Response to reviewers

Reviewer comments in black *- Answers in blue italic*

Reviewer 3:

Overview

This manuscript presents observations collected continuously over a few consecutive years at a mountain glacier, combined with modeling, to try to understand the spatial and temporal patterns in ice velocity and subglacial hydrology.

In general, the paper is well written with nice figures. Please see below for general and specific comments. With minor revisions to further improve clarity and strengthen the paper, I feel this work will make an excellent contribution to the glaciological literature.

We appreciate the Reviewer's positive assessment of our work and his comments, which have helped clarify the manuscript.

General Comments

1. First, I will say that this is a valuable dataset of observations to understand the system that can serve as an excellent modeling target. It is especially interesting to see the documented observations of the winter hydrological influence as measured through the persistent winter discharge (lines 181-182) and the evidence of winter subglacial water pressure controlling winter velocity (Fig. 6), also demonstrating that summer behavior is more complicated to predict.

We thank the Reviewer for his positive feedback of our dataset as a valuable modeling target and for highlighting the importance of our observations regarding winter hydrological controls on glacial velocity.

2. I have some questions about the nature of surface meltwater inputs to the bed at this glacier: Can you provide more details about location, timing, and magnitude of water inputs that likely reach the bed? The right bank of the surface is described as being heavily crevassed (line 225), but otherwise I don't see any description of surface water features. Are there moulins? Supraglacial ponds? How do these features change in different regions of the glacier, and over time (seasonally and interannually)? Without measurements to constrain meltwater inputs beyond the discharge measured downstream, even a qualitative description of this possible

distribution would be helpful, to give the reader a sense of where, when, and how much meltwater might drain from the surface to reach the bed.

We agree with the Reviewer that providing a qualitative description of the nature of surface meltwater inputs to the bed of the glacier is important information. While we do not have a direct inventory of surface water features, we have observed numerous small moulins across the study area, and as noted in the manuscript, the right bank is heavily crevassed, along with the terminus as can be seen in Fig. 1. Based on our fieldworks, we can confidently say that supraglacial streams do not remain on the surface for significant distances; rather, they percolate englacially through these crevasses and moulins. The absence of long-lived supraglacial streams support our model's primary assumption: a direct and relatively instantaneous connection between surface meltwater production and the subglacial system. We constrain the timing and magnitude of meltwater inputs using a degree-day model based on air temperature. To clarify this for the reader, we have added a qualitative description of these drainage features to Section 2.4.

3. In Eqs. 3 and 4, how are the values chosen for average bed bump height, intrinsic conductivity, and the exponents? This would be helpful to explain and justify the choices, as well as discuss the implications and limitations of these assumptions.

We thank the Reviewer for pointing this out. The values for the average bed bump height (h_r), intrinsic conductivity (k_0), and the associated exponents (p_1 and p_2) were initially selected to best fit the high-resolution direct measurements of sliding velocities from the subglacial cavitometer site (see figure S2 in Supplementary Information of Gilbert et al. (2022)). However, there is a trade-off between bump height and intrinsic conductivity, since both parameters play a similar role in the sheet discharge formulation. This is why the height of the bed bump has been fixed at the realistic value of one meter. We have added a brief justification for these choices and a discussion of the associated assumptions in Section 2.4.

4. Discussion and interpretation of subglacial geometry refers to cavity size and cavitation rates, yet the summer velocity and pressure observations suggest that a highly connected or channelized drainage system likely develops. Do you have any observations of channelization? What does the outflow at the terminus look like?

We thank the Reviewer for this insightful question. Previous studies at Glacier d'Argentière using seismic (Nanni et al., 2021) and borehole (Roldan-Blasco et al., 2024) observations have documented the existence of a single large efficient channel that forms in the center of the glacier. We interpret that during periods of high summer melt, water likely drains from the isolated or weakly connected cavities into this low *pressure primary channel. We have now explicitly written the role of channelization and its relationship to isolated cavity drainage in the Discussion (Section 4.1).*

5. I think it would be useful to add a “Limitations” section to the paper. This is currently missing, but would be a good place to discuss some of the assumptions involved in the observations and modeling methods, as well as opportunities for further research.

We thank the Reviewer for this suggestion. We agree that acknowledging the assumptions and limitations of the study is essential for a balanced interpretation of the results. Rather than creating a standalone 'Limitations' section, we have chosen to integrate these discussions directly within the relevant portions of the Methods (Section 2) and Discussion (Section 4). This way the limitations are contextually linked to the specific observations and modeling steps they affect.

6. I am interested to see the documentation of short-term velocity pulses in the summer (line 311). More discussion or interpretation about what drives these pressure variations would be insightful. For example, can you connect them with higher temperature or rainfall events that contribute large amounts of water to the system?

We agree with the Reviewer that the drivers of these short-term velocity pulses play a central role in summer subglacial dynamics. These high-frequency (mostly diurnal) variations are often triggered by daily meltwater input or rainfall events. We have now added Figure S1 to demonstrate the correlation between diurnal velocity cycles and meltwater input. Additionally, a detailed analysis specifically of these rainfall events is provided in a separate study (Togaibekov et al.,2024). We have expanded Section 4.3 in the Discussion to explicitly interpret the role of these short-term pressure pulses and how they relate to transient surface water inputs.

7. Finally, I am happy to see that you highlight the difference in seasonal behavior as observed at different parts of the glacier with different local characteristics. This shows that seasonal velocity and hydrology dynamics are more nuanced than how they are sometimes approached with different schemes of classification. This also raises the question of whether it is important to resolve these finer details across spatial and temporal scales, or not. That probably depends on the science question, but is something to consider, and this study nicely demonstrates that you can come to different conclusions about the nature of a glacier’s subglacial system depending on when and where you look.

We thank the Reviewer for these concluding remarks. We agree that the spatial heterogeneity we documented highlights the glacier-wide behavior is indeed complex. We hope that this work resolves these details and identifies the specific physical *mechanisms, such as local morphology and cavity connectivity, that will ultimately determine how glacier dynamics respond to a warming climate.*

Specific Comments

Lines 44-45: Remove either “although” or “yet” from this sentence

We thank the reviewer for identifying this error; however, the sentence has been removed during the revision of the manuscript.

Line 100-101: About how thick is the glacier at each location? This would be helpful to mention here.

Indeed, this information is very important. We have added the approximate ice thickness for each location in the revised manuscript: the glacier is approximately 250 m thick at the GNSS profile locations and approximately 55 m thick at the cavitometer site. The sentence reads: “The bed topography at these locations is distinct: the glacier is steep (20%) and thin (55 m) at the cavitometer location, whereas it is flatter (10%) and thicker (250 m) at the GPS network site (Gimbert et al., 2021a)”

Fig. 1: You might consider adding an inset with a map showing the location of the glacier in a broader geographic area for reference, for those not familiar with the location.

We thank the Reviewer for this suggestion. We explored adding a broader geographic inset map; however, we found that it significantly crowded the figure and reduced the readability of the high-resolution GNSS station labels and local topography, which we think are more important. However, we have ensured that the glacier’s location and coordinates are clearly stated in the text.

Equations 3 and 4: How do you choose the average bed bump height, intrinsic conductivity, and the exponents used in these equations? See General Comment 3.

As it was addressed above, the values for the average bed bump height (h_r), intrinsic conductivity (k_0), and the associated exponents (p_1 and p_2) were initially selected to fit the high-resolution direct measurements from the subglacial cavitometer site (Gilbert et al., 2022).

Line 182: I’m not sure that “circulates” is the right choice of word here, as it might imply water moving around without flowing out, which is not the point being made with the observation of winter discharge. Perhaps it would be more accurate to say the water “moves” or “flows” or “travels” beneath the glacier year-round.

We agree with the Reviewer that the word 'circulates' is not appropriate in this context; we have replaced it with 'flows' as suggested.

Figure 2 is great to see all the measurements together.

Thank you, we have further improved the figure by making it colorblind-friendly

Fig. 2b – interesting that the water pressure increases so much more significantly over the first instrumented winter (2019-2020) than the second (2020-2021), during which it remains more constant, also the big drop event during the first winter (any explanation?). How is water pressure measured?

We thank the Reviewer's attention to these details. Regarding the second year of the observations, we interpret the relatively constant and 'flat' pressure curve as that the borehole sensor became hydraulically disconnected from the active subglacial drainage network sometime in late summer 2020. This information is provided in the corresponding text in Section 2.2. We do not really know the nature of this sudden pressure drop in February 2020. It could be either a true physical signal or an instrumental malfunction, but the overall increasing seasonal trend is clear which is the main focus of this particular paper. Water pressure is measured in a borehole (yellow star in Fig. 1a) next to the GPS site ARG1 using a piezometer positioned 95 m above the bed. To obtain the basal water pressure, we add a constant pressure equivalent to the water column height of 95 m.

Fig. 2c – difference in vertical velocity and vertical GPS displacement. How is vertical velocity measured? Is that at the icefall with the cavitometer? It would be good to clarify in the caption here for easy reference.

We apologize for the lack of clarity regarding the labeling of our observables. We have updated the legend to explicitly include 'GPS separation velocity' and have expanded Section 2.3 to clarify how exactly we calculated bed separation and its rate.

Line 319: Rather than referring to "types II and III" seasonal patterns, you might consider briefly describing each pattern in a few words, for readers not familiar with that classification (or for readers who always forget which is which)

We thank the reviewer for pointing this out. We agree that the classification by Moon et al. (2014) was not introduced; we have now added a paragraph in the Introduction to define these categories and provide the necessary context for our results.