Dear RC2,

We thank you for providing thorough and constructive comments on our manuscript. They highlight important gaps in our workflow, analysis, and discussion. In response to these comments, we significantly revised the manuscript. Our response to each comment can be found below in italicized, blue-faced font.

The main changes to the manuscript are:

1. ***Refined Objectives:*** *We improved and clarified the objectives and made sure to clearly link them into discussion and conclusion of the paper. The objectives of the paper are to: 1) Describe the design and performance of smart stakes in a data rich environment; 2) Combine smart stake and remotely sensed data to inform a simple distributed mass balance model; and 3) Demonstrate how real–time ablation data can be used to examine the role of individual events on ablation.*
2. ***Enhanced Temperature-Index Model:*** *We integrated the Enhanced Temperature-Index model (ETI), while retaining the original Temperature-Index model (TI) from our original submission, and ran each model with multiple air temperature models. The ETI allows us to add incoming shortwave radiation, albedo, and snowfall to the analysis.*
3. ***Remote Sensing Analysis:*** *We added Sentinel-2 and Landsat 8/9 satellite imagery from the Harmonized Landsat Sentinel (HLS) dataset for snow cover mapping on the glacier. This HLS data is free and publicly available and complements the PlanetScope data that we used previously. We also use the HLS data to calculate broadband albedo over the glacier in the revised modelling framework.*
4. ***Lapse Rate Analysis:*** *We expanded our analysis of air temperature lapse rates and options for estimating air temperature across the glacier. We now test different combinations of stations (e.g. on glacier, off glacier) and different regression formulas (e.g. linear, polynomial). The highest performing model is a linear daily lapse rate of air temperature using only the on-glacier weather stations.*
5. ***Addressing the Katabatic Boundary Layer:*** *We discuss the importance of the katabatic boundary layer, and how future work could implement a study design that accounts for katabatic effects. We stress, however, that our experimental design is not ideal to evaluate the impact of katabatic flows on temperature downscaling to the glacier survey (investigating this phenomenon was never our stated goal in the paper).*
6. ***Geodetic Mass Balance:*** *We added lidar derived geodetic mass balance as a second independent validation dataset for our model. In our initial submission, the model did not perform very well against the independent mass balance data from manual ablation stakes. We suspect this poor performance was due to differences in the start/end dates of our logger experiment and those of the WGMS stake measurement program. Our hypothesis is partly supported by the good agreement between the geodetic and modeled mass change. We now discuss this in both the results and discussion section of the revised paper.*

7. ***Financial Cost:*** *We clarified the "low-cost" argument of the smart stakes. We moved the description of the overall cost of the smart stakes from the supplementary materials, where it was more cumbersome to find, to the main body of the paper. This strengthens the rational of the "low-cost" aspect of the project.*

8. ***Workflow Clarification:*** *We improved the description of the overall workflow in the methods and added a flowchart to simplify the explanation of the workflow. The flowchart helps guide the reader.*

9. ***Further Discussion of Site 4:*** *The model does not perform well at Site 4. We expanded our discussion on why this may be – the most likely contributor to the poor performance is that the stake was only drilled into snow (not into ice, as the snow was too deep) in the spring of 2024 and the stake likely shifted, tipped, or settled over time.*

This significant re-working of the paper strengthened the quality and defensibility of the science and the overall relevance of the work.

We would like to emphasize that our smart stakes remain, to our knowledge, the first low-cost and open-source solution to real-time ablation data using satellite telemetry.

To reduce the length of the manuscript resulting in the new additions, we moved the "Future Smart Stake Development" section to the supplement.

We thank you for your time and efforts reviewing our revised work.

Kind regards,

Alexandre Bevington
on behalf of the authors

Reviewer Comment 2 (RC2)

This manuscript describes the design and deployment of a novel "smart stake" system that monitors surface melt and air temperature in near real time. The authors apply the data collected to a simple spatial melt modelling framework and use them to evaluate the influence of heat waves on glacier melt at Place Glacier, British Columbia.

The manuscript presents a clear and detailed description of the smart stake design and deployment. The use of low-cost sensors and satellite telemetry is interesting and has the potential to make glaciological monitoring more accessible. The real-time transmission capability is a valuable feature, and the overall approach contributes to ongoing conversations about alternatives to traditional on-ice AWS.

While the smart stake concept is promising, I was not fully convinced of its added value relative to a conventional on-ice AWS setup, and I found the melt modelling and event attribution to be fairly simplistic. The manuscript covers many topics but could benefit from more depth in each of them. Addressing some of these limitations would be important before publication.

In summary, I enjoyed reading about the smart stake setup and seeing its performance and data outputs. However, I found the presentation of the subsequent analyses too simplistic. I detail these comments below.

We thank the reviewer for their detailed review of our paper and providing concrete ways in which we can strengthen our paper. In light of their comments and those of Referee #1, we completed additional analysis to address the major criticisms of our paper. As suggested, we now provide an updated ablation model that incorporates the influence of short wave radiation in our distributed model of surface mass balance. We stress, however, that the primary motivation of our paper was to describe the smart skate design and their general performance. Since we lack many of the key observations (e.g. wind speed over the glacier surface), we refrain from employing a full energy balance model to estimate distributed daily ablation for the glacier. We now alert the reader to the paper's primary objectives in the paper's introduction.

Major comments

Cost argument: The main stated benefit of the smart stakes is their low cost, but no cost assessment is provided in the manuscript. Including such an assessment would be very useful for evaluating this setup. Without an explicit comparison, the argument for "low-cost" deployment remains difficult to evaluate. Furthermore, several suggested improvements (e.g., adding sensors to address tipping or solar heating) could make the smart stakes nearly as complex as an on-ice AWS, which would further weaken the cost advantage.

Thank you for the comment. In order to streamline the initial draft of our manuscript, we decided to include the cost of the components in the paper's supplement (Table S1). To better support our claim for the stake's low cost, we moved this table into the main (now Table 1). The main cost advantage is the data logger and telemetry.

*We added: "The total overall cost of the smart stake is approximately $1,100 USD. Most of this cost is made up of the Iridium modem and the ultrasonic sensor (Table 1). This cost is only a fraction of typical costs for a real–time AWS, which are typically in the range from $10,000 to $20,000 USD." (**L119-121**).*

*The added suggestion for addressing the tipping issues could likely be addressed with an accelerometer/gyroscope (e.g. ~$ 13 USD here: https://www.adafruit.com/product/3886). And: "Similarly, an inexpensive tiltmeter could be added to the stake identify tilting." (**L501**)*

Increased spatial resolution: While the smart stakes did improve temporal resolution compared to seasonal mass balance surveys, the gain over a single on-ice AWS is less clear, particularly when combined with mass balance stake measurements. The poor performance of the upper site further reduces the usefulness of deploying four sites. Would a single smart stake or on-ice AWS at mid-elevation, combined with the off-glacier stations for lapse rates, provide comparable results? A stronger case for the sensors' value could be made by explicitly testing the added benefit relative to existing approaches, especially given the availability of two off-ice AWS at this site.

Thanks for this comment. We agree that the gain over traditional mass balance stakes is clear, and that the argument that smart stakes are better than an on-glacier AWS is less clear. We would like to clarify that the smart stakes do not attempt to replace on-glacier AWS. Rather, they aim to provide a *cost-effective solution to increasing the sampling of surface elevation change and air temperature across the glacier across multiple glacier surfaces and elevations.*

We added concluding remarks to this effect in: "The smart stakes also present a complimentary dataset to on–glacier AWS because of the low–cost and ease of installation. The gains over a single weather station from the increased spatial sampling include: 1) quantifying the spatial distribution of melt and melt factors over diverse glacier facies (e.g. debris covered ice, dirty ice, steep slopes, or shaded regions), and 2) a quantification of the spatial distribution of air temperature beyond a single point." ***L600-603***.

The gain from increased spatial sampling is especially important in areas where there is no repeat lidar, or other means of acquiring high-resolution elevation change, and important for understanding spatial distribution of air temperature. These are things that a single AWS is not able to do, and typically multiple full AWS are not deployed across elevations on a single glacier. There is no on-glacier AWS on Place Glacier, and the performance of the smart stakes against a single AWS was not tested. We add: "The smart stakes were tested in a data rich environment; however, they are suitable for any glacier and would provide important data at a low–cost for regions without repeat high resolution DEMs and in regions with poor optical satellite imagery." ***L604-606***

The poor performance of the upper site (Site 4) against the lidar data, and against the model results could be due to ice dynamics or potentially could be explained by snow settling beneath the stake, as it is the only stake which was not drilled into ice. We stress, however, that the confounding factor of ice dynamics is only important in our case where we are evaluating elevation change of the stakes against the geodetic data.

We do not believe that this poor performance is an argument against smart stakes but rather emphasises that quantifying ice dynamics and the full energy balance is likely required in complex topography. See ***L176-178****: "For Sites 1–3, the snowpack was thin enough during the initial installation to drill the poles into the underlying ice, but thick snow at Site 4 prevented drilling the poles into the underlying ice." And* ***L551-552****: "A likely explanation of the poor model performance at Site 4 could be that it is the only stake that was not drilled into glacier ice, it was only drilled into the snow and may have settled over time."*

Supplementary Figures S7 and S8 *show the performance of the melt models using multiple air temperature models.* ***Figure S6*** *shows the overall model performance of each of those combinations. This demonstrates that although the air temperature model selection is important, the model selection is more important, with the ETI model outperforming the TI model using any of the considered air temperature models.*

Spatial melt modelling: The modelling approach is quite rudimentary, applying uniform melt factors across snow and ice despite calculating melt factors at four individual stakes. As a result, it is not clear how the smart stake data meaningfully enhance the analysis. The model performs reasonably, but not particularly well, and the value added by the smart stakes is not evident.

This is a fair criticism. As now emphasized in the introduction of the paper, it was not our intention to introduce a state-of-the-art physical model in this paper but to use a rudimentary melt model and show how it might be calibrated to obtain distributed melt during the ablation season. However, *we did take this criticism seriously and decided to explore the importance of shortwave radiation in melt. We replaced the simple temperature index model with an Enhanced Temperature-Index Model. This model is now run using variable temperature records (**Section 4.3, Figure S7-S8**). In addition, we test melt factors from daily data, cumulative data, and from a multiple linear regression (**Table 3**). We also investigate the variability of melt factor values (**Figure 9**).*

As stated above, we remind readers that we are not proposing a new or better model but rather informing a simple melt model using a combination of remote sensing data and real-time observations.

Heat wave analysis: Much of the main ablation season is classified as "heat waves," making it unsurprising that a large fraction of melt occurred during those periods. More detail on how heat waves were defined, and how these events compare with other years, would strengthen this section. As currently framed, the analysis feels shallow, particularly since it relies heavily on site 4, which performed poorly compared to the lidar. The paper might benefit from focusing more deeply on either the melt modelling or the heat wave analysis, rather than presenting both at a fairly simplified level.

Thank you for this comment. We agree that the paper could focus on either the melt modelling, or the event-monitoring. In this case, due to the incomplete observational record (stakes tipped over), we require a melt model to complete the time series. That time series is then used for a simple assessment of event-scale monitoring across 4 locations over the glacier. We believe this is fully in the scope of a single paper and increases the strength and utility of the research.

*That said, we do agree that the term heat wave is not well defined. We opt for the term "heat events". **L391-392:** "We recorded three heat events, herein defined as times when the mean daily air temperature was above 10°C (Figure 8A)."*

Indeed, Site 4 performed poorly. We believe this is due to either: 1) unquantified drifting in of the field instrument (e.g. the sensor turned/pivoted), 2) it started tipping much earlier than the other sites as it was only drilled into snow, or 3) ice dynamics/velocity which are unaccounted for in our model. We believe that despite these challenges, this data and modelling exercise showcase high resolution, real-time applications of low-cost smart ablation stakes, which could support real-time melt modelling and event scale analysis in the future. Both of which are important steps forward in glacier monitoring.

*We also added the following sections to address the performance at Site 4: "The validation of smart stake measurements against independent lidar observations showed good agreement (RMSEs of 0.18–0.12 m for Sites 1–3), though Site 4's higher RMSE (0.55 m) highlights the importance of considering installation conditions, local topography and ice velocity when interpreting point measurements (Beedle et al., 2014). A likely explanation of the poor model performance at Site 4 could be that it is the only stake that was not drilled into glacier ice, it was only drilled into the snow and may have settled over time." **(L548-552)***

Minor comments

It was not clear to me why the ECCC station is included in the lapse rate calculation. This choice made the glacier sites appear bundled together and harder to interpret. Clarification would be helpful.

*We can appreciate why the reviewer was confused here. Our rationale to include this station was that it provided a low elevation site to estimate a lapse rate above the ice surface. To make it clear, we revised the air temperature lapse rate component of this paper. Our revisions include: 1) better description of the weather stations (**Table 2**), multiple lapse rate models tested (**Section 4.3.2 Spatial model implementation**), and a more thorough explanation of the lapse rate evaluation we employed (**Section 5.4 Lapse rates**).*

In several places, the writing alternates between very detailed and overly casual phrasing, which occasionally disrupted the flow. For example, line 99: "some 400 m away" . Could this be made more precise?

*We updated to: "The first, "Wx–Forefield", is a weather station run by NRCan located 412 m down valley from the glacier terminus located on bedrock in the glacier forefield. The second, "Wx–Ridge", is a new weather station installed in early summer 2024 on an alpine ridge above the glacier." (**L214-216**)*

When justifying sensor or method choices, referencing prior use is not always sufficient. For example, line 140 states that a method was "used in other glaciological studies." It would be stronger to explain whether it worked well in those studies and what was gained by its use.

*Thanks for the comment. We added more detail to what was done and what is recommended by Wickert et al. 2023: "It is specifically optimized for measuring snow and similar sensors have recently been used successfully by Wickert et al. (2023). The authors tested the sensor on multiple glaciers around the world, although without satellite telemetry, and provided useful recommendations for future field deployments that we were not aware of at the time of our installation. Wickert et al. (2023) recommend the MaxBotix MB7388, and also tested the MB7060, MB7389, and MB7386. A comprehensive comparison of the available sensors from MaxBotix was not done in this study." (**L127-131**).*

If the issue with using GOES is that the station might move and lose connection, could an option such as transmitting data by radio signal to the main off-ice station, and then using GOES, be feasible?

*Yes, this is a great idea and one in which we are actively exploring for future deployment. We now discuss the aspect in the third paragraph of Supplementary Section **Future smart stake development:** "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)."*