3rd report for the Brief communication paper: Increased glacier mass loss in the Russian Arctic (2010-2017)

The Cryosphere Discuss. https://tc.copernicus.org/preprints/tc-2020-358/

This 3rd report refers to the revised manuscript **tc-2020-358-manuscript-version4.pdf** and **tc-2020-358-supplement-version4.pdf** from 21.09.2021

Green: Response of the authors to reviewer 2
Blue: Report #3

Comments to the authors

Thank you for responding one more time to my comments and the changes implemented for improving the work. I address here the critical issues remaining to be clarified.

*As suggested, we applied the approach using the two-way power penetration to estimate the surface penetration depth instead of the trigonometric function. To estimate the refraction angle into the glacier surface, we referred to a reference study on in-situ experiments in Antarctica (see below). Using this approach, the following paragraphs would replace the former Eq. 1 (L.70) in the revised manuscript):

"The vertical differences between heights of autumn and winter DEM acquisitions are converted into depths of signal penetration into the glacier volume using Eq. 1 following (Dall, 2007):

$$l = \frac{d_p}{\cos(\Theta_v)} \; ; \; d_p = 2 \times h_b \qquad \text{Eq. 1}$$

where l is the penetration length and Θ_v the refraction angle into the volume. d_p is the two-way power penetration depth and can be approximated by two times the vertical elevation bias h_b (Dall, 2007). To derive the refraction angle (Θ_v), Eq. 2 (Snell´s law) is applied:

$$\sin(\Theta_v) = n_1 \times \frac{\sin(\Theta_v)}{n_2} \qquad \text{Eq. 2}$$

where Θ_l is the local incidence angle, n_1 the refractive index of air (1.000293) and n_2 the refractive index of glacier ice. For the permittivity of ice, various values have been reported in literature (Rasmussen, 1986; Dowdeswell and Evans, 2004). In general, the refractive index of ice increases with depths due to changes in density. Therefore, we refer to a detailed in-situ study on refraction measurements from the ice surface down to depths of 150m in Antarctica (Kravchenko et al., 2004). For glacier ice close to the surface (0 to -40 m depth), they found values between ~1.3 and ~1.5 as index of refraction. Thus, we apply a refractive index of ice (n_2) of 1.4 as the approximate permittivity of ice close to the glacier surface."

I would have preferred a revision in the manuscript directly to avoid confusion. The change of Eq.1 after (Dall, 2007) is welcome. In this paper the vertical penetration bias (h_b) is approximately the two-way power penetration depth (dp2) in the case of a small penetration compared to the height of ambiguity (eq. 13 in (Dall, 2007)). With dp the **one-way** power penetration depth is denoted.

But since you already have an observed height difference I suggest to derive the correction directly. In the manuscript dp is once defined as depth of penetration into the volume (line 61) and below (line 68) as penetration bias. These are not the same. In this case I guess EQ2 refers to the penetration related elevation bias h_b.

In Author's response Eq.2 right: sin Θ_l

But you don't need to apply Snell's law if the penetration is defined as vertical. If yes, please explain. Besides Kravchenko et al. report on measurements of the dielectric permittivity on the South Pole, with a density profile of cold polar firn, very different from that of the percolation zone of Arctic glaciers. The real part of permittivity of dry snow and firn can be computed from the density with a slightly non-linear relation (Ulaby and Long, 2014). Typical density profiles from the percolation zone of Artic glaciers have been reported in several papers (e.g. for Svalbard by Marchenko et al., 2017).

We also recalculated the signal penetration corrected elevation & mass change for Novaya Zemlya with this approach but the results are almost exactly the same as in the original version (original $\Delta h/\Delta t$ = -0.643 m/a and new $\Delta h/\Delta t$ = -0.644 m/a). The only significant change would be the estimated average vertical offset (3.5 m instead of 2.13 m).
However, we are not sure if this approach improves the accuracy of the estimate. The model presented by (Dall, 2007) assumes an infinite volume, i.e. the microwave signal is not scattered by any layer below the surface (volume scattering). While this might be the case for some glacier areas on Novaya Zemlya with rather high vertical offsets, it is not unlikely that there is a scattering layer below the actual surface (e.g. melt/refrezzing of a previous summer) for glacier areas with smaller vertical differences. For those areas, the new approach could overestimate the penetration depth and produce a rather high average penetration depth for all September acquisitions.
For those reasons, we did not include the two-way power penetration estimate into the revisedmanuscript yet, but we would be very interested to hear the reviewer´s opinion regarding those concerns.

EQ2 (line 70) should refer to the Δh_{W-A}.(or h_b) A plot of its altitude dependence over the overlapping areas (red dots in Figure S2a) would be crucial to understand how this regression was derived. The regressions shown in Fig 1c and Fig 1d are not explained at all. Hard to understand how they contribute to EQ2.

"We did not adjust for differences in incidence angle or effective baseline because the viewing geometries of the majority of the used SAR acquisitions are rather similar (Table S2). For 99% of the glacierized area ofNovaya Zemlya, the difference in incidence angles is not larger than 2° (39.3° - 41.3°) while for 93% ofarea the average baseline is 91.9 m (87.8 m – 95.4 m)."

Accepted.

“It is noteworthy, that the applied regional correction scheme can introduce a larger uncertainty at a local glacier scale caused by different surface and backscatter conditions between the specific TanDEM-X acquisitions (Fig. S2b). However, due to the limited extent of overlapping glacier areas (Fig. S2a), it is not possible to derive a date-specific intensity correction foreach DEM strip. Thus, the applied linear model does rather represent an average difference in surfacepenetration depth between autumn and winter SAR data.”

Accepted.

*The intensity images are created using the Gamma remote sensing software environment (Werner et al., 2000). The radiometric calibration of the amplitude to σ0 values is automatically performed by the conversion algorithm from the CoSSC to the Gamma data format (using the metadata of the CoSSC data product). The respective algorithms are part of the interferometry (ISP) module and described in the *Interferometric SAR Processor – ISP user´s guide* (GAMMA Interferometric SAR Processor (ISP), 2021) in section 2.2.7 (TerraSAR-X & TanDEM-X data read algorithms) and 2.4.5 (radiometric calibration procedure). A link to this user guide is provided in the reference list.

Still the backscattering values used for the signal penetration (Fig 1c and Fig 1d) are going down to -27 dB. The noise level (NESZ) for the beams around 37-41 deg incidence is around -24 dB. It is annotated in each CoSSC product. This questions additionally EQ2.

*Concerning the incidence angle, we revised Table S2 following the suggestions (see respective comment below) and extended the methods section (see second comment).
Accepted.

*The hypsometric bars shown in Fig. 2 refer to the normalized median absolute deviation of Δh/Δt measurements on glacier areas within each elevation bin. Therefore, the bars are largest a low elevations because the spread of measured Δh/Δt values is large due to the presence of strong thinning glacier termini. At high altitudes, the range of measured Δh/Δt values is in general much smaller (see also Δh/Δt maps of Fig.2) and thereby also the bar. We extended the caption of Fig. 2 because the description of the shown bars was missing. Regarding the geodetic error, we did not calculate a mass change error for each elevation bin but for the entire region (based on the mean regional elevation change and respective uncertainty).

The errors in dh/dt [m/yr] related to vertical co-registration do not depend on the magnitude of retrieved dh/dt, but on the uncertainty in co-registration, independent of the magnitude. Even zero dh/dt has the same error in respect to vertical co-registration. For the higher elevation zones (firn areas) where penetration-related errors are added, the error in the elevation change rate dh/dt [m/yr] should by higher in the firn areas than in ice areas of glaciers. Fig. 2 d to f: Please explain the term “normalized median absolute deviation of elevation change measurements of each elevation bin”. An equation would be helpful.

*Regarding to Eq. 1 (Supplement), unfortunately we do not quite understand the question referring to the mass change and elevation change uncertainty: The first term of the sum is the ratio between the Δh/Δt uncertainty ($\delta_{\Delta h/\Delta t}$) and the mean (glacier) Δh/Δt estimate. While the Δh/Δt estimate is derived on glacierized areas, the Δh/Δt uncertainty ($\delta_{\Delta h/\Delta t}$) mainly indicates the potentially remaining offsets on non-glacier areas after the co-registration (and also other sources of uncertainty, Supplement Eq.2). If Δh/Δt would be very small (and thereby also ΔM/Δt), the uncertainty of ΔM/Δt could still be relatively high if $\delta_{\Delta h/\Delta t}$ (off-ice) is high compared to Δh/Δt (on-ice). For example, the measured elevation change rate is rather small but there are a lot of artificial elevation offsets remaining after the co-registration. In this case $\delta_{\Delta M/\Delta t}$ would be high compared to ΔM/Δt.

Accepted. For Eq. 1 (Supplement) there was some misunderstanding because of the same symbol (delta) used for relative error (right hand side) and absolute error (left hand side). The error estimate refers to the total change of mass over an extended area (though not defined; should be explained). There is one (rather unlikely case), when the equation is wrong: if the retrieved Δh/Δt is exactly zero. According to Eq. 1 this yields zero error for the mass change.

*Fig. 1a shows a subset of backscatter values (5000 random samples) because otherwise the figure would be too busy. The acquisitions of December 2016 cover only a very small fraction of the Novaya Zemlya ice cap (~10 km²). For this reason, there are only very few December datapoints visible and the mean backscatter was only calculated and plotted for the lowest elevation bin. The mean value is almost the same as for October 2016 (triangle) and therefore difficult to identify in the figure.
Now I can see it. Thanks for the explanation!

*We changed Table S2 and included only one row per TanDEM-X acquisition instead of each CoSSC frame. The terminology was adjusted and the new columns include now, as suggested, acquisition date, acquisition start time, active satellite, orbit direction, relative orbit, strip length (number of CoSSC frames), effective baseline, height of ambiguity and incidence angle.
Accepted.

References:

Dall, J.: InSAR elevation bias caused by penetration into uniform volumes, IEEE Trans. Geosci. Remote Sens., 45, 2319–2324, 2007

Ulaby, Fawwaz & Long, David & Blackwell, William & Elachi, Charles & Fung, Adrian & Ruf, Christopher & Sarabandi, K. & Zyl, Jakob & Zebker, Howard. (2014). Microwave Radar and Radiometric Remote Sensing.

MARCHENKO, S., POHJOLA, V., PETTERSSON, R., VAN PELT, W., VEGA, C., MACHGUTH, H., . . . ISAKSSON, E. (2017). A plot-scale study of firn stratigraphy at Lomonosovfonna, Svalbard, using ice cores, borehole video and GPR surveys in 2012–14. Journal of Glaciology, 63(237), 67-78. doi:10.1017/jog.2016.118