Community comment 4 - Nicholas Steiner

[CC4-1] As a contribution to this discussion, I would like to submit some observations from remote sensing that may aid in interpretation of annual surface melting from modeling in Brun et al. (2002). In Scher et al. (2021) we created a record of surface melting over glaciers in the Himalayas from a time series Sentinel-1 synthetic aperture radar (S1-SAR). Melt is detected where annual backscatter is reduced as liquid surface water obscures the radar scattering from the glacier interior, resulting in a marked reduction in backscatter. For the South Col glacier, we observe radar signatures that indicate surface melting is occurring in 2019 over areas of exposed ice in the southern extent of the glacier (Figure 1, attached). From time series S1-SAR, we observe continuous indications of surface melting from June 26, 2019, until October 6, 2019, with approximately biweekly repeat observations during this period. Since seasonal snow over areas that are exposed on an interannual basis are not deep enough to contribute substantially to radar scattering, we infer that the melting signal originates from structural features (e.g., laying) in the glacier interior that result in enhanced backscatter during colder winter months. It is important to note that at C band frequencies backscatter is extremely sensitive to liquid water and it is difficult to differentiate very small amounts of surface melting from more extensive melting, and therefore our methodologies are not well suited to evaluate the amount of melting that may be occurring. For more details on our methodologies, please refer to Scher et al., (2021).

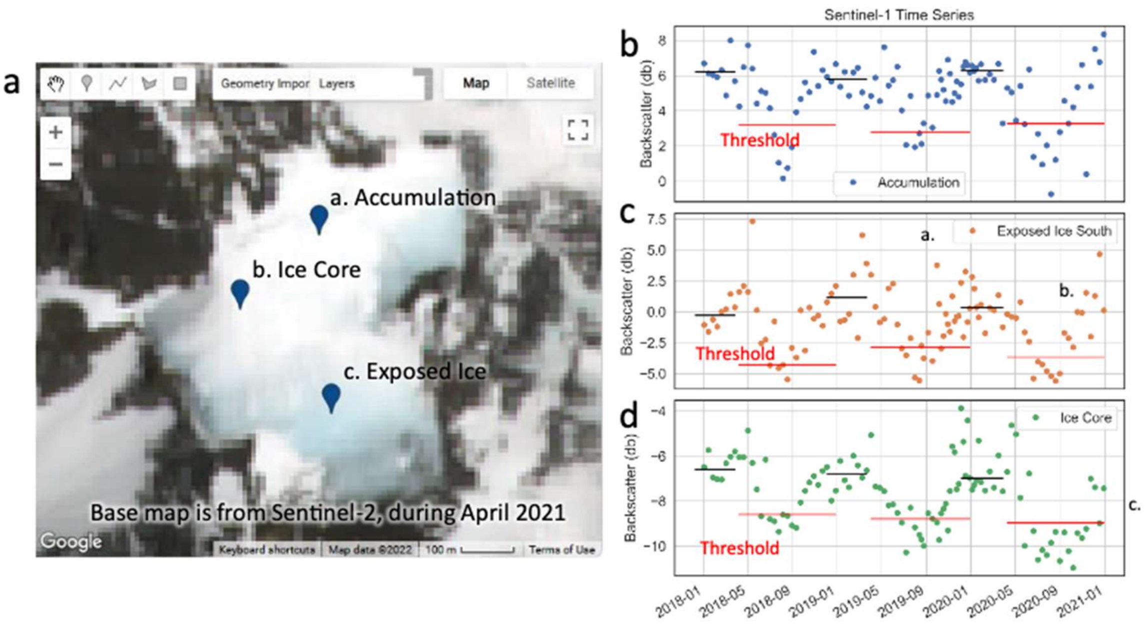


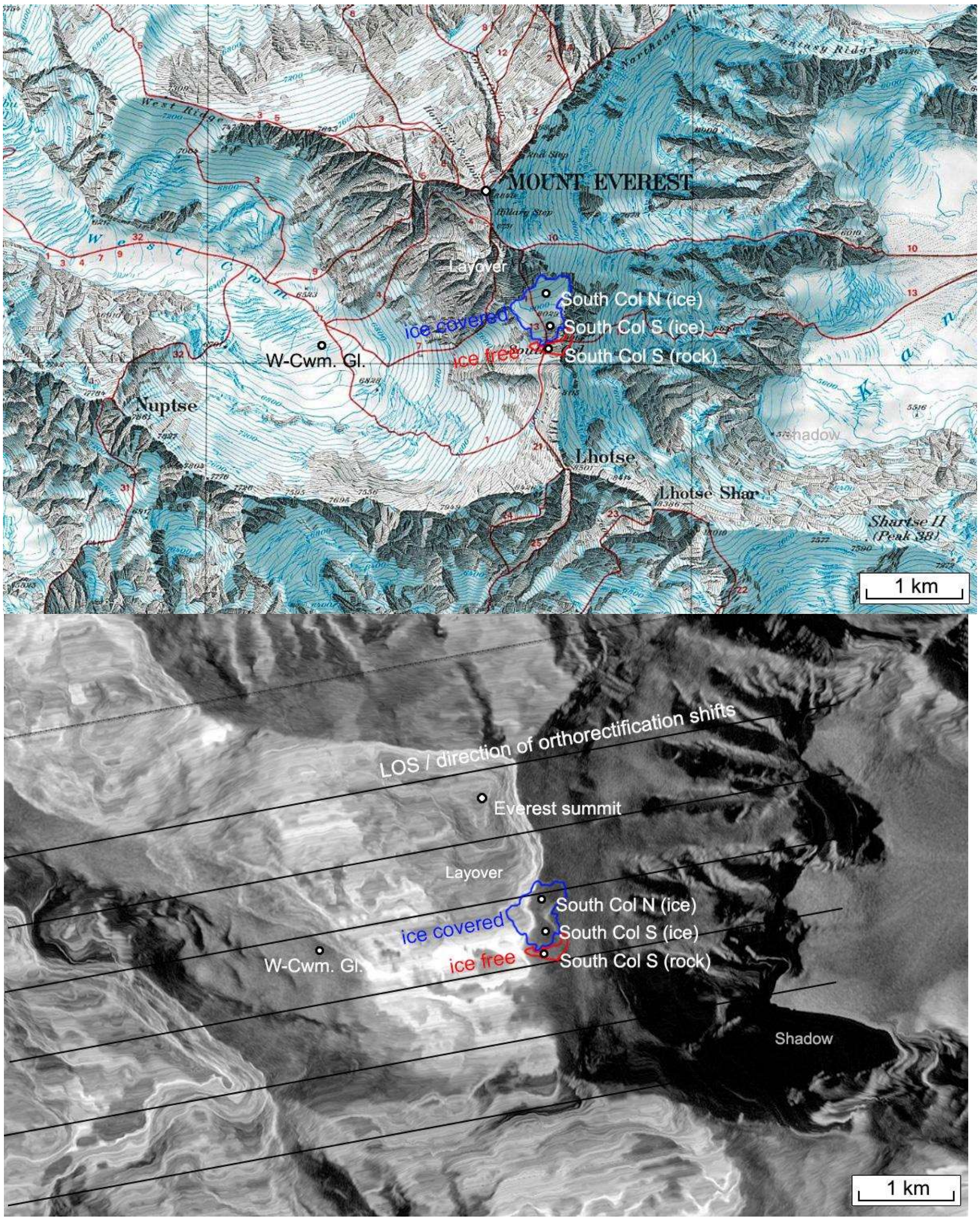
Figure 1 (a) A true-color map from Sentinel-2 during April 2021 of the South Col Glacier indicates areas of blue ice. Sentinel-1 time series synthetic aperture radar (SAR) from locations in (a) the accumulation zone, as designated by Brun et al., (2022) in Figure A6 indicate melting where observed backscatter is found to be ~3 db below (red lines) the winter mean (black-lines). For both the (c) exposed ice and the location of the (d) ice core site from Potocki et al. (2022) we find similar radar signatures that indicate surface melting.

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.

[ACC4-1] We would like to thank Nicholas Steiner who contributed to the general discussion. However, we want to raise some awareness about the direct interpretation of the results from Sentinel-1 (S1) backscatter data. We also note that the two dates provided by N. Steiner (2019-06-26 and 2019-10-06) correspond to acquisitions from orbit 121 descending where South Col is completely in radar layover. Therefore, we performed additional analysis of S1 data, which we show below.

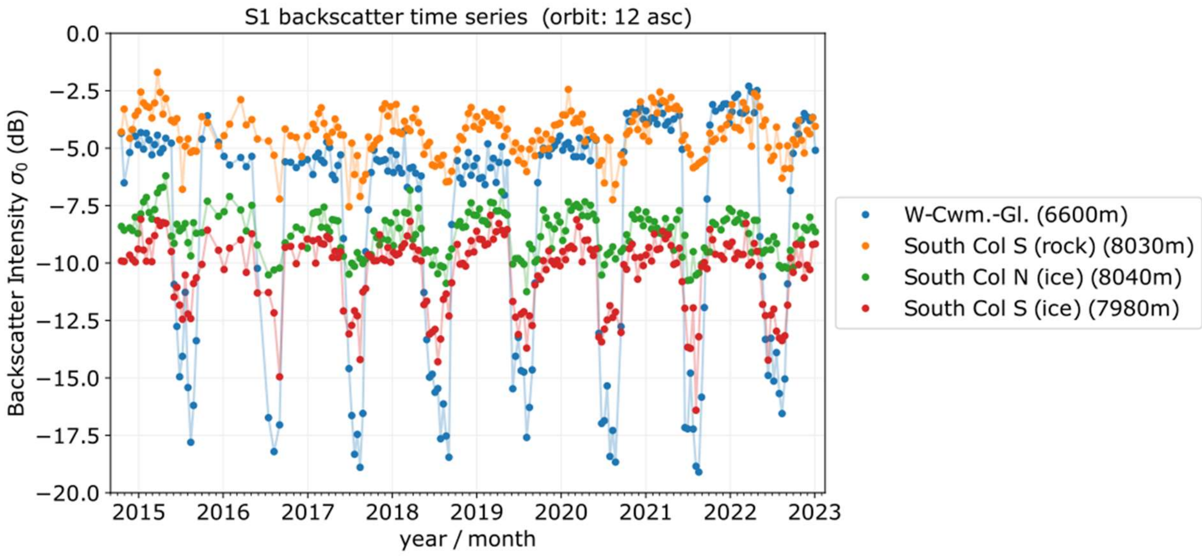
For the region of interest S1 radar data (IW, GRD) from two orbits are available (012 ascending and 121 descending). Due to the very steep topography, South Col is located completely in radar layover for orbit 121. Therefore, we analyzed data from orbit 012 where South Col is partially visible. For orbit 012, the approximate incidence angle relative to the ellipsoid is theta = 34°, the acquisition time: 12:13h UTC = 17:58 NPT local time. The data was preprocessed and downloaded from Google Earth Engine as orthorectified 8 bit grayscale data with 10m pixel spacing, VV polarization, and with sigma_0 ranging from -22 to +5 dB. Google orthorecitifies the data using the SRTM 30m DEM (https://developers.google.com/earth-engine/guides/sentinel1#sentinel-1-preprocessing).

Due to the steep topography, the SRTM can contain significant artifacts likely due to layover or phase unwrapping errors of the SRTM raw data. A comparison with the ALOS World 3D - 30 m DEM (AW3D30) shows that at South Col the SRTM is 30 to 90 meters higher than the AW3D30 while at other locations the difference is around zero (-+10m). The height errors of the SRTM cause horizontal shifts in the orthorectification in the direction of ground range (line-of-sight projected to the ground). At 34° incidence angle, a height error of Delta_h = +90 m corresponds to an horizontal shift of Delta_x = 90m/tan(theta) = 133 m to the west, therefore it is difficult to precisely geolocate S1 backscatter data as suggested by the figure provided by N. SteinerAs reprocessing the entire S1 data is beyond the scope, we rely on visual inspection and detection of features to accurately determine points for further analysis of the radar backscatter signal. Resp fig. 6 shows where in the radar image we identified the ice covered part of South Col (blue) and the ice free part (red).



Resp. Fig. 7: Location of points of interest on the swisstopo map (top panel) and on the S1 mean backscatter image (bottom)

From Venus and S2 data, we found that South Col Glacier is largely snow covered from June/July - Dec in 2016 - 2022. For an analysis of the backscatter time series we selected several points and averaged the backscatter intensity within a window of 90x90 meters: We selected two points in the ice-covered part of South Col (North and South of P. 8029), one point in the ice free / rock covered part of South Col, and one point on the West Cwm Glacier at an altitude of 6600m where the glacier is relatively flat and not strongly affected by ice avalanches. For all of these four points we plotted backscatter time series (Resp. Fig. 7).



Resp. Fig. 8: Time series of backscatter intensity for the locations identified in Resp. Fig. 7

We found that all points show seasonal variations in backscatter, very likely due to the presence of liquid water (we could exclude other reasons for backscatter reduction like refractive-index matching, smoothing of the surface, increase moisture in the atmosphere which all have weaker effects than 2-3 dB). There is a strong temporal correlation of the backscatter drop at West Cwm Glacier and at South Col, which we interpret as a strong indicator for the existence of wet snow/liquid water at South Col. However, the backscatter drops 12 - 15 dB on West Cwm Glacier where the snow is not only wet but also producing surface runoff. At an elevation of about 7000 m, S1 backscatter imagery indicates a transition from a strong reduction of backscatter in summer to a weaker, but still significant reduction, indicating a different kind/depth of snow or different liquid water content. Similarly, at South Col (~8040m), the backscatter drops only by 2 - 5 dB which is still significant compared to other effects affecting the backscatter. A backscatter drop is also observed for the ice-free/rock covered area at South Col, likely because the rock is covered by snow in summer.

From the S1 data, we conclude that wet snow/liquid water occurs at South Col, but we cannot quantify the amount of runoff.