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The Cryosphere
Discussions

Interactive comment on "Mapping seasonal glacier melt across the Hindu Kush Himalaya with time series SAR" *by* Corey Scher et al.

Corey Scher et al.

nsteiner@ccny.cuny.edu

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Author Response to Reviewers 2

This paper provides an application of C-Band Sentinel-1 imagery to map seasonal melting along the Hindu Kush Himalaya (HKH) for the period 2017-2019. The paper provides spatiotemporal time series of several metrics, as for example freeze onset, for the region. The authors detected horizontal (at the regional scale) and vertical differences that they assess resemble well established HKH glacio-climatic regimes while providing insights on scarcely described dynamics, such as the occurrence of melt signals at very high elevations. My

general assessment is that the paper is straight: it describes a method that naturally connects with the results. The application by itself is of great value in other regions for monitoring as well as for model validation, given the high resolution of the imagery and the mission's expected length of 7 years. After reading the paper several times, however, I am not fully convinced the paper fits in this journal in its present form instead of a more remote sensing oriented journal. I think it lacks a more in depth glacier-climate interpretation. Below I include some comments that argue my assessment.

General Response
We thank the Referee for their close consideration of our work. We have completed major revisions to the manuscript to aggregate melt retrievals by clearly articulated glacio-climate regions from Bolch, et al. (2019) and investigate high elevation melting signals with surface energy balance models of glacier melt and in situ automatic weather station (AWS) data from Matthews, et al. (2020) (Bolch, Shea et al. 2019, Matthews, Perry et al. 2020).
We have re-constructed summary statistics of melt retrievals across glacio-climatic sub-regions delineated in Bolch, et al. (2019) in order to create a baseline measurement of what will hopefully become a climatic record over the mission lifespan of Sentinel-1. We went through each figure in the manuscript and replotted data based on the delineations of sub-regions characterized by Bolch et al. (2019). We have included all of these figures in our author response (AR) (please see Author Response to Referee 1) and believe that summary statistics by recently defined glacio-climate subregions helps to illustrate that Sentinel-1 melt retrievals are able to capture heterogeneities in melt characteristics across glaciers and glacio-climate subregions conducive to support glacio- and meteo-climate studies across the HMA. We contend that Sentinel-1 snowmelt retrievals across a three-year record provide an important baseline measurement of melting within regions of High Mountain Asia (HMA). We have modified the discussion accordingly, and propose a brief section

comparing relative melt durations with post-2000 mass balance characteristics across HMA sub-regions tabulated in Bolch, et al (2019).

We hope that the development of an observational dataset on the glacier surface energy balance will provide means of model calibration and validation; supporting research into HMA weather, climate, and hydrology. Much of the remote sensing methodology used in our approach is very well established in prior research. It is applied here to address open questions in cryospheric sciences, for example, constraining the glacier surface energy balance. We provide detailed responses below.

General comments

(1) The paper provides a detailed description of the methods but to me the section "Results and Discussion" lacks discussion on glacier-climate regimes. The authors claim that melt dynamics coincide with different HKH glacio-climatic regimes. As far as I can tell, these regions correspond to operational inventory subdivisions (for CGI or RGI) and do not necessarily correspond to boundaries between well-defined glacier regimes. Perhaps just rearranging the narrative will clarify this, but I would suggest to expand the discussion including some reasons why these areas show these differences or whether other regional differentiation is possible.

AR 22: We have undertaken a re-analysis of our results to summarize by glacio-climatic subregions from Bolch, et al. (2019). For the purposes of elucidating differences between glacio-climatic regions of the HMA, we re-plotted all figures to resemble regions delineated in Bolch et al. (2019) and have included them in Figures AR1, AR2, AR3, and AR4. We have similarly proposed modifying the "Results and Discussion" section to incorporate comments and concerns from yourself and Referee 1. The re-worked "Discussion and Conclusion" section is detailed in AR6 to Referee 1. We suggest appending the "Discussion and Conclusion" section detailed in AR6 with a

brief discussion on glacio-climate regions, mass wasting, and Sentinel melt retrievals, by appending the following section to our discussion:

Melt Retrievals and Glacio-Climate Regimes

The three-year record of Sentinel-1 SAR retrievals of glacier melt status represent a baseline measurement for the HMA. The summary melt statistics are aggregated over glacio-climate subregions in a comparison between melt retrievals and subregional estimates of glacier mass wasting (Bolch, et al. 2019). Overall, the HMA subregions with the most rapid mass wasting between 2000-2010 tabulated in Bolch, et al. (2019) (Eastern Himalaya, Hengduan Shan, Nyainquntanglha) exhibit the greatest number of melt days on average in 2017-2019 from Sentinel-1 melt retrievals. Subregions with slower mass wasting, in steady state, or with mass slight gain (Eastern Hindu Kush, Western Pamir, Karakoram, Tibetan Interior) show on average one month less of melt duration relative to regions with accelerated mass wasting. Interestingly, the Gangdise and Eastern Tibetan Mountains subregions, both with some of the higher post-2000 rates of glacier wasting in the HMA, show annual melt durations of roughly 3 and 4 months respectively, which appears more characteristic of western regions of slower mass wasting. Although Sentinel-1 retrievals of glacier melt status for three calendar years does not make-up a climatic record, we observe that between 2017-2019 there was on average less duration of melting in regions where in situ data and climate models indicate that frozen winter precipitation contributes to glacier accumulation despite warming global climate (Karakoram, Hindu Kush, Eastern Pamir, Western Himalaya) (Palazzi, Von Hardenberg et al. 2013, Kapnick, Delworth et al. 2014, Kääb, Treichler et al. 2015). We interpret shorter duration of annual melt days in the western regions of the HMA as a potential indicator of the "Karakoram Anomaly" reflected in the Sentinel-1 data record. Because the meteoclimatic drivers of the Karakoram Anomaly are still under debate (Farinotti, Immerzeel et al. 2020), Sentinel-1 retrievals of melt duration might be useful for interrogating meteoclimatic drivers of heterogeneity in glacier wasting dynamics across the HMA.

(2) Along the same lines, I believe the paper needs to add some sort of longer climatic discussion. Currently, lines 418-419 present a reworked version of 131-132. Is it possible for the authors to include some literature or analysis on the possible weather patterns that would explain the findings for the studied period? Perhaps looking at re-analysis fields for the MO and/or FO days will allow the authors to further elaborate on the findings. In addition, this can be helpful in trying to explain the high elevation melting events.
AR 23: We have investigated high elevation melting events using in situ data from Matthews, et al. (2020). After analyzing surface energy balance (SEB) results and in situ AWS stations (detailed in AR3), we have added discussion on the relevance of surface air temperature to the retrieval of the presence of liquid water within a snow or firn matrix. We propose that, for the scope of this paper, we present relevant observational data and a methodology for operationalizing retrieval of these data, alongside an example of how these data can be used to constrain SEB model results from in situ AWS data. We seek to support further research into the climate and weather patterns governing glacier mass balance in the HKH but feel that broadening this discussion in too much detail is beyond the scope of the results that we are able to provide; including reanalysis temperature data, as it is likely to poorly constrain or describe melt dynamics at due to the SEB controls active at elevations greater than the 0°C isotherm.

(3) In line 374 I'm not sure if longwave energy is what drives melt at these elevations. I think that the Everest climate data is showing that the large input of shortwave energy and monsoonal activity allow for the glacier surface to reach melting temperatures despite below freezing air temperatures. Since the authors are seen this possible effect, I think there is a great opportunity to test whether some of the high-elevation melt events coincide with the conditions depicted in Matthews et al (2020), by looking at weather conditions around those

dates.
AR 24: We agree, the language in this section is misleading. We do not contend that longwave energy alone drives melting at high elevations. To better understand high elevation melting we have analyzed data from Matthews, et al (2020) in terms of air temperature and SEB characterizations of glacier melt. A new figure is included alongside an accompanying discussion as detailed in AR3 to Referee 1.

(4) L184: Can you provide more details on the methods included in the computing
AR 25: We will broaden our discussion on the computing method as detailed in AR1 to Referee 1.

(5) L206: Is it possible to attempt a sensitivity analysis of the b value? Could the choice of the b value be partially contributing to uncertainty in the results?
AR 26: The b value is a commonly used threshold to separate dry snow from melting snow. Since we lack widespread in situ measurements of surface melting, it is difficult to determine the optimal threshold in a systematic way. Compared to previous studies, 3 dB is the most common and most conservative of thresholds used in previous studies. To the best of our knowledge all previous studies have chosen a threshold between 1 and 3 dB.

(6) Figure 3: I think the validation data is insufficient to make general statements on the method for the whole region. I wonder if it is possible to make a comparison relative to reanalysis air temperature at equivalent geopotential levels for a larger region.
AR 27: It would be interesting to compare air temperatures from reanalysis fields however, we do not think these are appropriate to use in a validation effort. First, there is a large resolution mismatch between available reanalysis data and S1-SAR

observations. Further, downscaling estimates of snowmelt are prone to large errors especially in topographically complex terrain (Baldo and Margulis 2017). There is also a well-known cold bias in most reanalysis products (Margulis, Liu et al. 2019). Lastly, the basis of our observational record is the radar response to liquid water, and the radar has no direct temperature dependence. We show in Figure AR1 to Referee 1 that backscatter can be a more accurate indicator of melting than temperature alone.
As discussed in our response to Reviewer 1, to address measurement uncertainty to the best of our ability we have added a comparison of in situ data as presented in Matthews et al (2020) and detailed in AR3.

(7) Figure 5: wouldn't it be more straightforward to leave elevations in the y axis and DOY in the x axis? Also, although the spread of DOY do not seem to be statistically different there is an interesting divergence between about 5700 to 6700, where Karakoram and Western Himalaya tend to cluster differently relative to Central and Eastern Himalaya. Perhaps studying some air temperature and humidity dynamics at the corresponding geopotential levels will allow the authors to interpret that situation.
AR 28: We have switched the axes on Figure 5 and also recalculated melt statistics using glacio-climate regions delineated in Bolch, et al. (2019). Melt retrievals show interesting separation when calculated over these subregions. We have proposed to add analysis and discussion on air temperature and SEB dynamics as detailed in AR3.

References for Author Response to Referee 2

Baldo, E. and S. A. Margulis (2017). "Implementation of a physiographic complexityâĂŘbased multiresolution snow modeling scheme." Water Resources Research 53(5): 3680-3694.

Bolch, T., J. M. Shea, S. Liu, F. M. Azam, Y. Gao, S. Gruber, W. W. Immerzeel, A. Kulkarni, H. Li and A. A. Tahir (2019). Status and change of the cryosphere in the Extended Hindu Kush Himalaya Region. The Hindu Kush Himalaya Assessment, Springer: 209-255.

Farinotti, D., W. W. Immerzeel, R. J. de Kok, D. J. Quincey and A. Dehecq (2020). "Manifestations and mechanisms of the Karakoram glacier Anomaly." Nature Geoscience 13(1): 8-16.

Kääb, A., D. Treichler, C. Nuth and E. Berthier (2015). "Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya." Cryosphere 9(2).

Kapnick, S. B., T. L. Delworth, M. Ashfaq, S. Malyshev and P. C. Milly (2014). "Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle." Nature Geoscience 7(11): 834.

Margulis, S. A., Y. Liu and E. Baldo (2019). "A joint Landsat-and MODIS-based reanalysis approach for midlatitude montane seasonal snow characterization." Frontiers in Earth Science 7: 272.

Matthews, T., L. B. Perry, I. Koch, D. Aryal, A. Khadka, D. Shrestha, K. Abernathy, A. Elmore, A. Seimon and A. Tait (2020). "Going to Extremes: Installing the World's Highest Weather Stations on Mount Everest." Bulletin of the American Meteorological Society.

Palazzi, E., J. Von Hardenberg and A. Provenzale (2013). "Precipitation in the HinduâĂŘKush Karakoram Himalaya: observations and future scenarios." Journal of Geophysical Research: Atmospheres 118(1): 85-100.

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