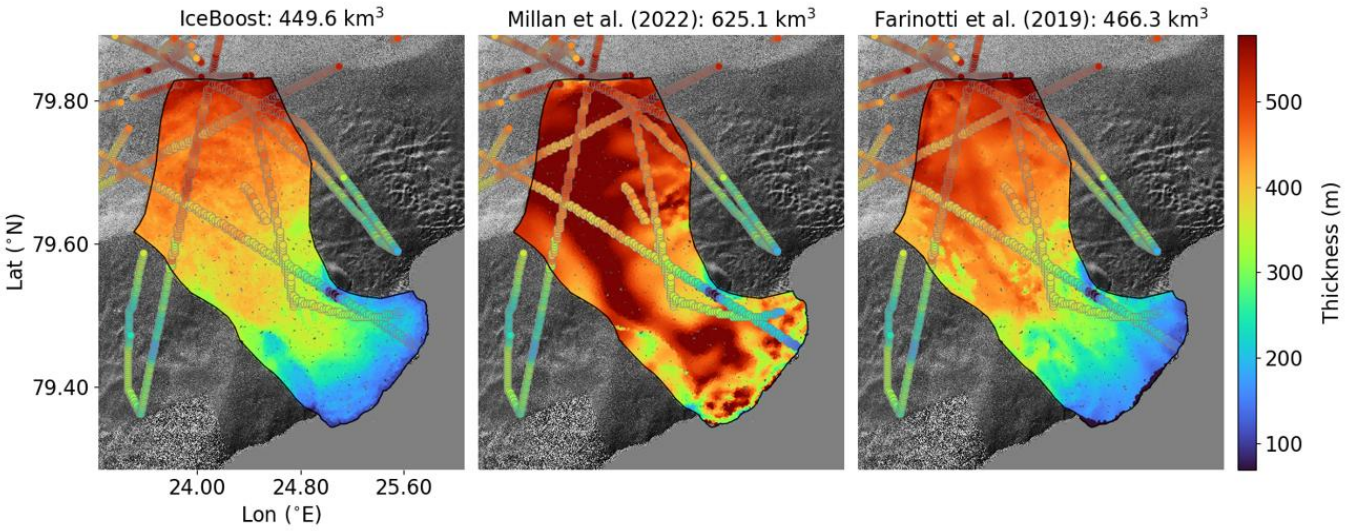

Figure S66: Glacier RGI60-07.00027. Back to Table S2.

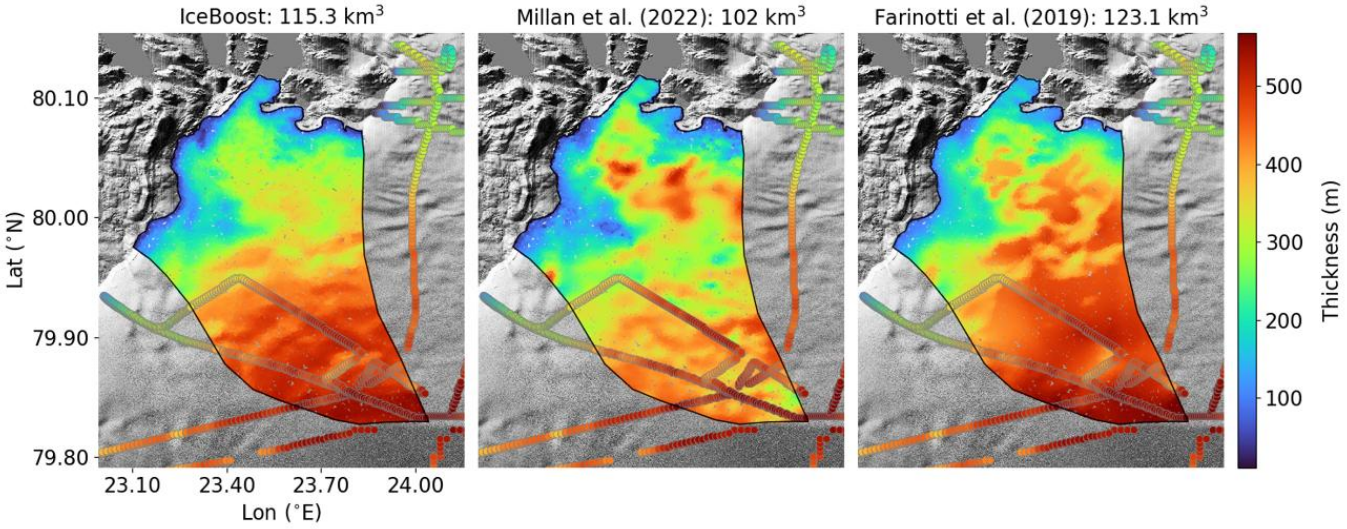

Figure S67: Glacier RGI60-07.00552. Back to Table S2.

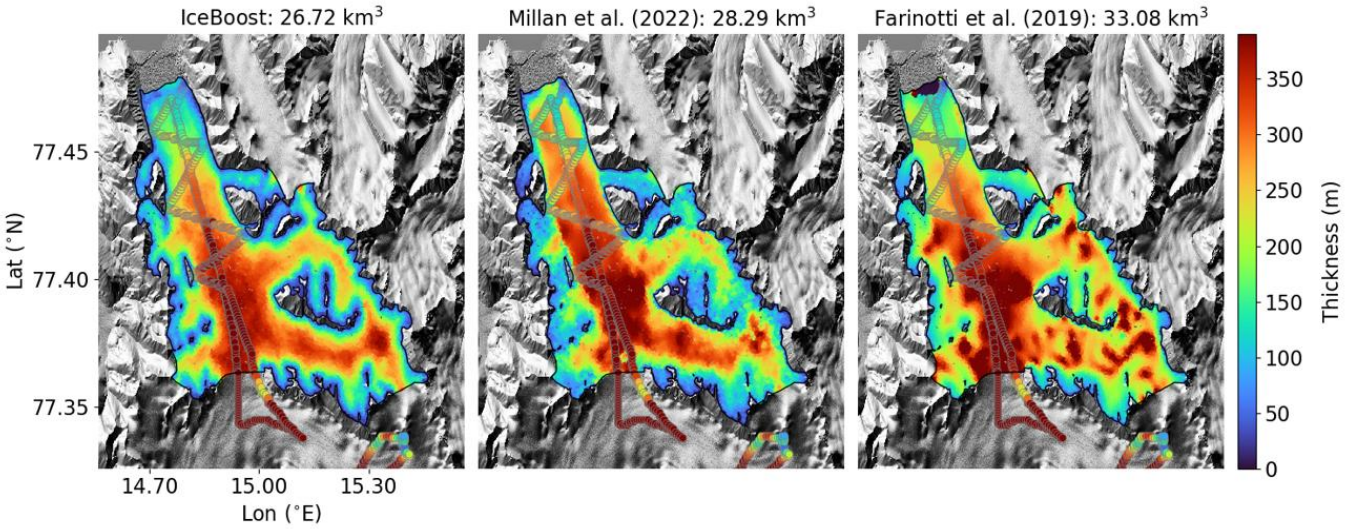

Figure S68: Glacier RGI60-07.00228. Back to Table S2.

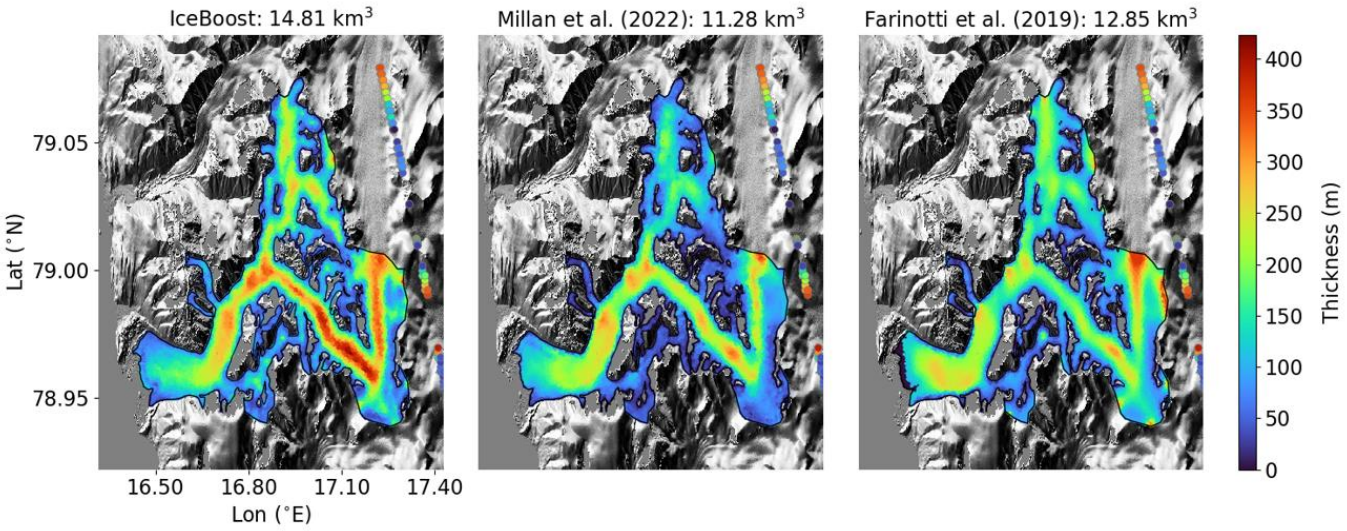

Figure S69: Glacier RGI60-07.00832. Back to Table S2.

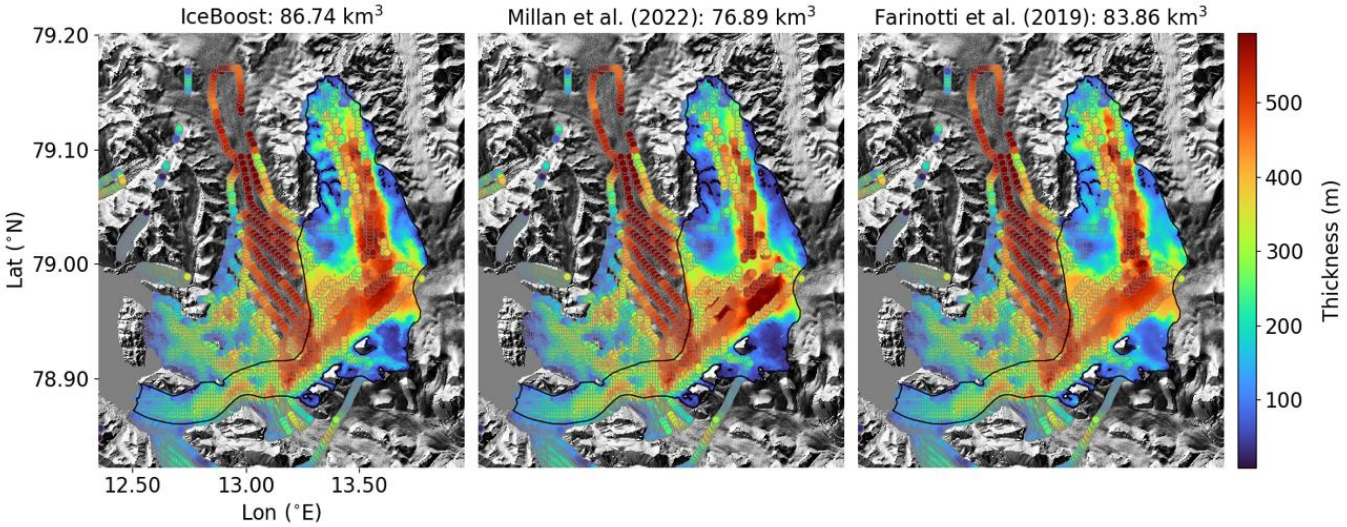

Figure S70: Glacier RGI60-07.01464. Back to Table S2.

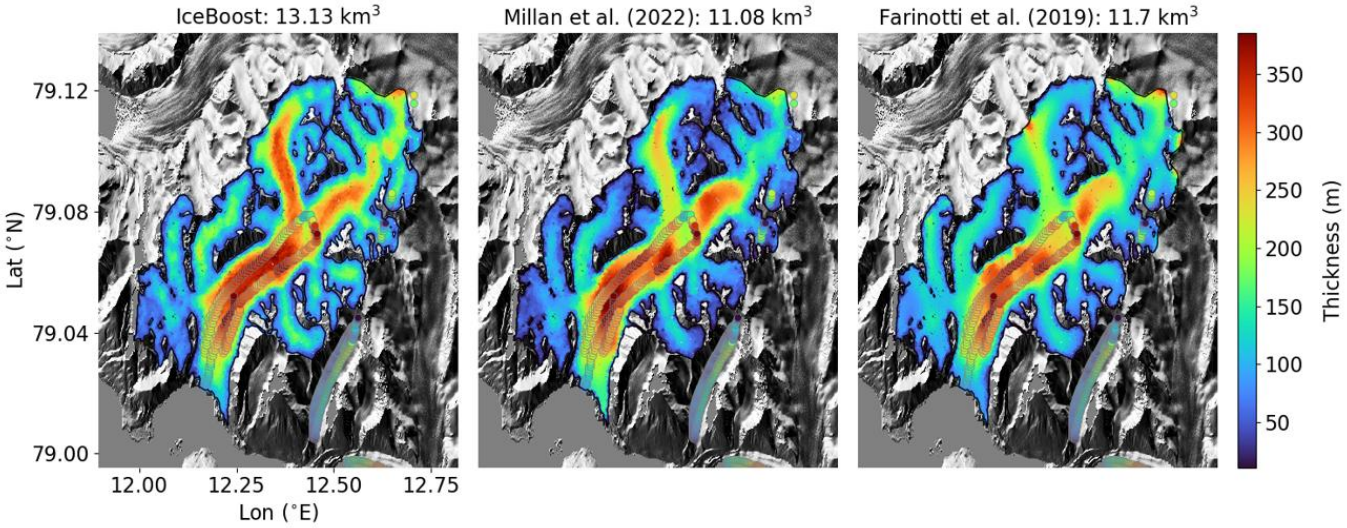

Figure S71: Glacier RGI60-07.00558. Back to Table S2.

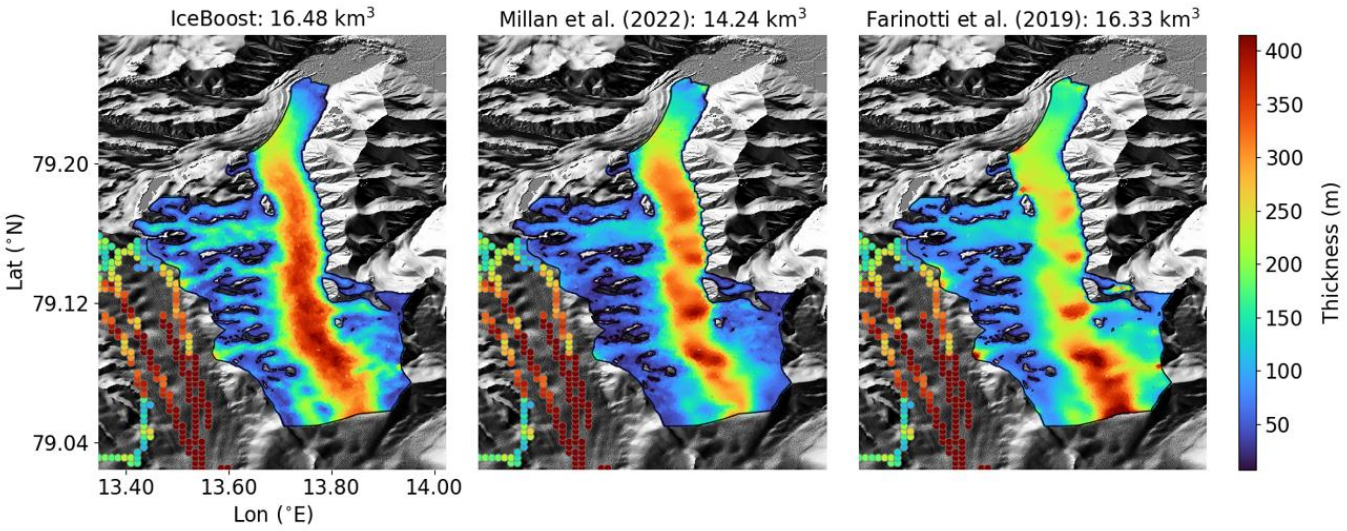

Figure S72: Glacier RGI60-07.01495. Back to Table S2.

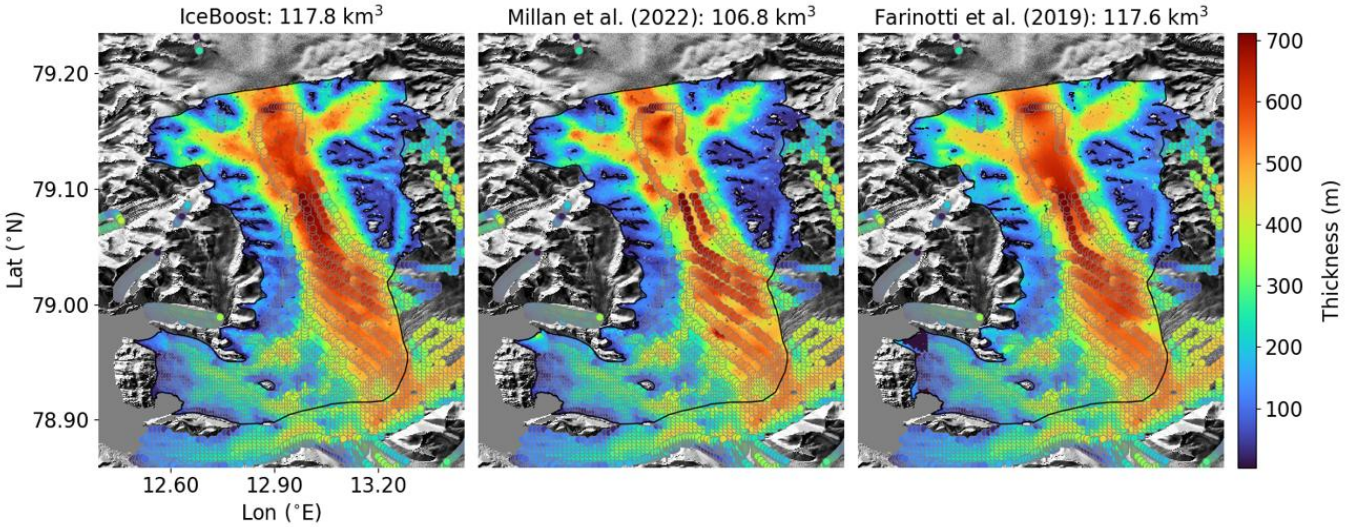

Figure S73: Glacier RGI60-07.01482. Back to Table S2.

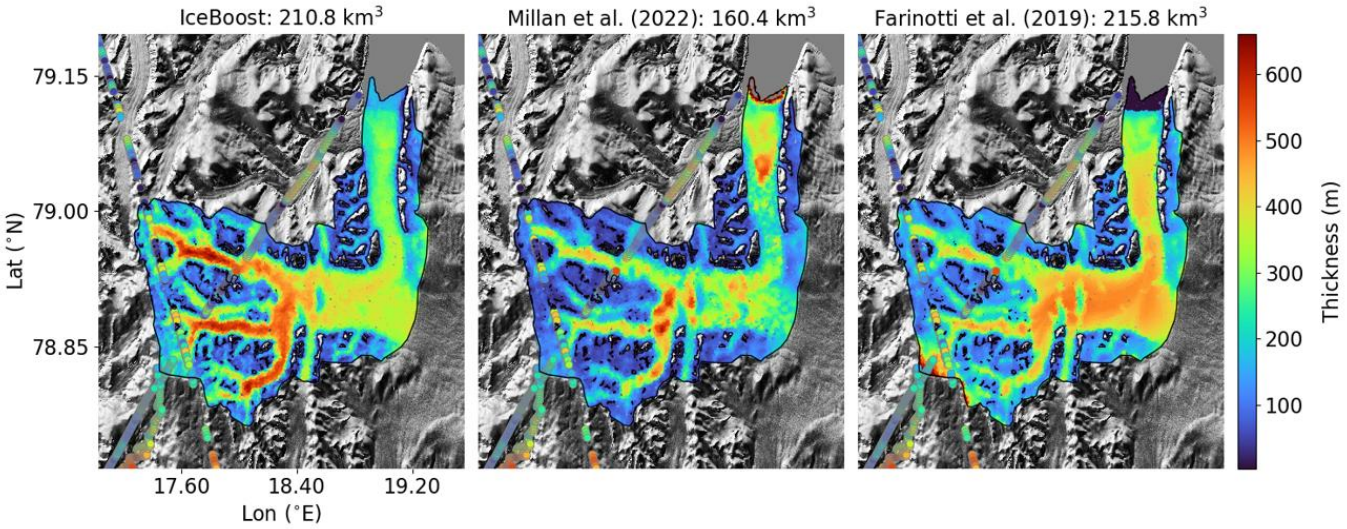

Figure S74: Glacier RGI60-07.01559. Back to Table S2.

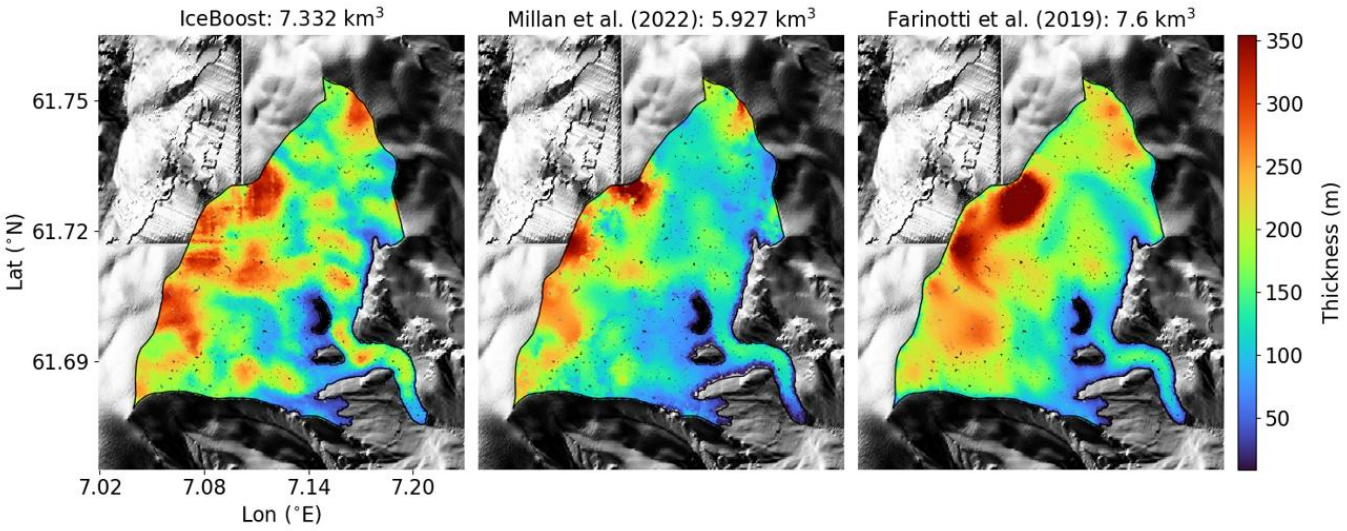

Figure S75: Glacier RGI60-08.01126. Back to Table S2.

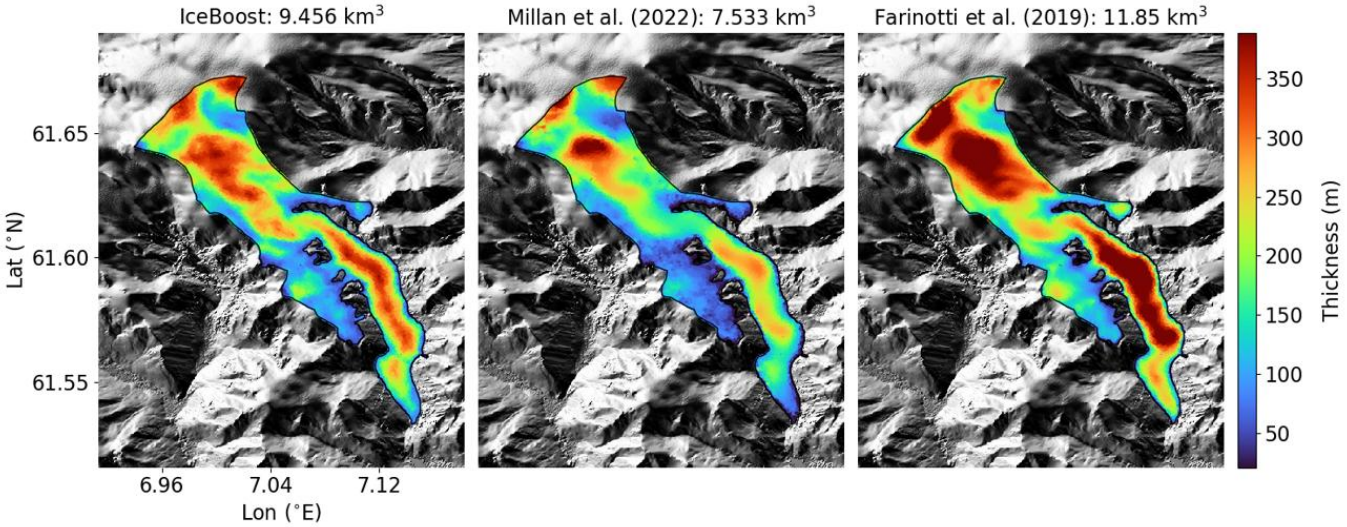

Figure S76: Glacier RGI60-08.00434. Back to Table S2.

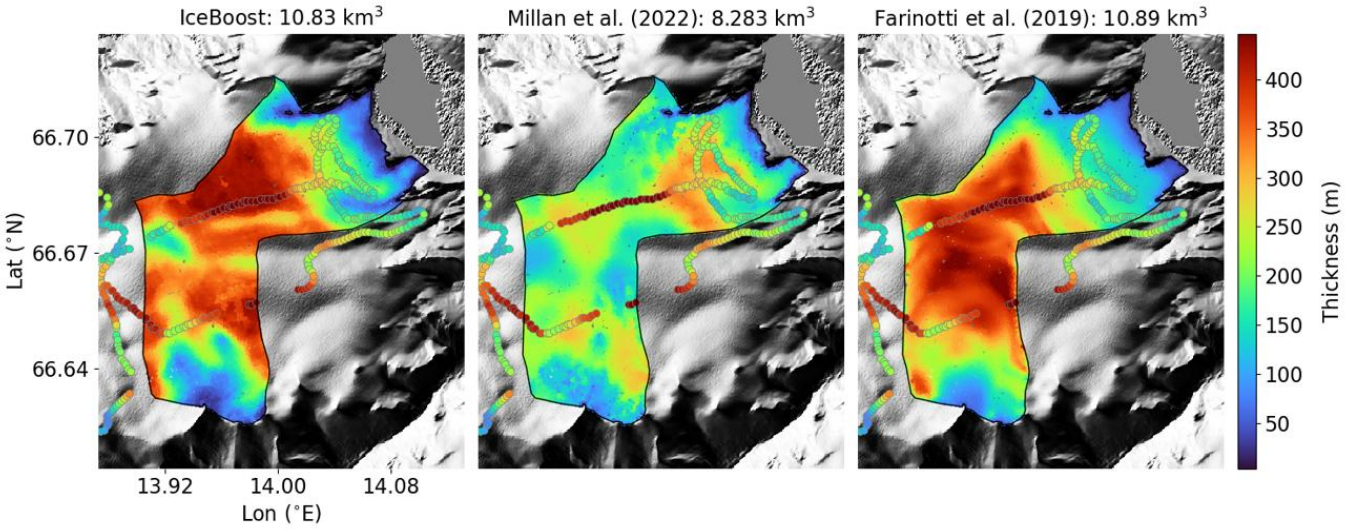

Figure S77: Glacier RGI60-08.00287. Back to Table S2.

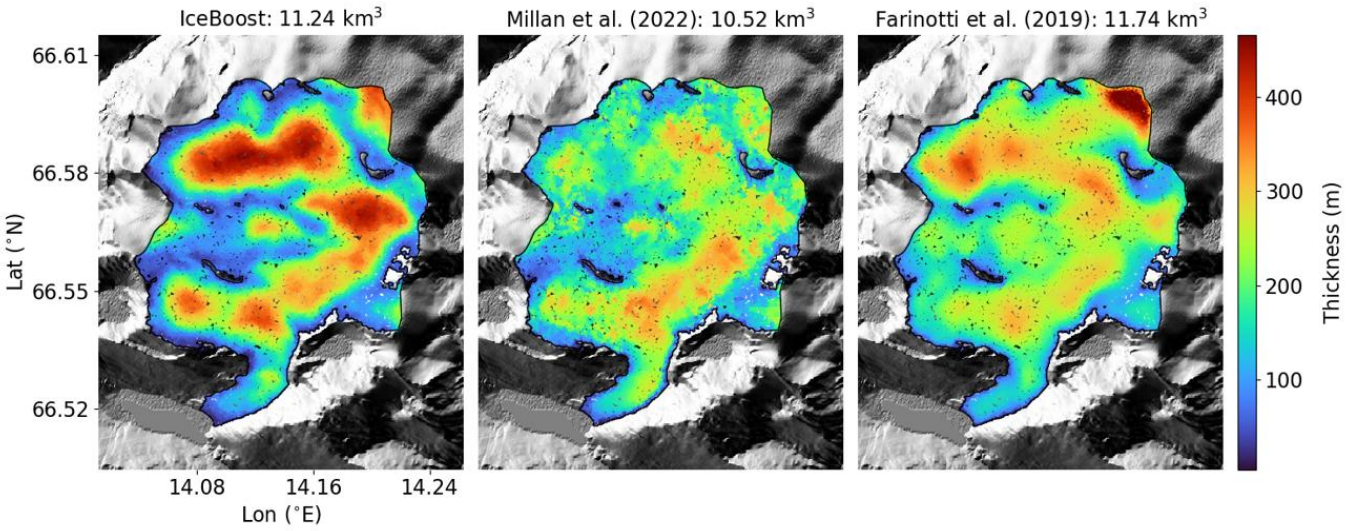

Figure S78: Glacier RGI60-08.00281. Back to Table S2.

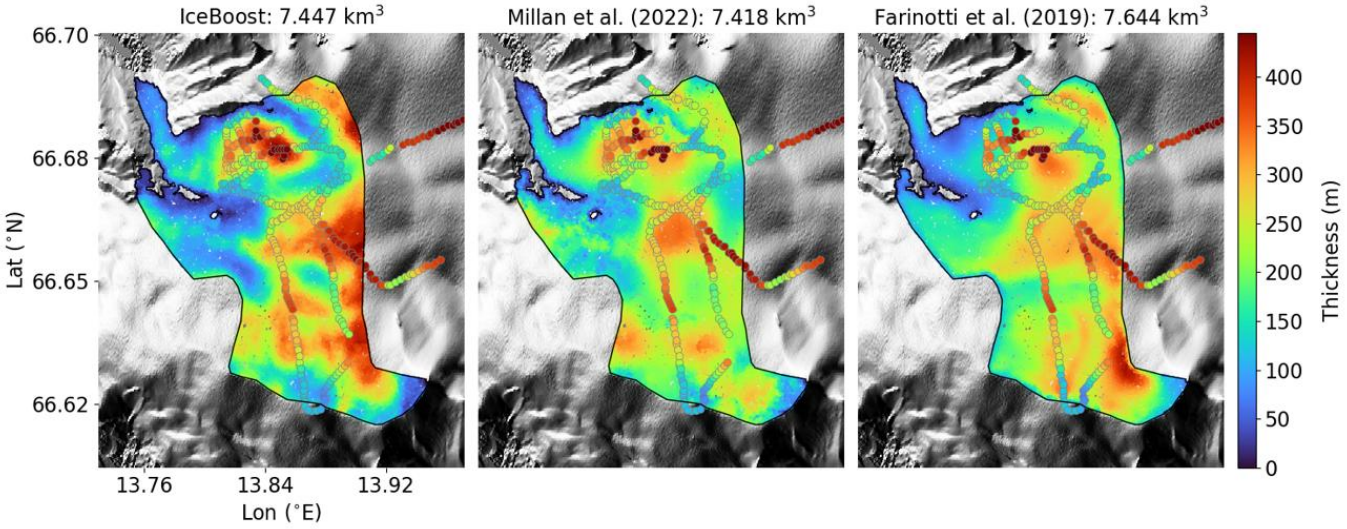

Figure S79: Glacier RGI60-08.01657. Back to Table S2.

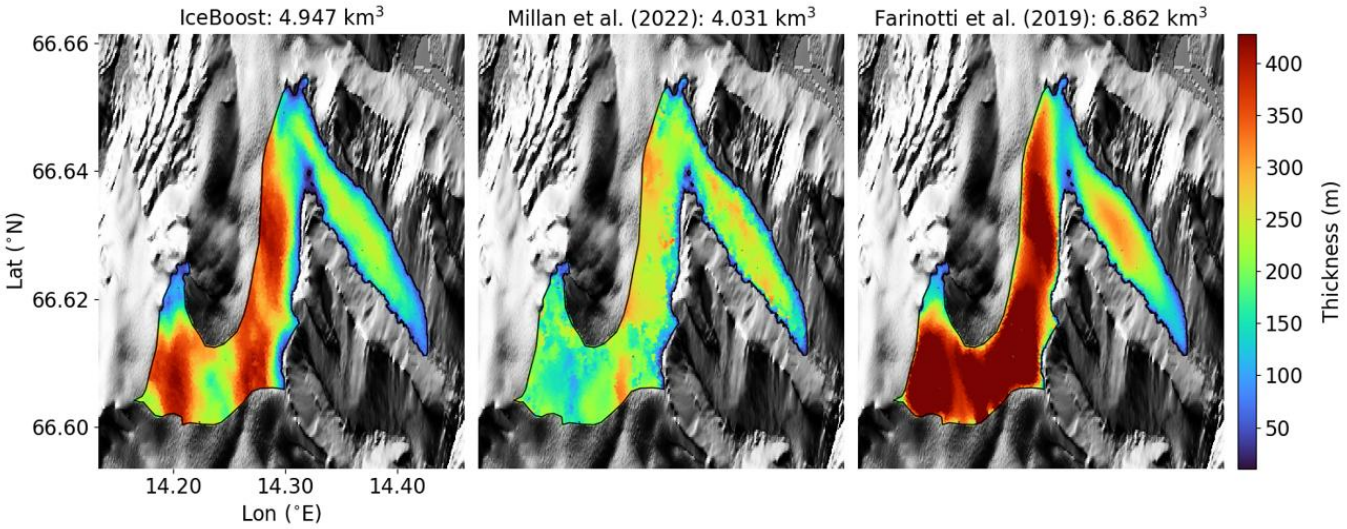

Figure S80: Glacier RGI60-08.01490. Back to Table S2.

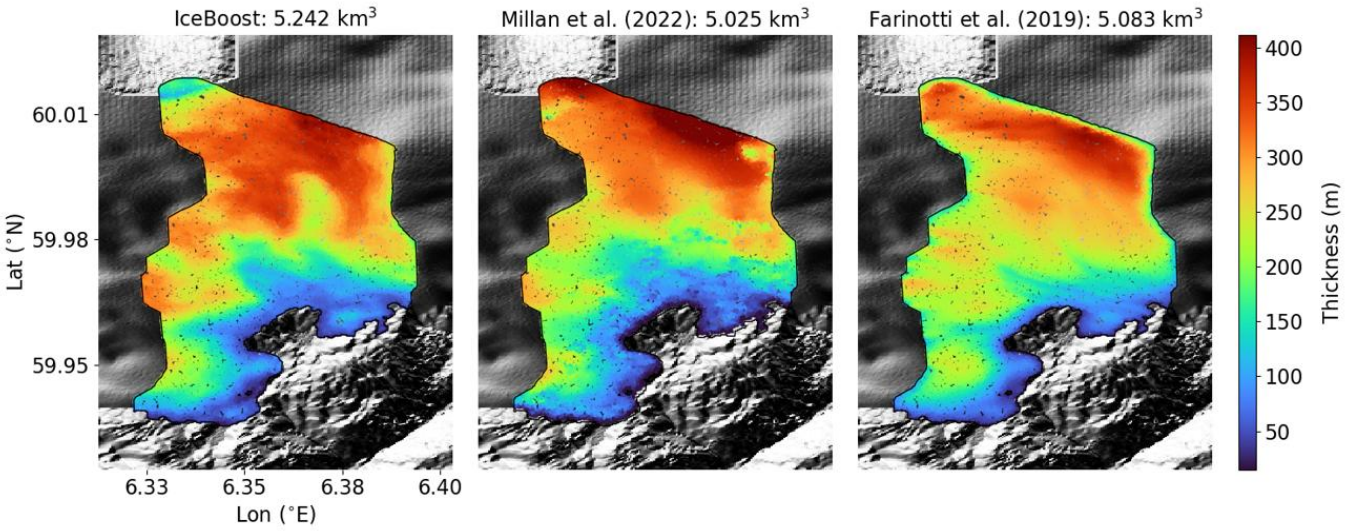

Figure S81: Glacier RGI60-08.02969. Back to Table S2.

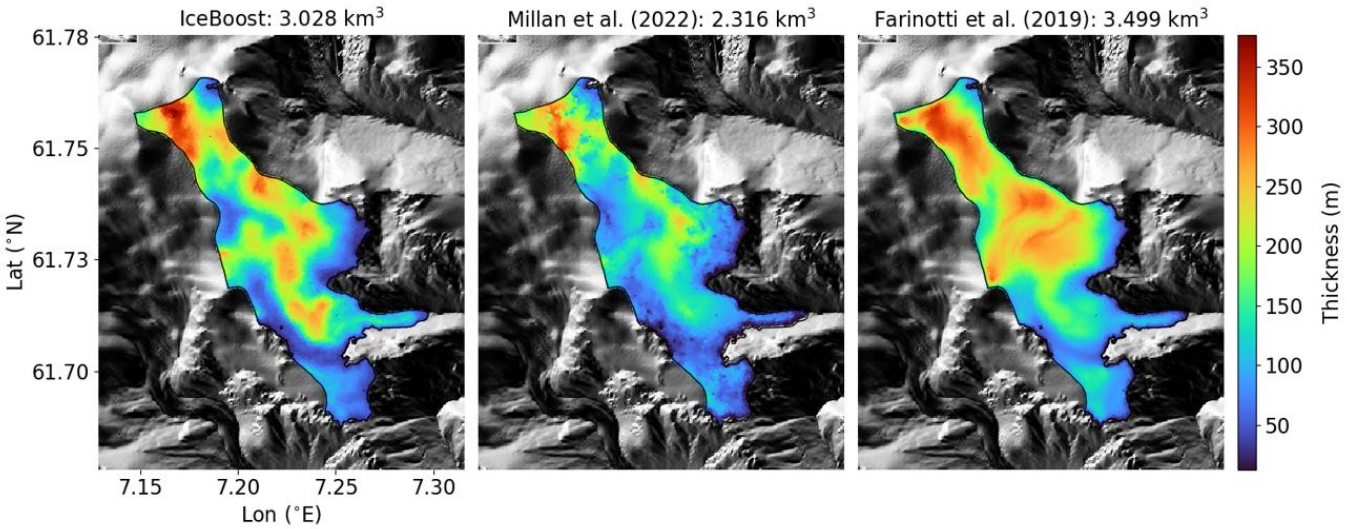

Figure S82: Glacier RGI60-08.01133. Back to Table S2.

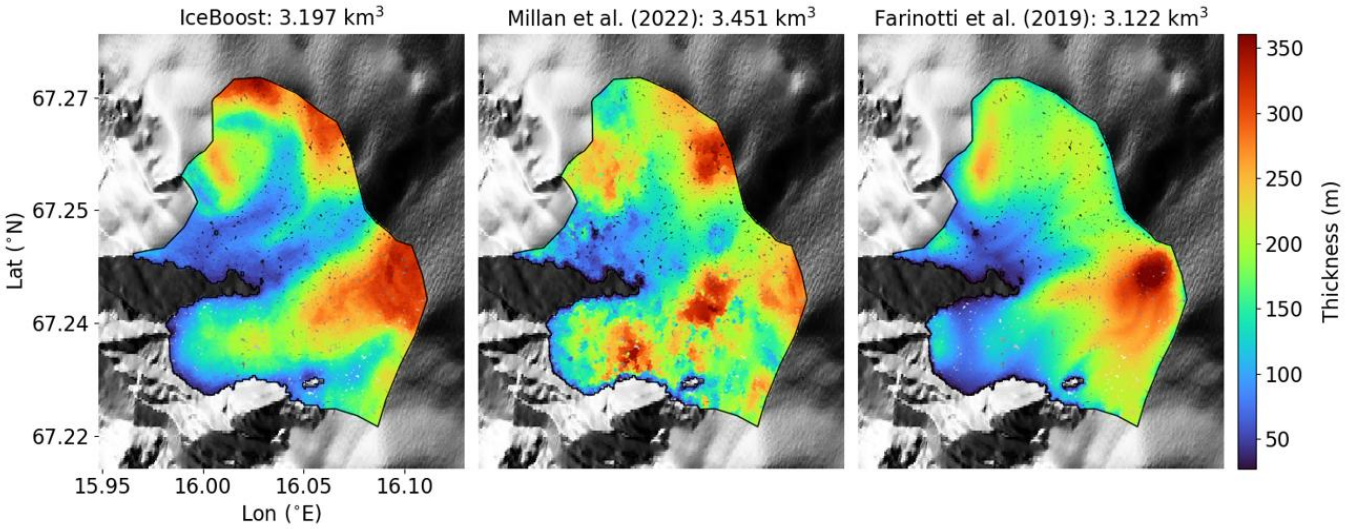

Figure S83: Glacier RGI60-08.02383. Back to Table S2.

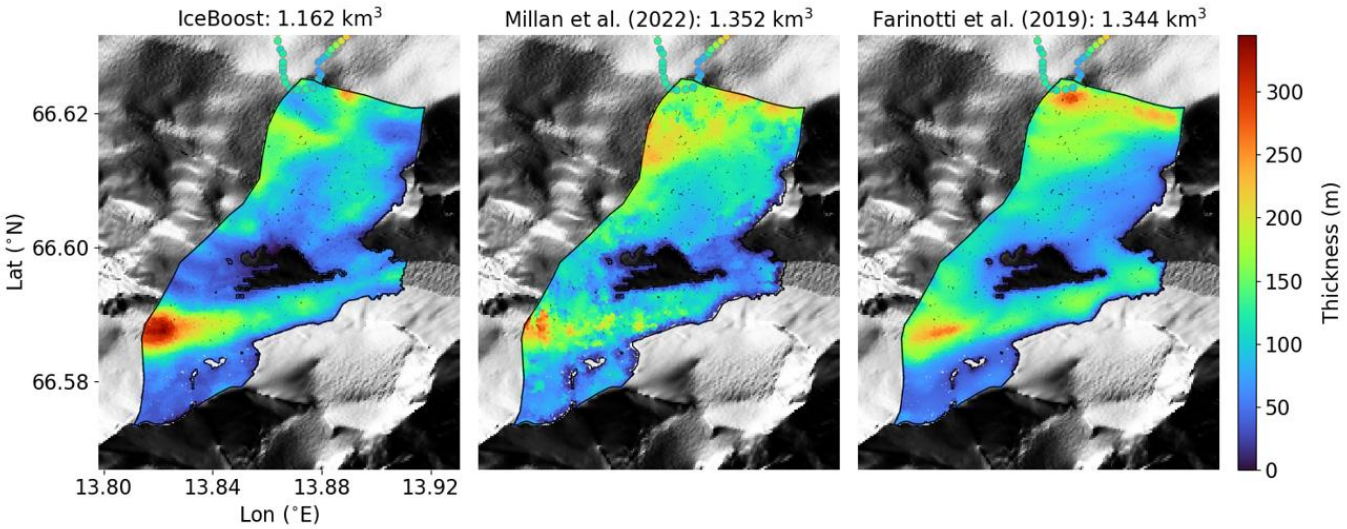

Figure S84: Glacier RGI60-08.00290. Back to Table S2.

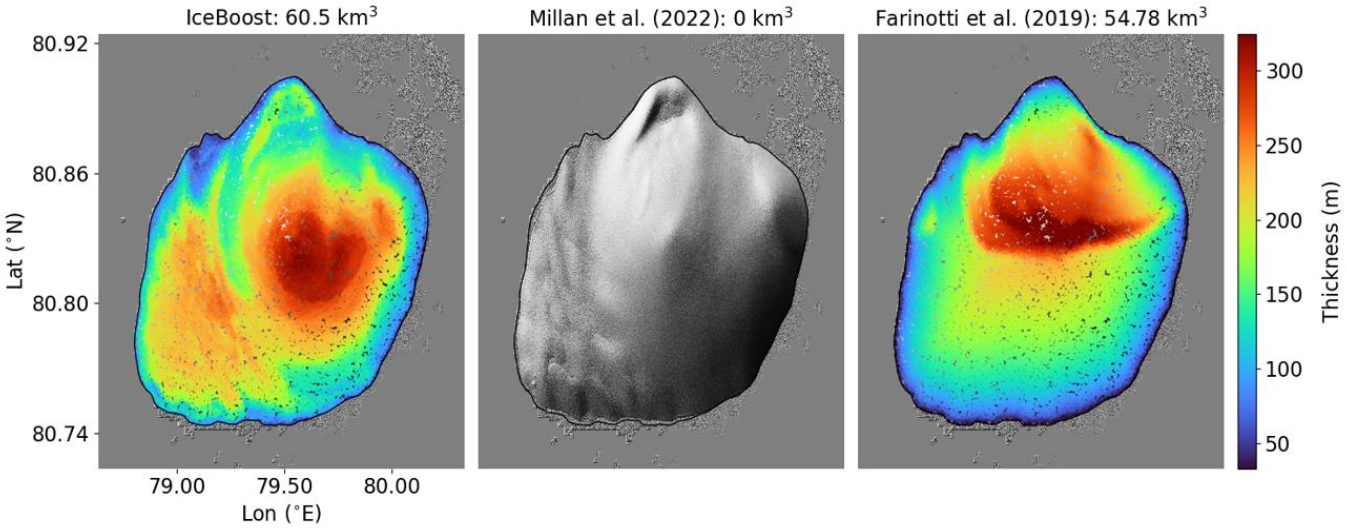

Figure S85: Glacier RGI60-09.00909. Back to Table S2.

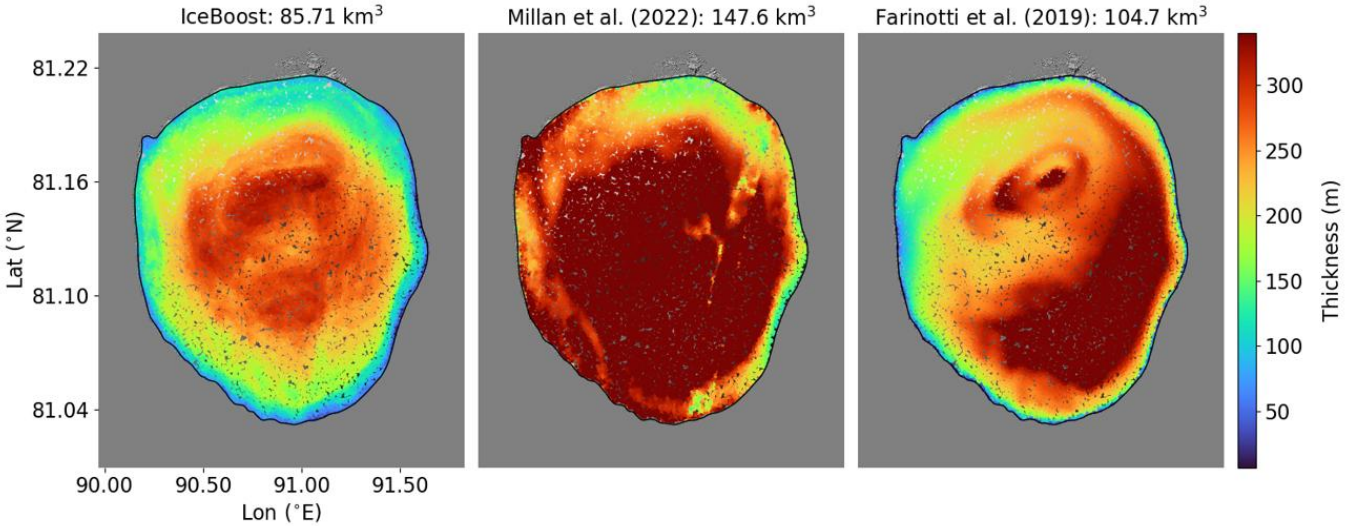

Figure S86: Glacier RGI60-09.00520. Back to Table S2.

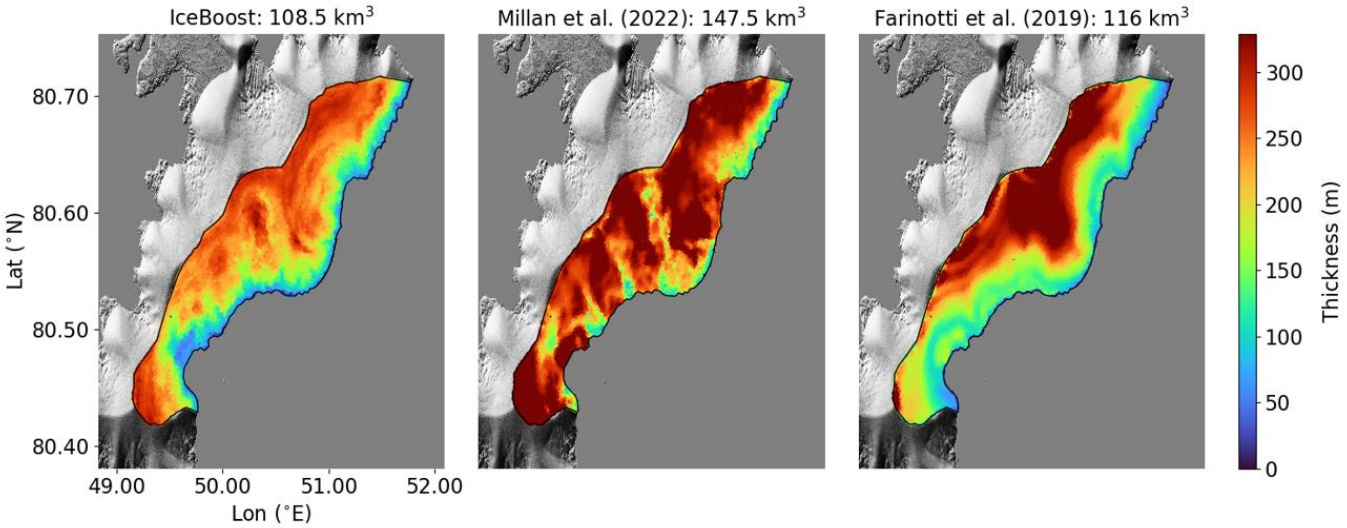

Figure S87: Glacier RGI60-09.00697. Back to Table S2.

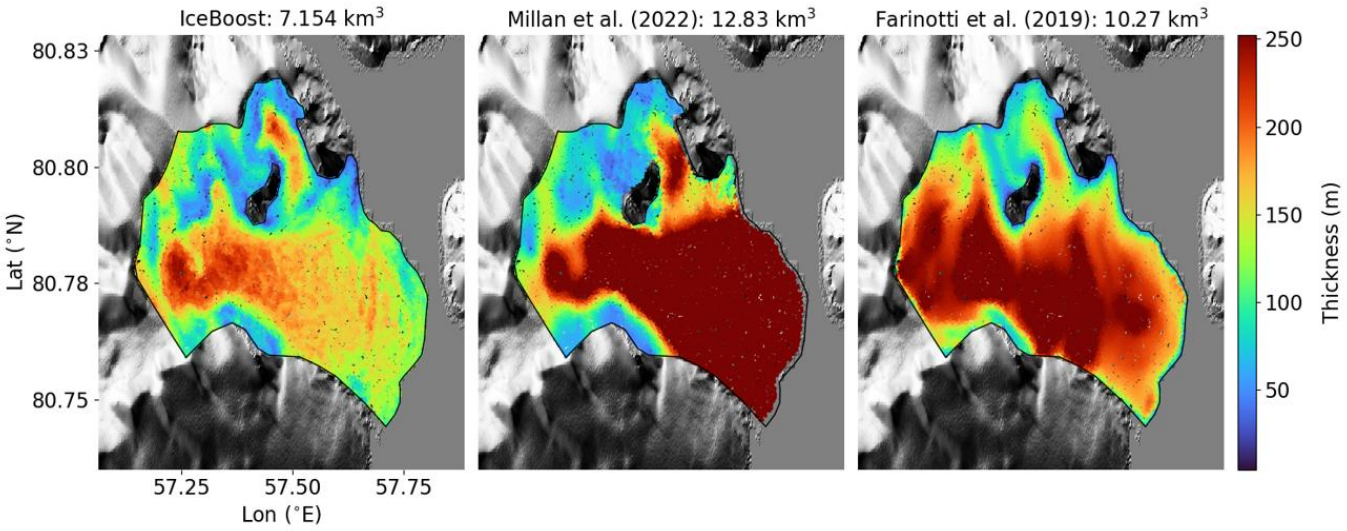

Figure S88: Glacier RGI60-09.00801. Back to Table S2.

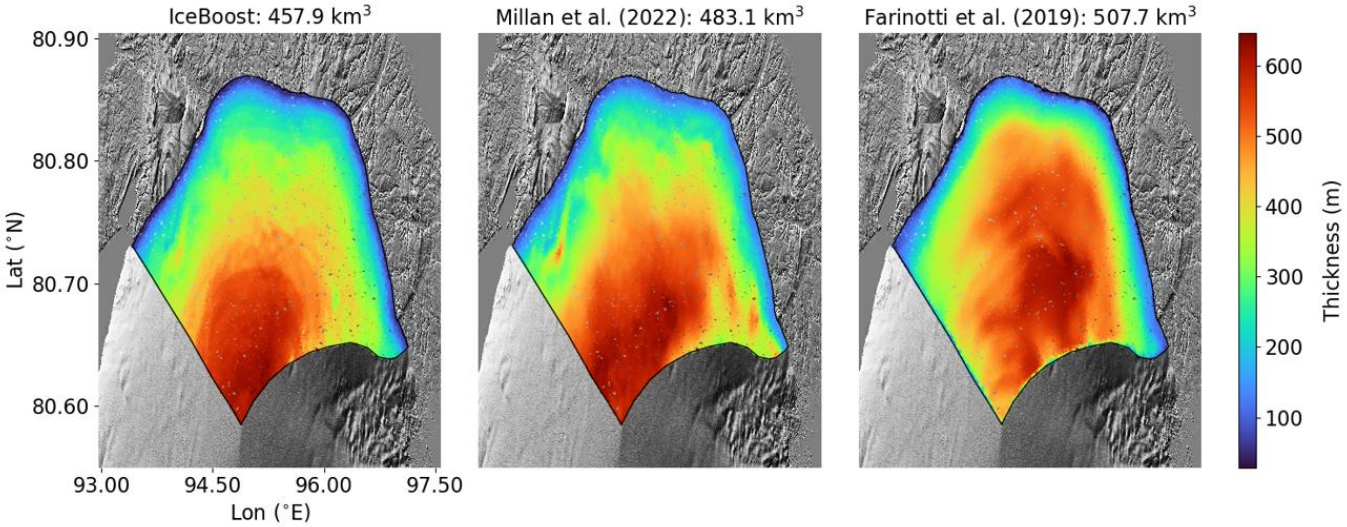

Figure S89: Glacier RGI60-09.00918. Back to Table S2.

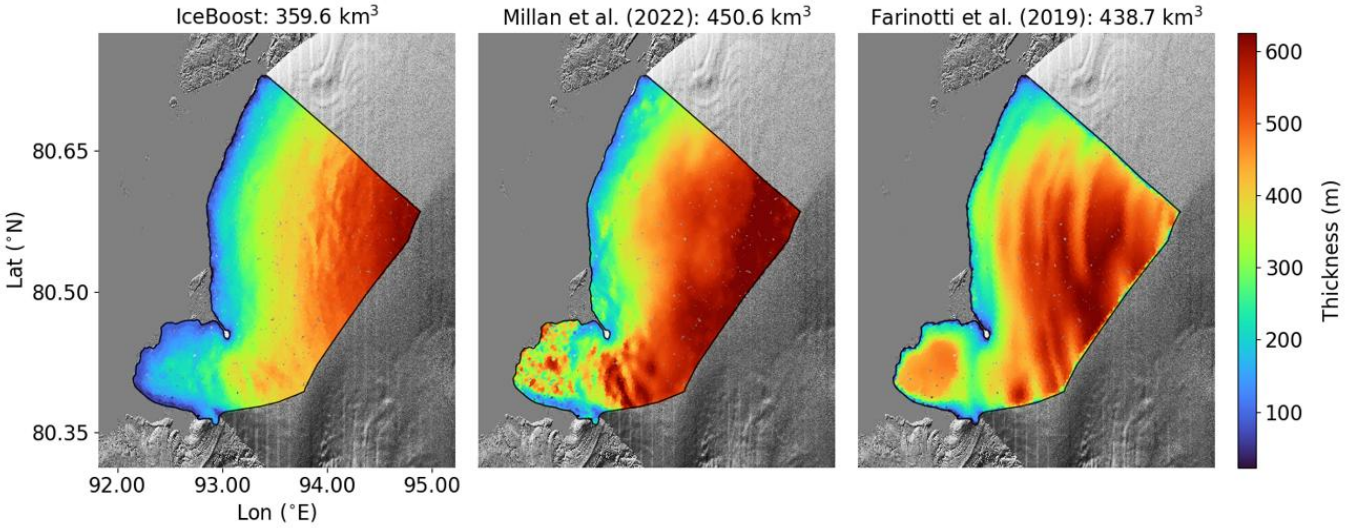

Figure S90: Glacier RGI60-09.00969. Back to Table S2.

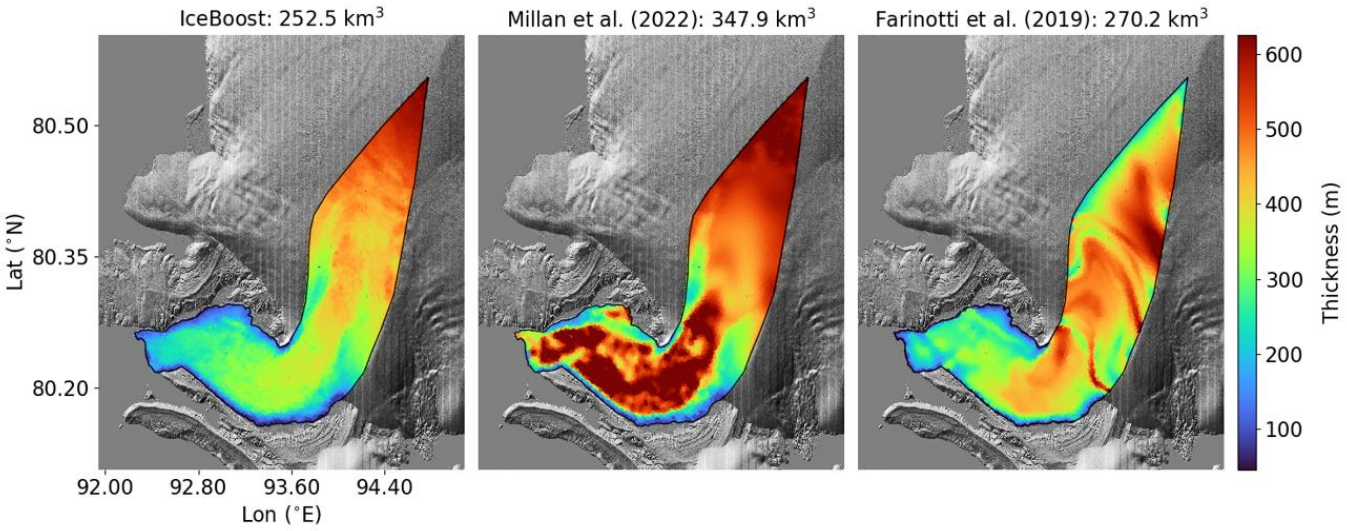

Figure S91: Glacier RGI60-09.00911. Back to Table S2.

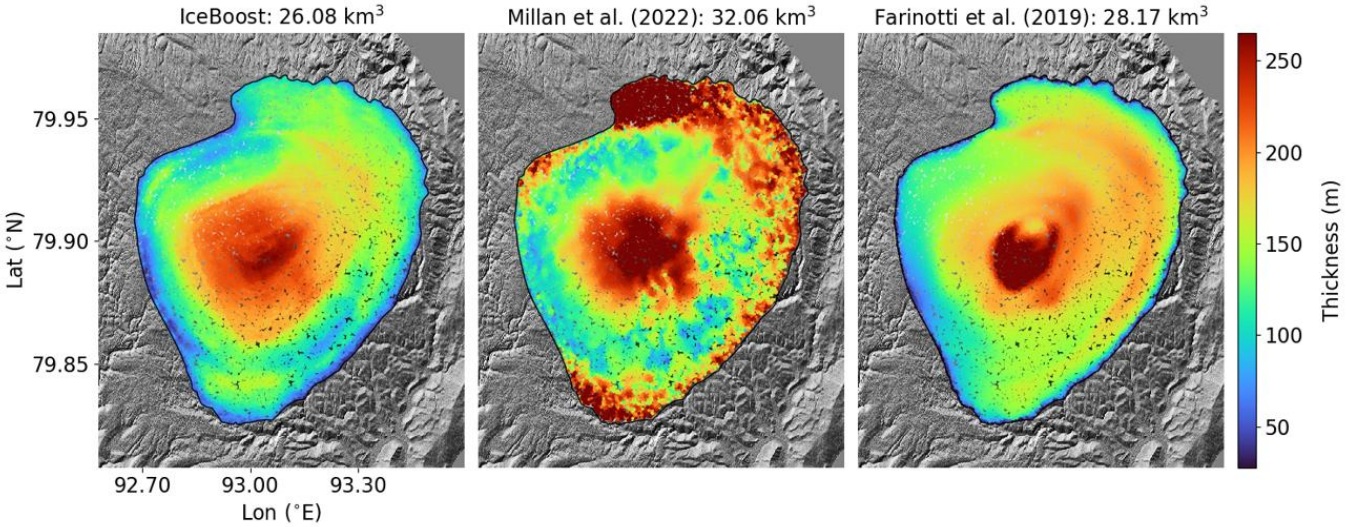

Figure S92: Glacier RGI60-09.00484. Back to Table S2.

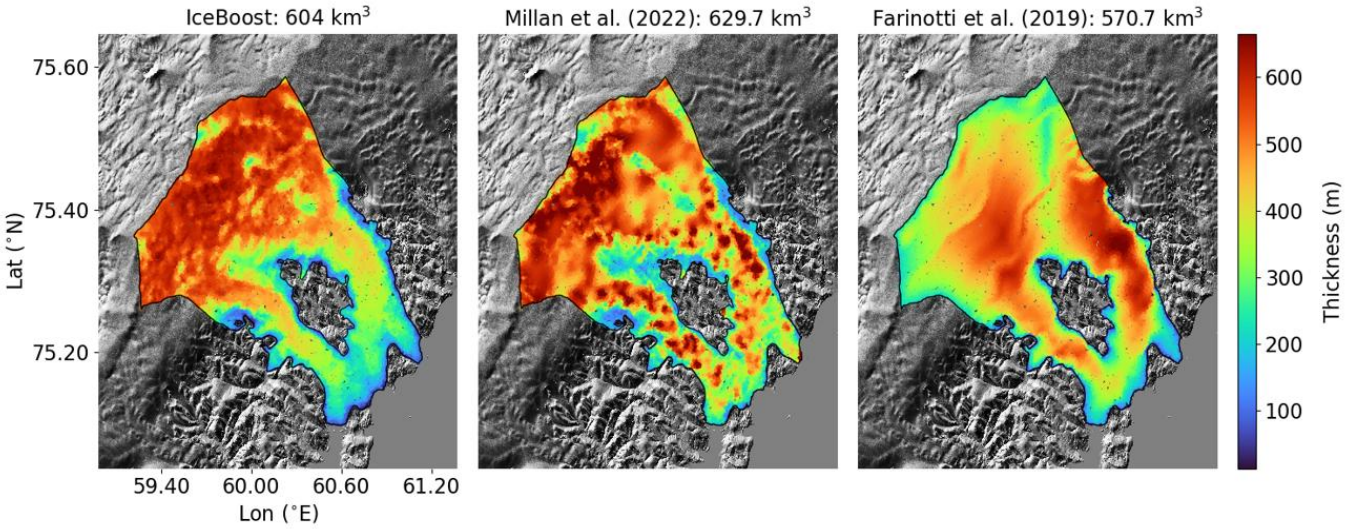

Figure S93: Glacier RGI60-09.00116. Back to Table S2.

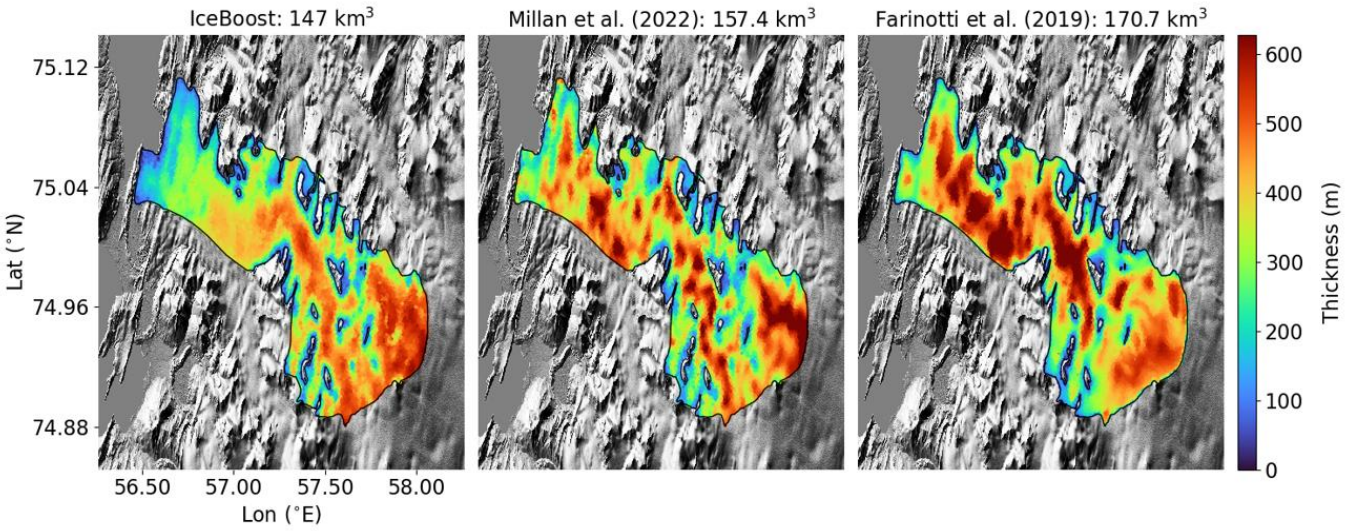

Figure S94: Glacier RGI60-09.00051. Back to Table S2.

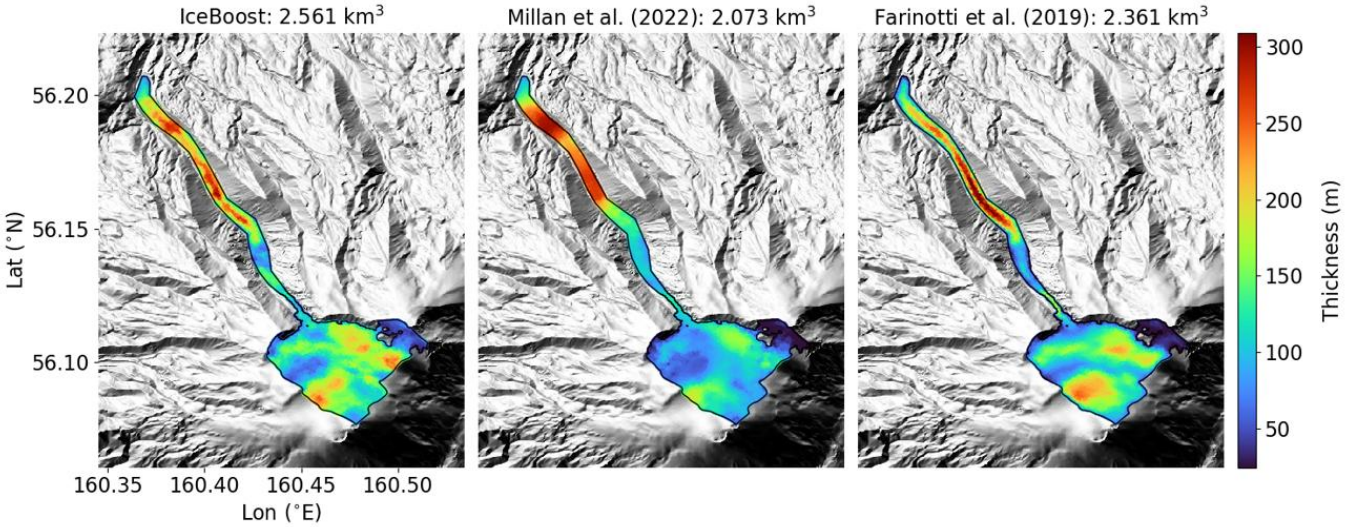

Figure S95: Glacier RGI60-10.04017. Back to Table S2.

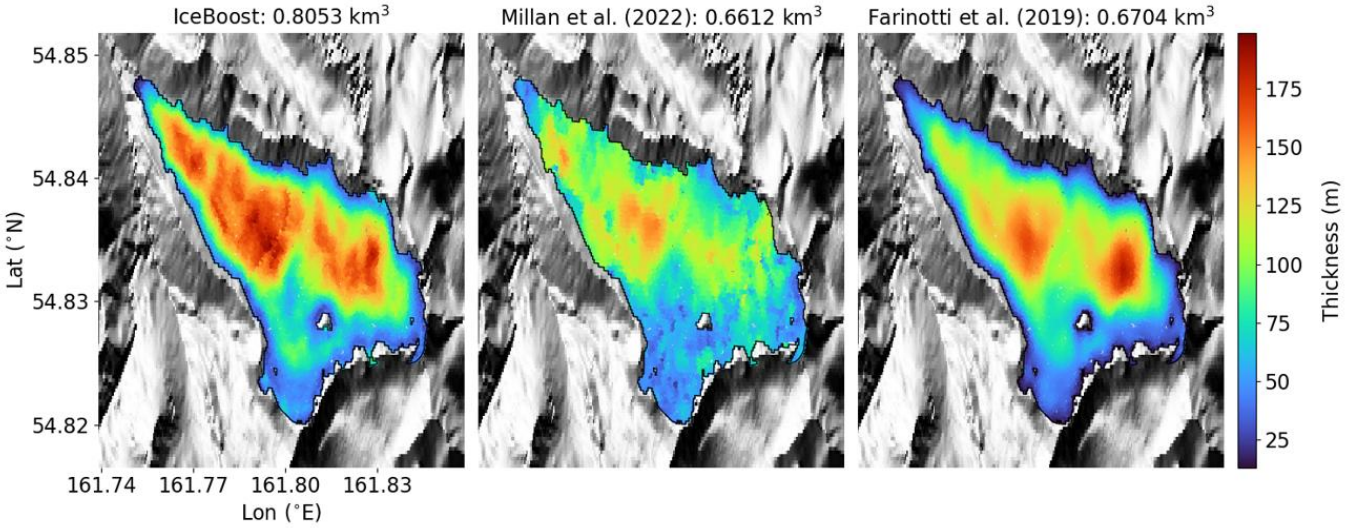

Figure S96: Glacier RGI60-10.04358. Back to Table S2.

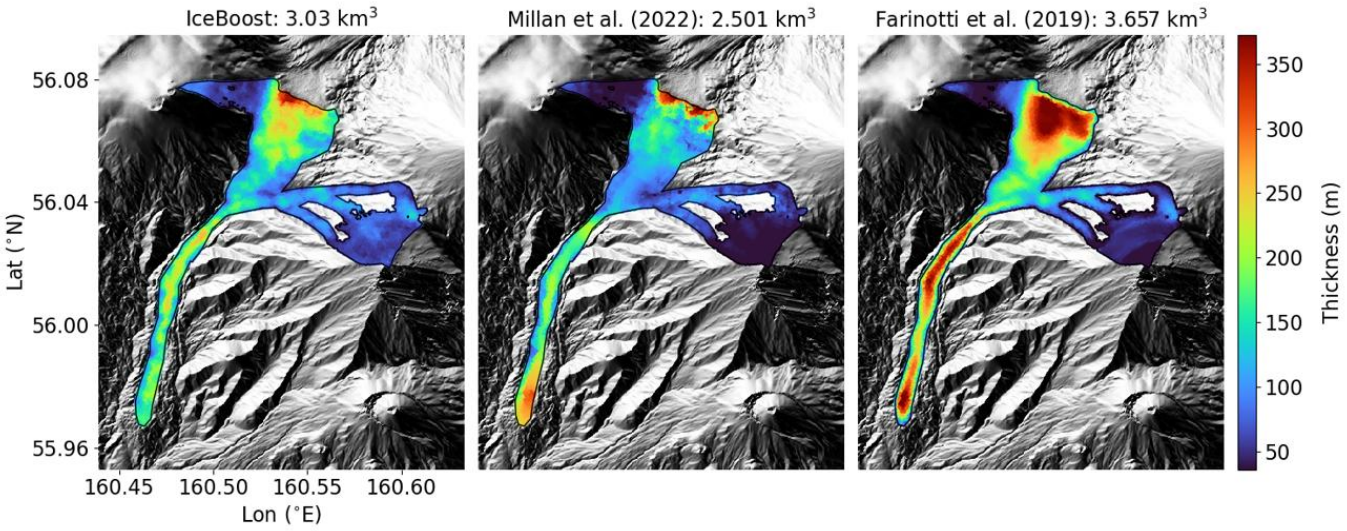

Figure S97: Glacier RGI60-10.03999. Back to Table S2.

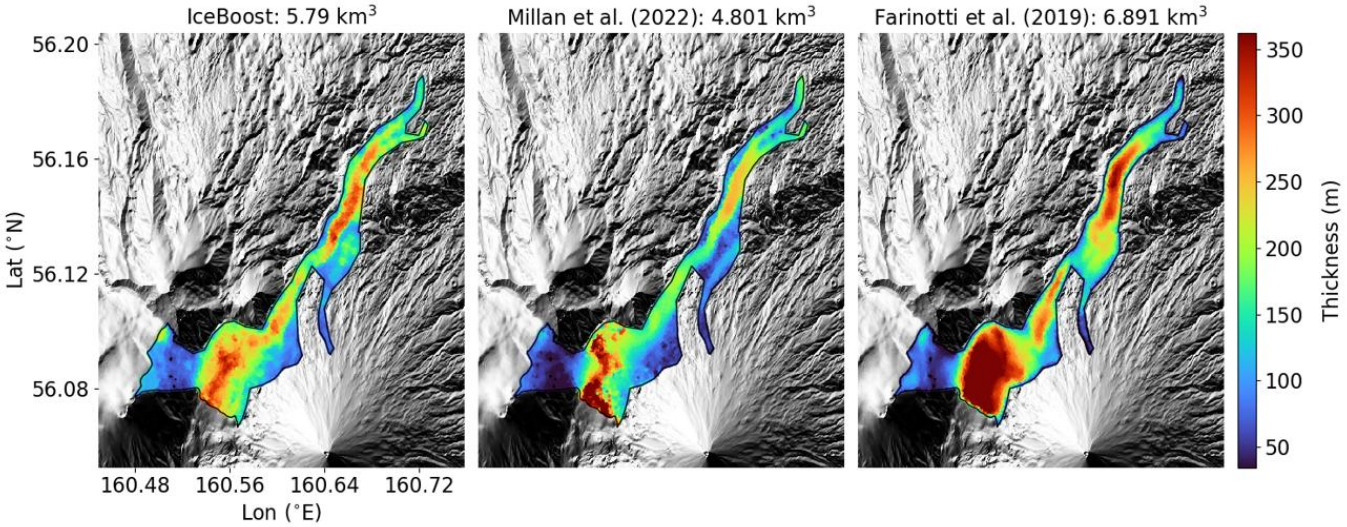

Figure S98: Glacier RGI60-10.04024. Back to Table S2.

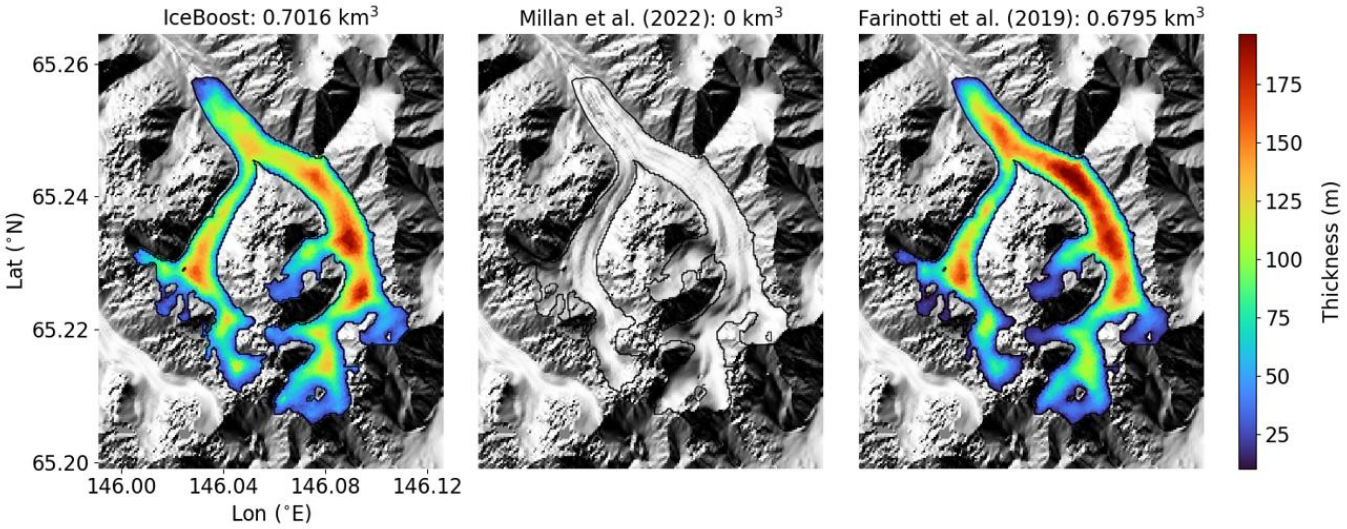

Figure S99: Glacier RGI60-10.03162. Back to Table S2.

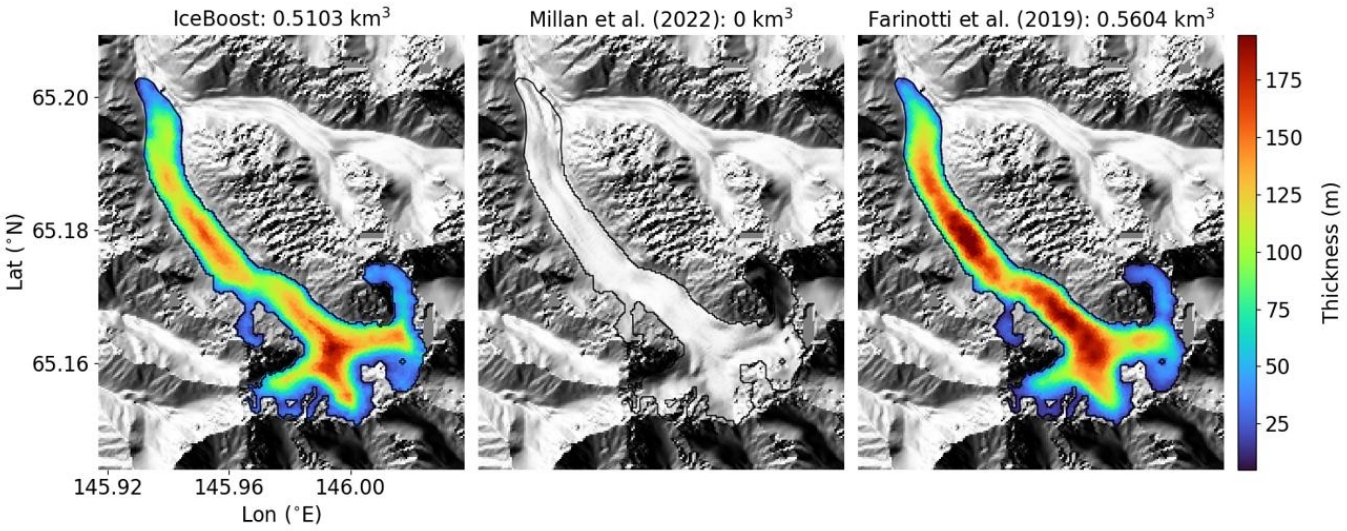

Figure S100: Glacier RGI60-10.03195. Back to Table S2.

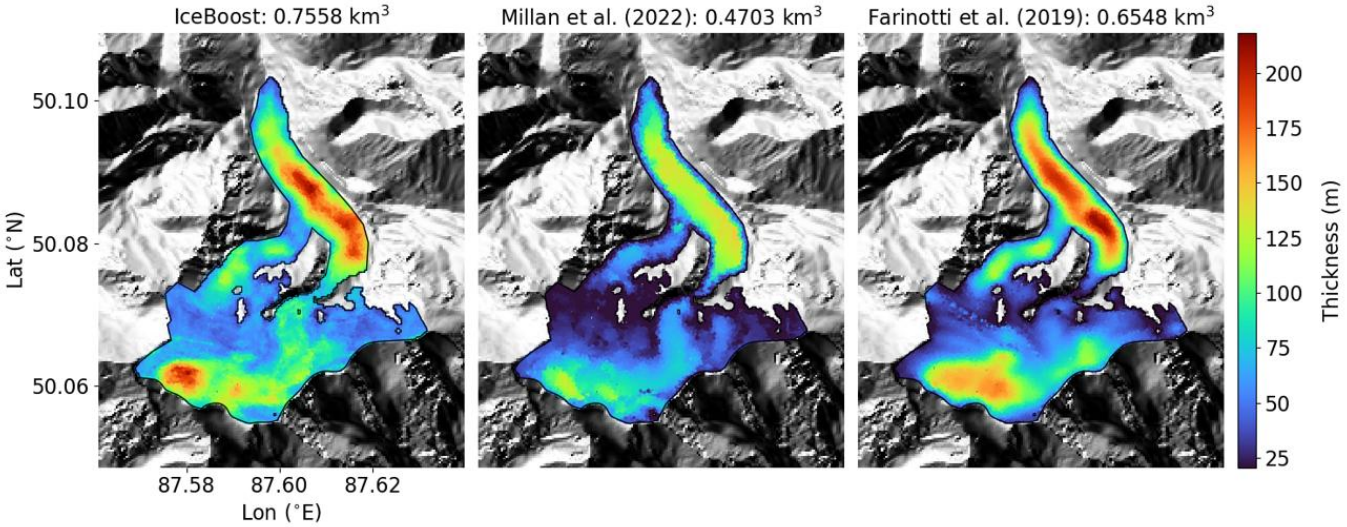

Figure S101: Glacier RGI60-10.05151. Back to Table S2.

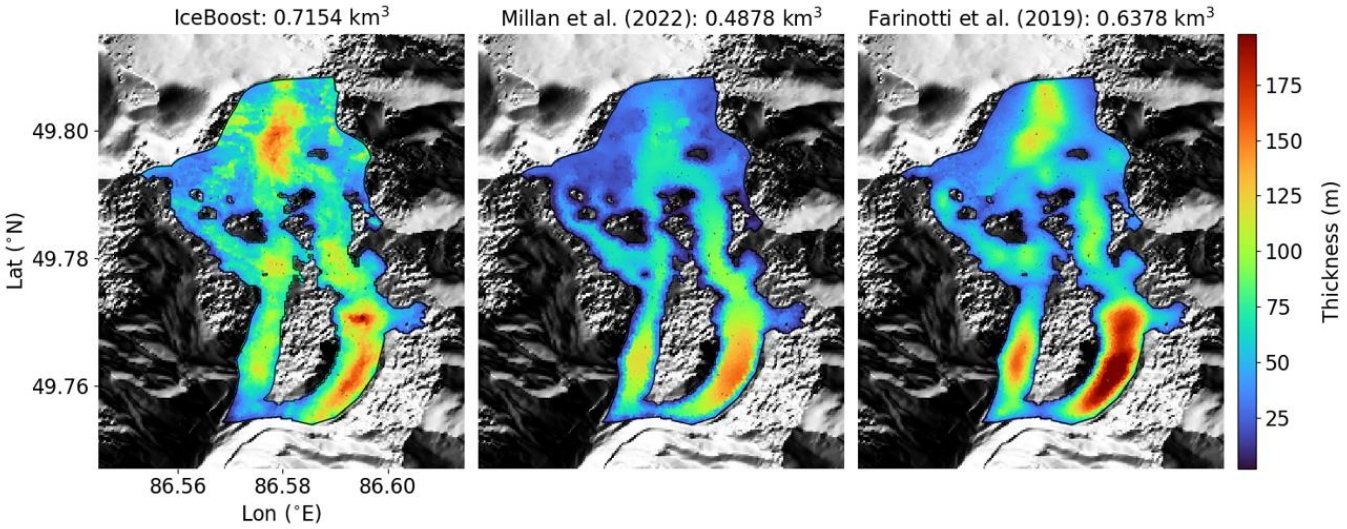

Figure S102: Glacier RGI60-10.01115. Back to Table S2.

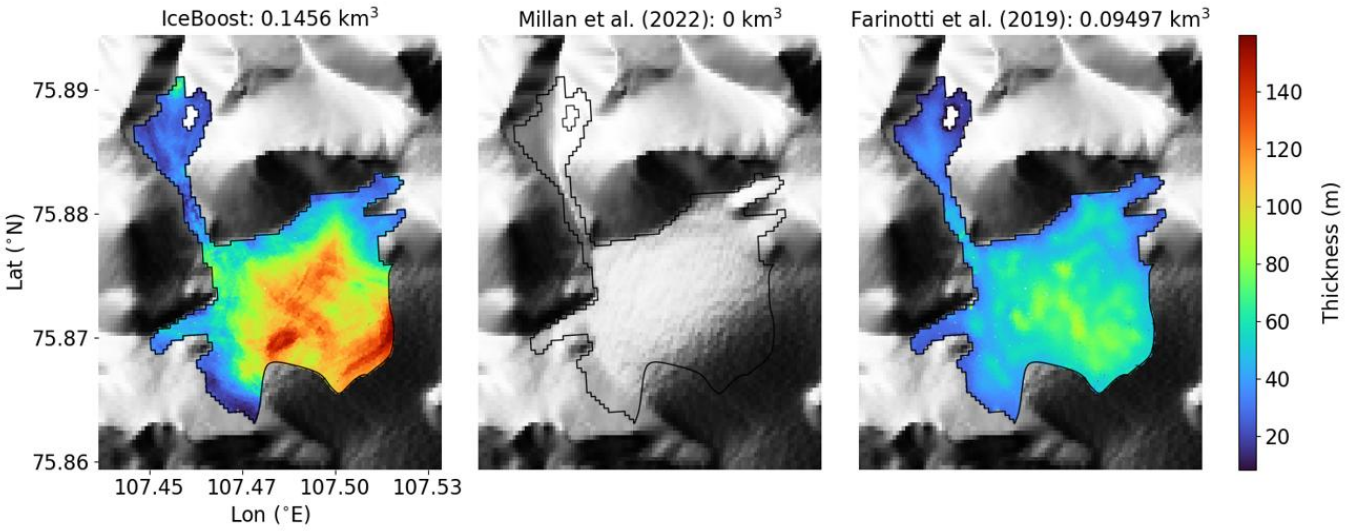

Figure S103: Glacier RGI60-10.00560. Back to Table S2.

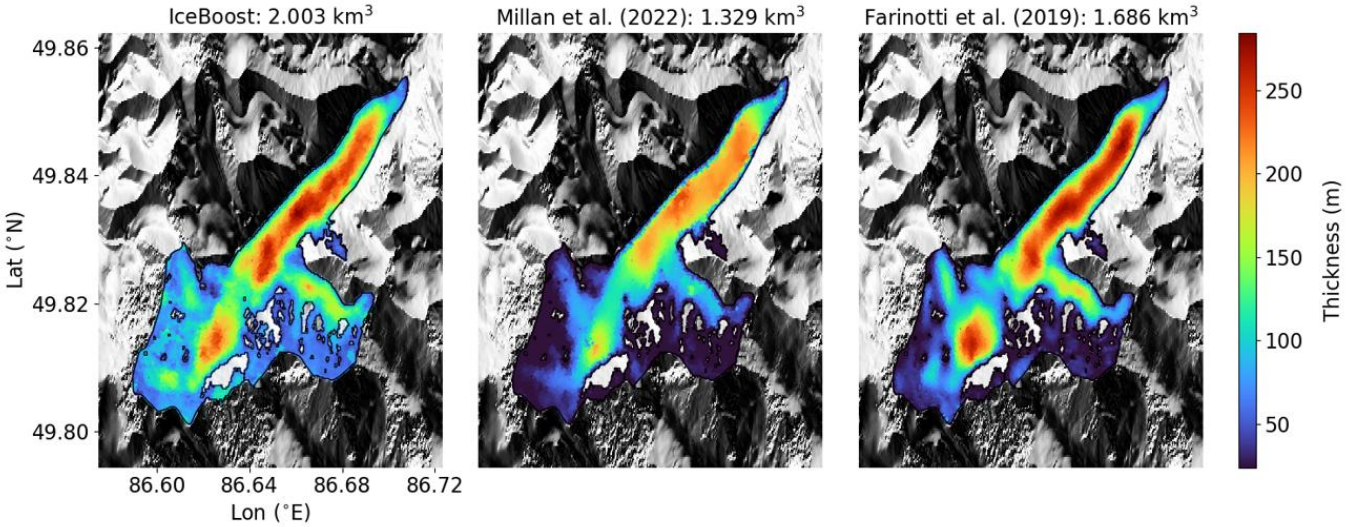

Figure S104: Glacier RGI60-10.01111. Back to Table S2.

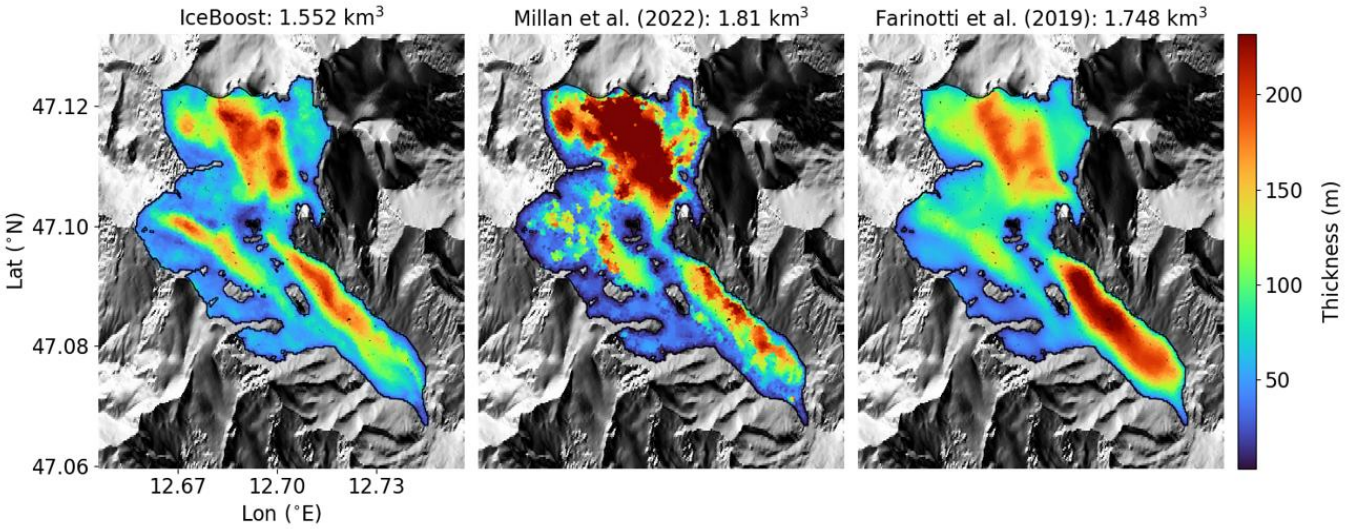

Figure S105: Glacier RGI60-11.00106. Back to Table S2.

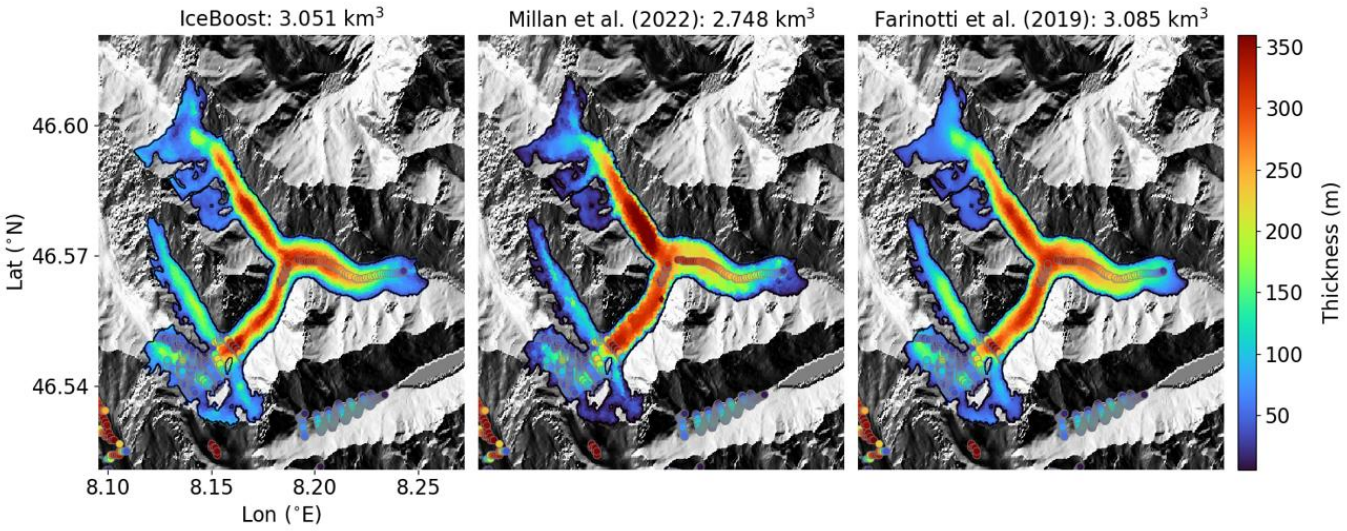

Figure S106: Glacier RGI60-11.01328. Back to Table S2.

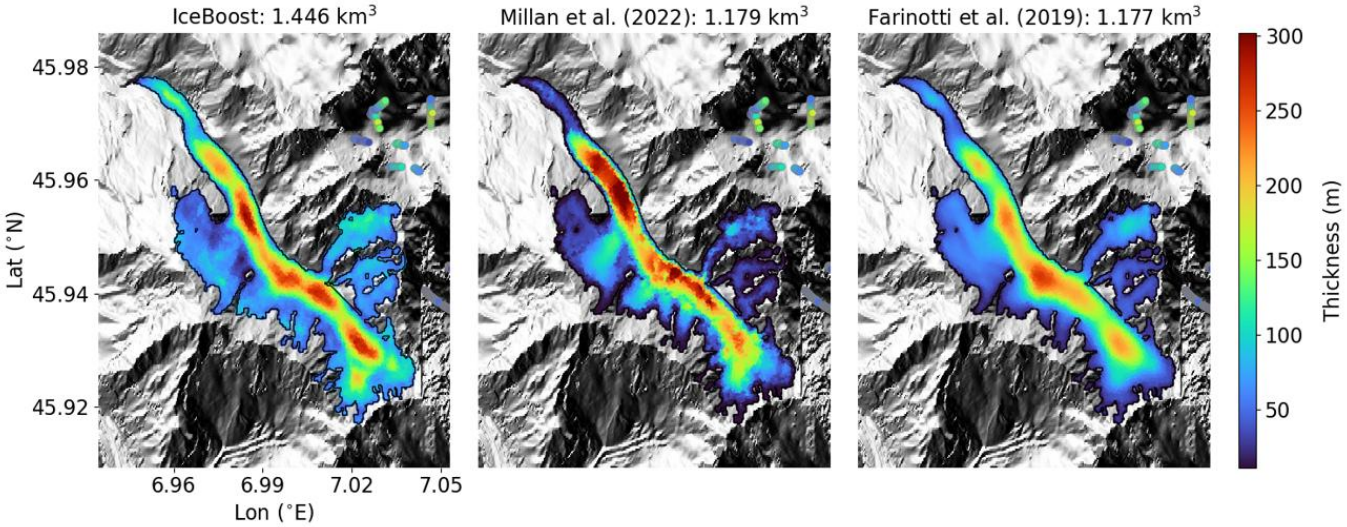

Figure S107: Glacier RGI60-11.03638. Back to Table S2.

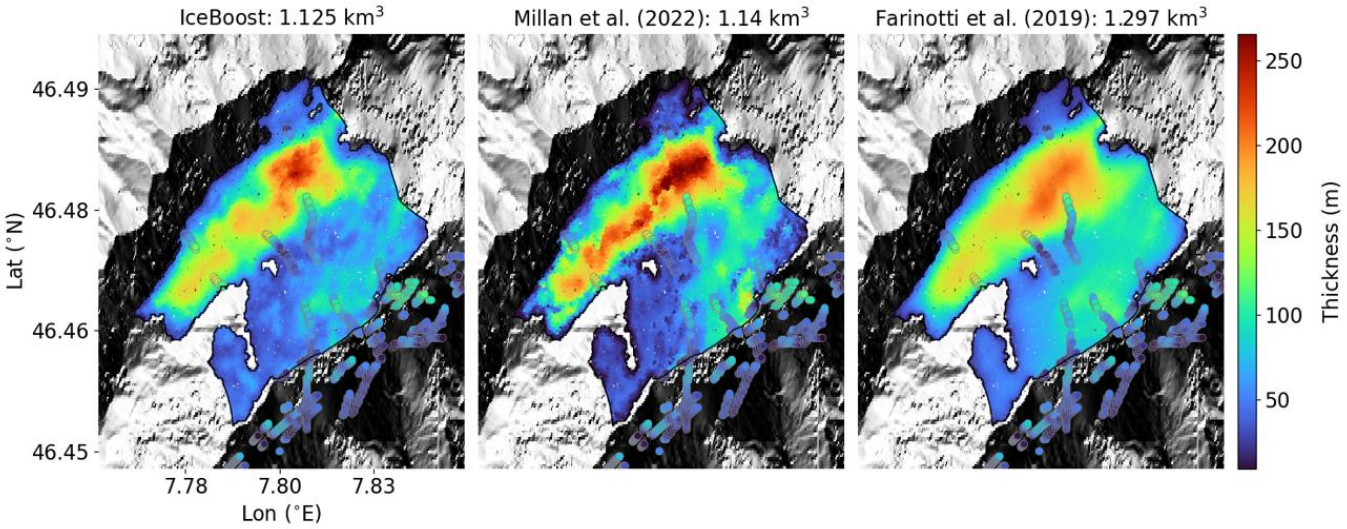

Figure S108: Glacier RGI60-11.01702. Back to Table S2.

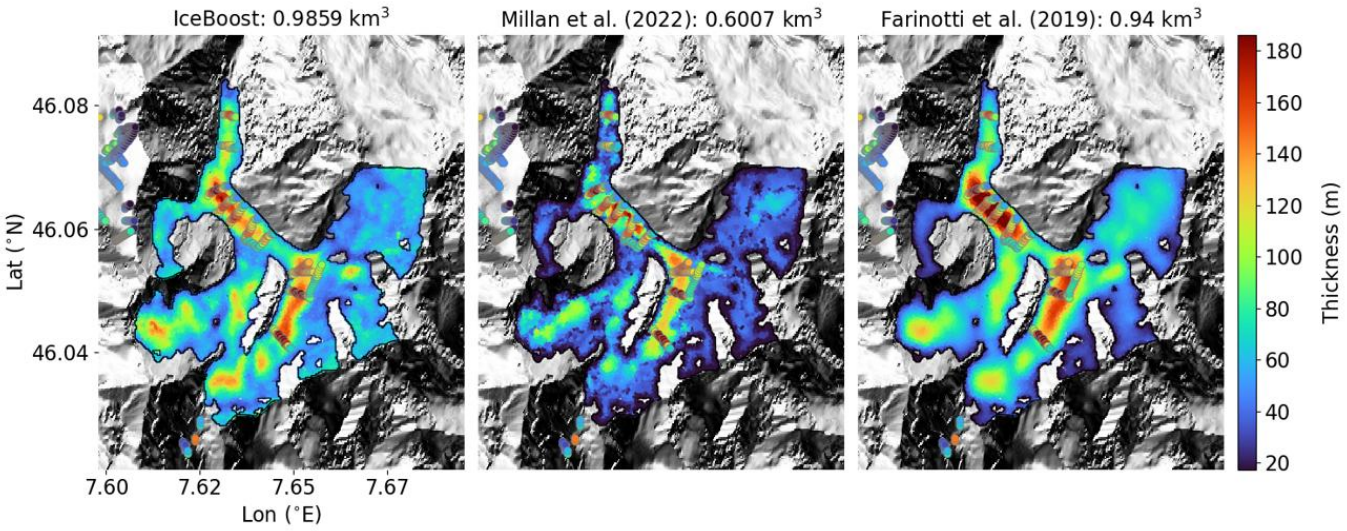

Figure S109: Glacier RGI60-11.02630. Back to Table S2.

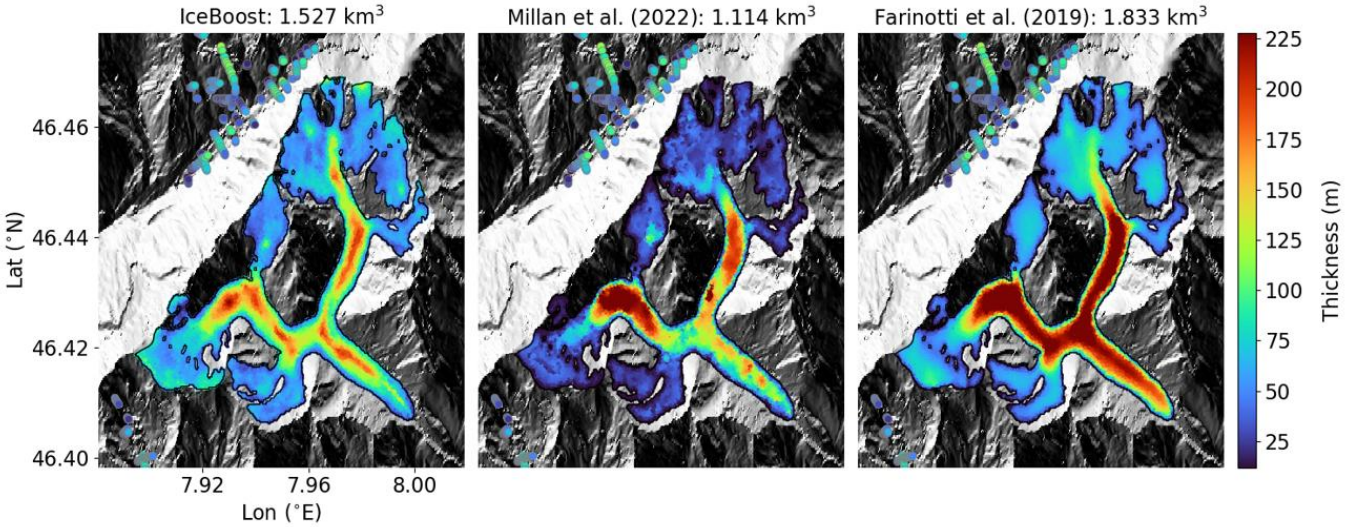

Figure S110: Glacier RGI60-11.01827. Back to Table S2.

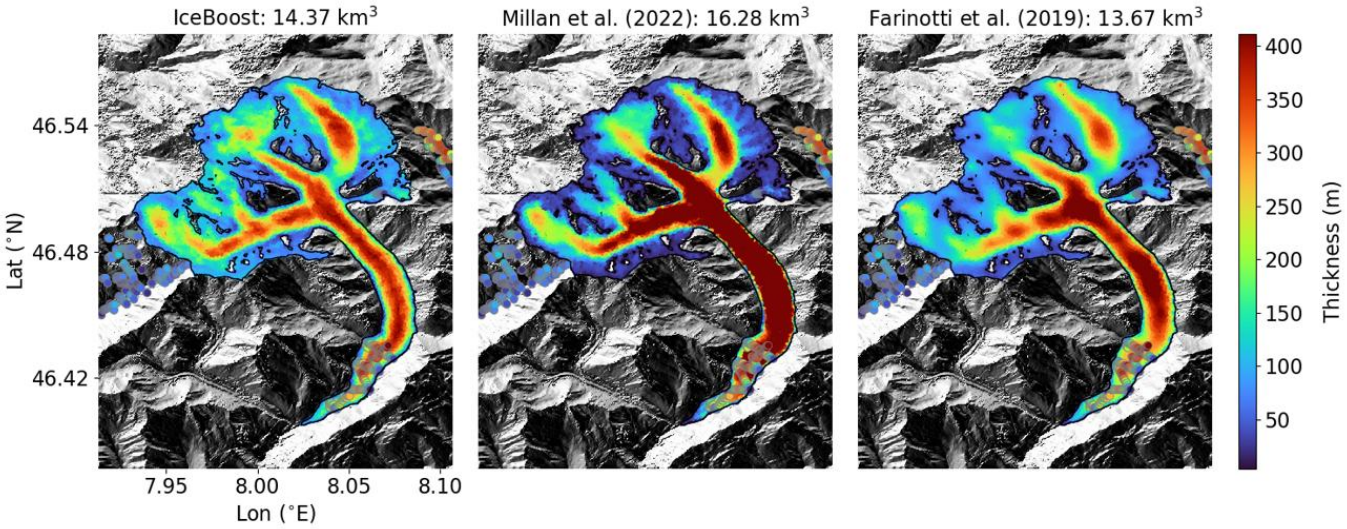

Figure S111: Glacier RGI60-11.01450. Back to Table S2.

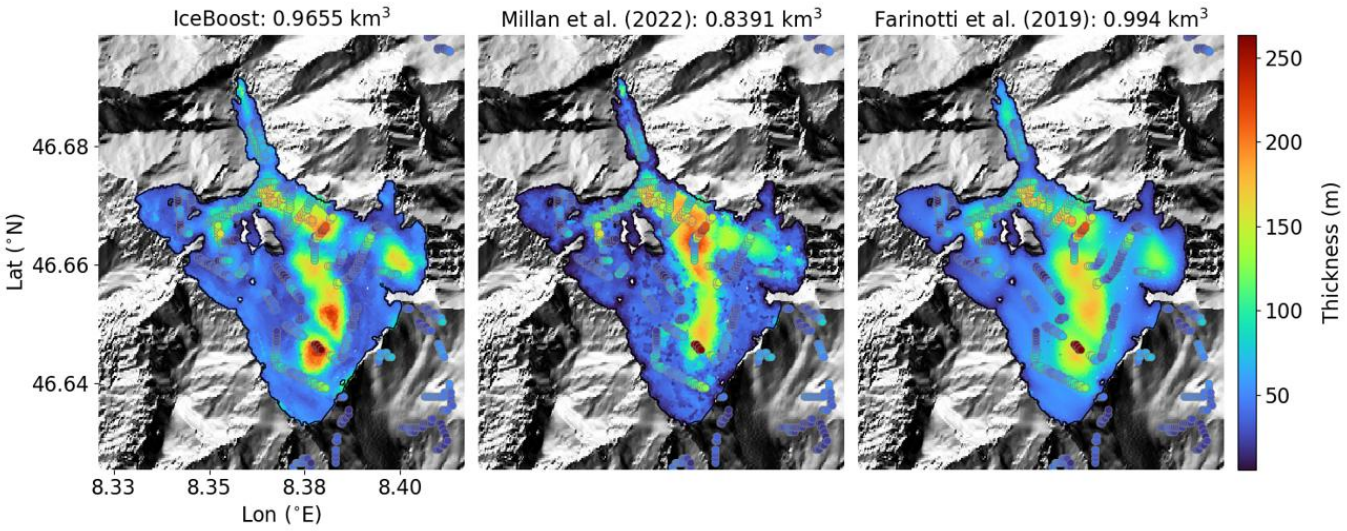

Figure S112: Glacier RGI60-11.01198. Back to Table S2.

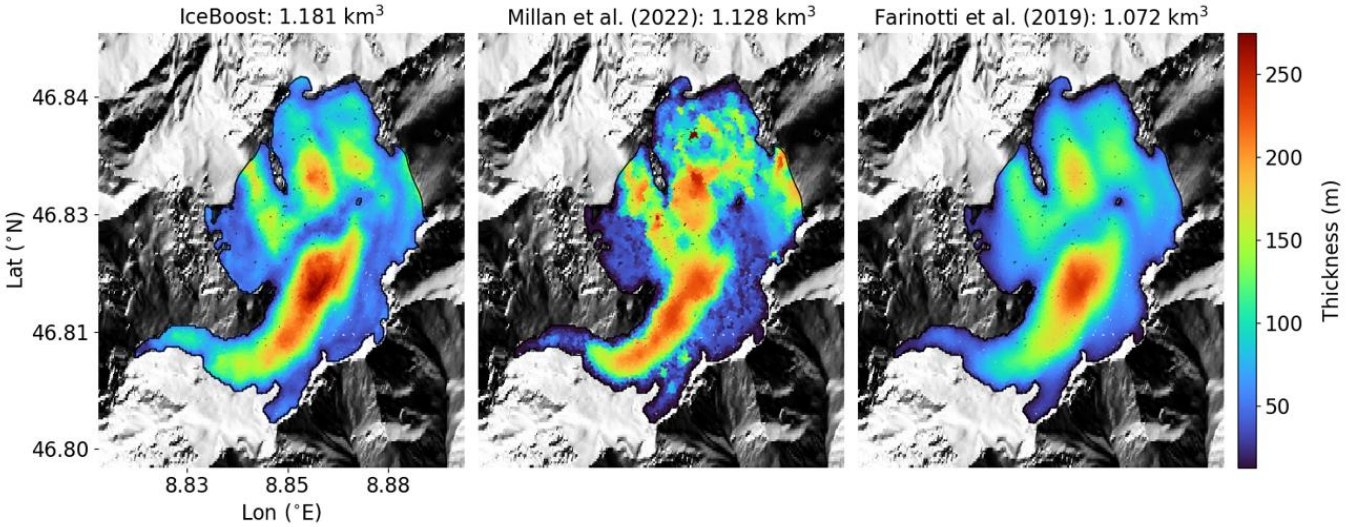

Figure S113: Glacier RGI60-11.00872. Back to Table S2.

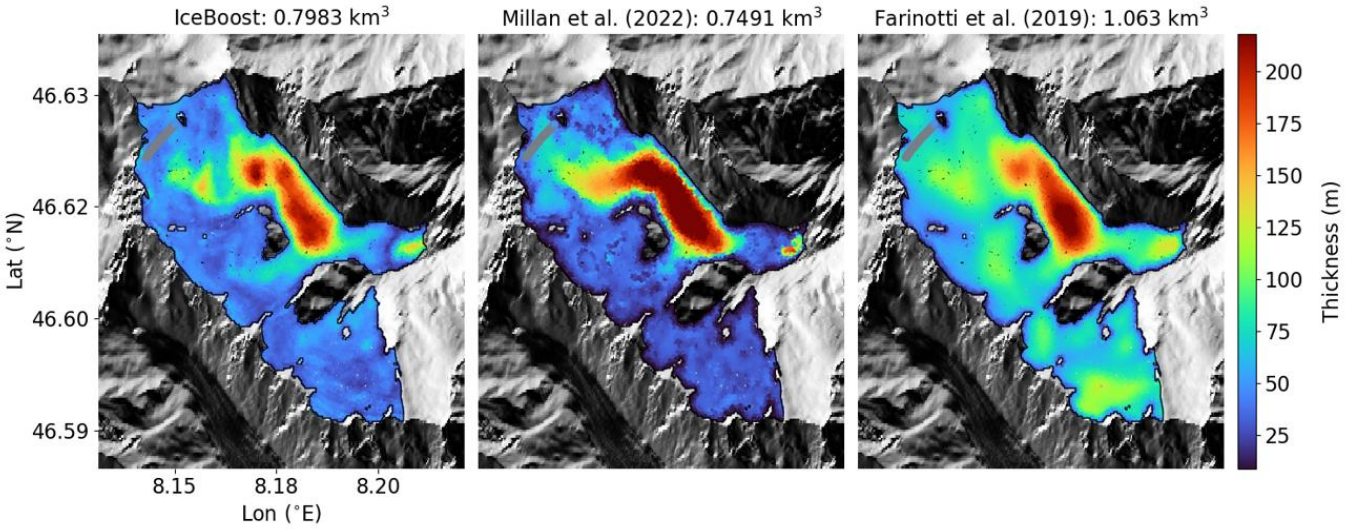

Figure S114: Glacier RGI60-11.01275. Back to Table S2.

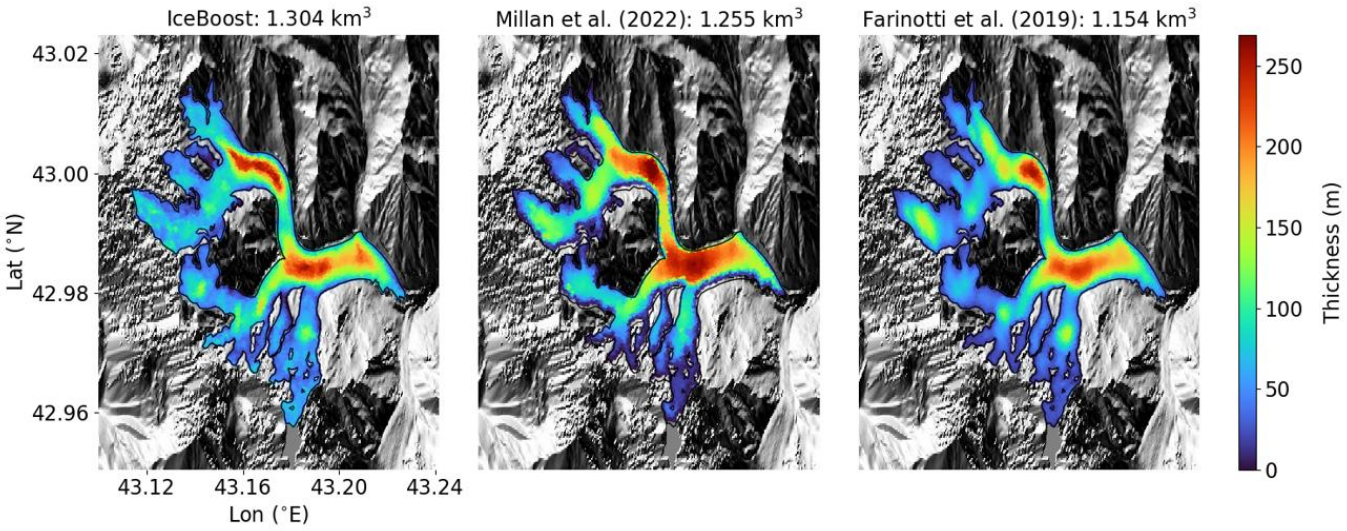

Figure S115: Glacier RGI60-12.00577. Back to Table S2.

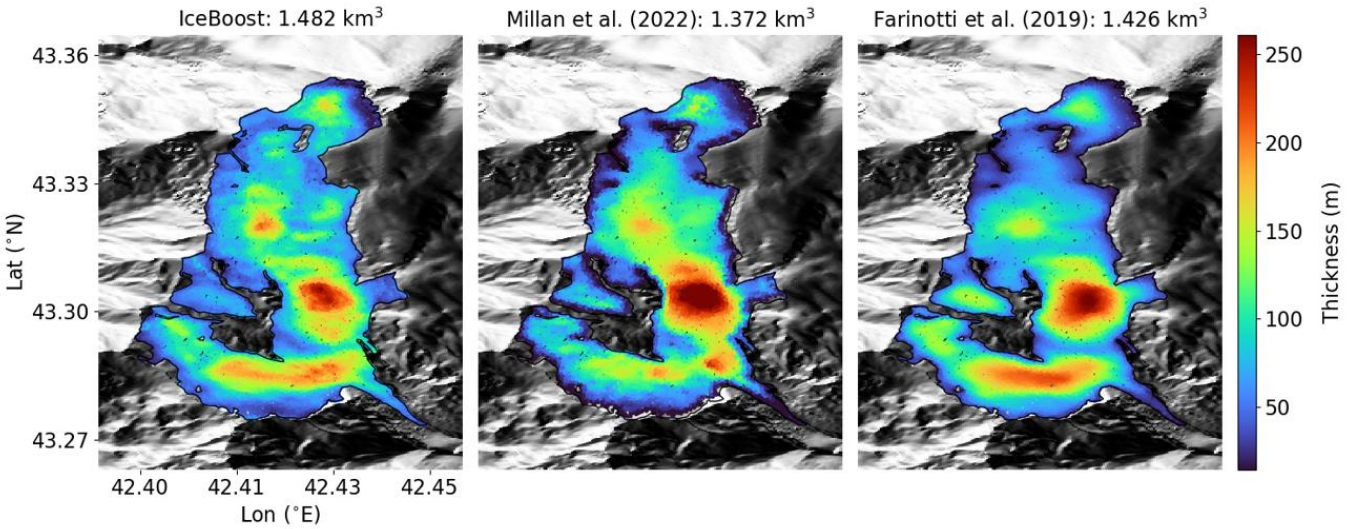

Figure S116: Glacier RGI60-12.00080. Back to Table S2.

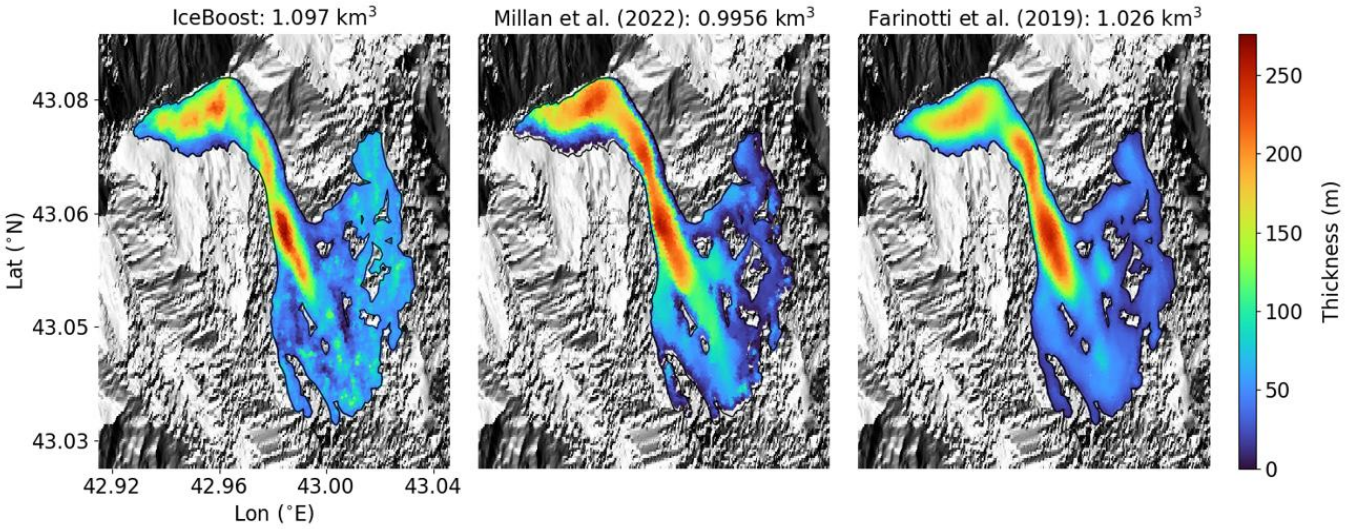

Figure S117: Glacier RGI60-12.00089. Back to Table S2.

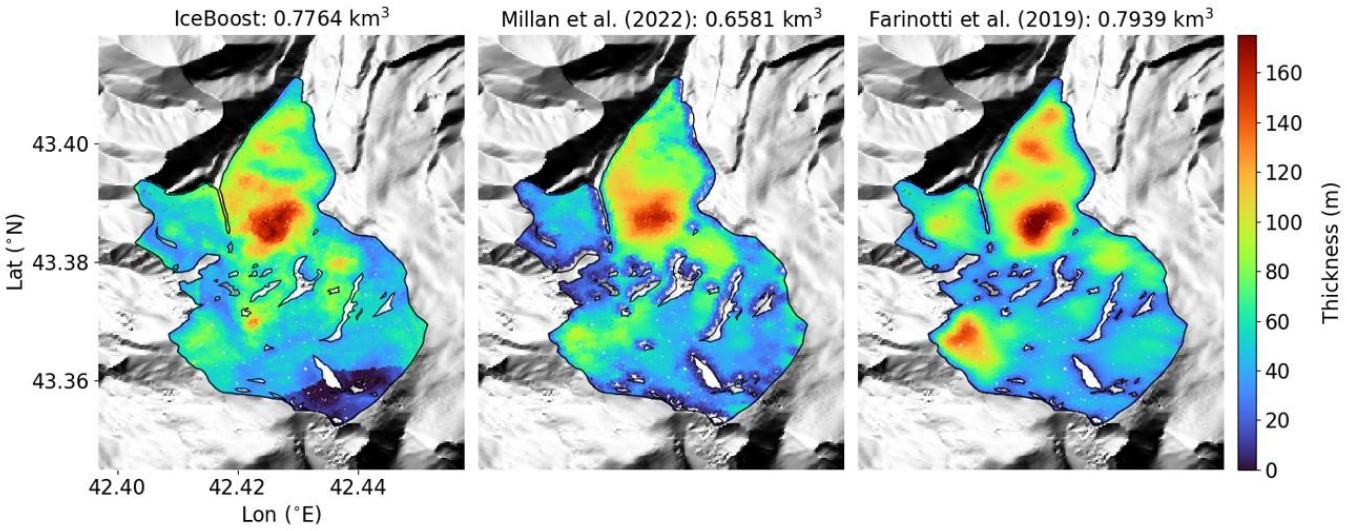

Figure S118: Glacier RGI60-12.00014. Back to Table S2.

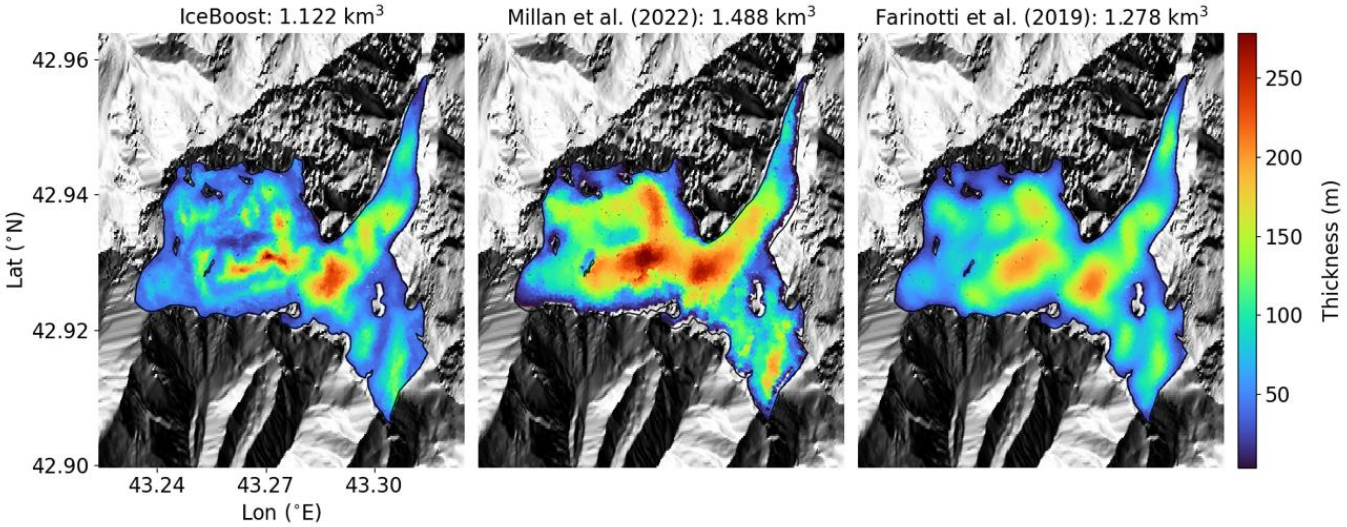

Figure S119: Glacier RGI60-12.00552. Back to Table S2.

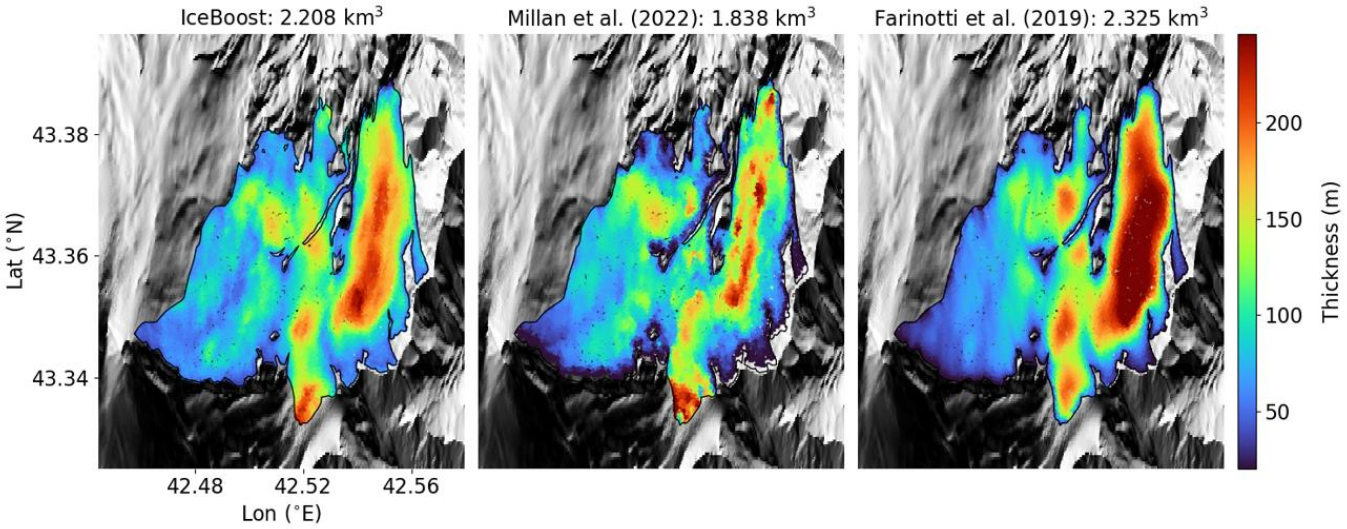

Figure S120: Glacier RGI60-12.01061. Back to Table S2.

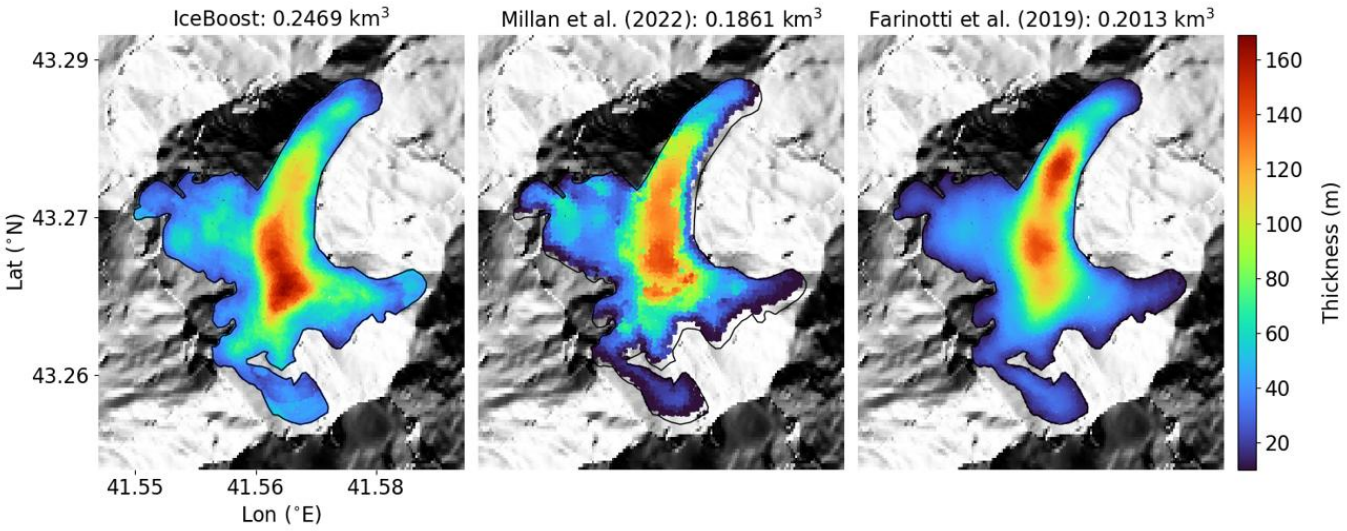

Figure S121: Glacier RGI60-12.00115. Back to Table S2.

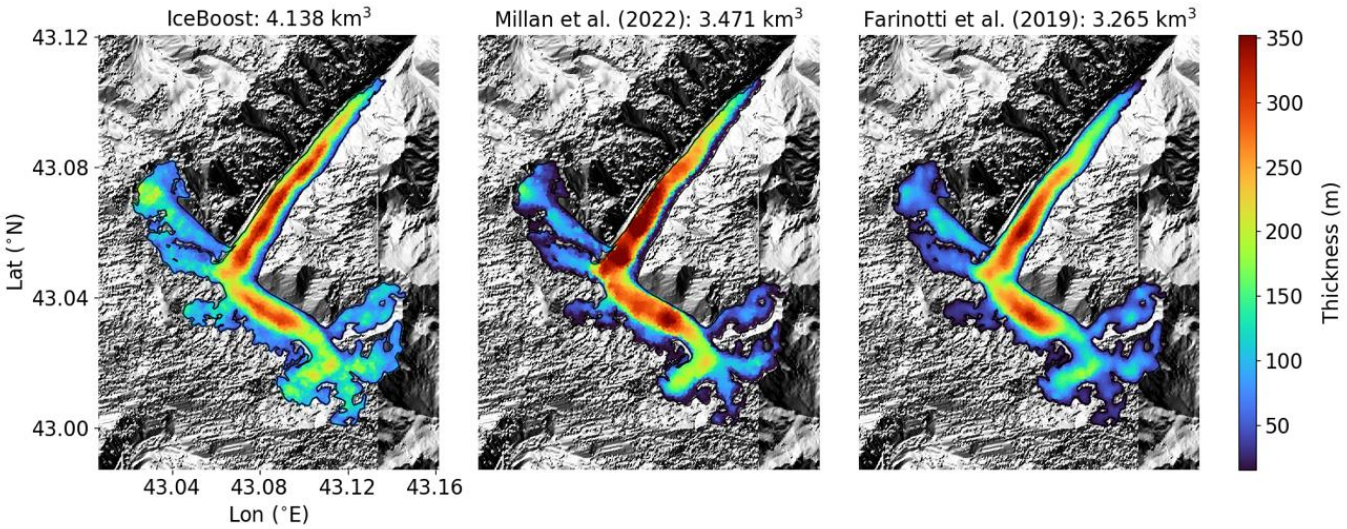

Figure S122: Glacier RGI60-12.01252. Back to Table S2.

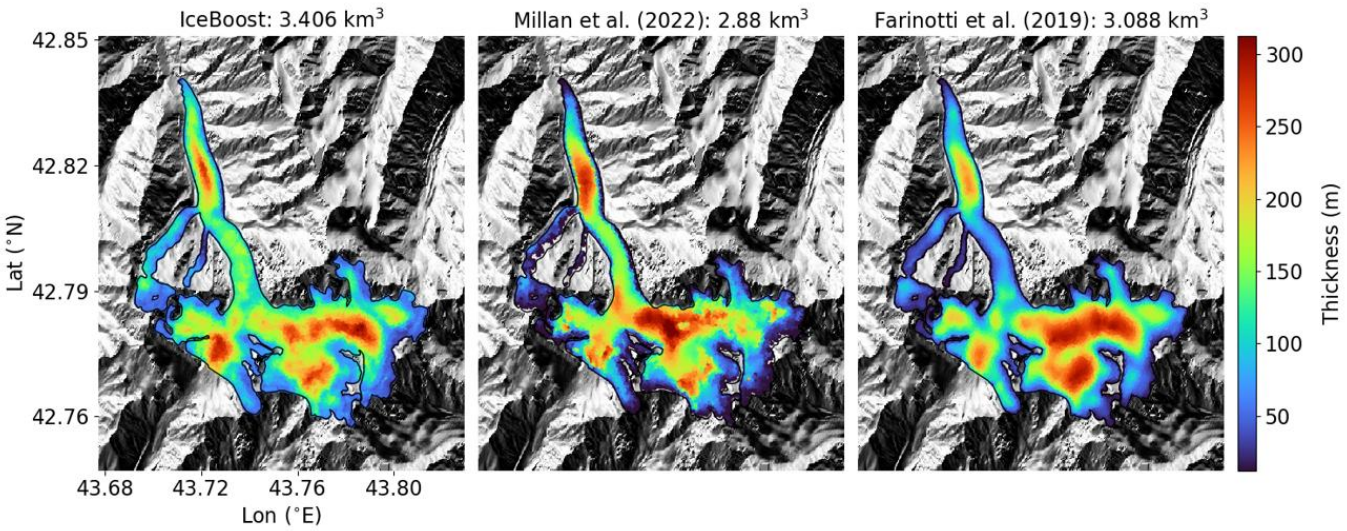

Figure S123: Glacier RGI60-12.00611. Back to Table S2.

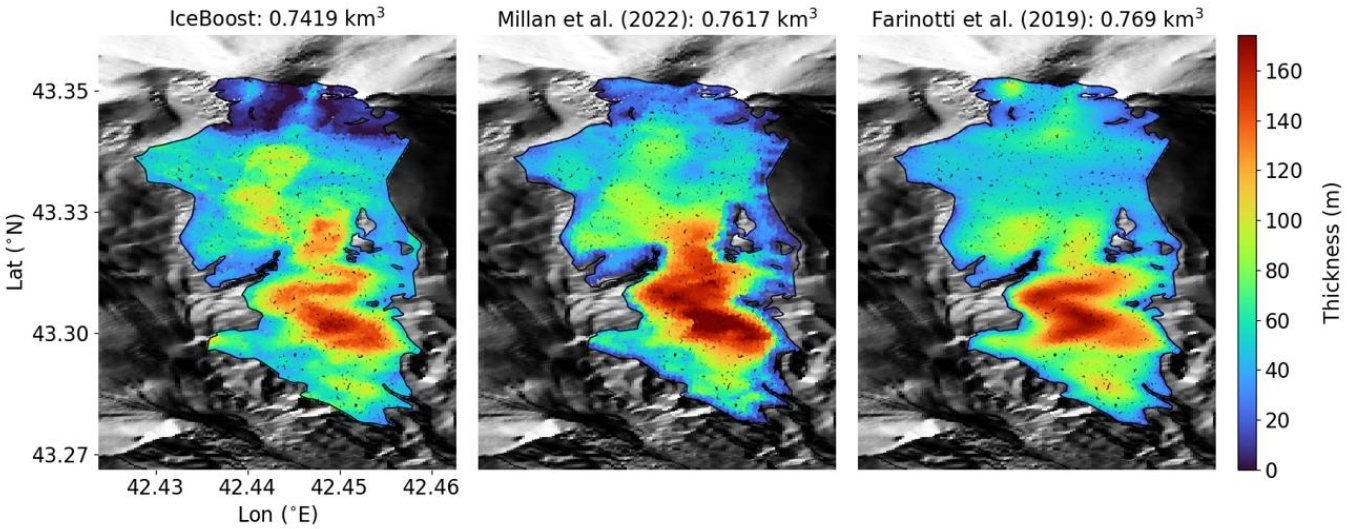

Figure S124: Glacier RGI60-12.00168. Back to Table S2.

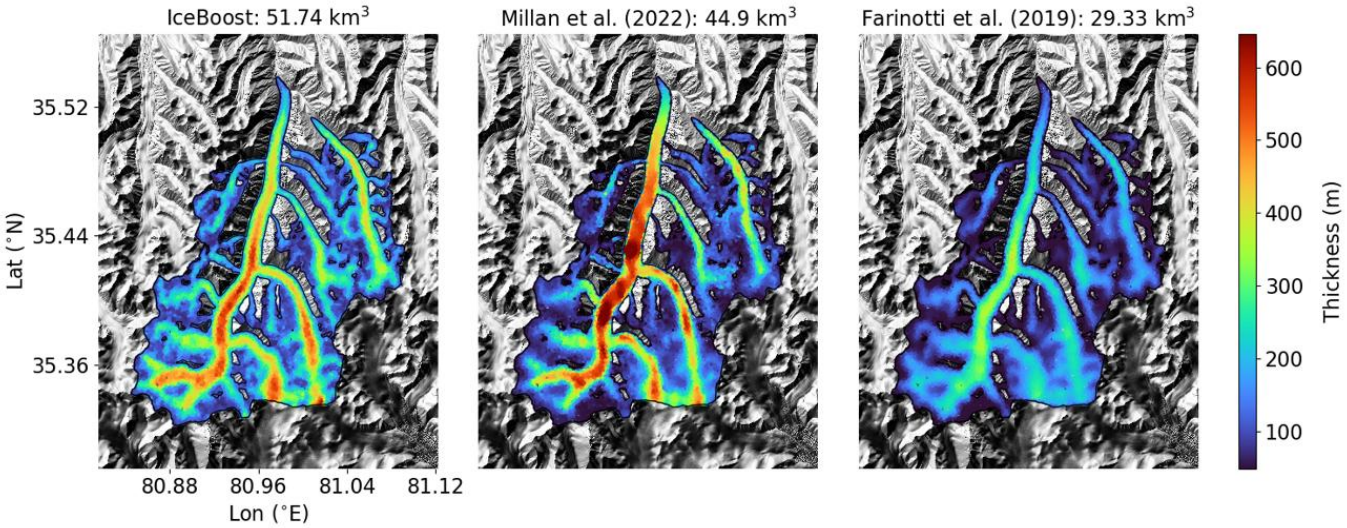

Figure S125: Glacier RGI60-13.37753. Back to Table S2.

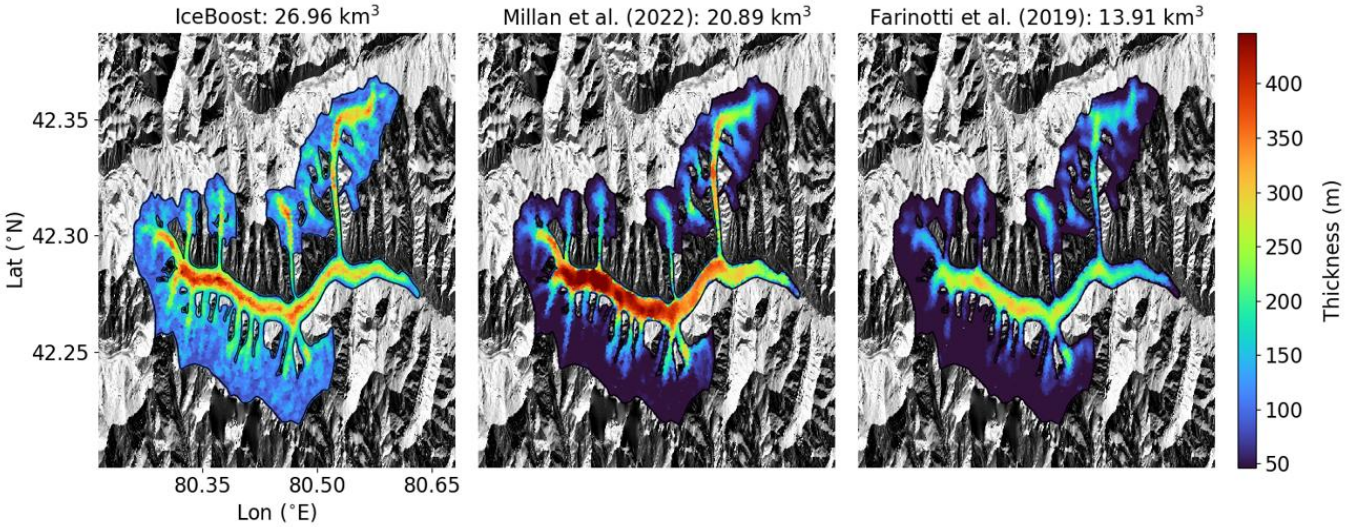

Figure S126: Glacier RGI60-13.43528. Back to Table S2.

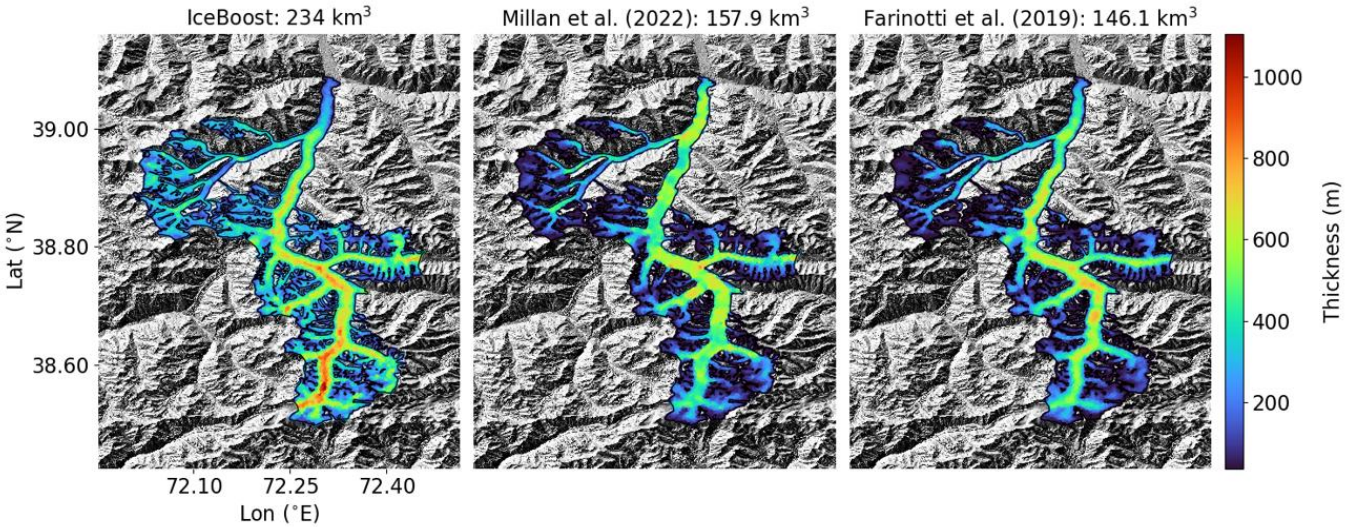

Figure S127: Glacier RGI60-13.54431. Back to Table S2.

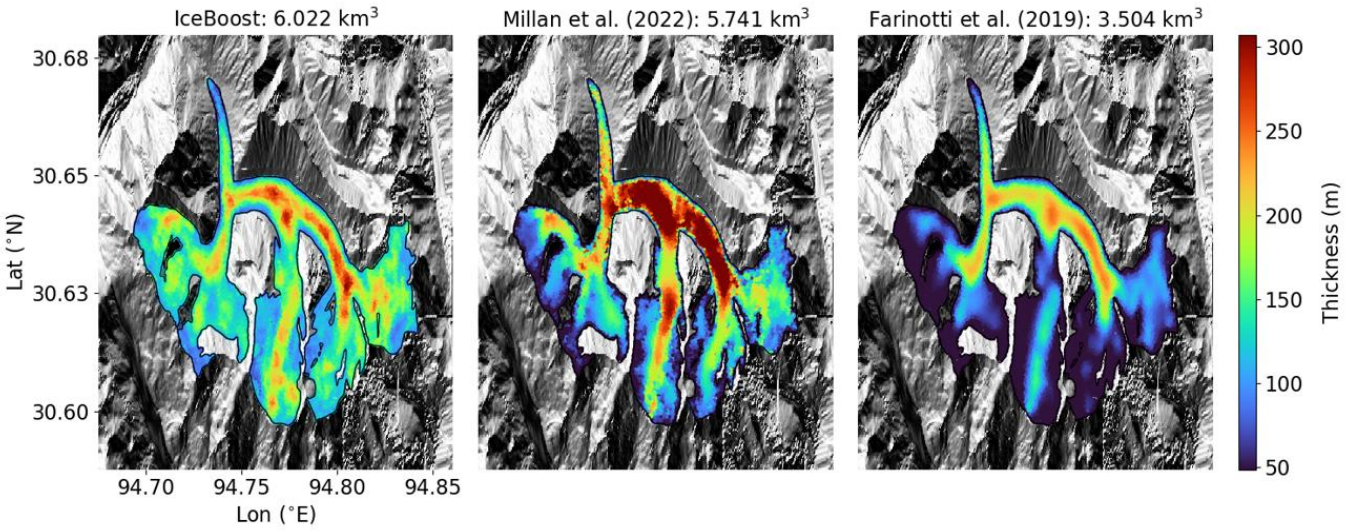

Figure S128: Glacier RGI60-13.01231. Back to Table S2.

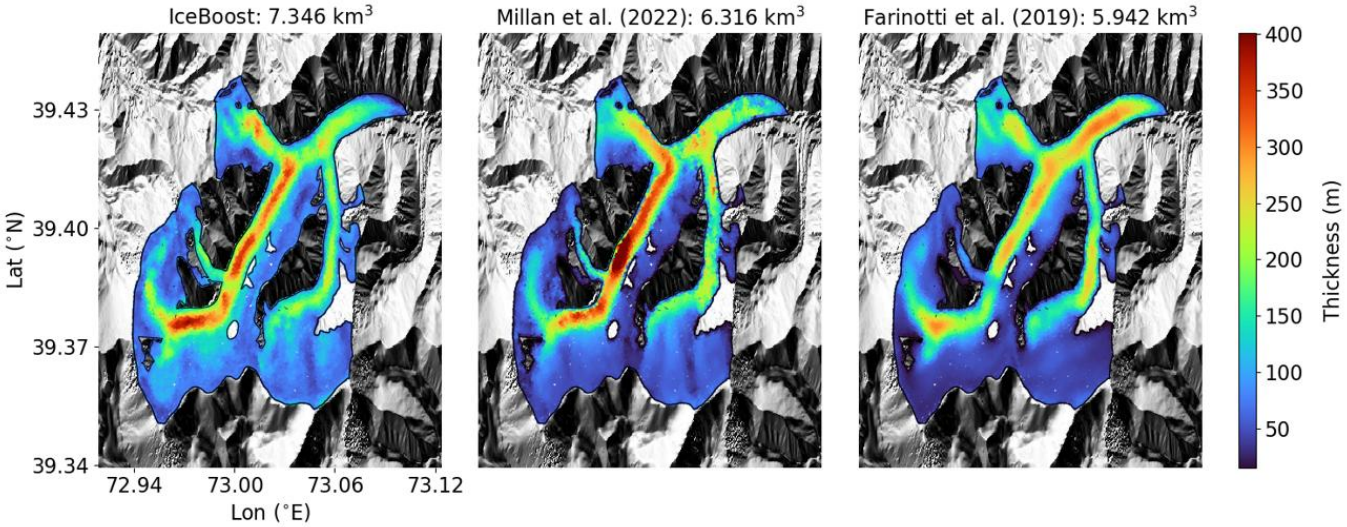

Figure S129: Glacier RGI60-13.13260. Back to Table S2.

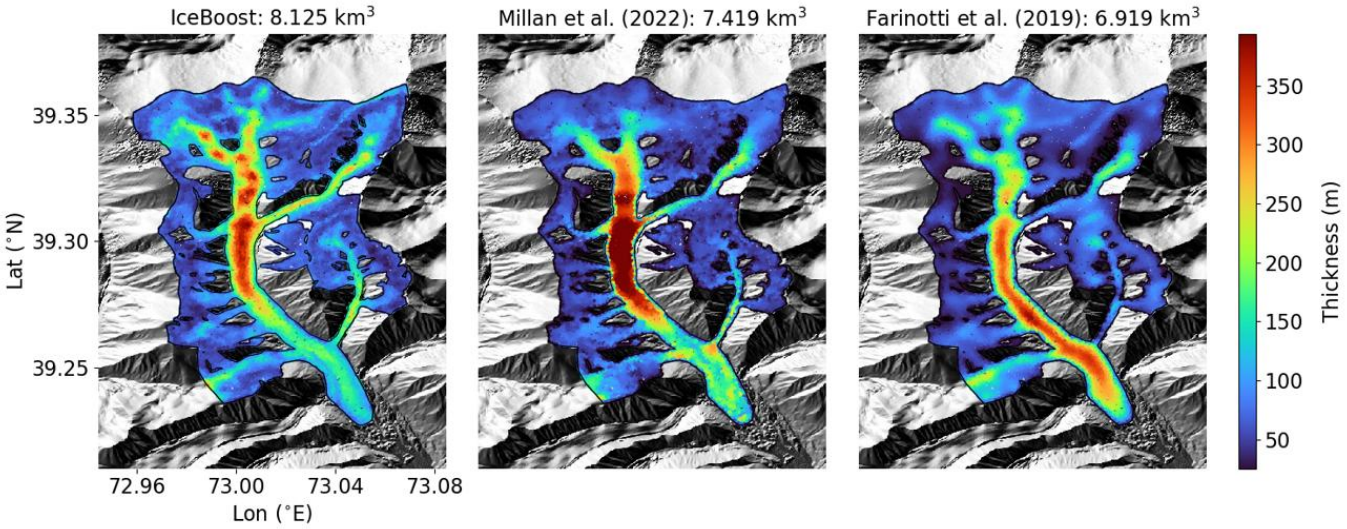

Figure S130: Glacier RGI60-13.13261. Back to Table S2.

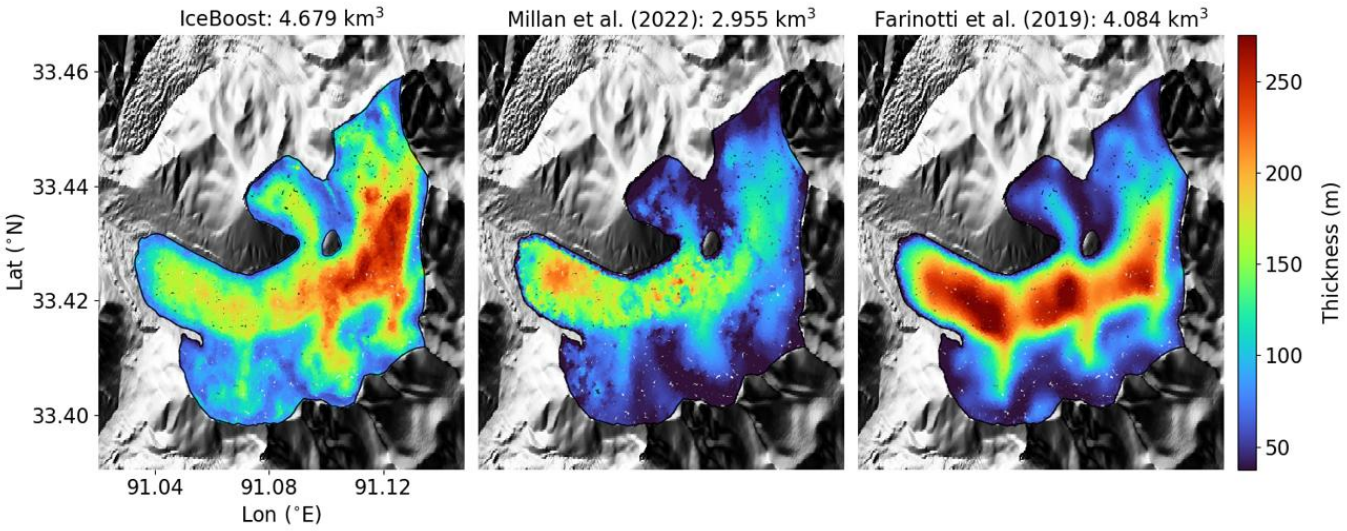

Figure S131: Glacier RGI60-13.24821. Back to Table S2.

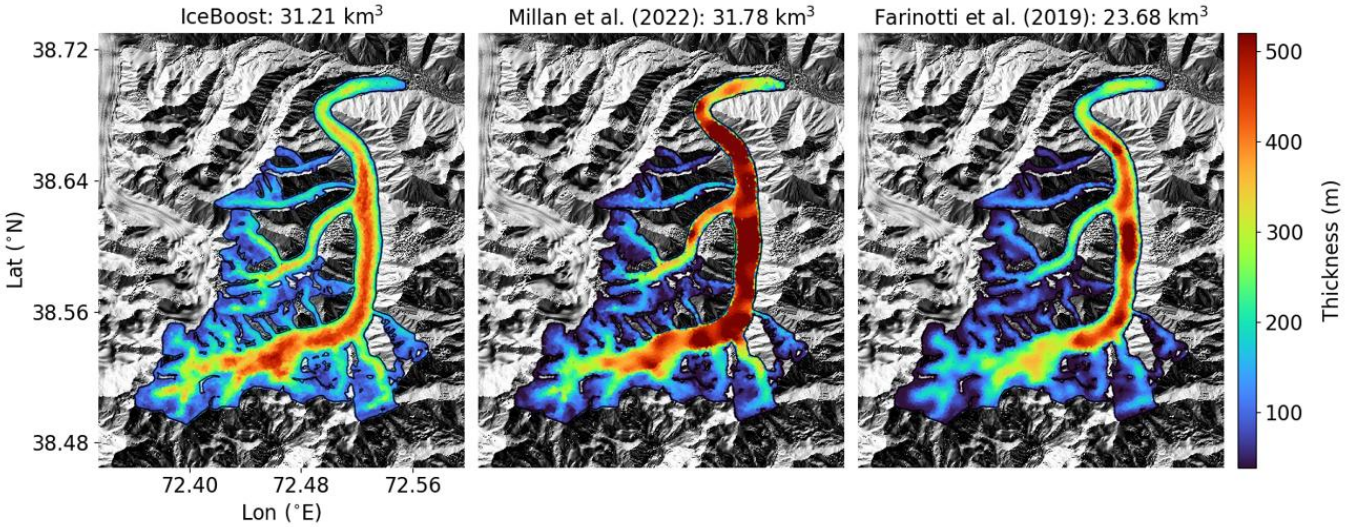

Figure S132: Glacier RGI60-13.13574. Back to Table S2.

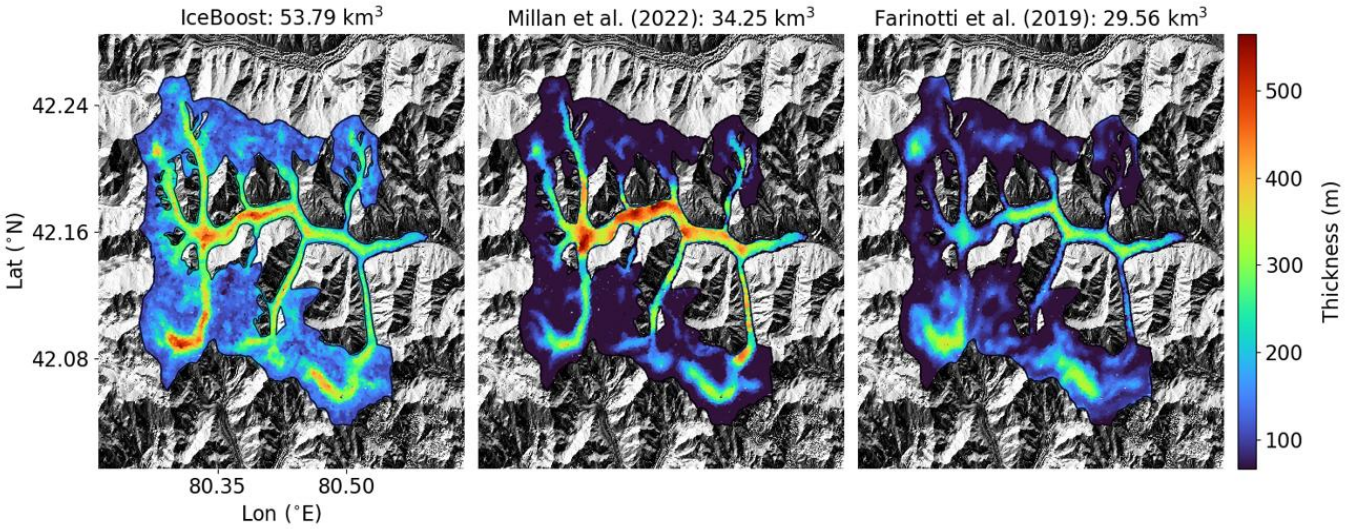

Figure S133: Glacier RGI60-13.43483. Back to Table S2.

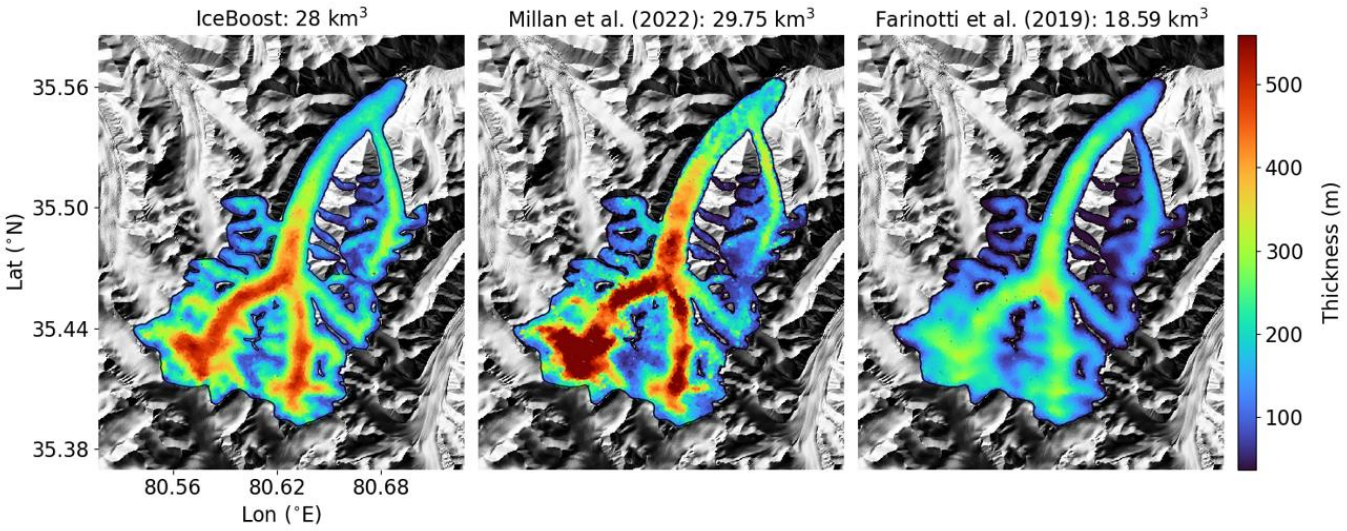

Figure S134: Glacier RGI60-13.37647. Back to Table S2.

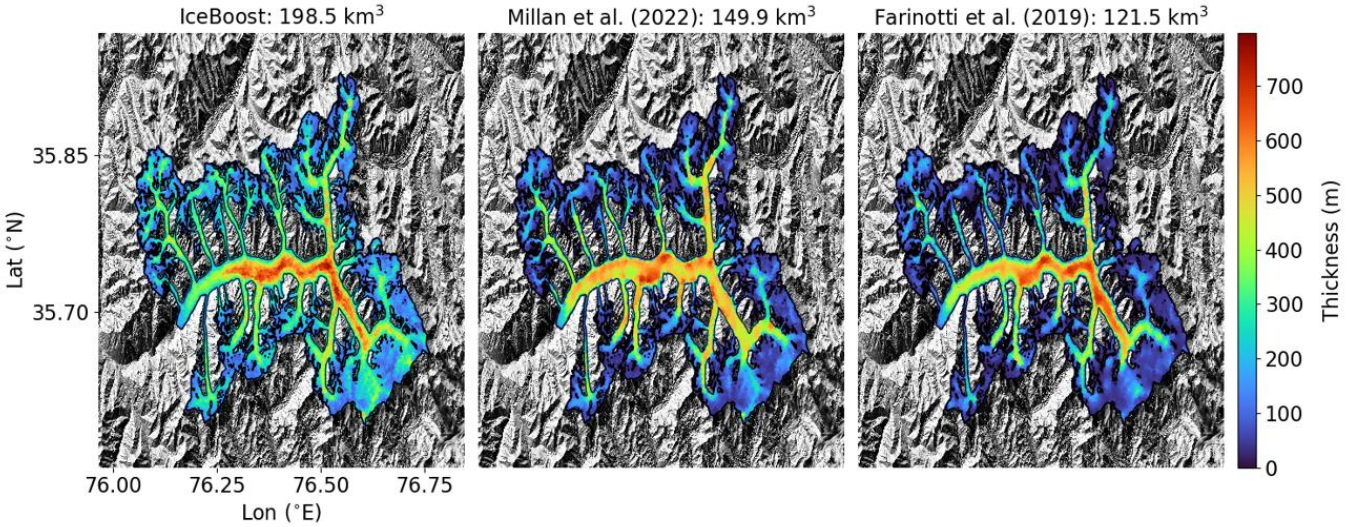

Figure S135: Glacier RGI60-14.06794. Back to Table S2.

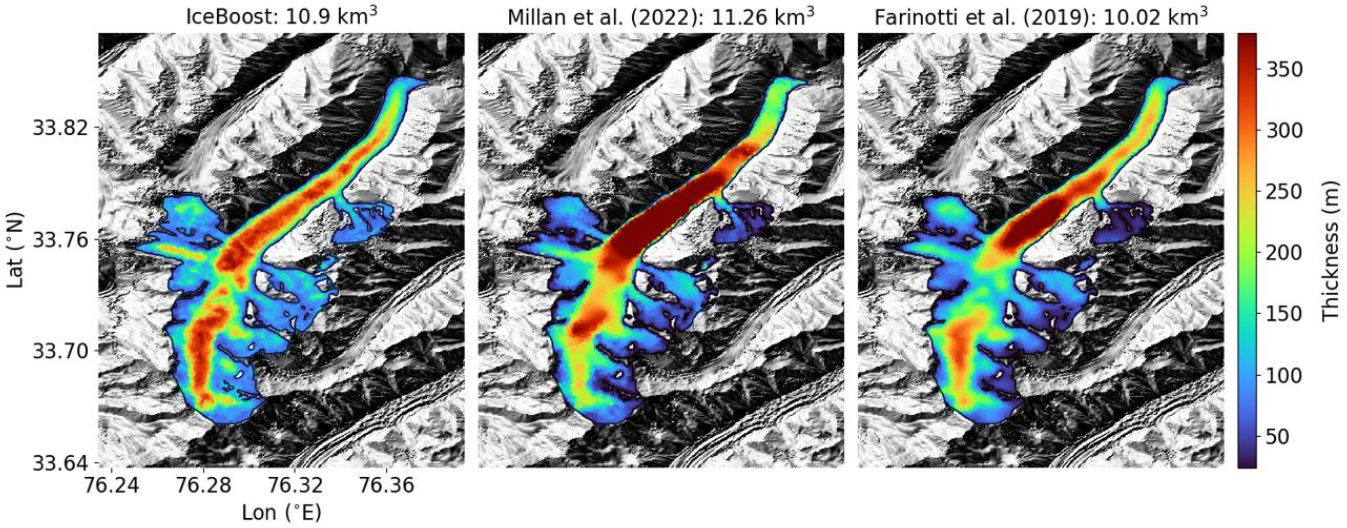

Figure S136: Glacier RGI60-14.18948. Back to Table S2.

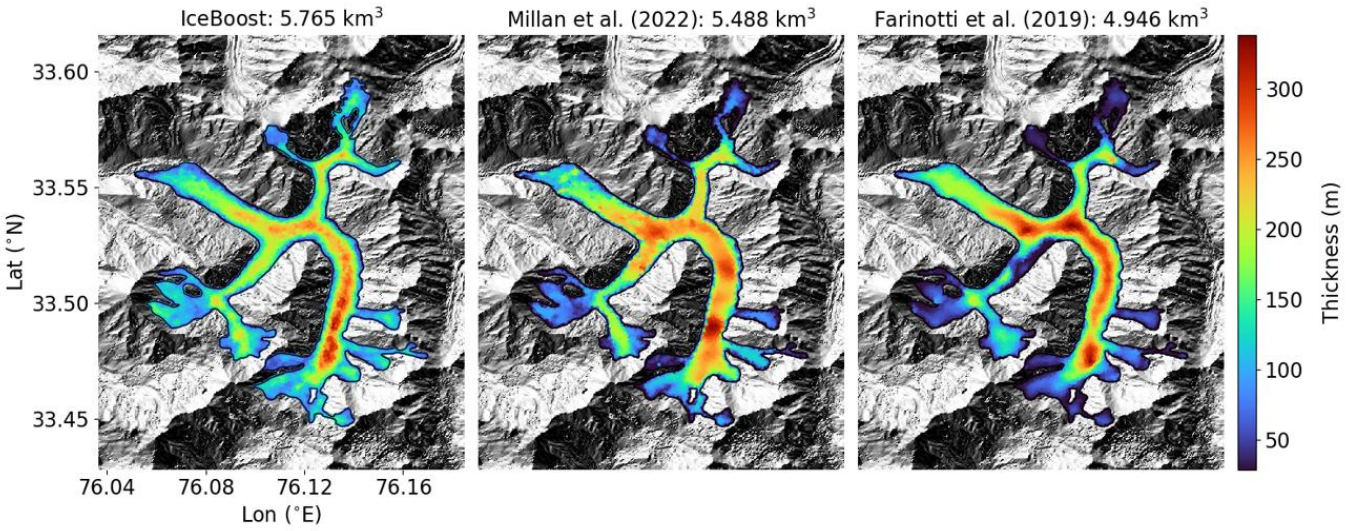

Figure S137: Glacier RGI60-14.18970. Back to Table S2.

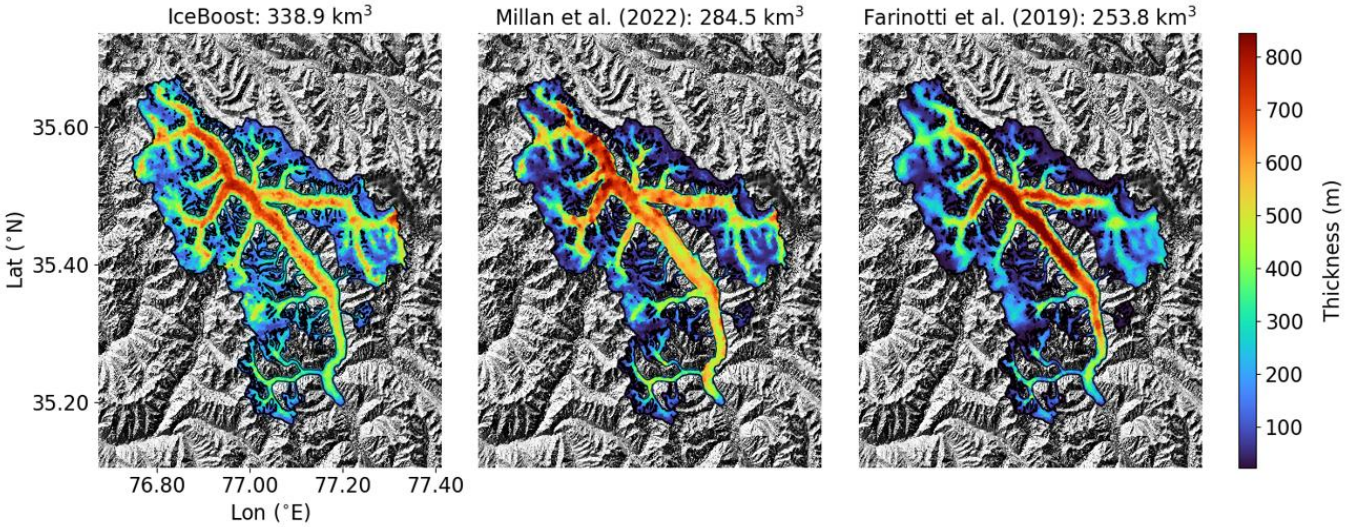

Figure S138: Glacier RGI60-14.07524. Back to Table S2.

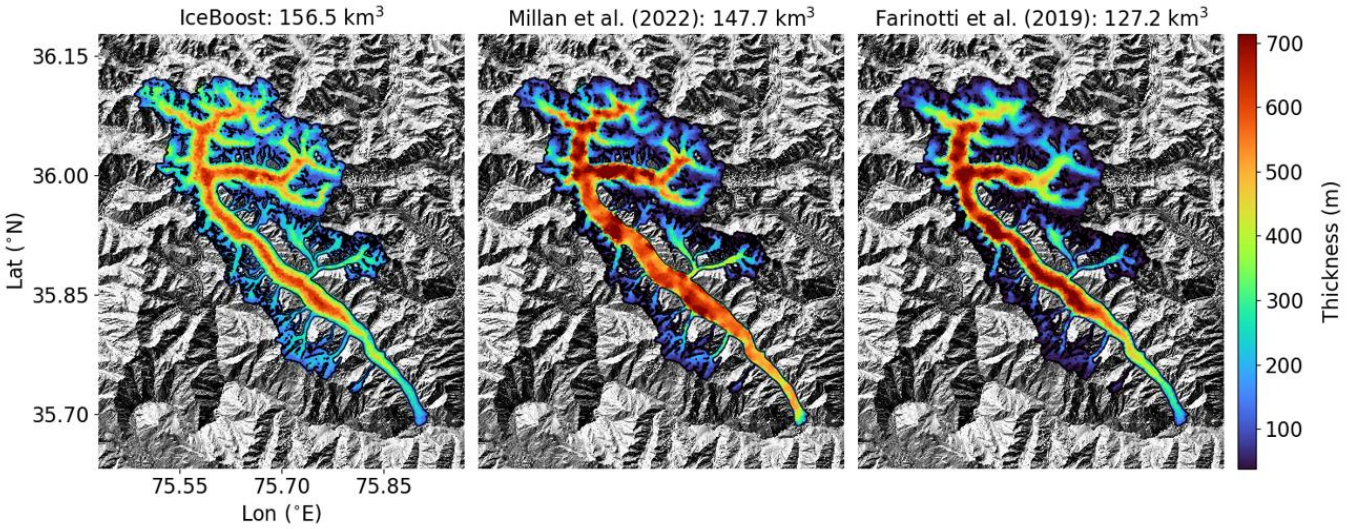

Figure S139: Glacier RGI60-14.00005. Back to Table S2.

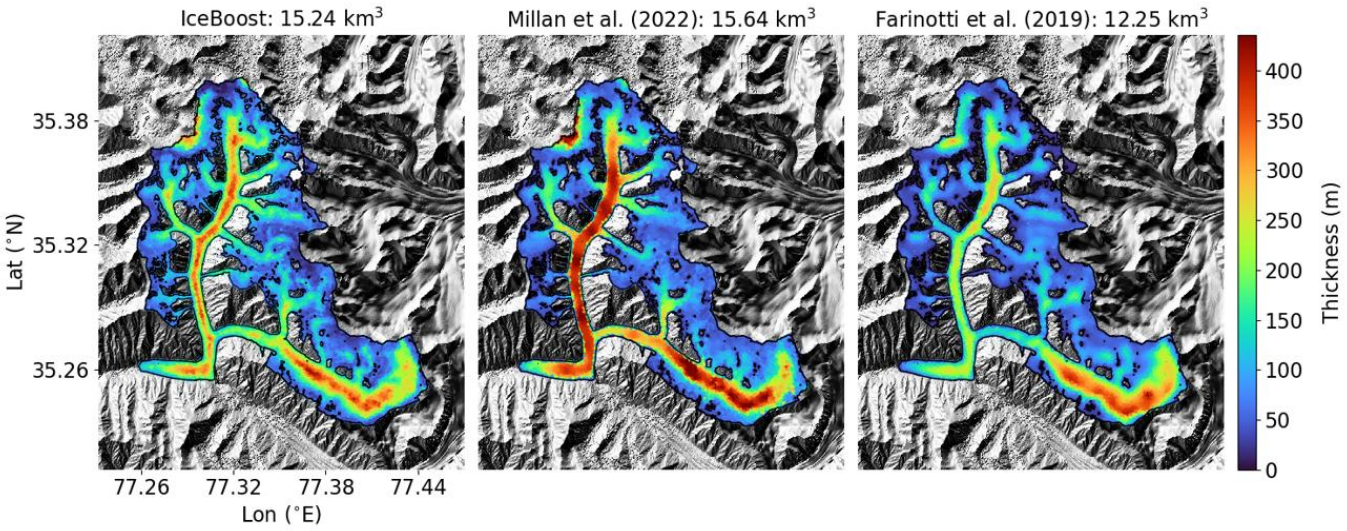

Figure S140: Glacier RGI60-14.07756. Back to Table S2.

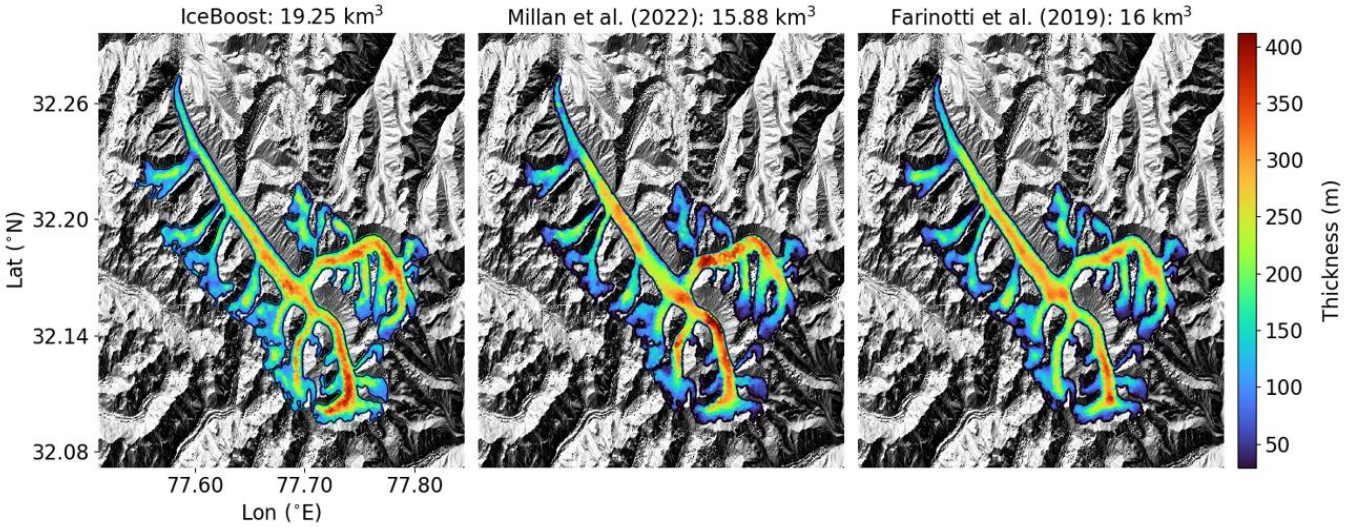

Figure S141: Glacier RGI60-14.15447. Back to Table S2.

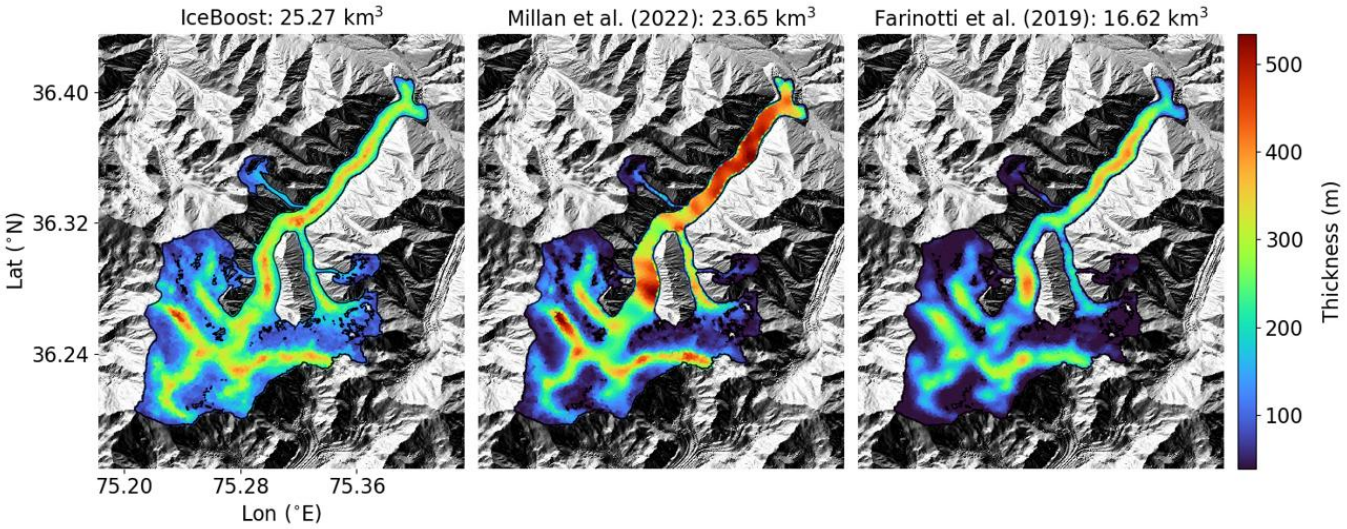

Figure S142: Glacier RGI60-14.03334. Back to Table S2.

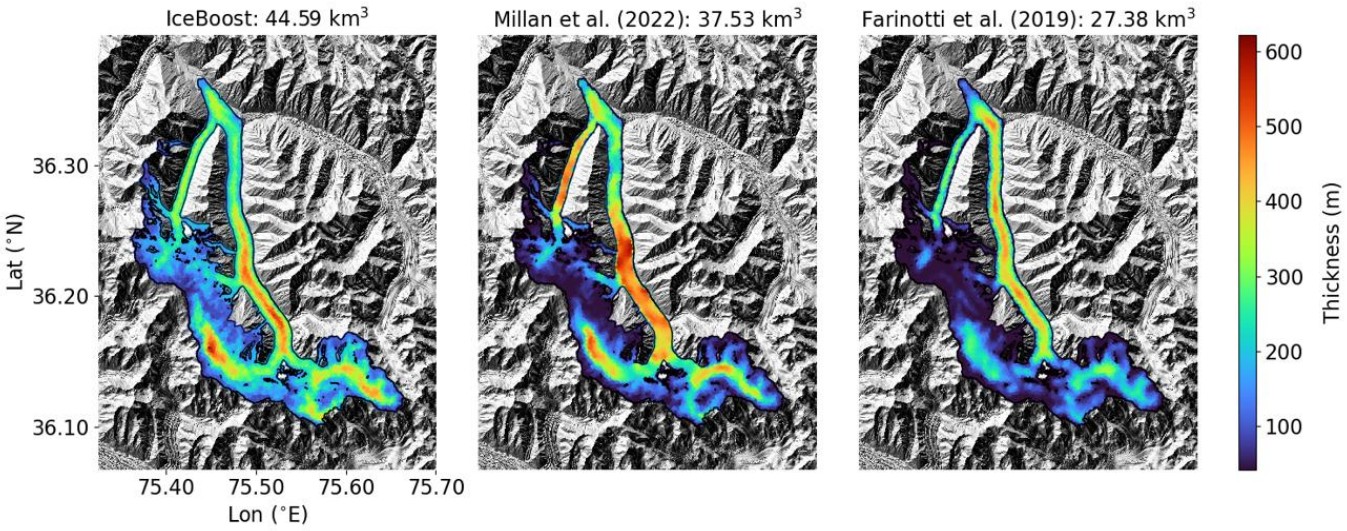

Figure S143: Glacier RGI60-14.04404. Back to Table S2.

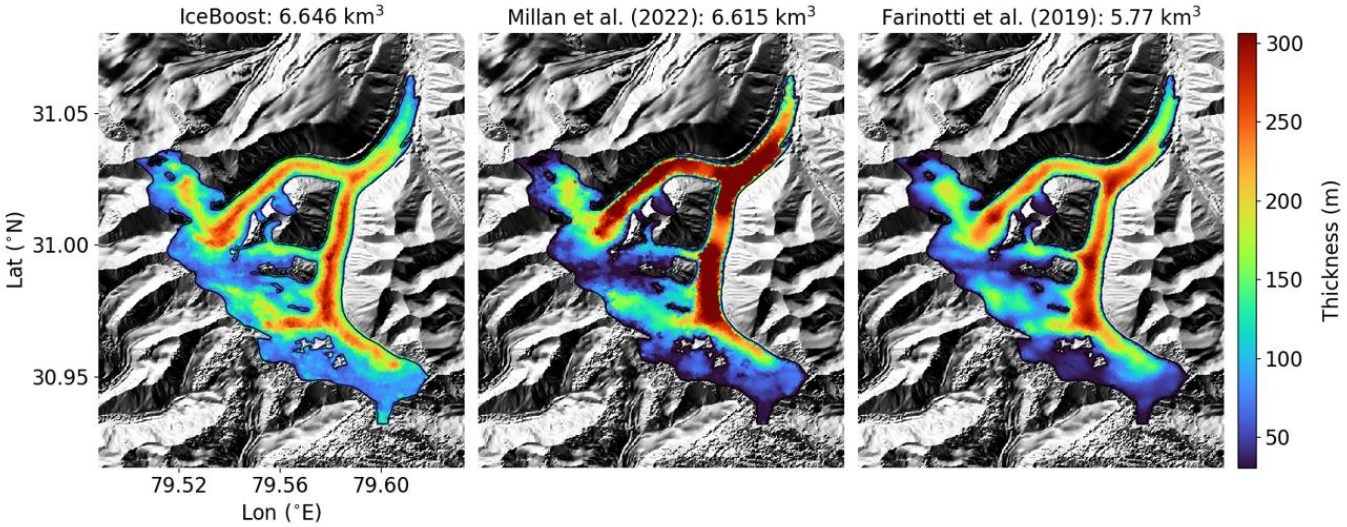

Figure S144: Glacier RGI60-14.26942. Back to Table S2.

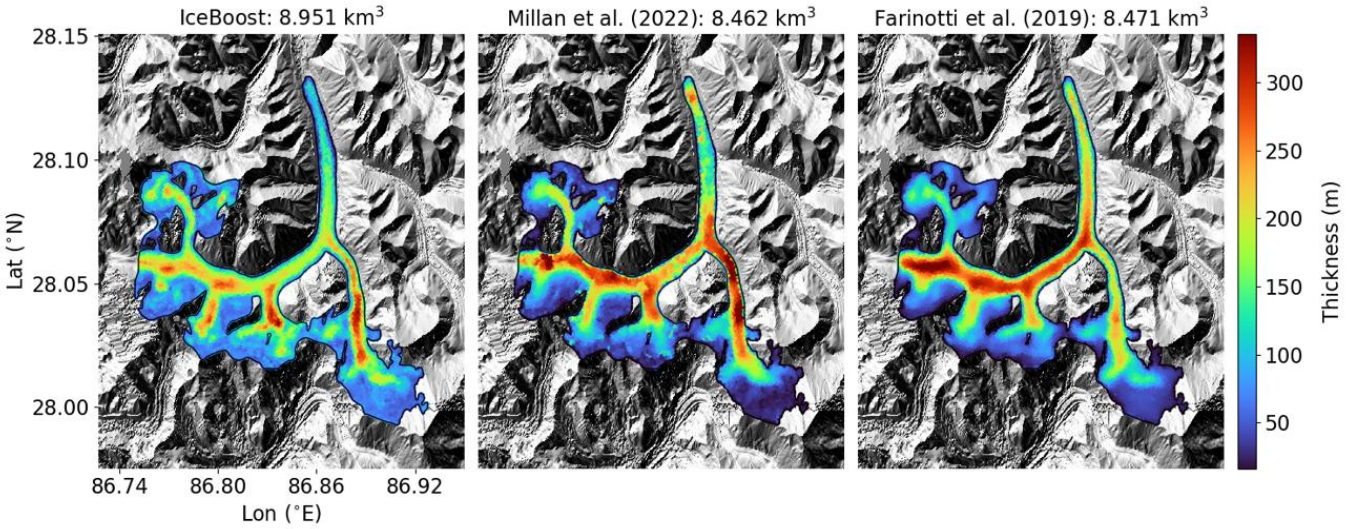

Figure S145: Glacier RGI60-15.09991. Back to Table S2.

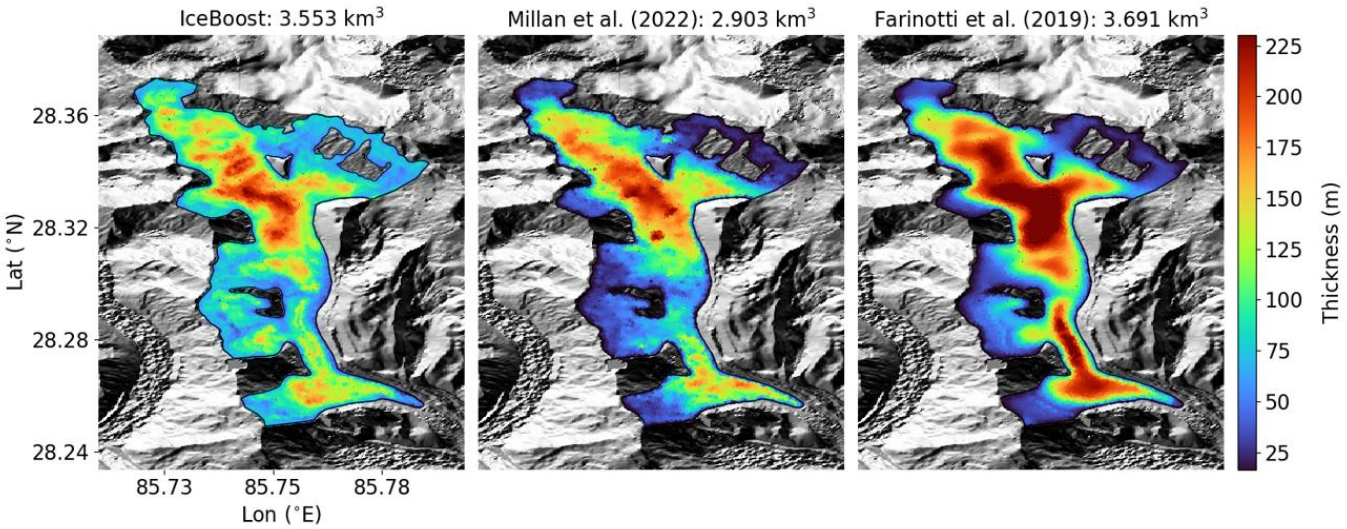

Figure S146: Glacier RGI60-15.09474. Back to Table S2.

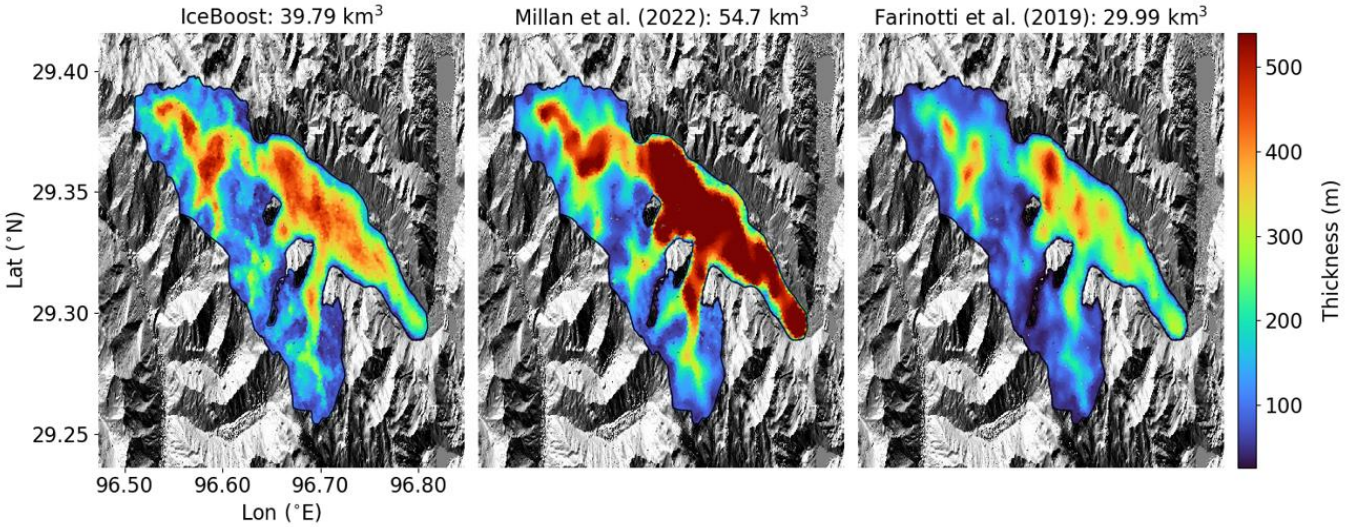

Figure S147: Glacier RGI60-15.11909. Back to Table S2.

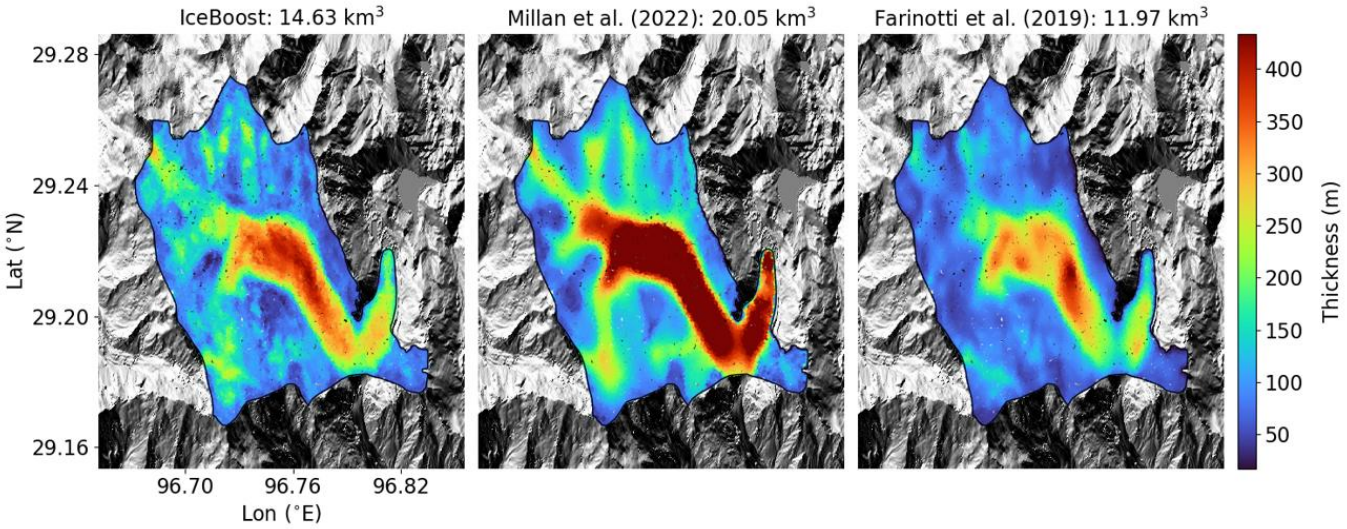

Figure S148: Glacier RGI60-15.11926. Back to Table S2.

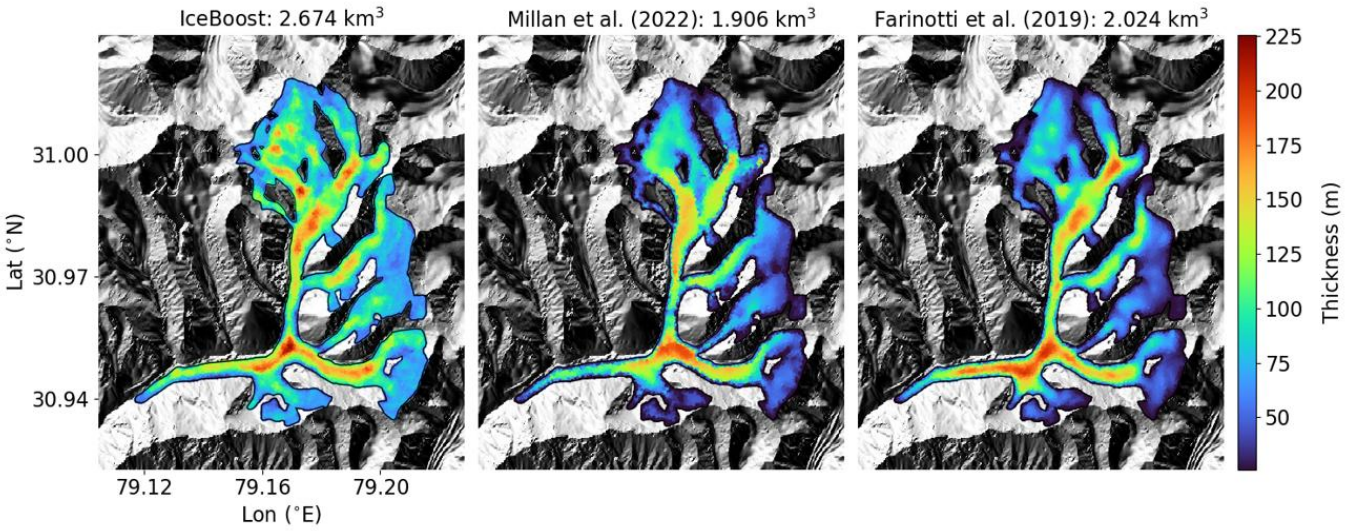

Figure S149: Glacier RGI60-15.06574. Back to Table S2.

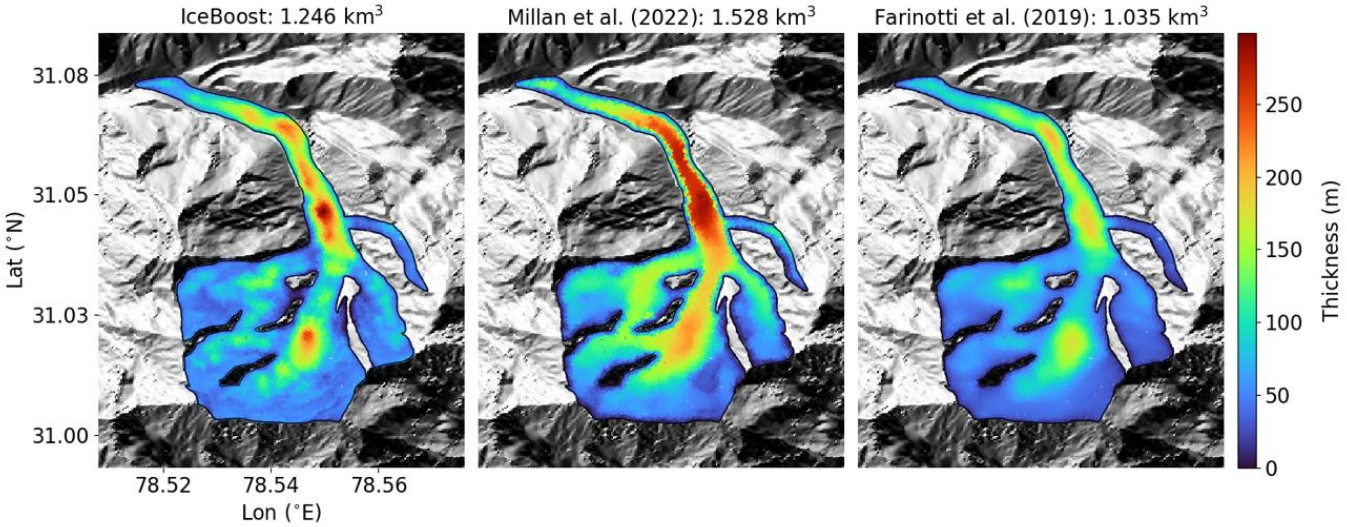

Figure S150: Glacier RGI60-15.07519. Back to Table S2.

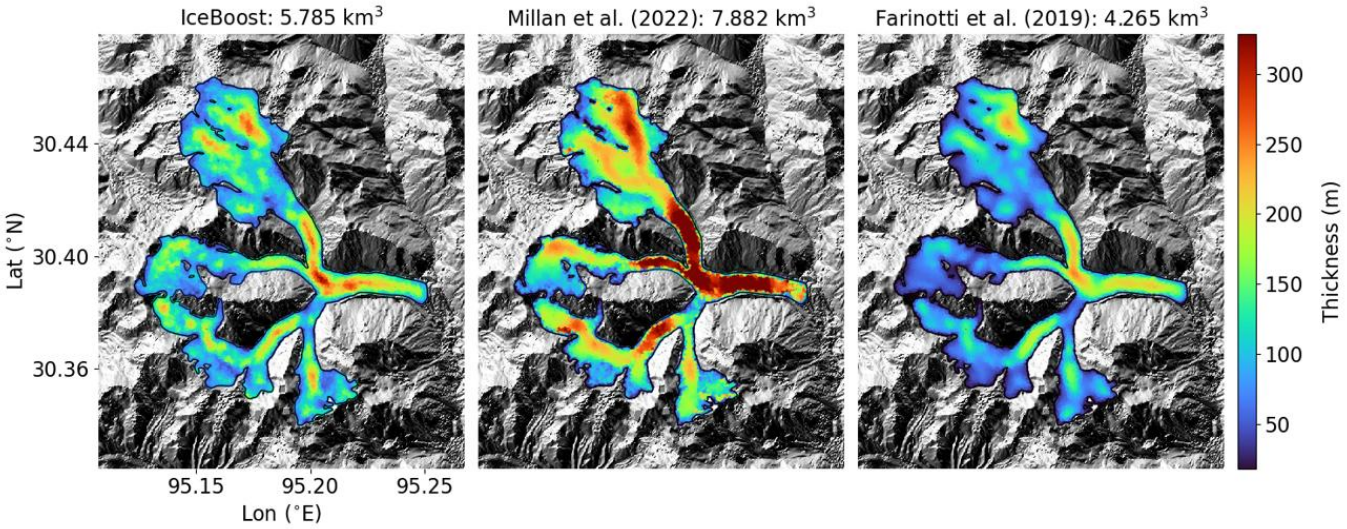

Figure S151: Glacier RGI60-15.01078. Back to Table S2.

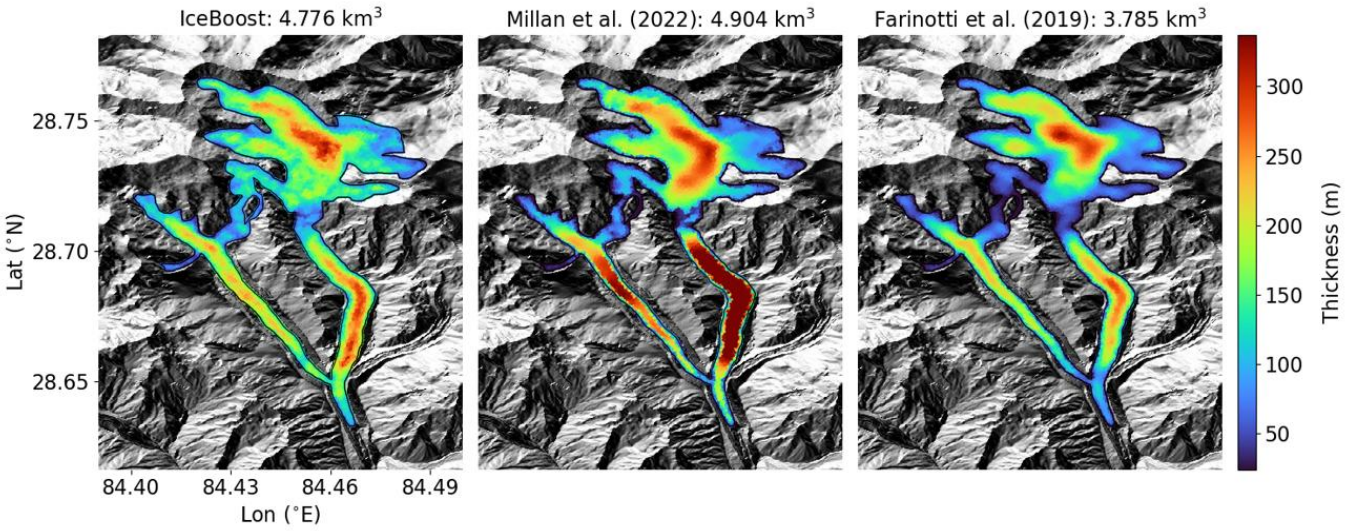

Figure S152: Glacier RGI60-15.04541. Back to Table S2.

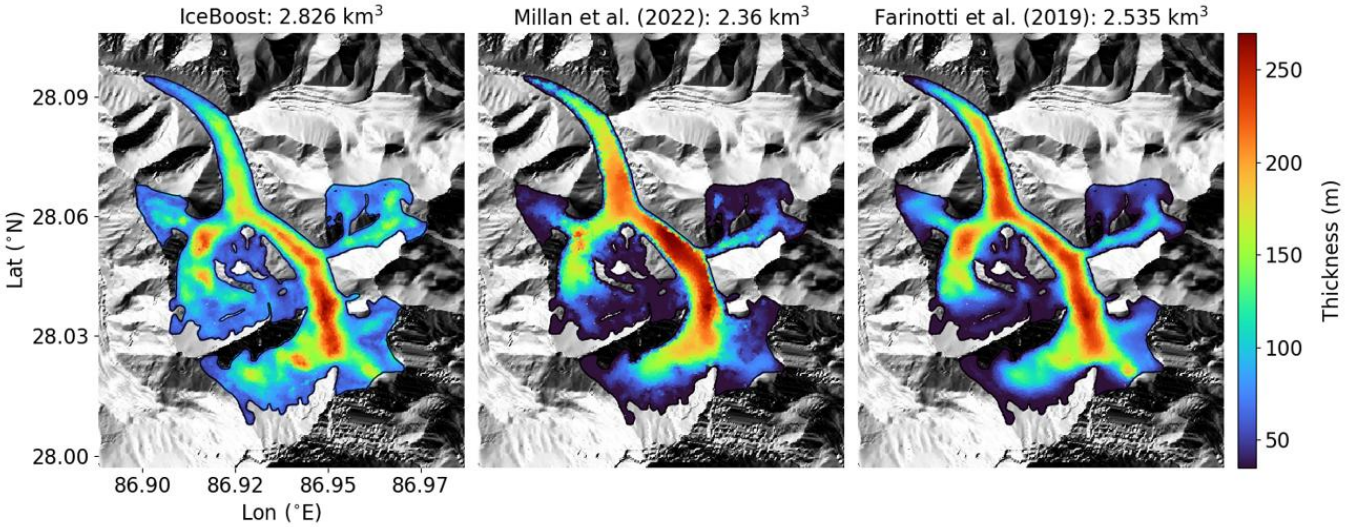

Figure S153: Glacier RGI60-15.10055. Back to Table S2.

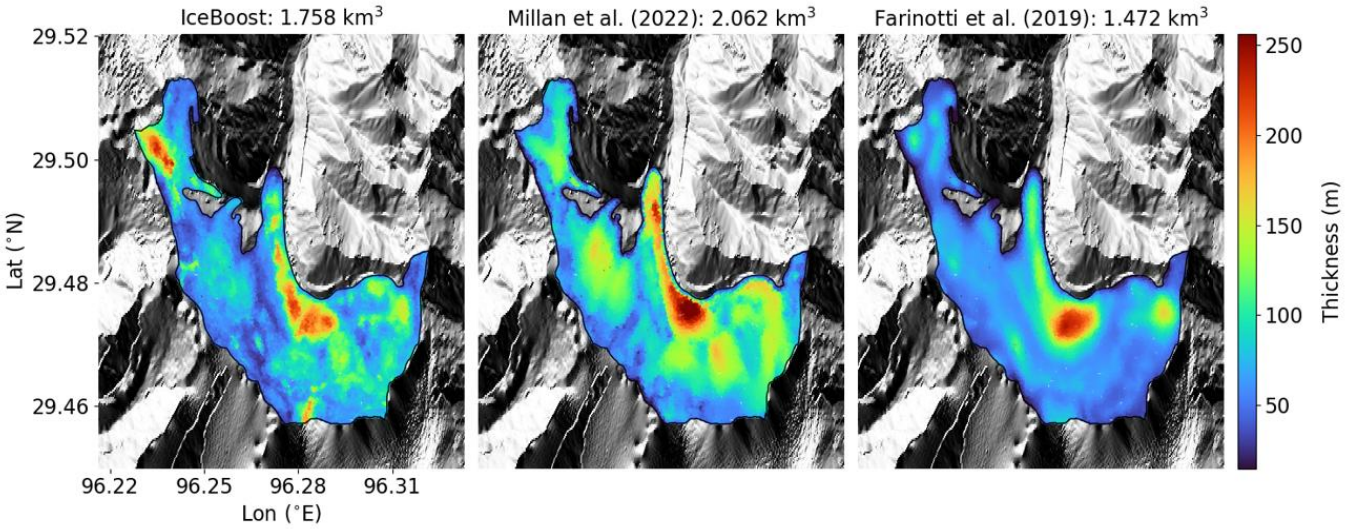

Figure S154: Glacier RGI60-15.11855. Back to Table S2.

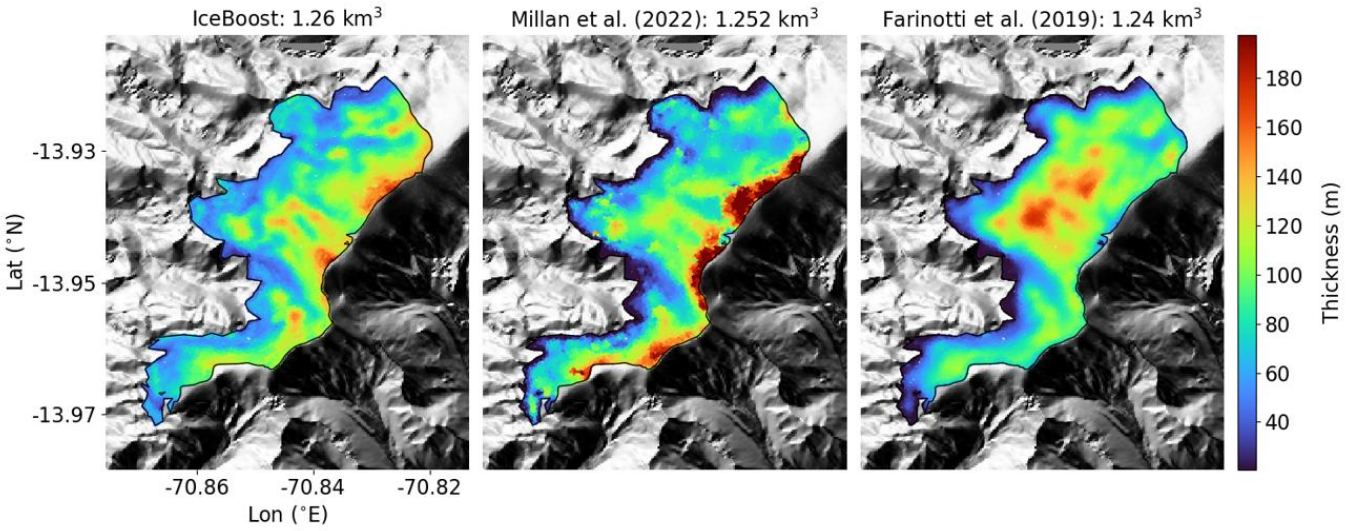

Figure S155: Glacier RGI60-16.01251. Back to Table S2.

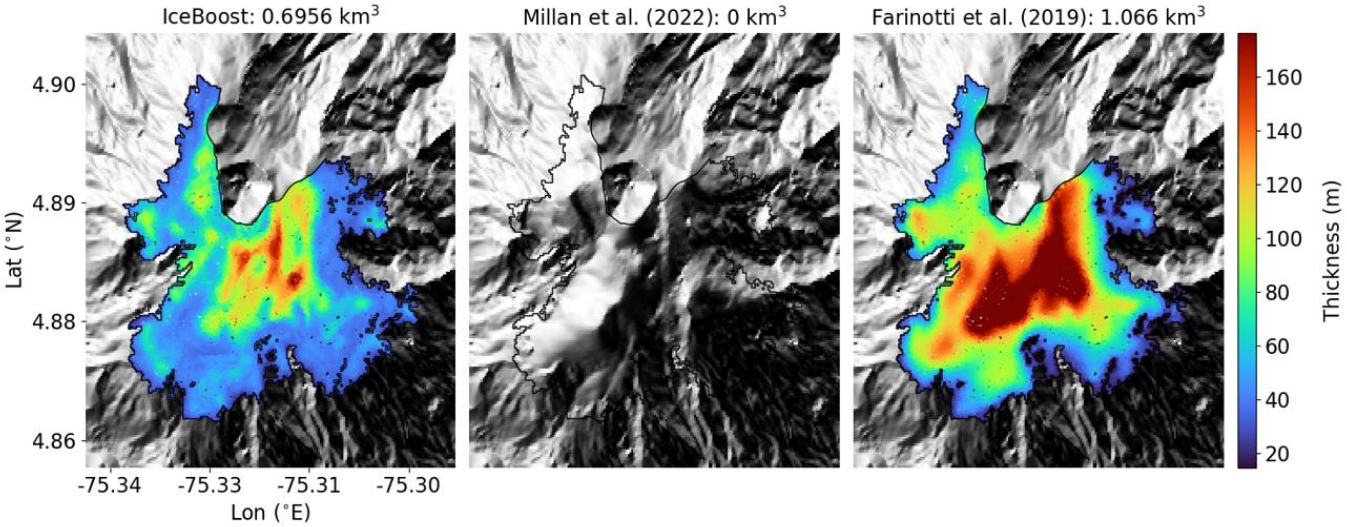

Figure S156: Glacier RGI60-16.01359. Back to Table S2.

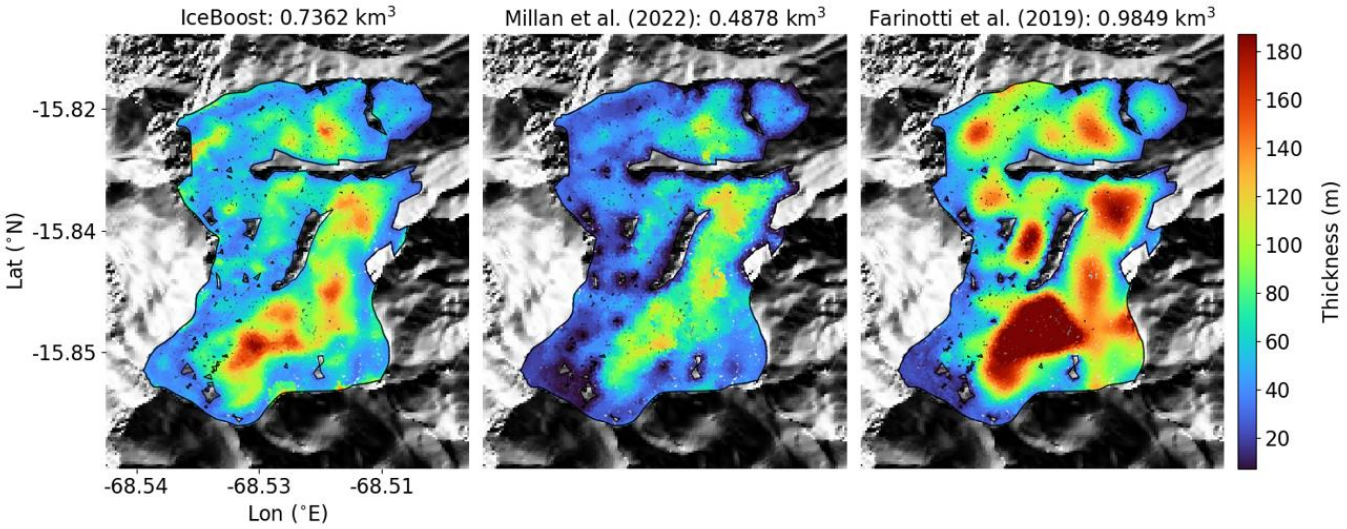

Figure S157: Glacier RGI60-16.00735. Back to Table S2.

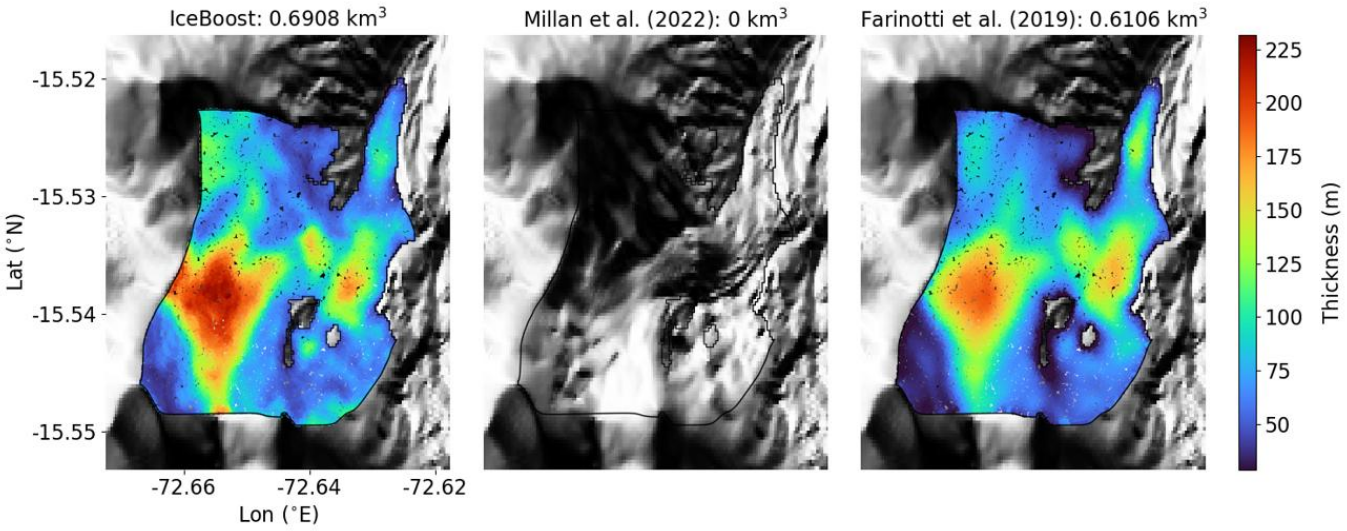

Figure S158: Glacier RGI60-16.01473. Back to Table S2.

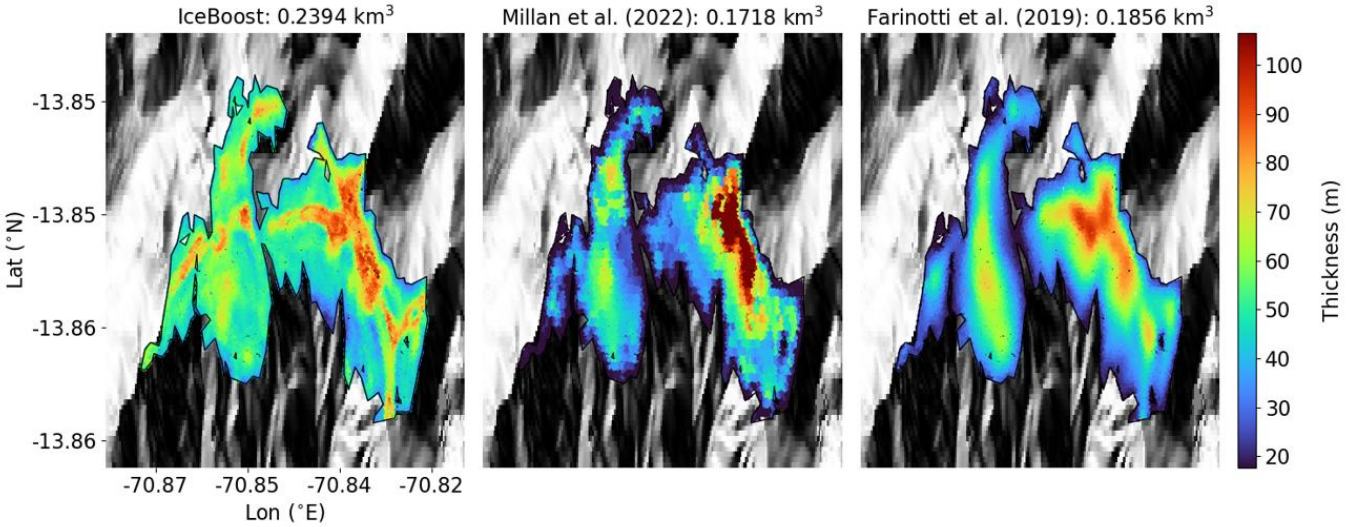

Figure S159: Glacier RGI60-16.01259. Back to Table S2.

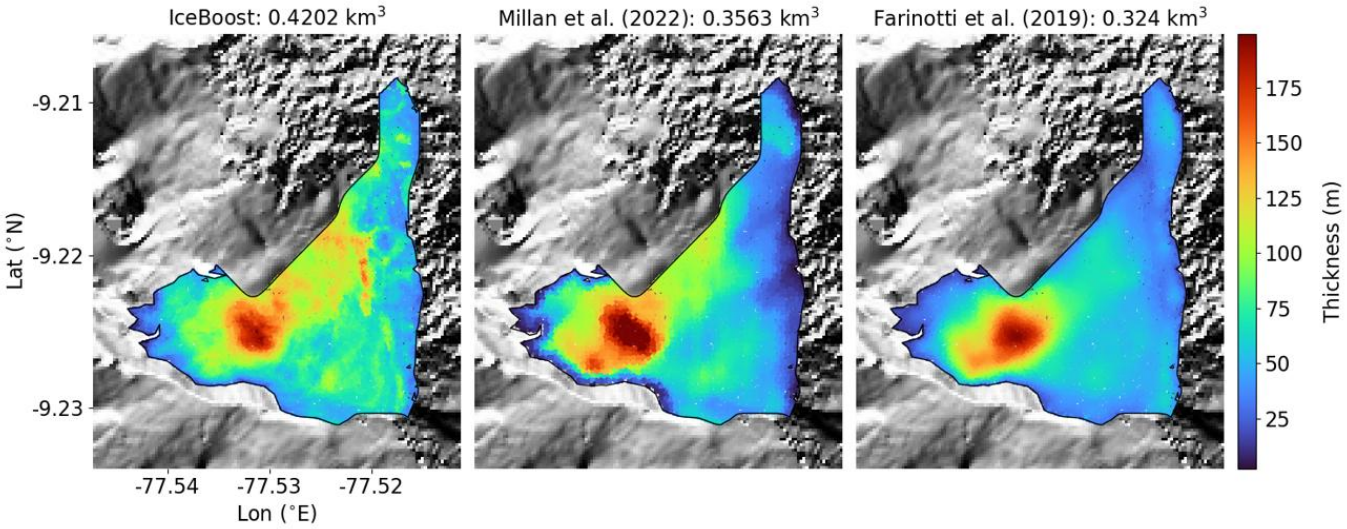

Figure S160: Glacier RGI60-16.02304. Back to Table S2.

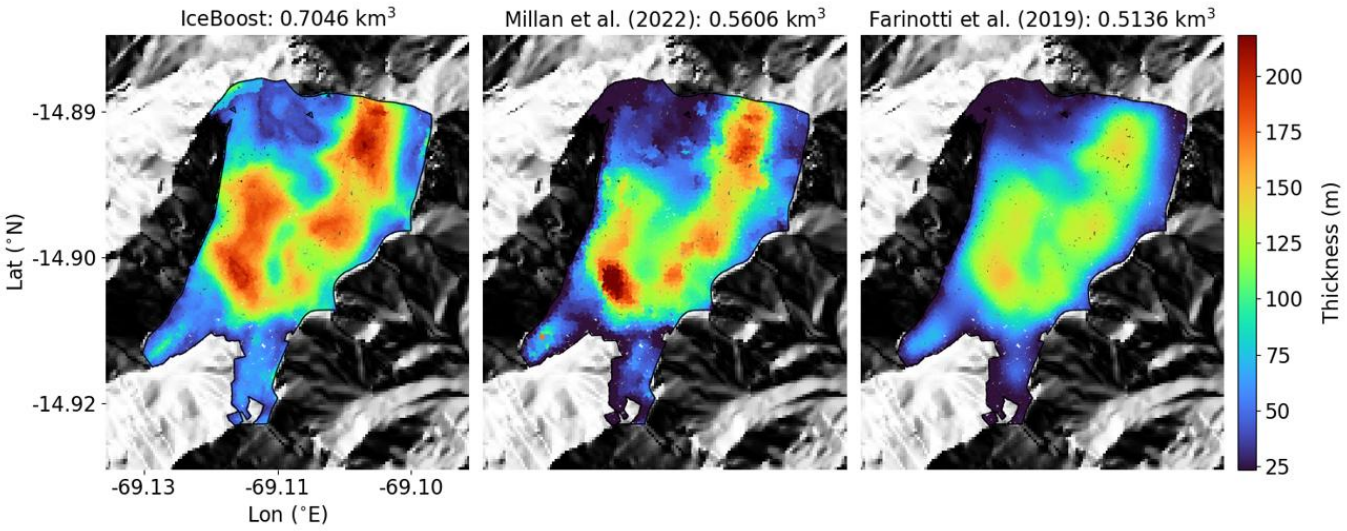

Figure S161: Glacier RGI60-16.00799. Back to Table S2.

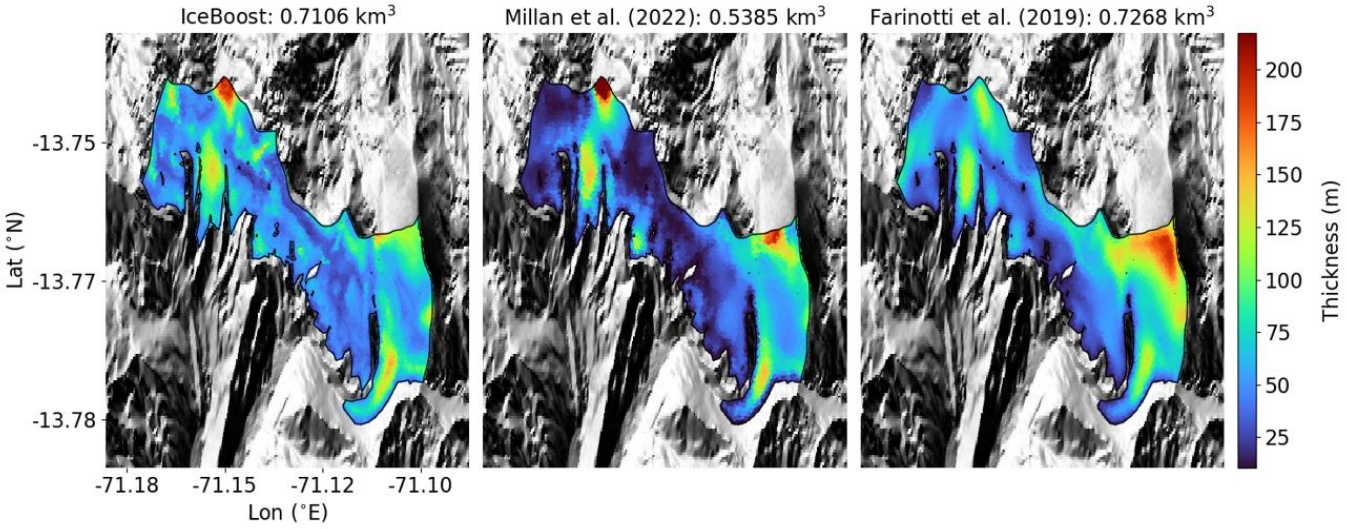

Figure S162: Glacier RGI60-16.01286. Back to Table S2.

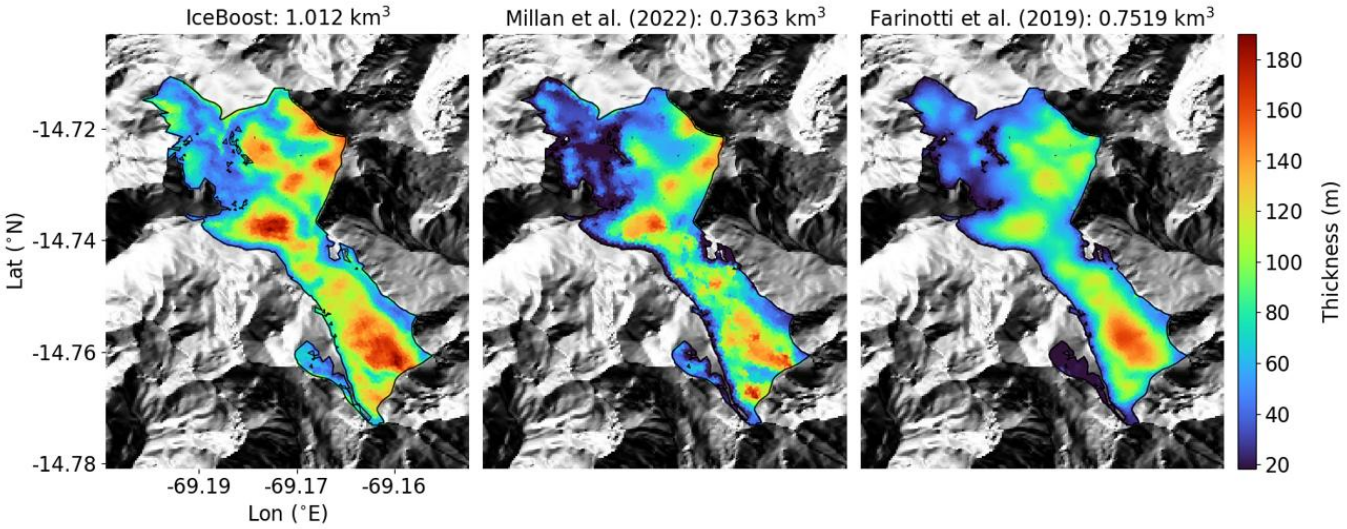

Figure S163: Glacier RGI60-16.00905. Back to Table S2.

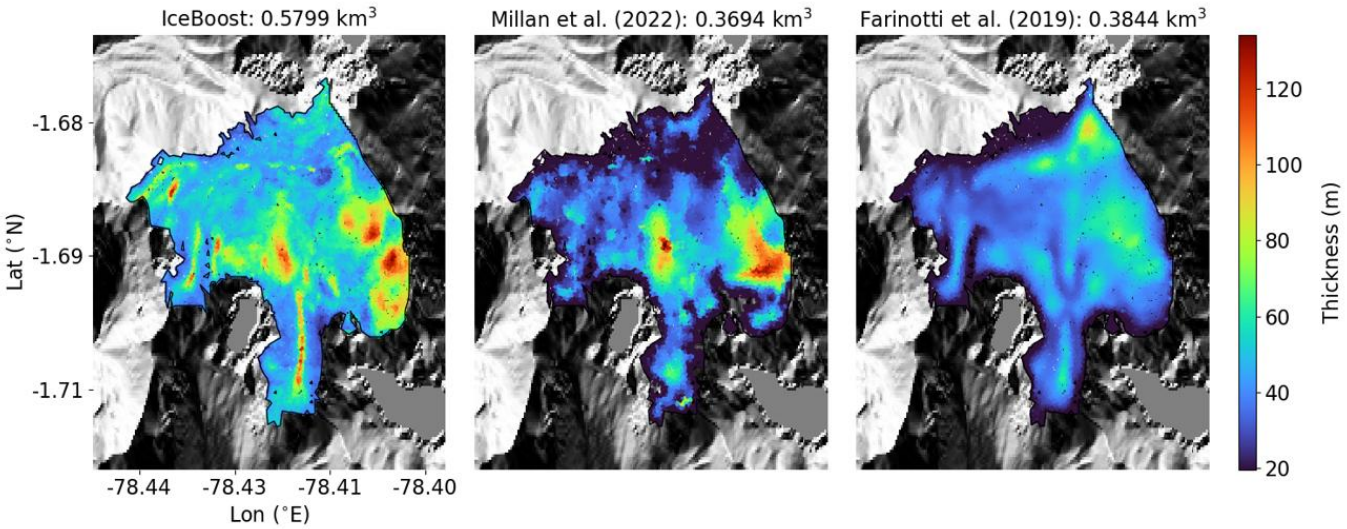

Figure S164: Glacier RGI60-16.01443. Back to Table S2.

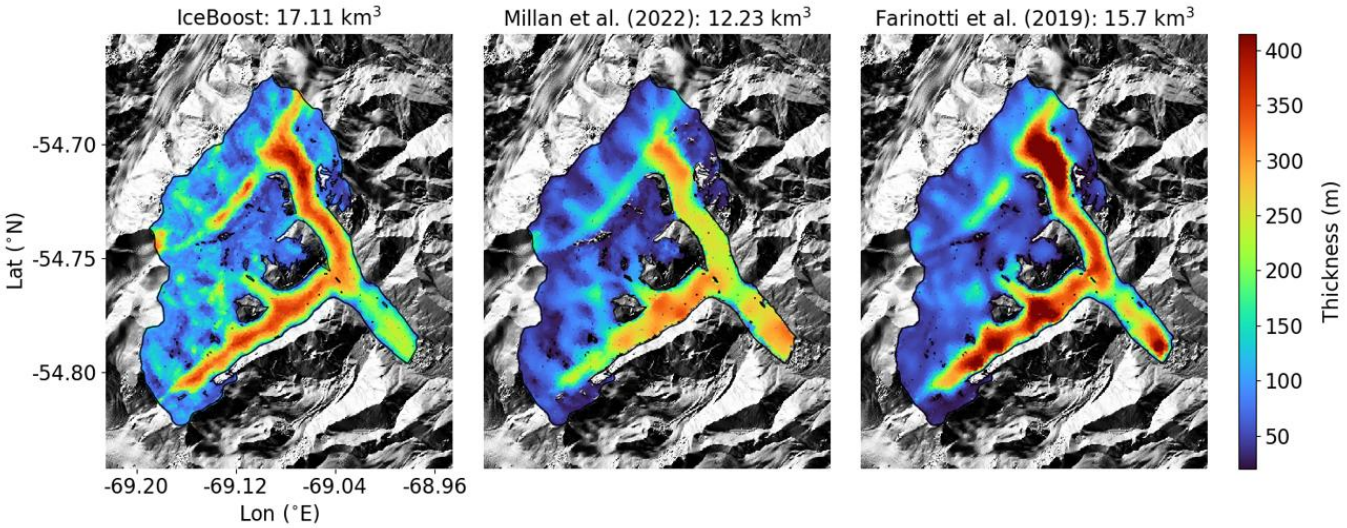

Figure S165: Glacier RGI60-17.02519. Back to Table S2.

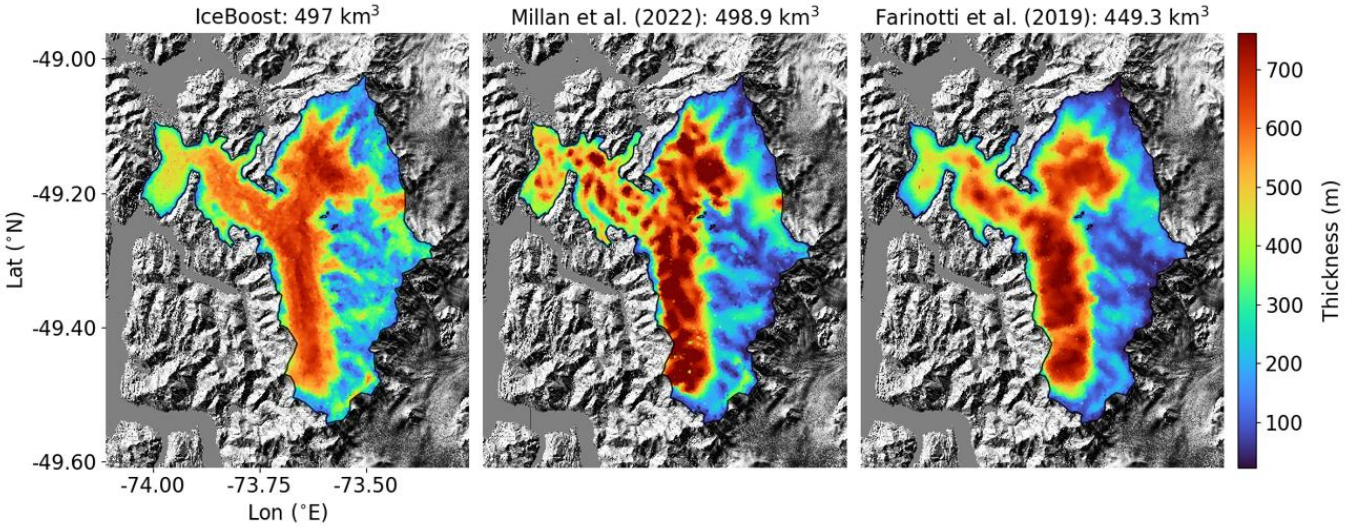

Figure S166: Glacier RGI60-17.05181. Back to Table S2.

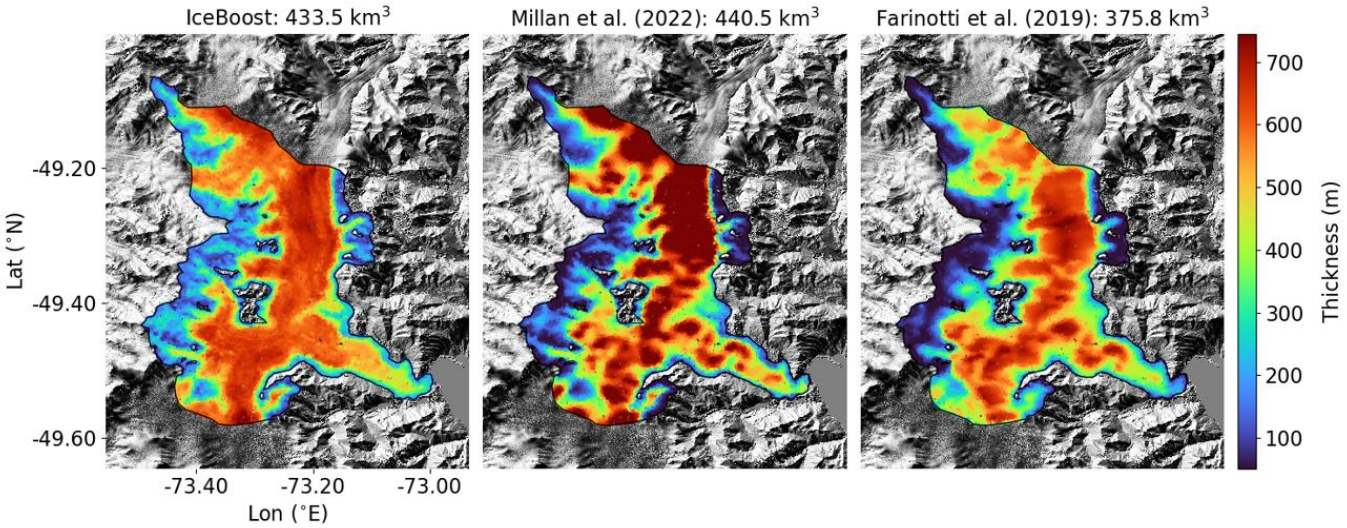

Figure S167: Glacier RGI60-17.05076. Back to Table S2.

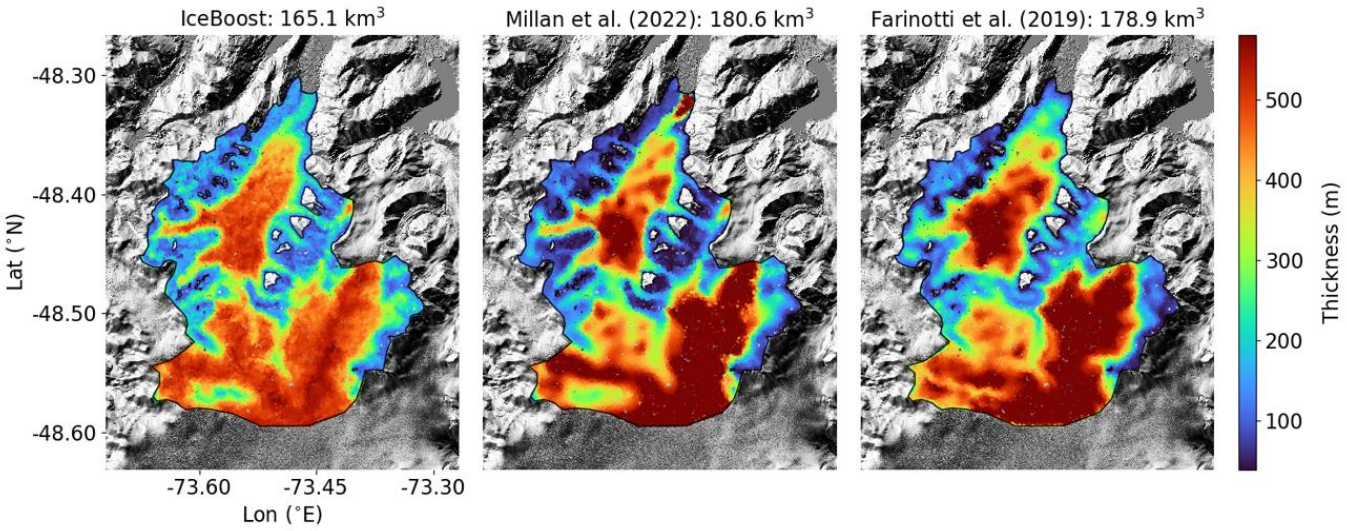

Figure S168: Glacier RGI60-17.06074. Back to Table S2.

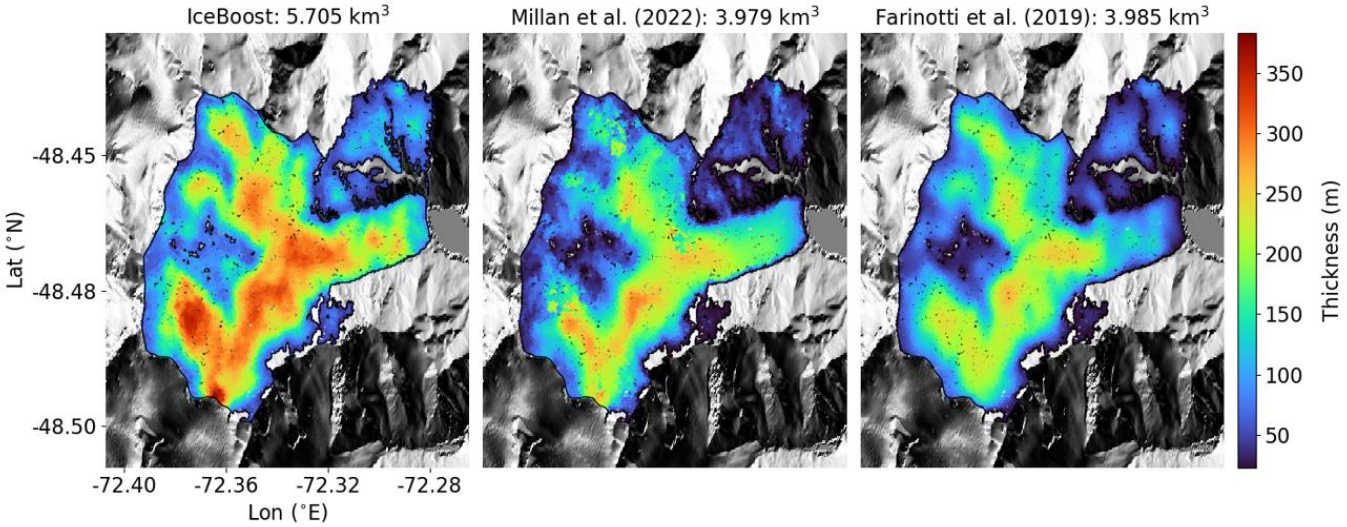

Figure S169: Glacier RGI60-17.05909. Back to Table S2.

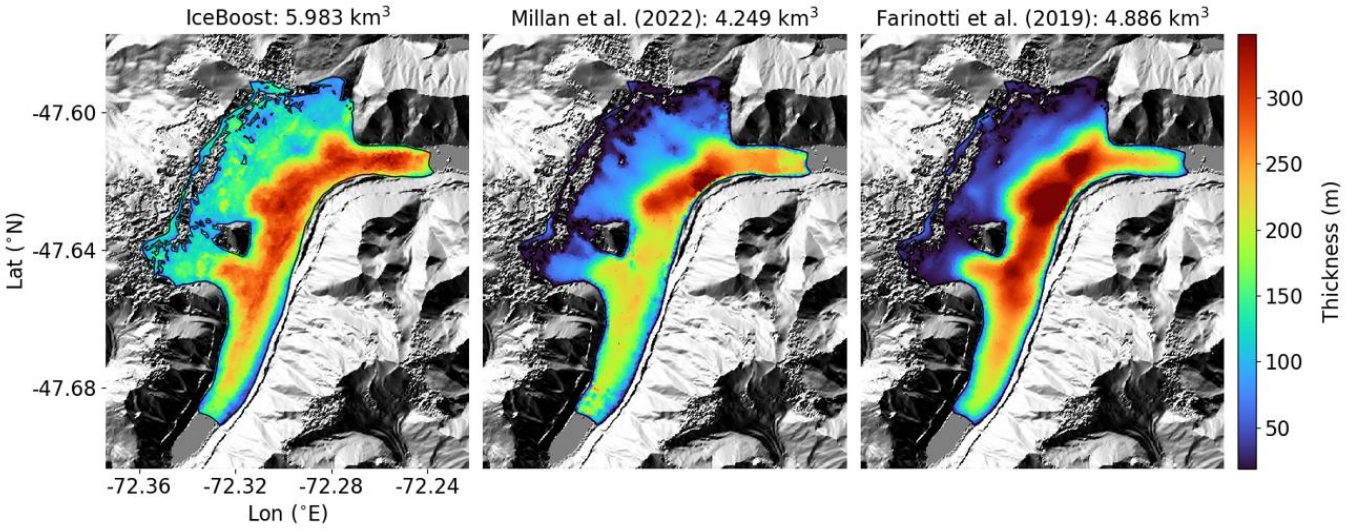

Figure S170: Glacier RGI60-17.07137. Back to Table S2.

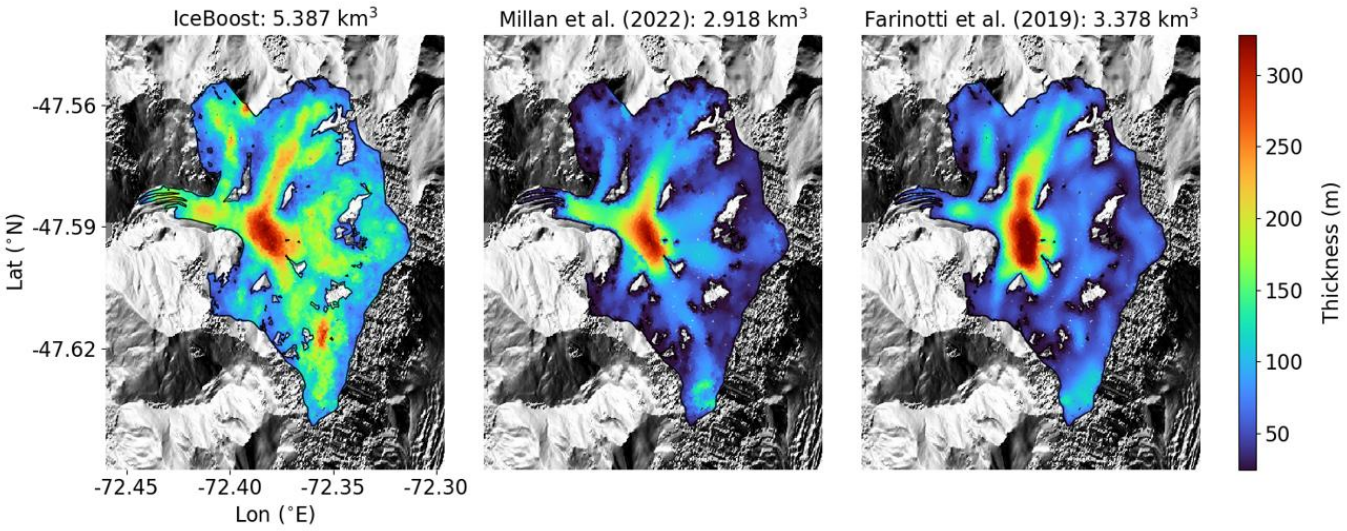

Figure S171: Glacier RGI60-17.07250. Back to Table S2.

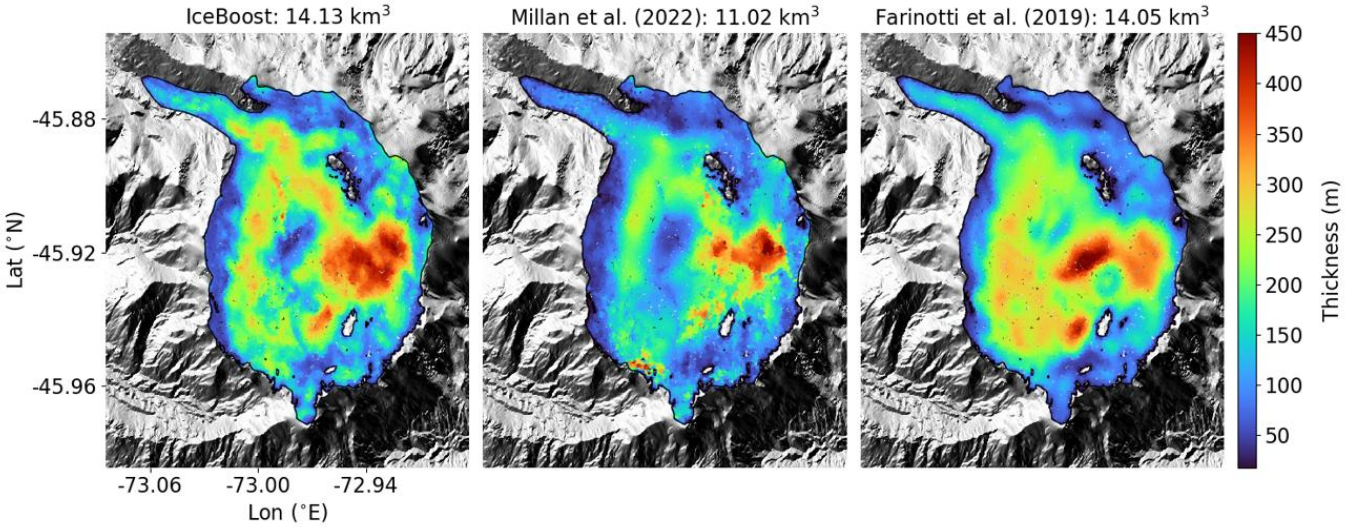

Figure S172: Glacier RGI60-17.09519. Back to Table S2.

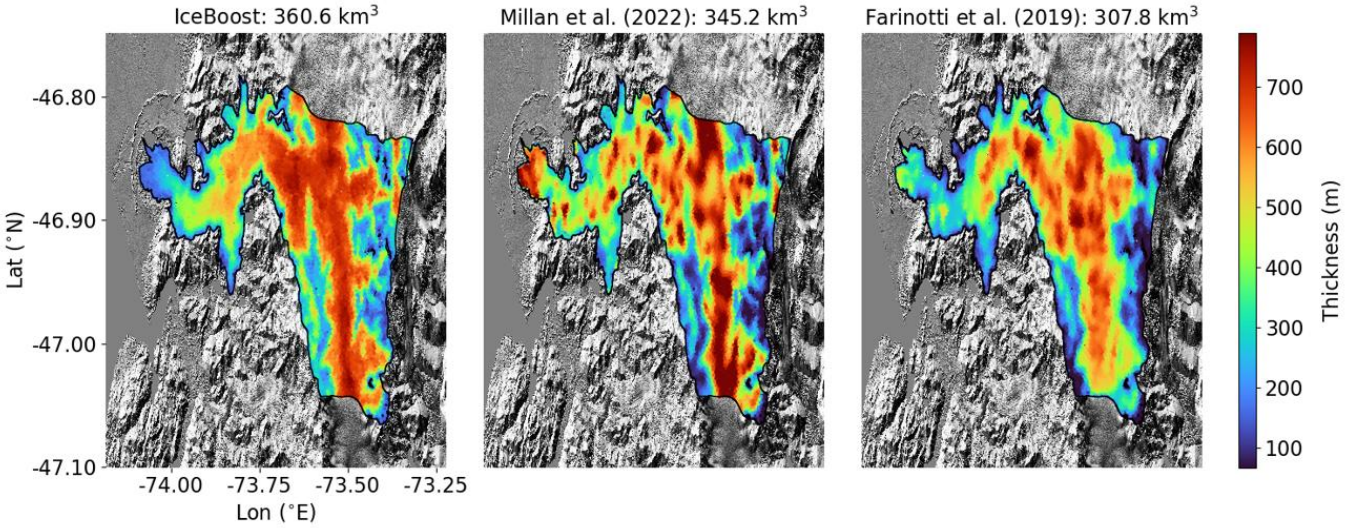

Figure S173: Glacier RGI60-17.15804. Back to Table S2.

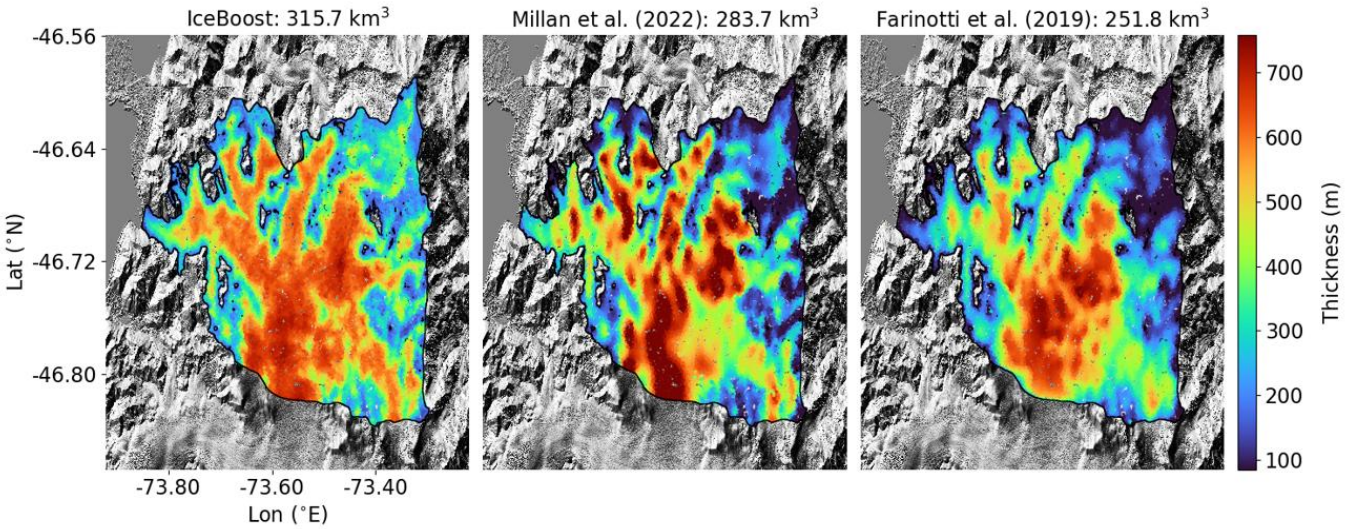

Figure S174: Glacier RGI60-17.15808. Back to Table S2.

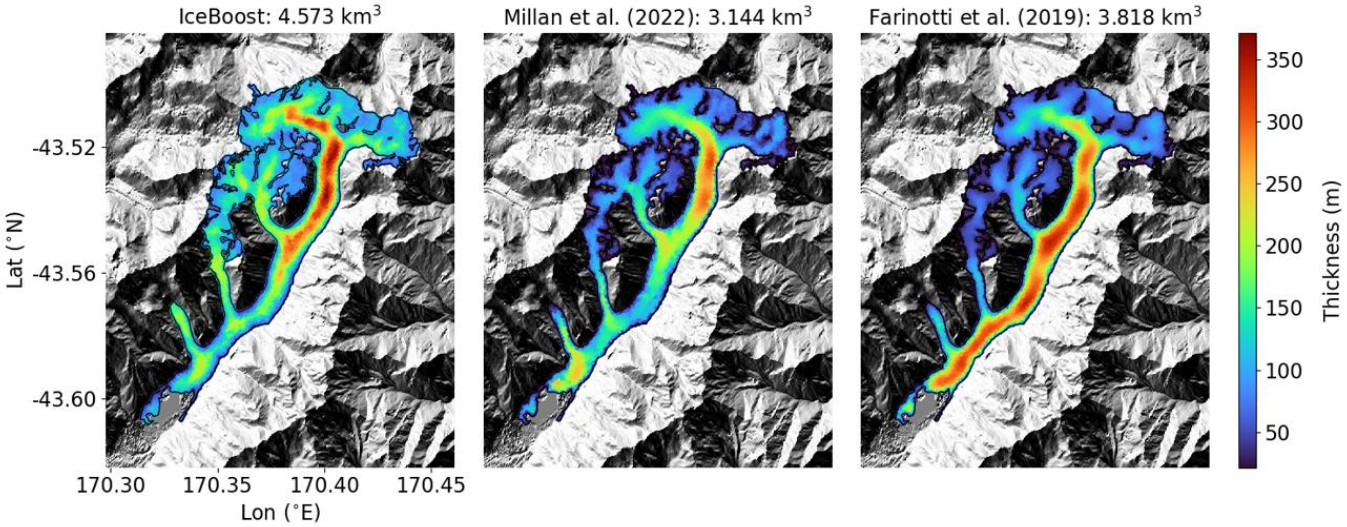

Figure S175: Glacier RGI60-18.02504. Back to Table S2.

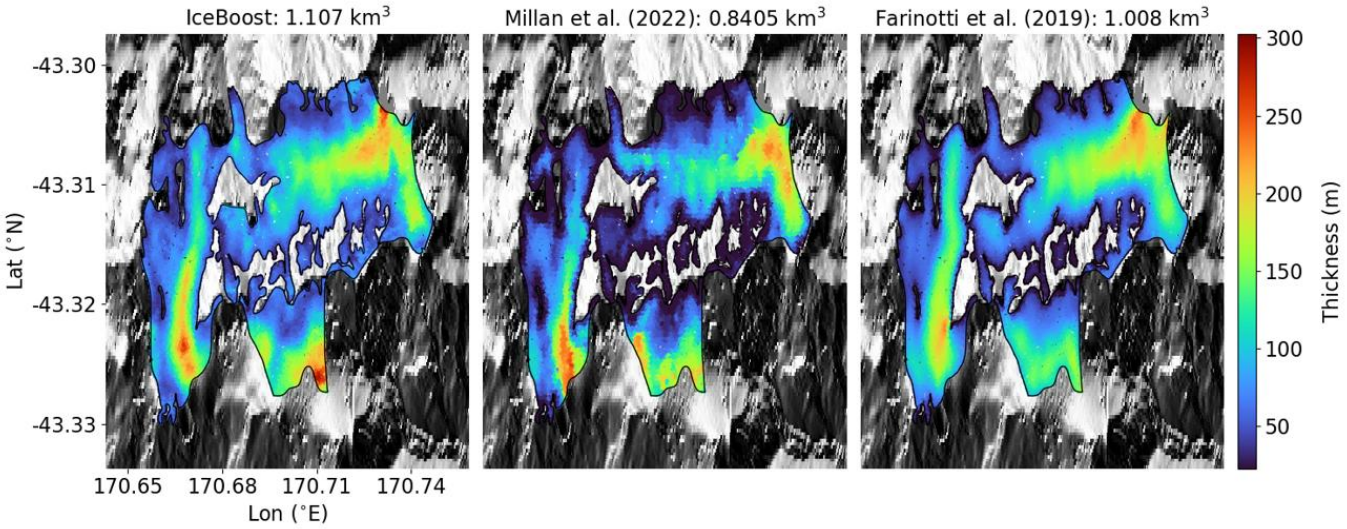

Figure S176: Glacier RGI60-18.03217. Back to Table S2.

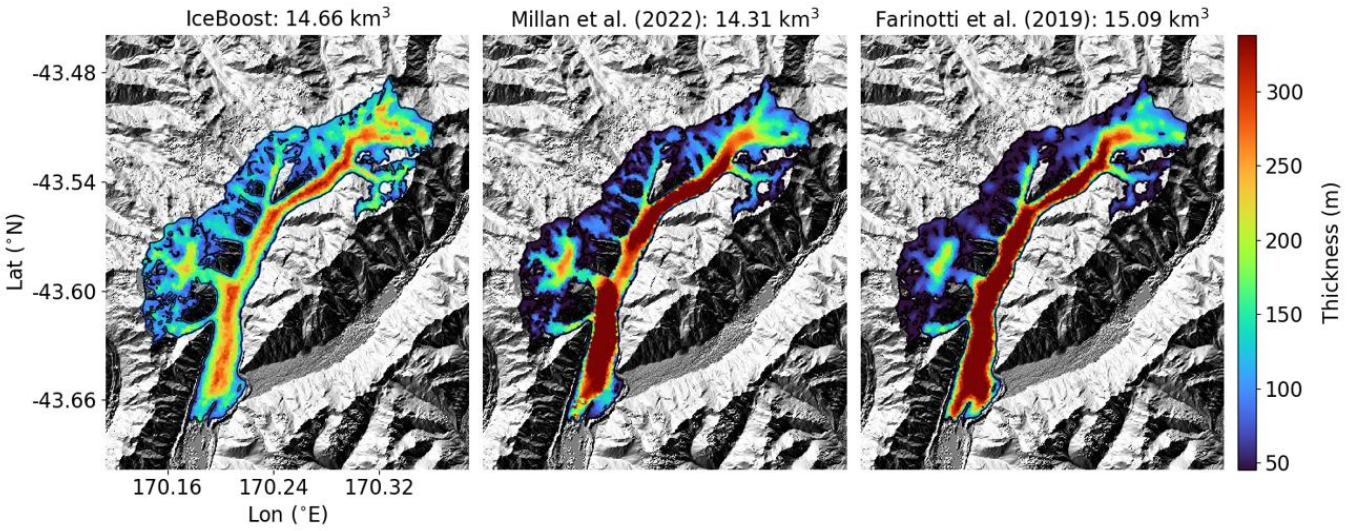

Figure S177: Glacier RGI60-18.02342. Back to Table S2.

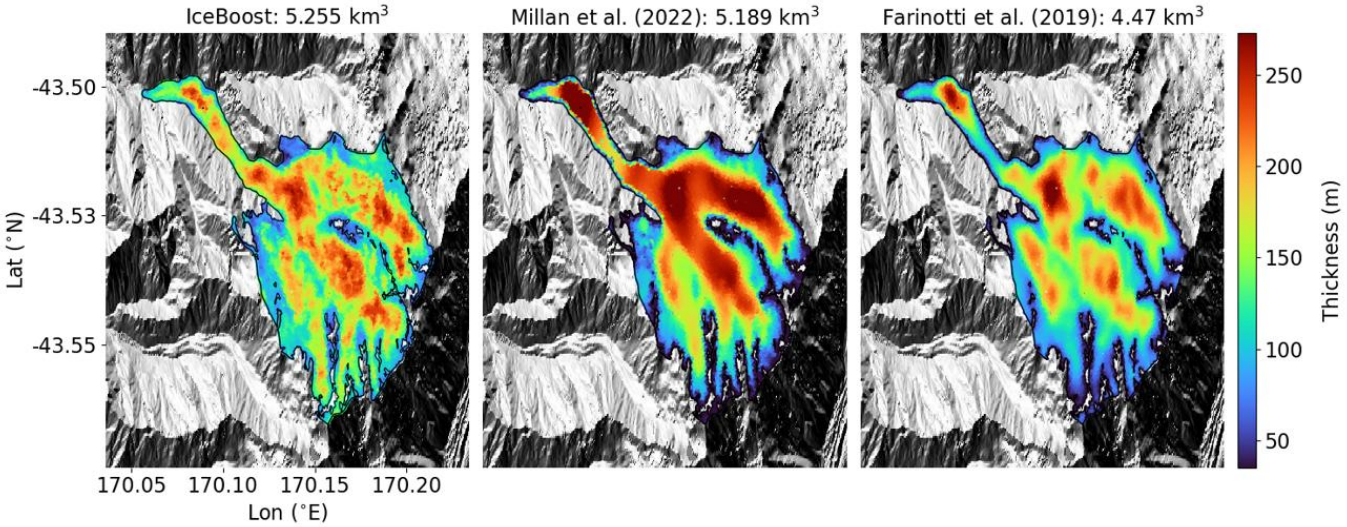

Figure S178: Glacier RGI60-18.02375. Back to Table S2.

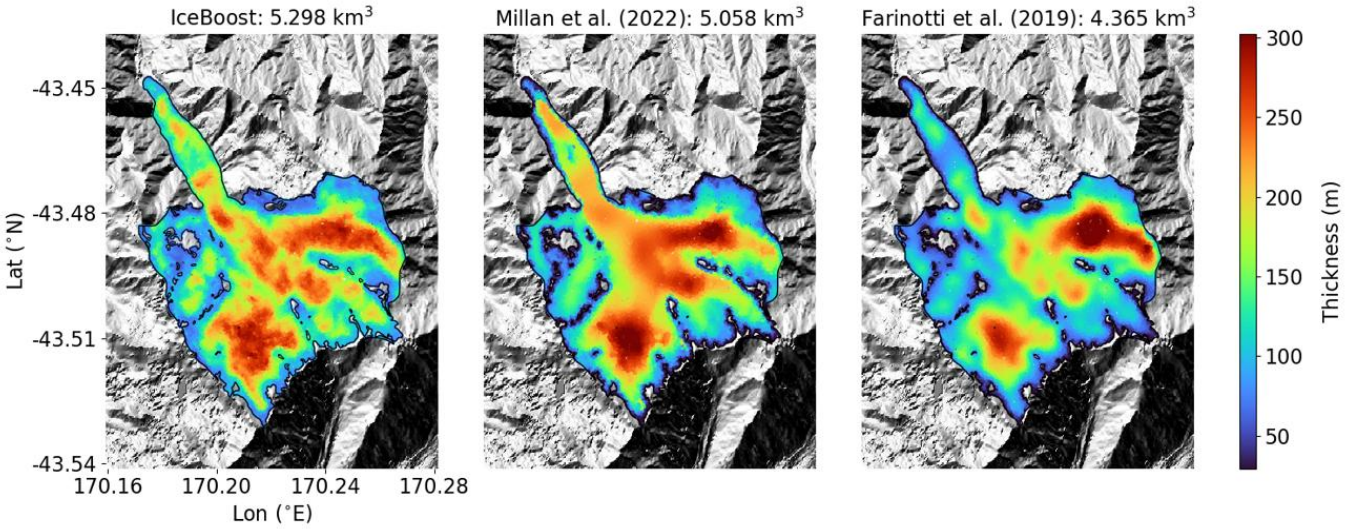

Figure S179: Glacier RGI60-18.02397. Back to Table S2.

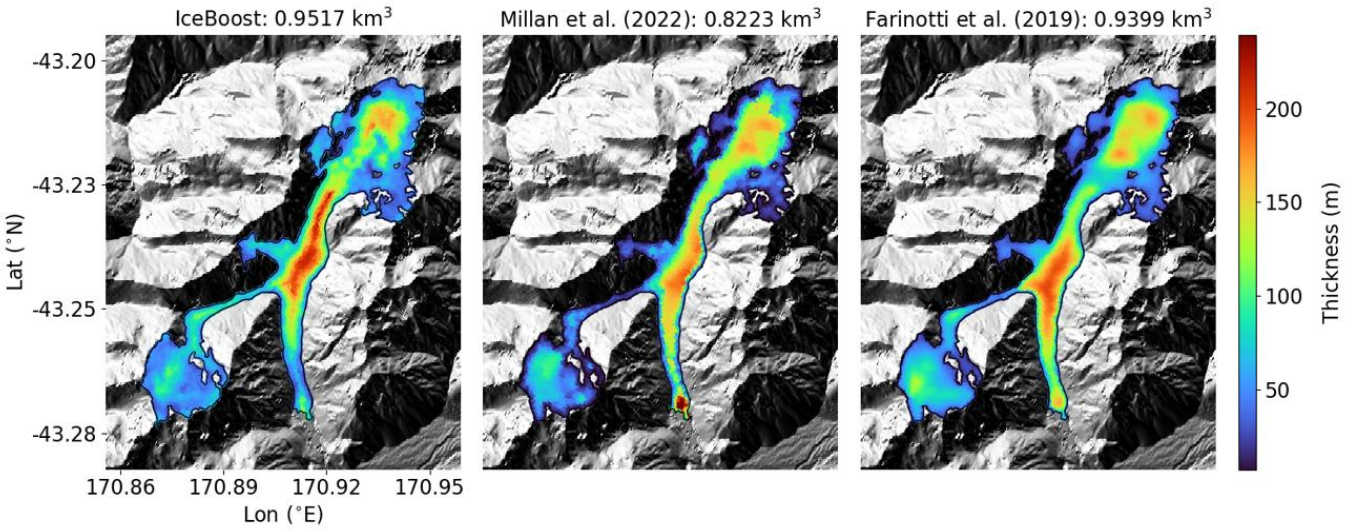

Figure S180: Glacier RGI60-18.03156. Back to Table S2.

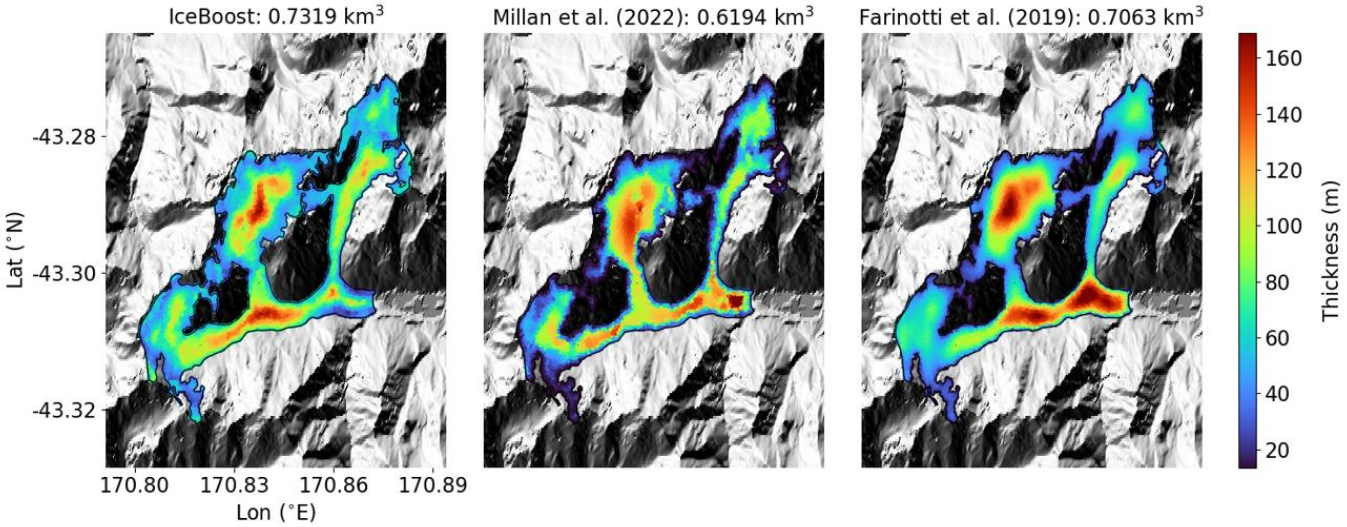

Figure S181: Glacier RGI60-18.03066. Back to Table S2.

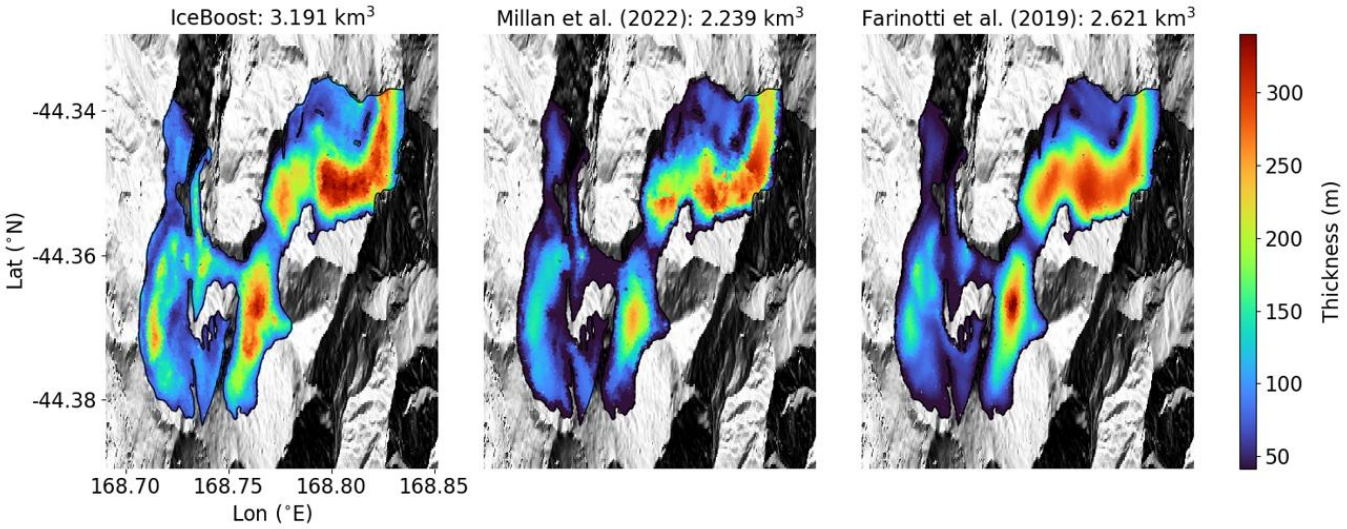

Figure S182: Glacier RGI60-18.00947. Back to Table S2.

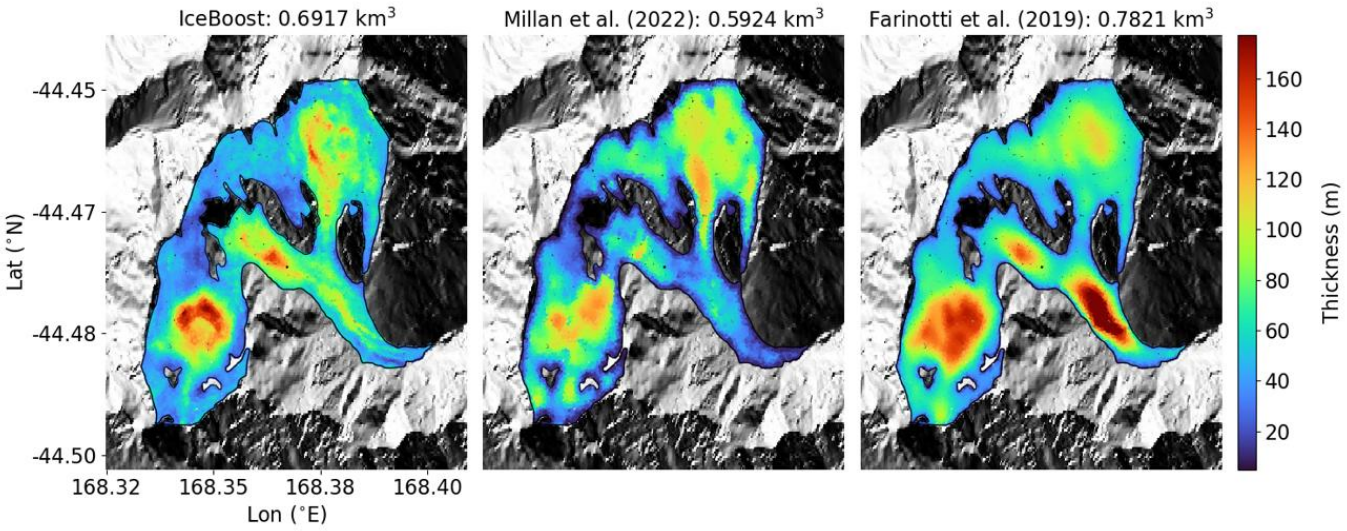

Figure S183: Glacier RGI60-18.00853. Back to Table S2.

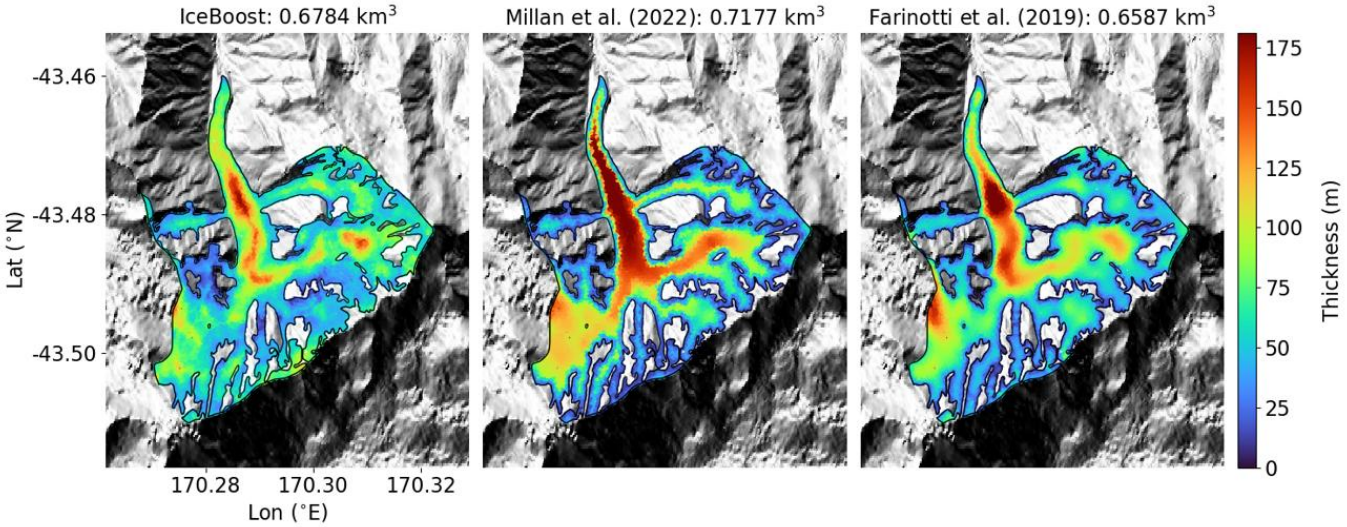

Figure S184: Glacier RGI60-18.02450. Back to Table S2.

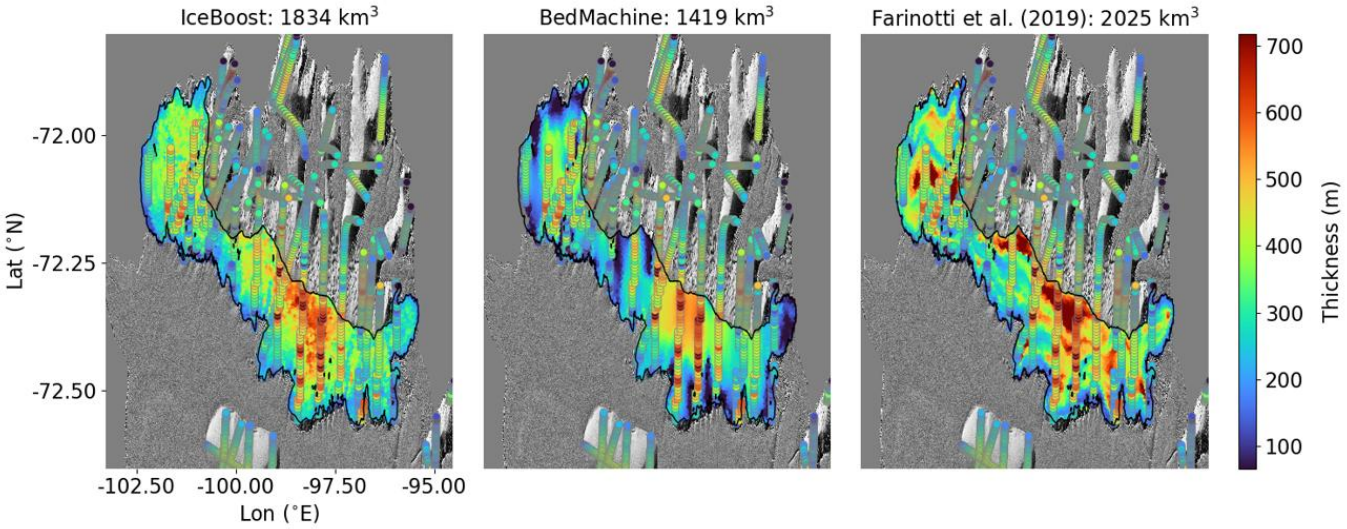

Figure S185: Glacier RGI60-19.00423. Back to Table S2.

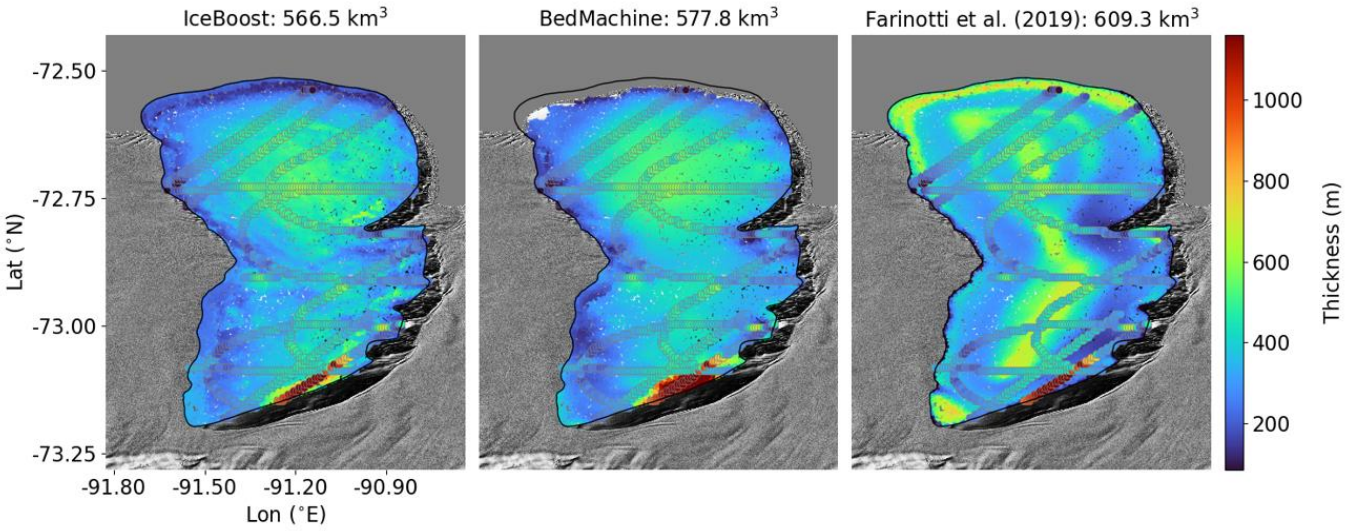

Figure S186: Glacier RGI60-19.01294. Back to Table S2.

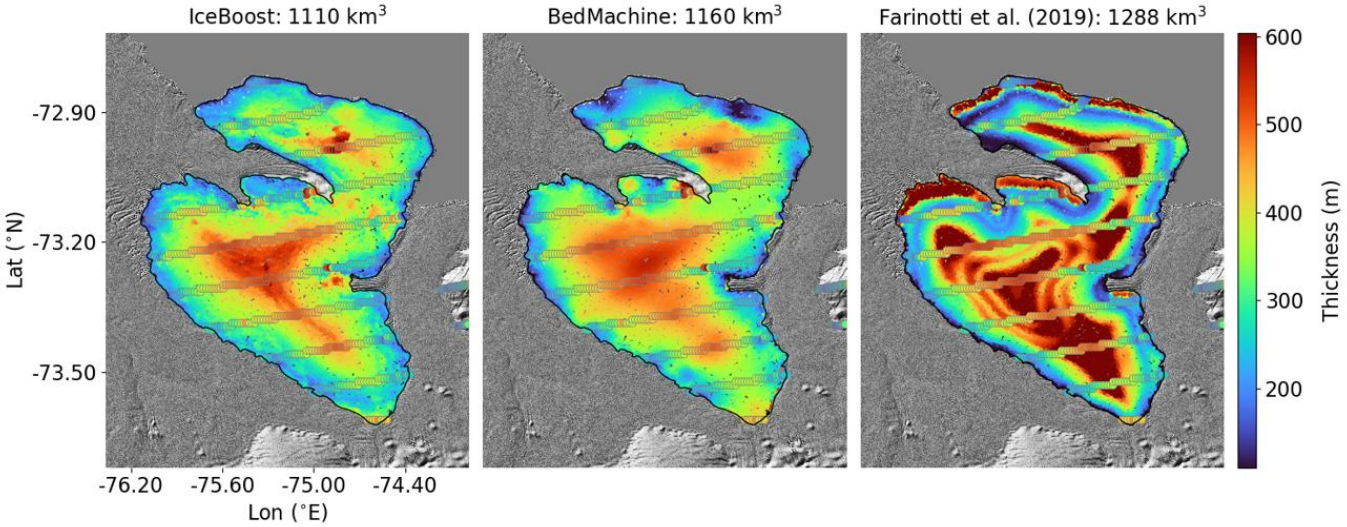

Figure S187: Glacier RGI60-19.00554. Back to Table S2.

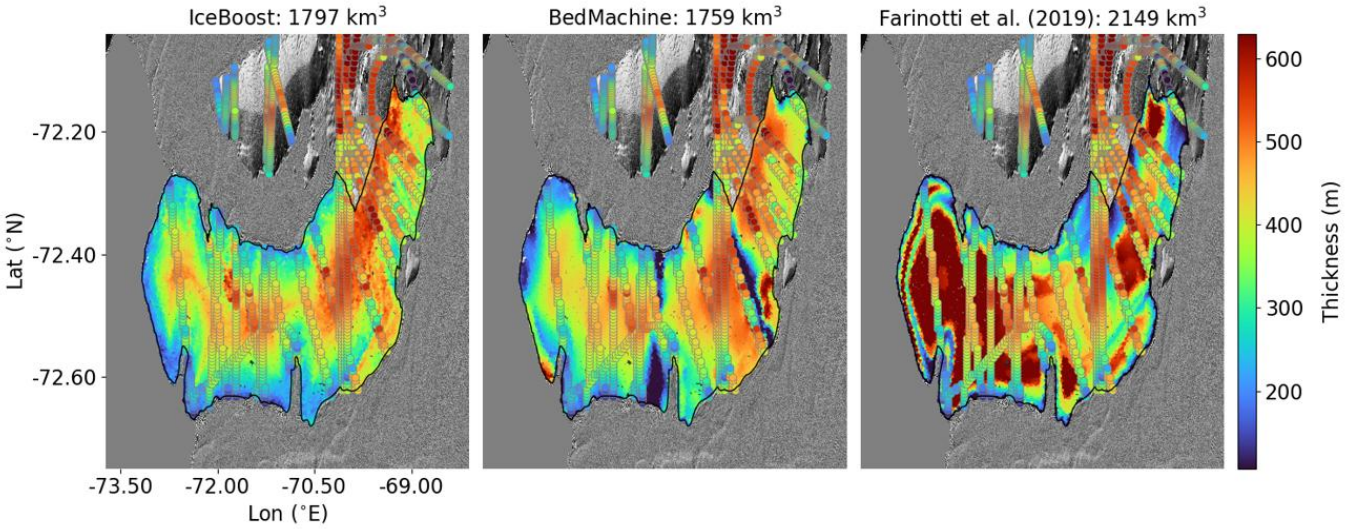

Figure S188: Glacier RGI60-19.00124. Back to Table S2.

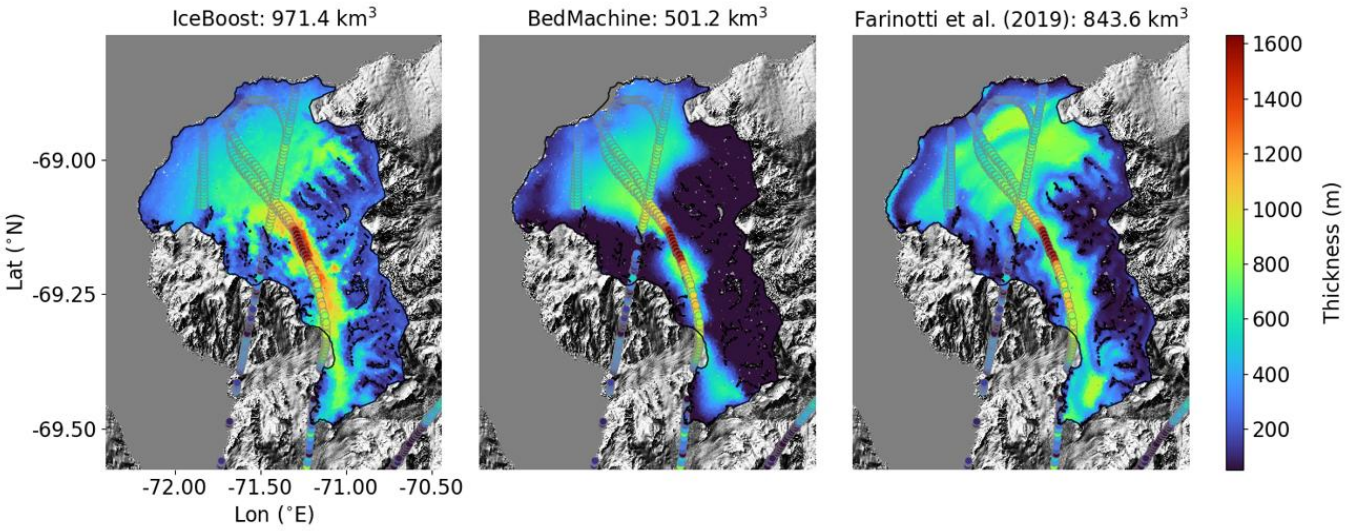

Figure S189: Glacier RGI60-19.00103. Back to Table S2.

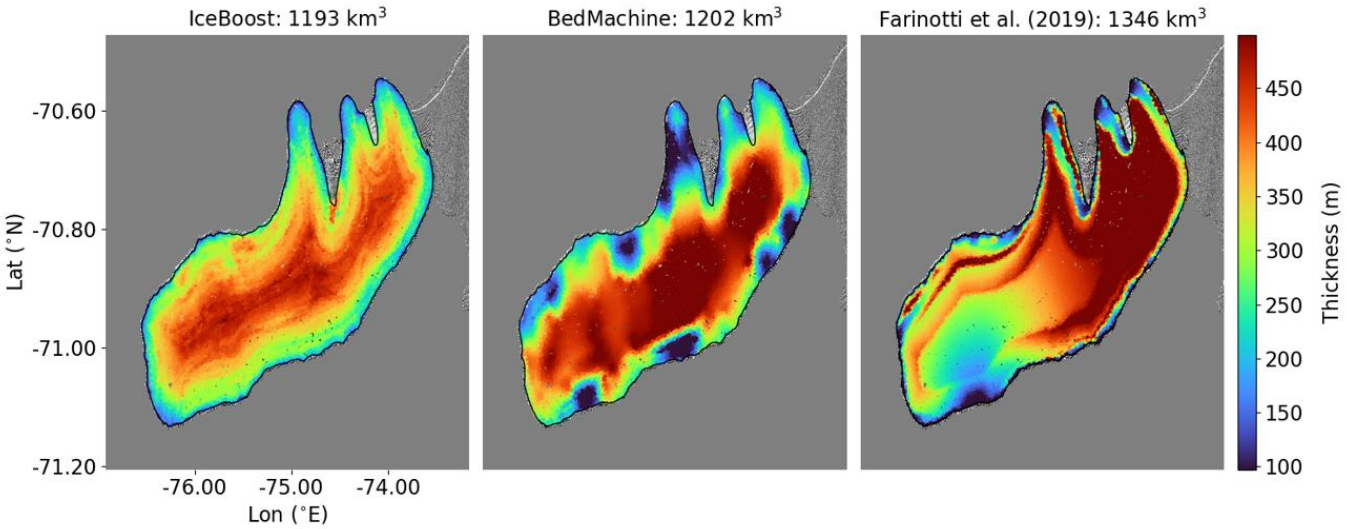

Figure S190: Glacier RGI60-19.00746. Back to Table S2.

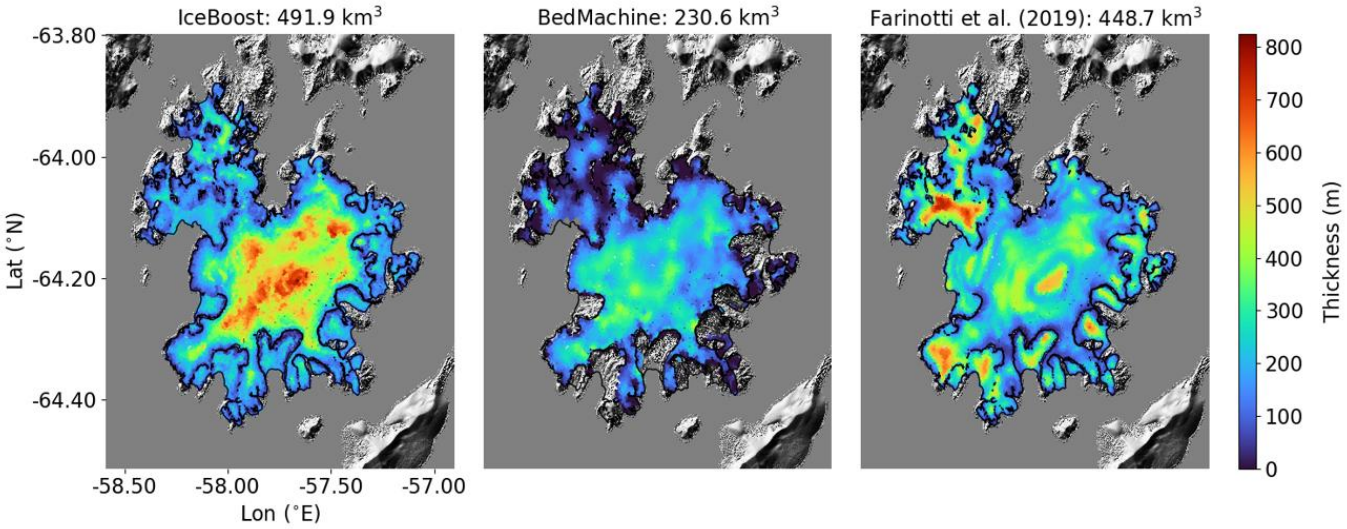

Figure S191: Glacier RGI60-19.00707. Back to Table S2.

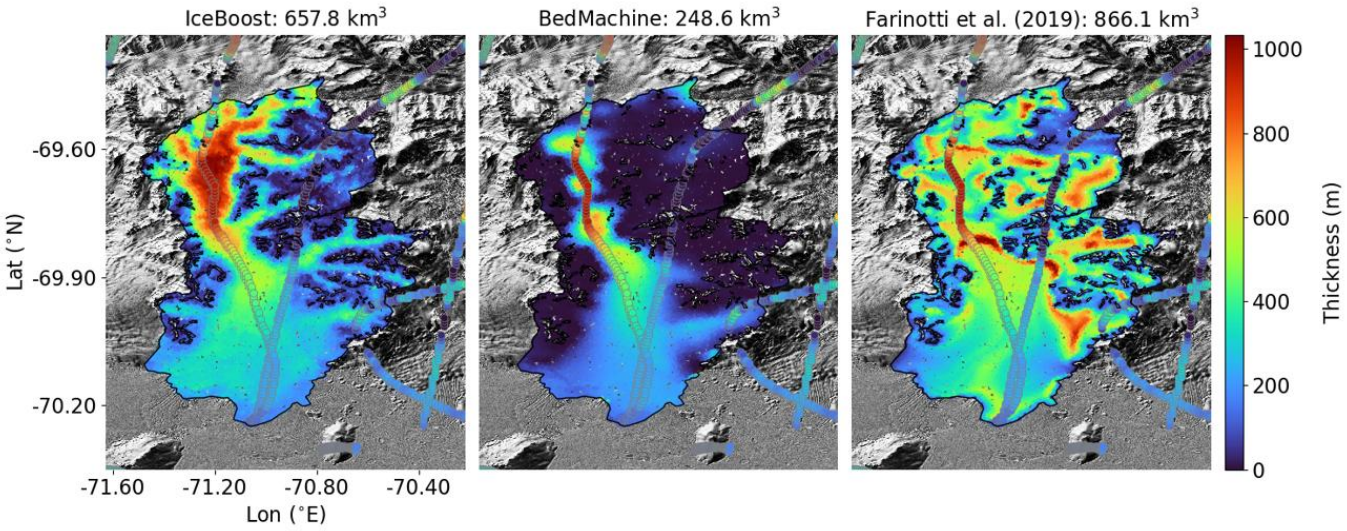

Figure S192: Glacier RGI60-19.00119. Back to Table S2.

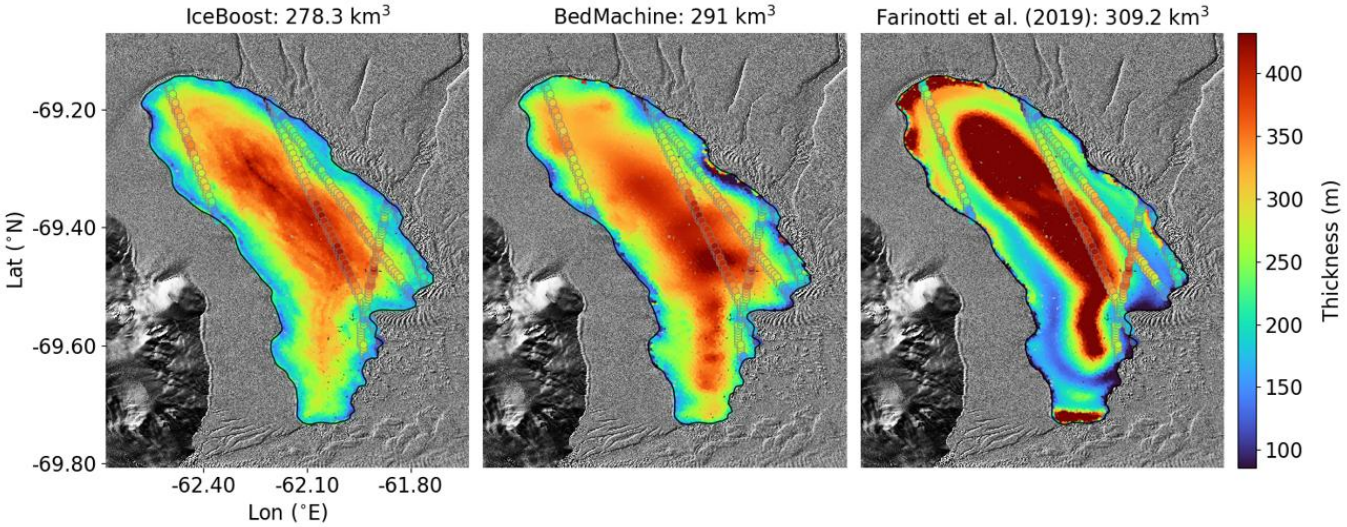

Figure S193: Glacier RGI60-19.00737. Back to Table S2.

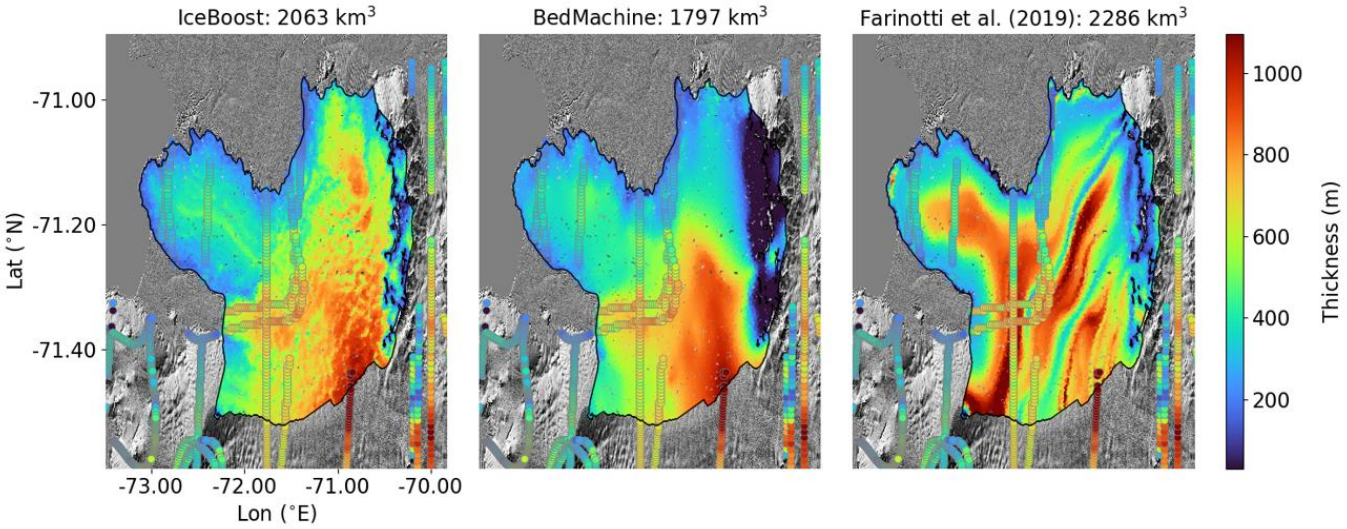

Figure S194: Glacier RGI60-19.00134. Back to Table S2.