Review of “Mapping Seasonal Snow Melting in Karakoram Using SAR and Topographic Data”

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General comments

This paper proposes an improvement to the Nagler family of SAR-based wet snow mapping methods, making use of a gaussian mixture model and newly proposed metrics “wet snow index”, “topographic snow index” and “integrated snow index” in order to better separate wet snow from no snow / dry snow by incorporating terrain data and a more dynamic clustering algorithm. This method is evaluated against Sentinel-2 derived snow cover maps, and the authors found improved wet snow identification performance when compared to the Nagler et al., 2016 method. The authors apply their method over the Karakoram, a challenging domain for wet snow identification, to analyze snowmelt dynamics from 2017 to 2021.

I appreciate the authors focus on improving SAR-based wet snow mapping–there is still a lot of room for our community to improve these methods, and this research does a nice job focusing on two important considerations of these algorithms: the incorporation of terrain information and more complex clustering methods. In this paper, I particularly enjoyed the beautiful plots (especially figures 5 and 8!) and the application of this method for time series analysis over multiple melt seasons. This was really great to see, thanks for yall’s hard work!

However, I believe the authors should address some important methodological concerns and should also have a chance to improve the overall clarity of the paper. In particular, I think the newly proposed metrics need to be given more motivation and context, especially when it comes to the physical interpretation of different mathematical and methodological operations. I am particularly concerned with the topographic snow index and the implication of its pixelwise multiplication with the wet snow index that yields the integrated snow index. Additionally, some of the analysis and discussion could use some more consideration. Finally, in terms of writing, while I enjoyed the style, I think this paper might benefit from another couple of skims to address issues related to clarity, verb tenses, unnecessary initialisms, misspellings, etc. I’ve provided more detailed comments and grouped them by subject below. For these reasons, I recommend revisions before publication.

Specific comments

Methods

Line 128: Do you follow the full Nagler et al., 2016 method, or just the steps listed in your section 3.1? Might want to think about the implications of evaluating against Rc instead of the complete Nagler method.

Line 133: Maybe find some way to motivate the introduction of Rc, or at least give a more thorough explanation of what it is and why we are using it, and why it might be better than VV or VH alone. Perhaps consider adding a line about why a weighting factor W can be helpful in the first place… local incidence angle (LIA) dependence of wet snow detection, etc.

Line 137-139 / 153-154: The wet snow index is a bit unclear to me. Why is Rc insufficient? What is WSI exactly, and what are you claiming it represents? It is not clear to me why you cap the WSI to 10… if WSI were capped at 1, given two Rc values, I see how the absolute differences between their WSI values would be scaled, but don't the relative distances between their two WSI values remain the same? I guess I don't follow how this allows larger Rc variations.

Line 155-157: I think you should motivate why the GMM is necessary…GMM adaptively determines k based on cluster separation, but what does that equate to in practice?

Line 160-172: How do you control for the different wet snow backscatter response at different LIAs / polarizations? Rc combines VV and VH as a function of LIA, which gets at whether VV or VH has more wet snow detection capability at a given LIA. Does using Rc as the basis for WSI muddy the water in some way because each pixel is measuring a different proportion of VV and VH data?

Line 160 / 174-176: I am concerned with TSI and its implications on SI / your final wet snow classification. I understand your scaling intent, but I think you may be biasing your wet snow detection across different topographic bins. If my understanding is correct, you calculate WSI at each pixel for an entire scene, then group pixels into the topographic bins, and then take the median WSI in each bin which gives you TSI. Then you get pixelwise SI values by multiplying WSI by TSI. Does this mean you are implicitly assuming something about the relative proportions of wet snow and dry / no snow in each bin? Consider two scenarios: for a lower elevation bin, assume 10% of pixels have wet snow in the summertime SAR image. The majority of the WSIs should be close to 0, and your TSI will likely be low. For those pixels in the bin that are indeed wet, their WSI value now gets multiplied by a very low TSI, and now has a much greater chance of going undetected as wet due to a low SI. Now instead consider the case for a much higher elevation bin, in which the summertime SAR image shows 80% of pixels containing wet snow. The TSI will likely be closer to 10, and so even a pixel with a WSI of 1.5 will end up with an SI of 15. Given how sharp the TSI changes in Figure 4, this could be concerning because it seems like TSI forces pixels towards the classification of the majority of pixels in their topographic bin, potentially overriding each pixel's individual backscatter response. I believe this can be seen in Figure 7… notice how below 5000m, you almost always are underpredicting snow cover relative to S2 snow cover. This consistent low bias / false negatives at lower elevations would be expected with the issue mentioned above. *I would really like to see a plot of F1 score or other classification metric aggregated by your TSI bins (same axes as figure 4)--this could reveal the influence of TSI on your classification performance*. To address this issue with minimal changes to your methodology (if you are truly confident in your method despite these concerns), you might consider some sort of figure that shows spatial maps of Rc, WSI, TSI, SI, SI classification, and S2 snow cover map all included, ideally all with histograms? So something similar to figure 5 but adding in WSI and TSI maps and histograms. I think this may help readers build intuition for WSI and TSI, and especially how combining these via multiplication into SI ultimately improves your classification.

Line 179-181: I'm confused on how 3.5 was chosen, it feels relatively arbitrary. Is there an analysis of different coefficients and how they affect the results? Does the coefficient vary across basins, and does it vary annually / based on summer image? If a claim of this paper is to be able to make snow detection algorithms more robust to different locations, will this cutoff have to be chosen dynamically?

Line 268-270: Hmmm, can you just scale to 365 like this? Is this a common practice? I would be concerned about sampling, I'm sure there might be a better way to quantify SMD, maybe day of (last day of wet snow - day of first wet snow)?

Interpretation of results

Table 2: The adaptive SI thresholds seem to be quite different for these three study sites that are relatively close to each other. It would be helpful to see more interpretation on this.

Line 203-206: This gets at two important limitations… it is possible at the date you select, not all snow pixels are wet, and even across scenes where snow is wet at all pixels, your choice of summer date likely influences how much liquid water is in the snowpack and therefore backscatter response (Baghdadi et al., 2000; Karbou et al., 2021). My guess is that the backscatter drop is more pronounced during certain portions of the melt season. Given this, I think it is important to see how your adaptive SI thresholds change with your choice of summer scene.

Line 211-213: It might be helpful to mention that the noisy patterns over the glaciers are harder to ascribe to the variables you list because of glacial movement. Not sure of the glacier speeds in this area, but it is possible that you are seeing large backscatter changes due to glacier movement that occurred between your winter scenes and summer scene.

Line 213-215: I'm not sure it's correct to claim SI reduces the noisy pattern because of the rescale to WSI, I think it's just the multiplication of TSI which is essentially smoothing the pixels in those particular bins, right?

Line 216: You could consider showing these distributions you mention, it would be really helpful to contextualize SI ranges.

Line 217-219: I'm not too sure you can say this is effective over glacier surfaces… you predict very little wet snow on glaciers, but wouldn't we expect the glacier surface to have a significant amount of wet snow or wet ice in the summer, which should significantly drop the backscatter and be classified as wet snow (even though technically it could be wet ice)? For SAR identification of glacier melt, I would check out Scher et al., 2021. I am concerned about this, especially because in 5c not a lot of glacier area in the insets seem to be identified with wet snow. I think the TSI plays a large role in reducing the SI in these locations (especially with the two slope bins). It may be worthwhile to consider removing glaciers from your analysis, due to these reasons and the fact that significant glacier motion has likely occurred between the winter and summer scenes, so the area in a pixel in your reference image is not the same area in the same pixel in your summer image.

Figure 8: Really pretty plot! For each elevation band, I'm guessing WSE is (wet snow pixels / total number of pixels), not (wet snow pixels / total number of snow pixels), right?

Line 245-288: It would be great to know how sensitive the WSE and SMD analysis is to the choice of your baseline winter composite and summer image. Do you apply this algorithm to one image and use those SI thresholds? Or do you do it separately for every image in the time series? If it is every image separately, it would be great to know how your WSI/TSI/SI distributions change, and how your SI threshold changes.

Clarity

Figure 1: Are the black boxes scene footprints? Maybe make this explicit, and if you keep the boxes, maybe label them or color code them with relative orbit information and add a legend? And I think your colorbar may be flipped?

Line 81: I'm not too sure what this sentence is getting at, perhaps reword?

Figure 4: Not sure if a red and blue diverging color map is most appropriate here. I feel like the white values don't play an especially important role (a value of ~5 for TSI doesn't seem particularly important), and the color map could cause confusion with the reader thinking it is the same quantity as Figure 5's Rc plot (though I think the red and blue color map for that Rc plot is great!).

Line 179: Clarify "...where 3.5 implied the condition applied to the TSI…"

Line 225: What percentage of your pixels were excluded, and why was 5500 m a.s.l. chosen?

Line 237: I would clarify what you mean by "...comparative sensitivity of the SAR signal to dry snow in both methods."

Figure 5: It is not clear where the S2 snow cover map is coming from. Is this output from the let-it-snow algorithm? If so, where is this ice/water class coming from? Also, it might be helpful to say in the caption that these are all three basins.

Line 289-291: Definitely a really neat approach, but maybe temper your claim of great improvement here, or provide the specific stats.

Line 301-304: I think this is a more fair interpretation of TSI! It should be helpful for understanding aggregate backscatter response of topographic bins, I'm not sure about the added use of using it as a scale factor for WSI.

Line 316-318: Provide citation

Line 324: You haven't previously talked about mitigating uncertainty, so I would avoid introducing this idea in the conclusion.

Line 324-325: I feel like the purpose/definition of TSI shifts around a bit in this paper. Is it supposed to take into account the influence of topography on snow presence or the influence of topography on the backscatter response of wet snow?

Technical corrections

Line 5: For the abstract, I would use "a" instead of "the" in front of both Wet Snow Index and Topographic Snow Index so it's clear to that these are metrics that you are introducing
Line 10-11: Remove "the" in between under and climate
Figure 1: "tree" -> "three"
Line 47: "inlucdes", also check tenses / plural of this line
Line 53: Remove "of"
Line 67: "meting" -> "melting"
Line 67: "watersheds" -> "watershed"
Line 69-72: Make verb tenses agree
Line 89: "snow melting changes" -> "snowmelt"
Line 108: "the" -> "a"
Line 116-118: unclear
Line 122: "backscattering intensity images" -> "backscatter images"
Line 123: "firstly" -> "first"
Line 131: add "is" before "the reference image"
Line 216-217: Check tenses
Line 218: "well" -> "good"
Line 221: Consider rewording "greatly false positives"
Table 3: "corresponded" -> "correspond"

Line 278: Consider “This trend” -> “This change”
Line 280: Maybe avoid “significant”, might be confused for an actual test of significance
Line 284: Remove “significant”
Line 305: “was” -> “were”
Line 306: Should there be a dash between the two aspects here?
Line 311: “Management” -> “management”
Line 312: Remove “been”
Line 319: Remove “significant”
Line 320: “observation” -> “observation record”
Line 325-326: Wording of this sentence is a bit confusing, consider rewriting and remove “significant” unless some sort of hypothesis testing was done.
Line 328-329: Remove “such as” since these were the only two variables analyzed in the paper.
Many lines: Check usage of initialisms (GMM, BOA, RMSE, MSE, WSI, SVM, RF, ML, TSI, etc). Often initialisms are introduced multiple times, and some initialisms are introduced and never used (or sometimes used once)
Many lines: Tenses are often inconsistently used, I would skim over to make sure they agree!

References

Baghdadi, N., Gauthier, Y., Bernier, M., & Fortin, J.-P. (2000). Potential and limitations of RADARSAT SAR data for wet snow monitoring. *IEEE Transactions on Geoscience and Remote Sensing*, *38*(1), 316–320. IEEE Transactions on Geoscience and Remote Sensing. https://doi.org/10.1109/36.823925

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Scher, C., Steiner, N. C., & McDonald, K. C. (2021). Mapping seasonal glacier melt across the Hindu Kush Himalaya with time series synthetic aperture radar (SAR). *The Cryosphere*, *15*(9), 4465–4482. https://doi.org/10.5194/tc-15-4465-2021