

Quantifying degradation of the Imja Lake moraine dam with fused InSAR and SAR feature tracking time series

Brencher et al., 2024

The authors describe a very interesting study using a combination of InSAR and SAR feature tracking to document the degradation of the Imja lake moraine dam. Their work offers valuable insights into ongoing changes, which can be useful for hazard assessment. Generally I find the study carefully executed and the results are largely convincing. To better convey the message, however, I believe that the manuscript would benefit from some mild restructuring and occasional rewording. Below, I provide some general comments and a number of specific recommendations that I believe will address these shortcomings.

General comments

- Given the focus of the group within which this work was performed, I am surprised that no DEM differencing was performed. Given the main findings (ice melt / surface lowering), it seems like DEM differencing would be the an important source of information? Personally, I would be delighted to see the manuscript supplemented with this information, but I recognize that this is a big ask. In any case, it would be interesting to say why this could not or was chosen not to be done.
- I think the discussion falls a bit short of expectations. It nicely discusses the study results, but I think it would deserve a slightly boarder view on how and why this information matters. I have included a number of questions that the authors could consider addressing (more as a menu than an expectation that they are all addressed, and I am sure the list is not comprehensive).
- The manuscript is generally well written, but frequently uses very short paragraphs, which can disrupt the reading. I recommend combining some of these in such a way that a paragraph is at least 3-5 sentences (and less than half a page). For my taste subsections in the intro are not needed (use carefully crafted topic sentences instead). A clear statement of the aim of the paper and the chosen approach to address the knowledge gap are missing in the introduction / the information is scattered throughout, consider tightening. What is true for paragraphs is also true for subsections (e.g., 4.4. and 4.5)

A note on literature review statements: If you avoid having the citation at the start of the sentence – effectively making it the grammatical subject of the sentence – the relevant information becomes more apparent. Compare the following:

Hambrey et al. (2008) used both GPR and ERT to document buried glacier ice tens of meters thick (over 40 meters in places) overlain by up to 20 m of debris along the eastern portion of the moraine.

vs.

Thick glacier ice – over 40 m in places and overlain with up to 20 m of debris – has been documented along the eastern portion of the moraine (Hambrey et al., 2008) [I removed the reference to GPR and ERT because you already stated this in a previous sentence]

Specific comments

L36: Consider mentioning early warning systems in addition to engineering solutions? A good reference could be Niggli, L., Allen, S., Frey, H., Huggel, C., Petrakov, D., Raimbekova, Z., Reynolds, J., Wang, W., 2024. GLOF Risk Management Experiences and Options: A Global Overview, in: Oxford

Research Encyclopedia of Natural Hazard Science. Oxford University Press.

<https://doi.org/10.1093/acrefore/9780199389407.013.540>

L39: You jump directly to “moraine dams” here, but might want to introduce to reader first to the different types of dams that exist? A good reference to include would be Rick, B., McGrath, D., Armstrong, W., McCoy, S.W., 2022. Dam type and lake location characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019. *The Cryosphere* 16, 297–314.

<https://doi.org/10.5194/tc-16-297-2022>

L40: Add strong precipitation events as possible trigger?

L44: It’s not clear here whether you imply that the evolution of the moraine dam reduces or increases the GLOF likelihood (I guess only lowering is implied here?). Both are plausible in my mind, maybe specify?

L64: It seems relatively uncommon to reference Fig. 1 already in the introduction. I don’t think it’s necessary, and it makes the reader’s life unnecessarily hard when trying to refer to the figure during the “study site” section. Consider moving it and the first reference to it to section 2.

L105: rotational failures (does it have to be rotational?) into the lake or on the other side of the dam? Either it could be a trigger for a GLOF or simply weaken the moraine. Maybe specify? You could also reference the South Lhonak Lake event.

L114: I think there is a conceptual error here, since feature tracking velocities are not along the line of sight.

L116: My understanding is that measuring flow velocities of glaciers is/was only possible with quite some uncertainty and only in specific locations. Maybe specify a bit more in detail when this is possible (and when not!). Saying that this can be done with mm-level precision is likely overselling it a bit.

L129: Consider adding reference to Jacquemart, M., Tiampo, K., 2021. Leveraging time series analysis of radar coherence and normalized difference vegetation index ratios to characterize pre-failure activity of the Mud Creek landslide, California. *Natural Hazards and Earth System Sciences* 21, 629–642. <https://doi.org/10.5194/nhess-21-629-2021> for the coherence.

L153: I found myself wondering if the rate holds true for the period after the publication of the reference given here (Watanabe 2009), since almost 20 years have passed? Do you have a sense of how constant it has been over time?

L163ff: It would be neat to plot the ERT / GPR lines of other studies (color coded by ice depth?) in Figure 1 if you can get your hands on the data. It would greatly facilitate the description of the ice (thickness) distribution. In one case you refer to “ice bottom depth” and in another place simply “40 m thick”. Do these values mean the same?

L167: Can debris in the dam really be fully saturated while retaining its stability?

L174ff: I would have expected these detailed values in the discussion, rather than in the study site. I think for the description of the study site, a brief overview of where what kind of motion has been measured would suffice and be easier to remember (e.g., this corner moved most in this direction, this other part didn’t move much etc.) Decide on GNSS or GPS (Technically these should also be defined). Not clear who “the authors” are in the last sentences.

L197: consider supplementing “azimuth” and “range” with along-flight and across-flight directions such that these are defined here for future use and comprehensibility for non-radar experts.

L216: consider simply saying (or specifying) that a *downsampling* factor of 5 was used in the range direction while the native resolution was kept for the azimuth. The “looks” terminology is very radar specific.

L221: how high did you chose your mean coherence for the reference and stable areas? What is the difference between the “reference” and “stable” area? Why are they different?

L237: I presume you mean horizontal velocity here?

L245: the feature tracking is not along the line-of-sight (but along slant-range and azimuth direction).

L250: over what period is the median? The whole stack or the subset of pairs based on the temporal baselines?

L254ff: I am confused about this procedure. I am probably just misunderstanding, but here's what trips me up: First, you speak about converting the feature tracking offsets to radians. Why do you do/need this? Is it required by MintPy? Then you mask pixels with a SNR lower than 8 (how/where was the SNR calculated, and why do you choose this value?), then you remove pixels with displacement more than 10 m. But I thought you had converted the displacements to radians? So do you do the filtering first? Why do you remove measurements with a high InSAR coherence? Wouldn't the overlapping measurements provide additional robustness to your findings? I think some more details would be helpful here.

Section 4.2: You could consider adding a flow chart or other graphical representation of all the steps in your processing. Currently it's a bit hard to follow. This would also benefit from a geometric diagram, showing the LOS, the azimuth and (slant) range directions, since these can be quite confusing for non radar-experts.

L268: A threshold of 0.6 is quite high, why did you chose it?

L270: I don't understand how or to what the per-pixel median feature tracking velocity products were scaled.

L273: What were the per-pixel displacement measurements inverted to, I don't fully understand.

Sec. 4.3: Did you do all this in MintPy or with code of your own? My understanding is that MintPy is able to do this, no?

Sec. 4.4: Doesn't this just belong to Sec. 4.3? I would combine ☺

Sec. 4.5: This information seems incomplete. What did you then do with these coherence maps? Did you visually compare where there were changes and mapped these? Did you use some kind of threshold? How did you deal with snow decreasing the coherence in winter? Can you specify what months the maps cover? Is it the same as what you present in Fig. 2?

Sec.5.1/Fig.2:

- You list 8 temporal baselines, but I can only count 5, maybe 6 in the figure. Consider removing the ones that are not in the figure, if they are indeed missing?
- I would also recommend changing the color scale of plots C,G,D, and H to something different from panels A,B,E,F because they show very different quantities, and it is initially very confusing (e.g., you could use viridis for one and magma for the other).
- You outlined the area with lower coherence at the front of the lake, but the moraines along the lake also show up as low coherence areas. Why did you exclude those from the "moving area"? Is something else causing the low coherence area there? Or are they also ice-cored? (→ address in the discussion)

Sec.5.2/Fig.3:

- I believe (as highlighted elsewhere, sorry for the repetitive comments) that the LOS you mention in connection with the feature tracking is actually the slant-range. Replace throughout.
- I am a little bit perplexed as to why the velocities from your feature tracking show positive velocities in both orbits. How do you interpret this? Combined with the rather low SNR over this whole area, do you believe that these are indeed horizontal displacements? Or do you think they are in fact a component of large-scale subsidence? Without getting too discussion-y, it would be nice to give a bit more context here.
- I ask this also because the same signal appears on Lhotse glacier, in the top-right corner of your panels. On that note, somewhere in the manuscript (maybe in the study section?) it would be nice to point out that there is another glacier there, which also shows a signal. That way, the readers can understand those spatial patterns.

Sec. 5.3/Fig.4:

- What I miss between section 5.2 and 5.3 is a comparison / context regarding the different magnitudes of motion. In 5.2 you describe the results in terms of velocities in cm/year, and then

in 5.3 you provide total displacements. For me, these are hard to reconcile in my head. Can you somehow standardize?

- Between sections 5.2 and 5.3, the reader is provided with many different quantities and numbers, but it's relatively hard to do much with this information. At the end of section 5.3, you provide an overarching interpretation of the combined patterns. My suggestion would be to put that information upfront and say something like: "The observed patterns of deformation are consistent with downward and eastward motion of the moraine, as is evidenced by the feature tracking and InSAR inversion. The feature tracking shows ..."
This might even remove the requirement of having the two subsections 5.2 and 5.3.
- On a related note, I was somehow surprised not to see the results from the InSAR on its own. Can you provide these or justify in the text why you don't see the need to do so? Personally, I would very much like to see a few wrapped interferograms to judge the data quality coming from the InSAR.
- Fig.4 E-H: Is this the combined cumulative displacement or just from InSAR? The label on the y-axis should probably be cumulative displacement. Can you additionally mark (in the maps and in the profile lines) a few more points (e.g., 2 above and 2 below the mean? That would provide a bit of insight into the spatial patterns and lend credibility to your inversion.
- Fig. 4 A-D: Personally, I would use a different colormap (e.g., magma) for the vertical displacement because you are showing a new quantity. I would also appreciate a slightly more permissive color range (+/- 3m?) to show more small scale patterns.

Sec. 5.4:

- L380: For my taste you don't need to reiterate the velocities of the stable area here, since you clearly made the point that they are negligible.
- Try to avoid "noun trains" (e.g. moraine dam moving area vertical velocity"). Why not say "the vertical velocity of the moraine dam increased from May to October, when it reached a maximum of ..."
- Rather than speaking of "vertical velocity" (here and earlier on, but here at the latest), why don't you call it subsidence? This would be more clear.
- Fig.5: This is a detail, but I am personally bothered by the "plastered on" scale bars ;-). Can you put them next to each other (both horizontal) between panels B and C?
- I don't believe that section 5.4 deserves its own subsection, since it's just another result of the combined inversion. I would integrate with the other part(s).

Sec. 5.5

- This section (2 sentences!) is a bit comical ;-). Since this comes directly from the coherence analysis, why do you not just integrate it with section 5.1? It's the obvious interpretation of your coherence analysis, and lays the perfect justification for why you primarily detect downward motion with your other analyses.

Discussion:

L442: Could you compare the values for the ice flow during the cold months to what would be expected for a glacier from only the internal deformation / creep component (Cuffey and Patterson, sec. 8.3, I think)? Are they anywhere in the same range?

L468: Can you speculate about why the flow direction may have reversed? Did the overall slope change since the early 1990s?

L471: Some confusion here: are you saying that the direction of the ice flow mentioned above (L466) was actually the direction of the ice flow of the original glacier? Or were these measured post separation?

L475: Are you saying here that Imja Lake is actually still a supraglacial lake? Or what do you mean by “complete decoupling from the active glacier will remove compressive stresses”? Specify clearly (and here in the Study Site, for I certainly missed this if it is at all addressed there).

Sec. 6.3: As elsewhere, I would integrate these findings with the discussion of the subsidence.

Questions that I would like / was expecting to see addressed in the discussion:

- How does the subsidence / ice melt compare to measurements from other places? Can you estimate from this how long you expect the ice core to stick around? What will Imja lake look like, once it's all gone? How does it affect the hazard?
- What implications do you think these kinds of measurements can have for operational monitoring. What drawbacks or caveats?
- Under what circumstances do you think your approach can work (in terms of geometry of the moraine/valley)? Would this work on most glacial lakes in HMA or is there something special about this one (on that note, a justification about why you chose Imja in the Study Site description would be nice).
- All the numbers presented in the Study Site (with regards to the changes measured by others) should be presented in the discussion, I think, giving context and comparability of your results. If possible, it would be really cool to put all the different numbers on map.

S6.4: It unfortunate to end your strong manuscript with a long discussion of the limitations, because you leave the reader with information that suddenly calls into question all the work you just presented. As a reader, it requires me to re-evaluate what I just read and put the interpretations in light of the limitations I am only provided with now. I would recommend moving the different parts of the limitations discussion (e.g., why the InSAR might underestimate your subsidence) to the various parts of the methods/results/discussion where they are relevant. For example, you could say something along the lines of “InSAR may underestimate the total displacement, explaining why so and so measured more than we did, but our measurements give a good indication of blababla”. Joshua Schimel (“Writing papers that get cited and proposals that get funded” calls this the “but, yes” approach, rather than “yes, but” ;-)

Conclusions:

L520: I agree with you that this assessment is probably more accurate than any of the techniques on their own, but the I still somehow stumbled over the sentence since you don't actually assess the accuracy of the different approaches against each other or against some supposed ground truth. Not a big issue, but you could consider rephrasing slightly.

L523: I must have somehow missed the part about the “most vulnerable below the current lake level”, but I was wondering how you can actually assess this, if you can't actually measure displacements under the water level. If this indeed true (and I don't really doubt it, since it makes sense conceptually), it would deserve to be highlighted more prominently in the results.

Technical corrections

L26: insert % after ~29 (if you are using LaTeX, $\SIrange{...}{...}$ automatically formats this correctly).

L30: *can result* instead of result

L40: impats

L51: suggest removing references in this topic sentence, I don't think you have to reference a statement like “the landscape is changing”

Fig1: I suggest changing figure title (panel A does not show moraine dam). Make red things yellow in panel A (colorblind friendly)

L151: consider labeling Ombigaichen in Fig. 1

L152: tongue of the Imja Lake → remove the

L153: move “coalesced” to after “supraglacial lakes”

L219: omit two mentions of “burst”

L380: write “January through March” instead of listing the months individually.

L406: can you just write “surface geometry” instead of “surface morphometry”? (Simpler and not much different?)

L525: Note that you suddenly switched tenses (demonstrated, observed ... → show, find). I suggest sticking to the past tense.

L529: Subsidence instead of “downward vertical velocity”?