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Satellite telemetry of surface ablation to inform spatial melt modelling and event-scale monitoring, Place Glacier, Canada

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Supplementary Figures

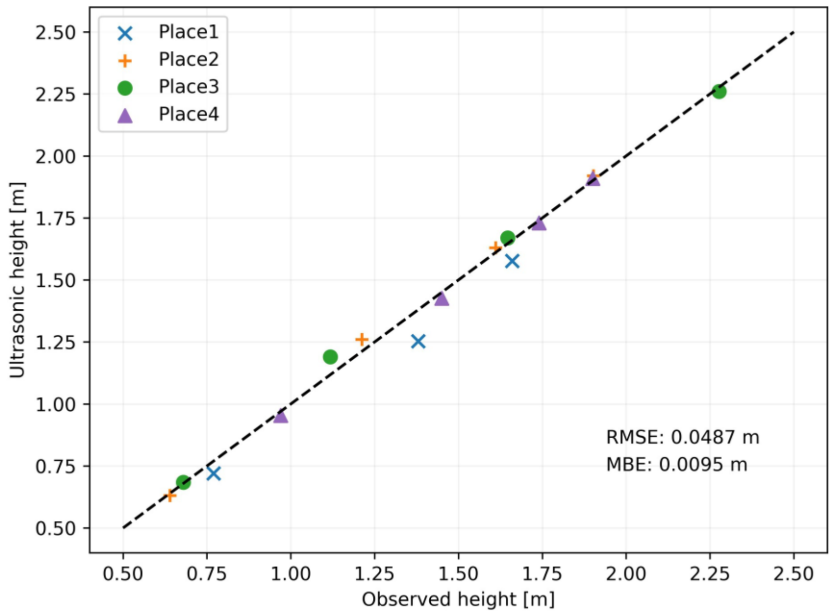

Figure S1: In–situ manual calibration of MaxBotix MB7374 ultrasonic sensor readings. The root mean square error (RMSE) and the mean bias error (MBE) are shown.

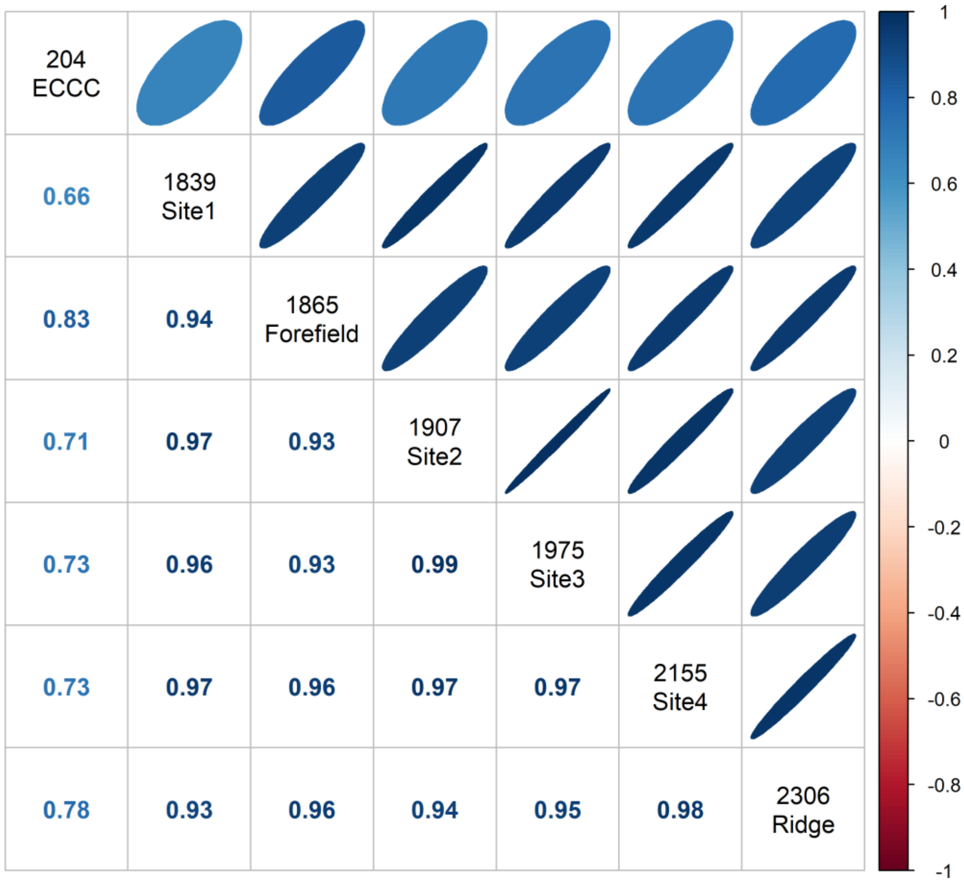

Figure S2: Correlation plot of air temperature among air temperature records over the ablation season (Station information in Error! Reference source not found.**). The lower left section of the plot is the Pearson Correlation. The number associated with each station is the elevation of the station above sea level.**

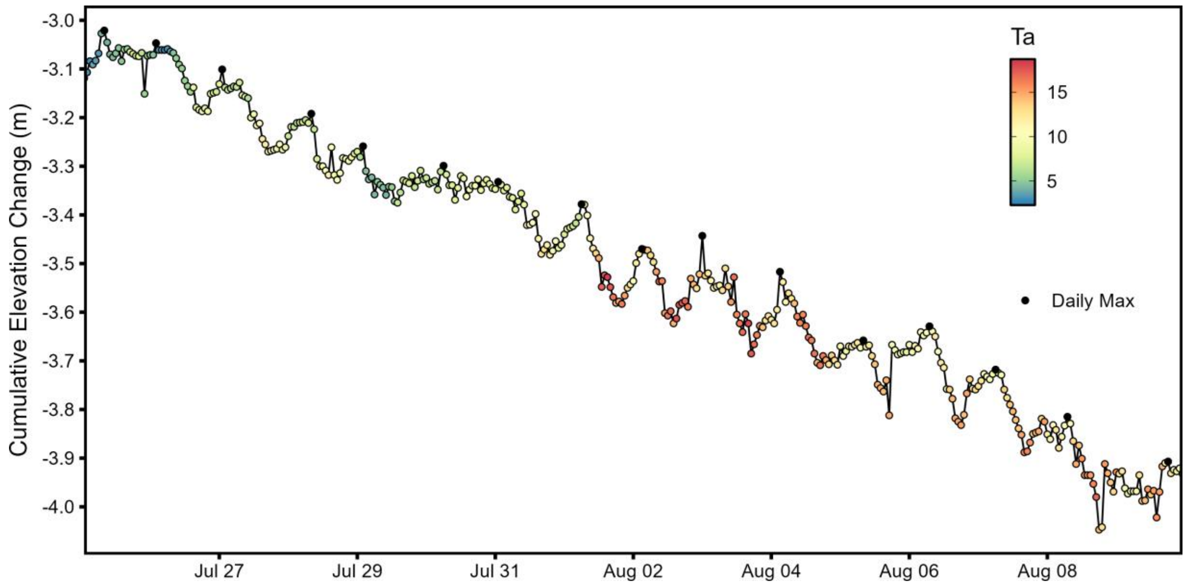

Figure S3: Time series of cumulative elevation change (in meters) of the glacier surface since installation at Place Glacier 1. The points are colored by air temperature, and the daily maximum is shown as a black dot. The diurnal pattern arises from heating and cooling of the sensor from air temperature and incoming solar radiation.

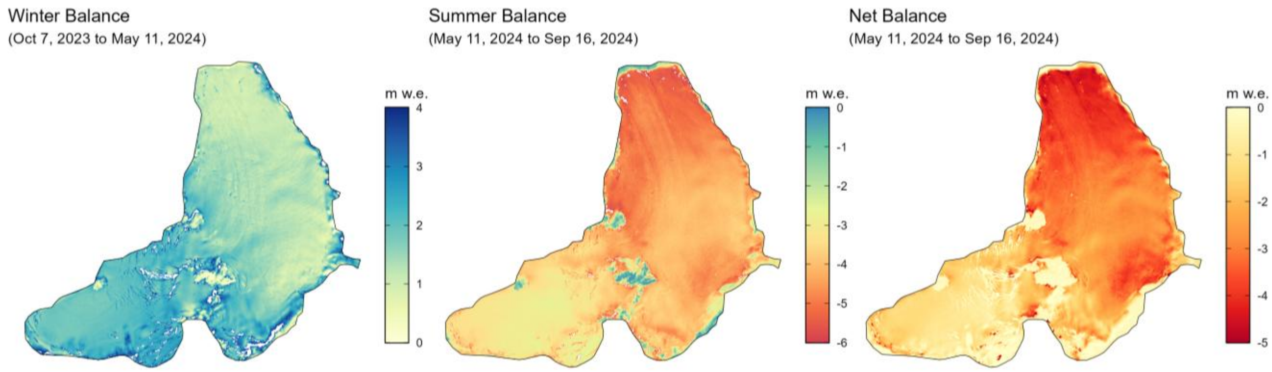

Figure S4: Geodetic winter, summer and net mass balance from repeat airborne lidar.

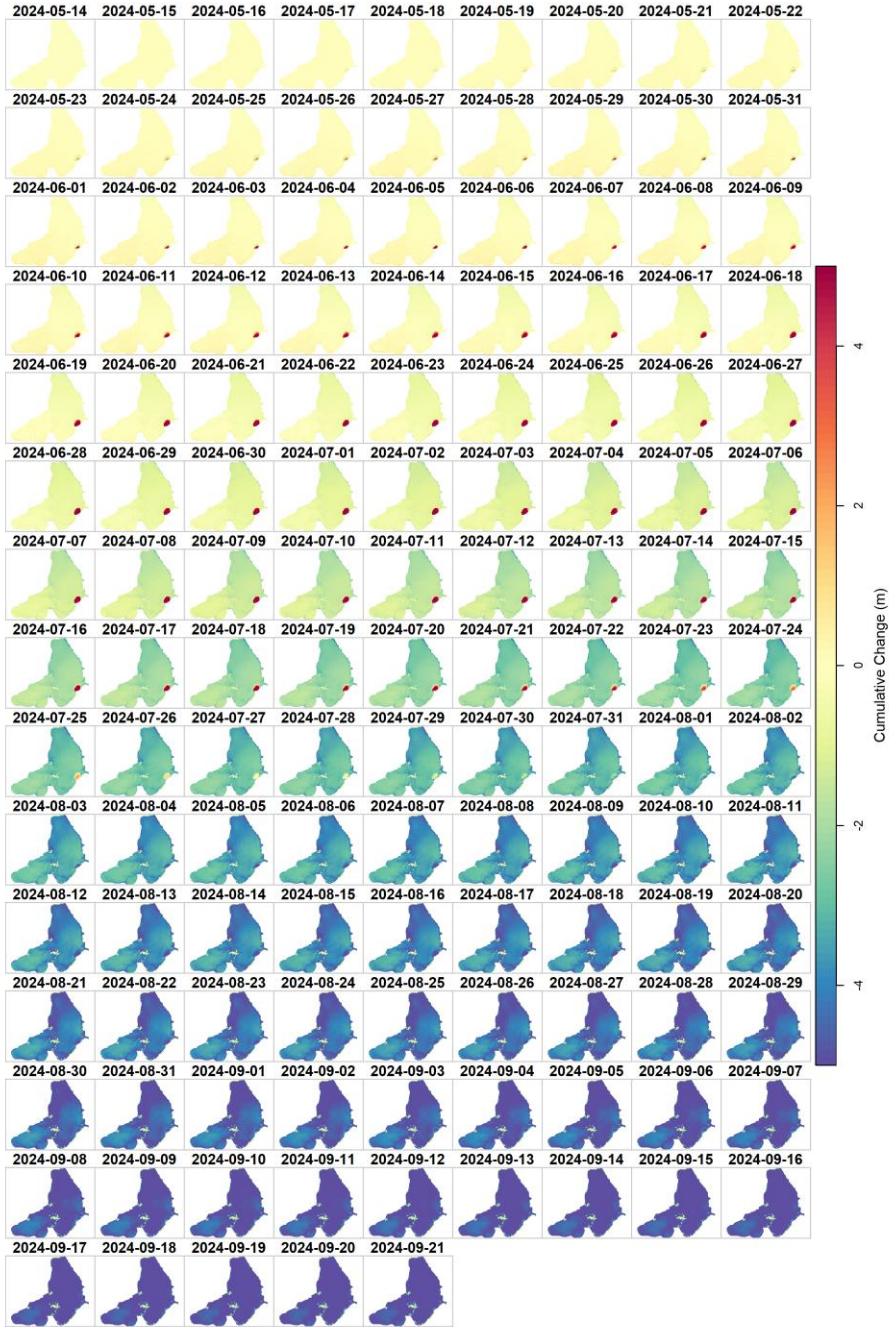

Figure S5: Interpolated daily 5 m resolution lidar digital elevation model from May 14 to September 21, 2024. The time series is expressed as the cumulative change from May 14, 2024.

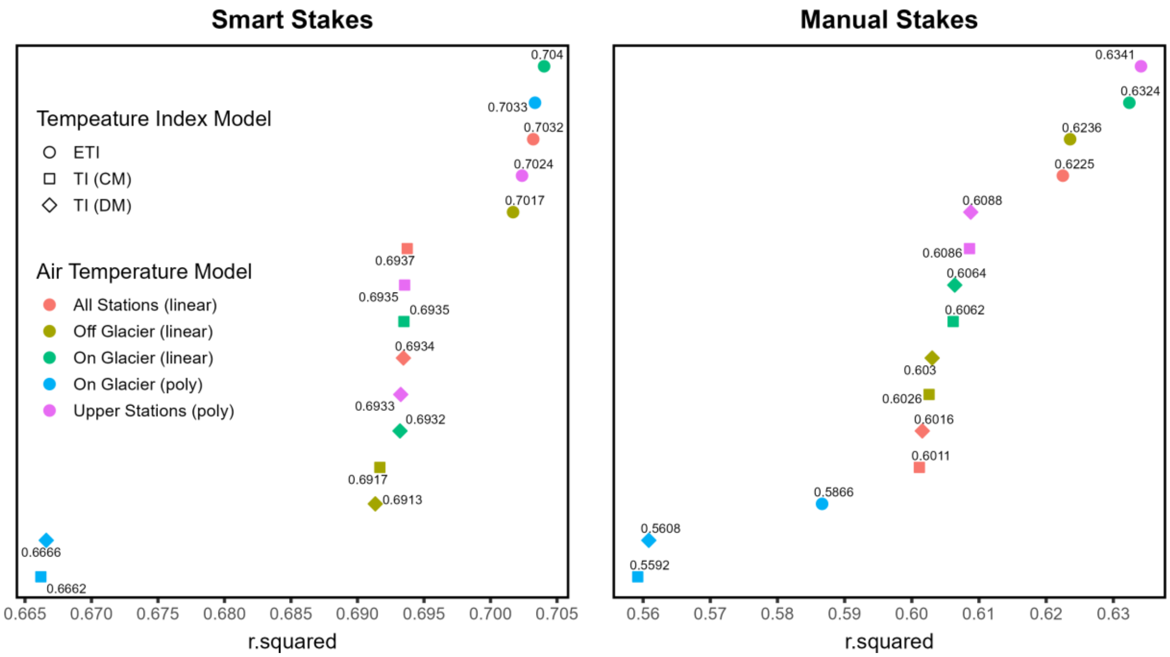

Figure S6: Melt model performance evaluating the total seasonal melt against the four smart stakes (left) and the network of independent manual seasonal ablation stakes (right). Labels show the r^2 values per point.

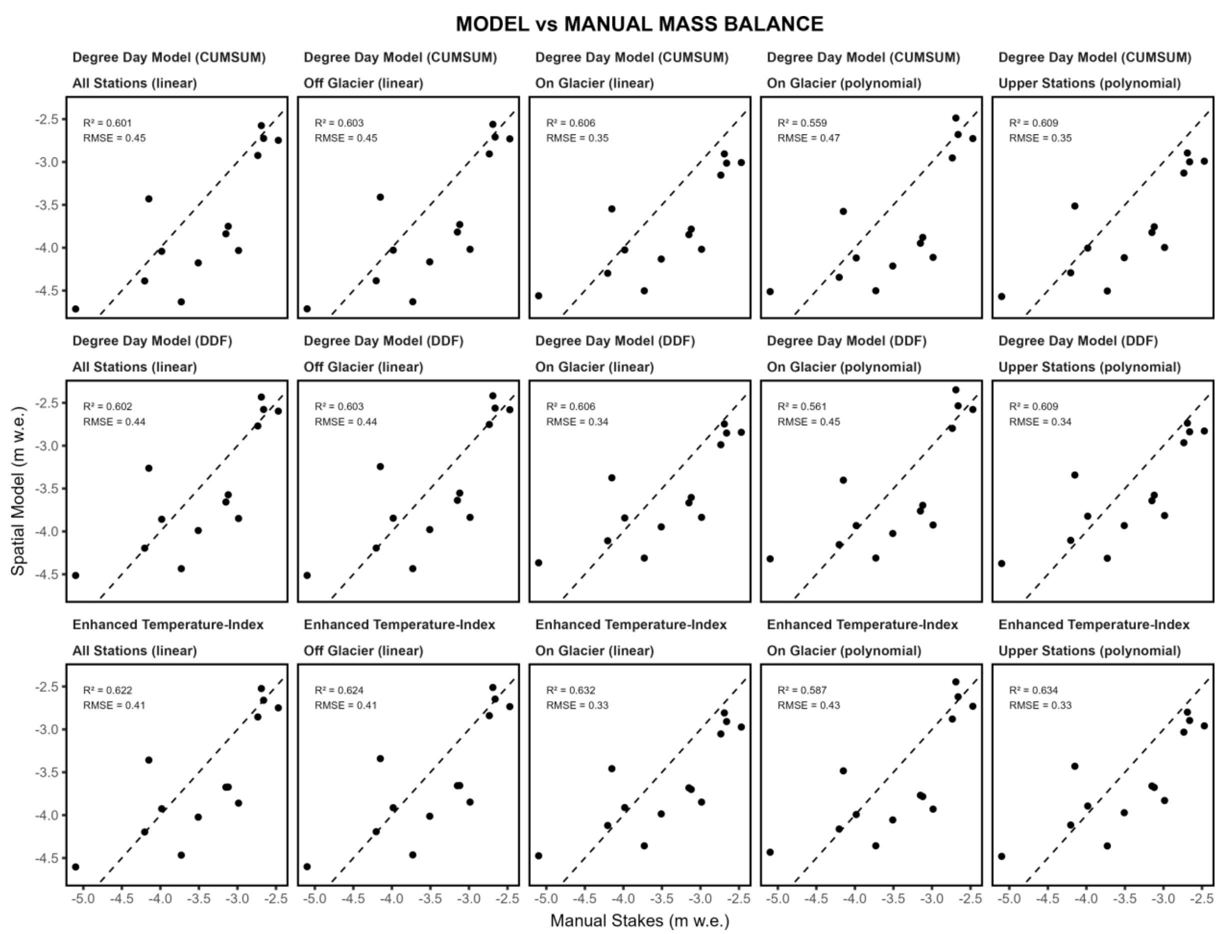

Figure S7: Total seasonal melt from the manual ablation stakes (x–axis) and the ETI model with on–glacier linear lapse rate (y–axis).

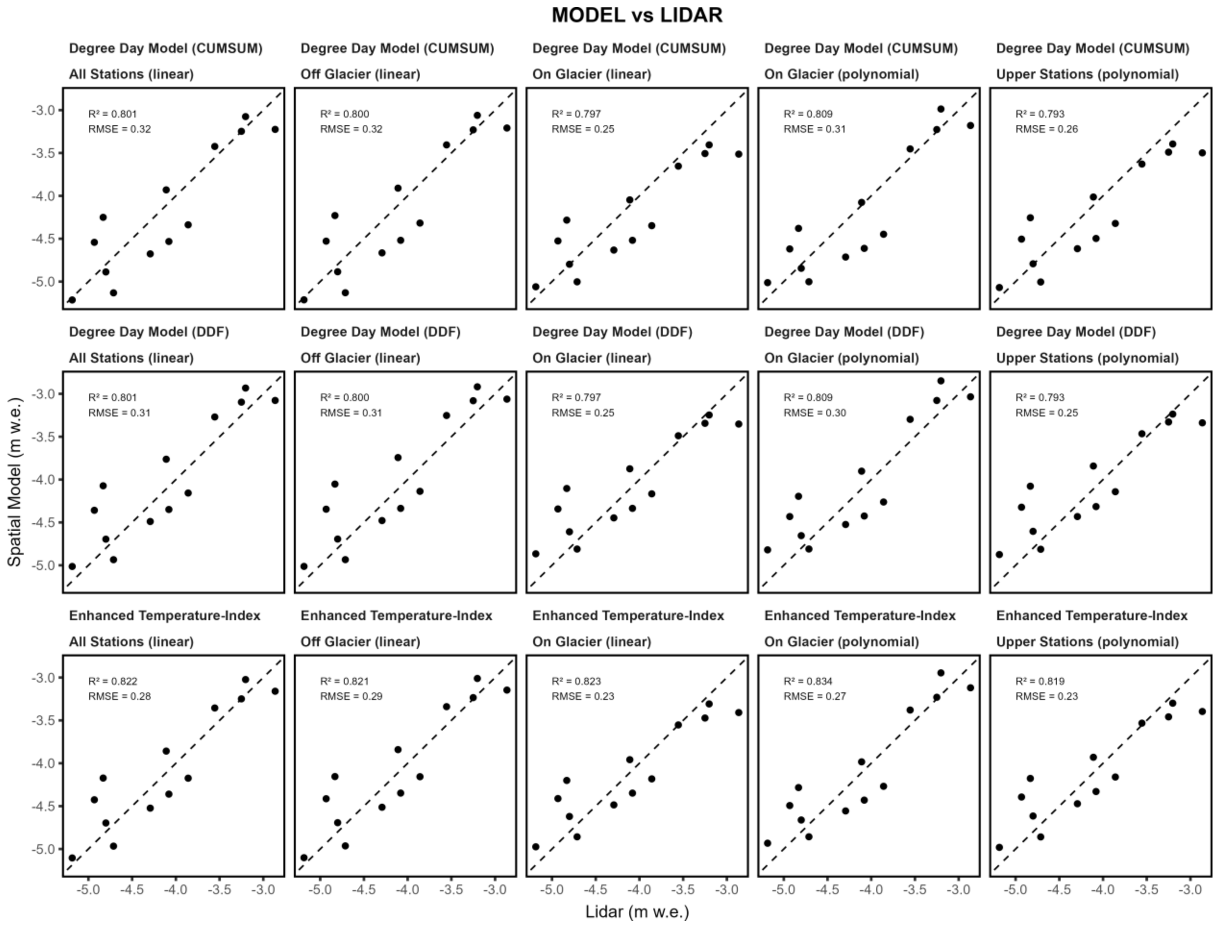

Figure S8: Total seasonal melt from the geodetic mass balance (x–axis) and the ETI model with on–glacier linear lapse rate (y–axis).

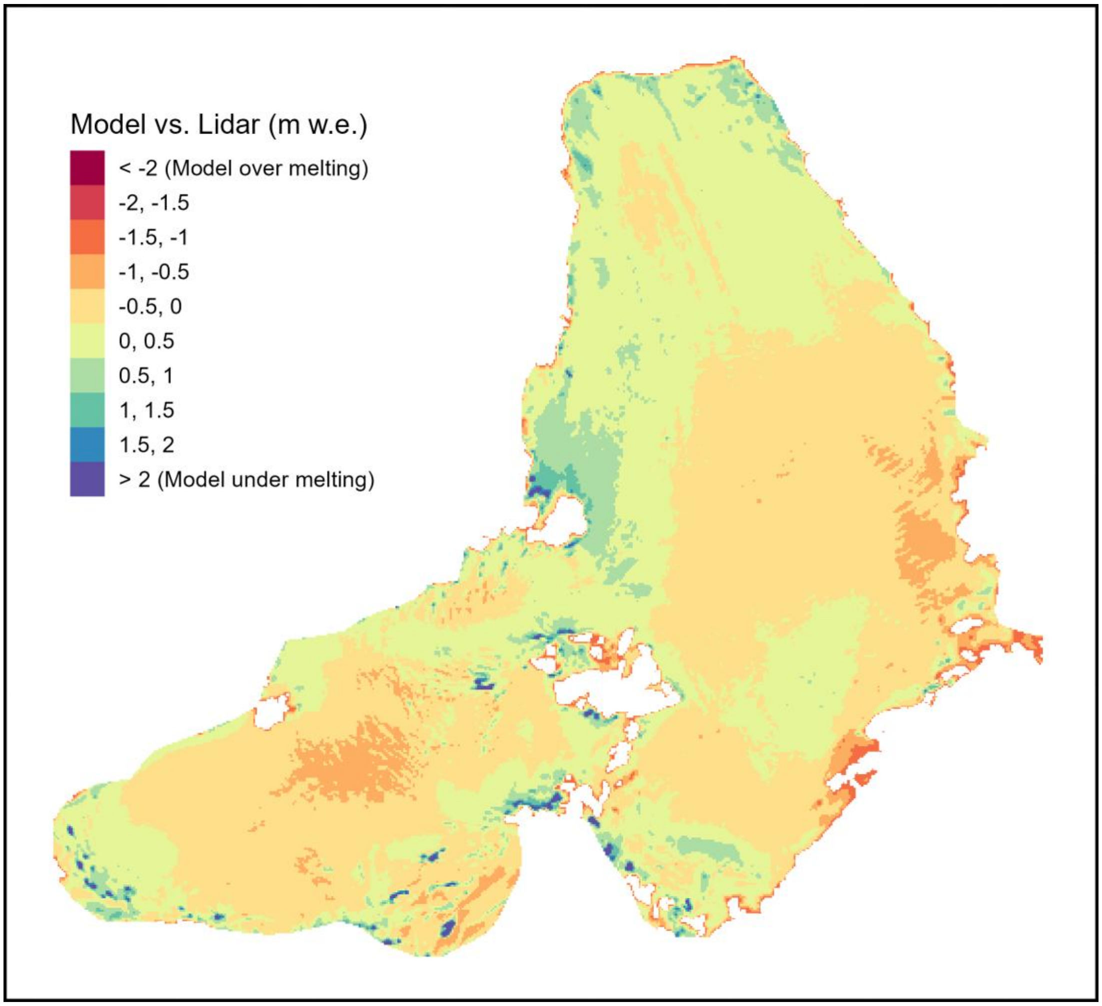

Figure S9: Difference between the melt model and the lidar–derived geodetic mass balance. Negative values indicate that the model is over melting, whereas positive values indicate that the model is under melting. Nunataks and ice marginal areas have been masked out from this plot. There is an overprediction of melt along the glacier margins and the mid-glacier bedrock nunatak. This overprediction is expected in these regions since they represent areas where ice cover either does not exist (nunatak) or areas where ice disappeared between the two lidar surveys.

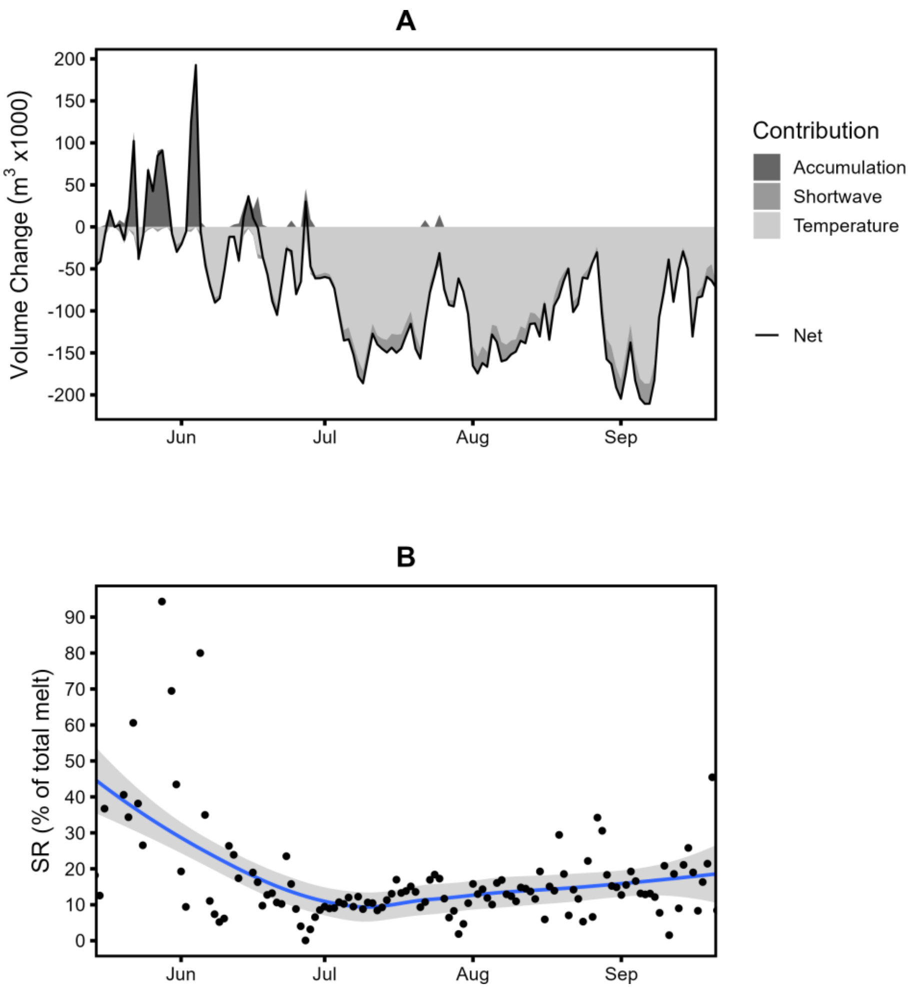

Figure S10: A) Proportion of the total daily volume change from the ETI model (snow accumulation, shortwave radiation, and air temperature); B) Percent contribution of melt from shortwave radiation relative to air temperature in the ETI model.

Future smart stake development

Future development of smart stakes can benefit from several technological and methodological enhancements. In terms of logger construction and user interface, a key improvement would be the fabrication of custom Printed Circuit Boards (PCBs), which would facilitate faster assembly and standardized construction (Wickert et al., 2019). The current reliance on the TPL 5110 for power management has proven problematic due to inconsistent wake–up times. Additionally, building an Arduino library could streamline code management, while the creation of a graphical user interface (GUI) would improve device configuration and monitoring in the field.

Sensor integration is another area of potential advancement. Incorporating external temperature compensation could improve the accuracy of ultrasonic sensors (de Pablo and Rosado, 2025; Wickert et al., 2023). Secondary time–of–flight sensors, such as laser rangefinders, would add redundancy and enhance reliability (Denissova et al., 2025). Also, integrating a compass, inclinometer, and accelerometer would allow for automated detection of stake tilt and orientation. Position tracking could be enabled through low–cost GPS or RTK GPS modules (Broekman and Gräbe, 2021). Furthermore, implementing a non–mechanized self–adjusting cross–arm to keep the air temperature at approximately 2 m from the glacier surface would mitigate issues of inconsistent sampling heights relative to the glacier surface.

For communication and power, implementing low–frequency radio communication between stakes and a central hub could significantly reduce telemetry costs (Denissova et al., 2025). Exploring alternative satellite telemetry options, such as the RockBLOCK 9704 modem or other satellite constellations, could further enhance connectivity (e.g. GOES). Adaptive sampling strategies based on observed melt rates and battery voltage would optimize power usage. Designing compatibility with a 12 V battery bank could reduce reliance on solar power, increasing the system's robustness in variable weather conditions.

Physical design and field deployment protocols also warrant refinement. Developing alternative stake structures or anchoring methods could improve long–term stability under challenging conditions. For example, a collar that stabilizes the pole and lowers with the snow surface could prevent tilting. Enhanced shielding for sensors would reduce bias from solar radiation. Field procedures should include regular dGPS surveys to accurately track glacier surface elevation changes. Additionally, frequent snow density sampling would provide valuable calibration data for melt models.

Finally, improvements in data processing and analysis are essential to maximizing the utility of smart stake systems. Automated quality assurance and control routines would help maintain data integrity. The development of machine learning algorithms could uncover patterns in high–resolution melt data. Real–time alert systems for pronounced melt events would offer critical insights for early–warning applications. Accounting for stake movement in data correction routines and processing spatial melt patterns in near real–time with each new data point would enhance both the accuracy and responsiveness of the system.