Brief communication: IncreasedAccelerated glacier mass loss in the Russian Arctic (2010-2017)

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Abstract. Glaciers in the Russian High Arctic have been subject to extensive atmospheric warming due to global climate change, yet their contribution to sea level rise has been relatively small over the past decades. Here we show surface elevation change measurements and geodetic mass balances of 93% of all glacierized areas of Novaya Zemlya, Severnaya Zemlya and Franz Josef Land using interferometric synthetic aperture radar measurements taken between 2010 and 2017. We calculate an overall mass loss rate of -23±65 Gt a^{-1}, corresponding to a sea level rise contribution of 0.06±0.021 mm a^{-1}. Compared to measurements prior to 2010, mass loss of glaciers on the Russian archipelagos has doubled in recent years.

1 Introduction

The Arctic has undergone large environmental changes due to polar climate changeincreases in temperature and humidity (Box et al., 2019)., and aAn increase in glacier mass loss has been observed in many polar regions (Morris et al., 2020; Zheng et al., 2018; Ciracì et al., 2020). The Russian High Arctic, including the archipelagos Novaya Zemlya, Severnaya Zemlya and Franz Josef Land, is one of these regions. Despite a glacierized area of ~52,000 km², in-situ observations of glacier mass change are sparse. Previous regionwide assessments were mostly limited to the early 21st century and based on gravimetry (Gardner et al., 2013; Jacob et al., 2012; Matsuo and Heki, 2013; Wouters et al., 2019) and altimetry (Ciracì et al., 2018; Moholdt et al., 2012). Most of these studies show mass change rates ranging from -5 to -10 Gt a^{-1}. However, both methods have limitations: altimetry requires interpolation while uncertainties of the gravimetric approach might arise from the scattered ice caps and various corrections related to surrounding oceans, surface hydrology and glacial isostatic adjustment (GIA)surrounding ocean. In this study we have measured surface elevation changes of most Russian Arctic glaciers from digital elevation models (DEM) to derive geodetic mass changes between 2010 and 2017. We use synthetic aperture radar (SAR) DEMs of the TanDEM-X satellites which are independent from cloud cover. Additionally, we apply a correction for differences in SAR penetration depth due to temporal offsets between acquisitions based on backscatter intensity.temporal offsets between acquisitions to account for varying SAR penetration.

2 Data & methods

Glacier elevation change rates are calculated by comparing DEMs of the TerraSAR-X add-on for Digital Elevation Measurement mission (TanDEM-X), operated by the German Aerospace Center and Astrium Defence and Space. For the Russian Arctic, TanDEM-X acquisitions of winter 2010/11 (Dec-Feb, Apr) and autumn/winter 2016/17 (Sep-Feb) are available.

2.1 Glacier elevation & mass change

Glacier elevation change rates are calculated by comparing DEMs of the TerraSAR-X add-on for Digital Elevation Measurement mission (TanDEM-X), operated by the German Aerospace Center and Astrium Defence and Space. For the Russian Arctic, TanDEM-X acquisitions of winter 2010/11 (Dec-Feb, Apr) and autumn/winter 2016/17 (Sep-Feb) are available. Elevation models are derived from TanDEM-X Co-registered Single look Slant range Complex (CoSSC) data, closely following the workflow of Braun et al. (2019) and Seehaus et al. (2019). A detailed description of the interferometric DEM generation, co-registration and uncertainty assessment is provided in the supplement. Eventually, the co-registered TanDEM-X DEMs are merged to create two elevation mosaics of winter 2010/11 and 2016/17 and differenced to derive glacier elevation and mass change rates based on glacier areas of the Randolph Glacier Inventory (Pfeffer et al., 2014).

Interferometric elevation models are created from TanDEM-X CoSSC tiles. Compared with previous studies (Braun et al., 2019; Sommer et al., 2020), we use the TanDEM-X Global DEM (German Aerospace Center (DLR), 2018) as a reference surface. Due to the unknown pixel acquisition dates, the Global DEM cannot be used directly to compute change rates. However, it provides a reliable reference surface without data voids for the interferometric processing of date-specific TanDEM-X acquisitions. To exclude ocean areas and water bodies from the processing, we use the OpenStreetMap coastline and the HydroLAKES dataset (Messager et al., 2016). DEMs are created and co-registered as described by (Braun et al., 2019). The 2010/11 acquisitions are co-registered to the Global DEM while the 2016/17 DEMs are referenced to the 2010/11 mosaic. Thereafter, the mosaics are differenced and change rates are calculated using the respective dates of each individual track (Seehaus et al., 2019). Data voids in the resulting elevation change map are filled by applying an altitude dependent elevation change function on each archipelago. Eventually, the elevation change measurements are converted to geodetic mass changes ($\Delta M/\Delta t$) based on glacier areas of the Randolph Glacier Inventory (Pfeffer et al., 2014) and two density scenarios (ρ) with a) 850±60 kg m^{-3} as recommended by a study on alpine glaciers (Huss, 2013) and b) 900±60 kg m^{-3} as an approximation of the density of ice. Possible changes in the density conversion scenarios (e.g. firn compaction) are not considered, since we do not have any quantitative information on this for the Russian Arctic. The resulting mass change does not include subaqueous ice melt nor calving as the geodetic approach can only resolve elevation change above sea-level.

2.2 X-band surface penetrationUncertainty assessment of glacier mass change

The interferometric TanDEM-X DEMs provide a high spatial resolution and almost complete coverage of the Russian Arctic archipelagos but can suffer from SAR signal penetration into the glacier surface. The depth of signal penetration is related to the prevailing glacier surface conditions at the time of the SAR acquisition. In general, SAR penetration is close to zero for melting snow surfaces and bare glacier ice and increases during dry and frozen conditions. X-band penetration depths of several meters have been observed in different regions (e.g. Millan et al., 2015; Zhao and Floricioiu, 2017; Abdullahi et al., 2018; Li et al., 2021). When comparing elevations of different TanDEM-X scenes the relative difference in penetration depths is determined by the acquisition dates and seasons. The TanDEM-X data used at most glacierized areas of the Russian Arctic archipelagos were acquired during winter 2010/11 (94% of total glacier area) and winter 2016/17 (83%) at temperatures well below zero degrees Celsius and frozen ice surfaces. It is likely that for those acquisitions the difference in X-band penetration depth is small as the SAR data was acquired in the same season and the presence of surface melt or liquid water is very unlikely in the Arctic winter months. However, for some glacier areas of Novaya Zemlya (35%) and Franz Josef Land (6%), SAR data from September 2016 had to be included to calculate elevation changes because there were no respective winter scenes available. Using those DEMs without further correction can bias the measured surface elevation change as seasonal changes in snow and ice of the glacier surface have significant impacts on the SAR penetration depth (Abdullahi et al., 2019).

The uncertainty analysis (Eq. 1) of the regional geodetic mass changes ($\delta_{\Delta M/\Delta t}$) considers uncertainties from the DEM differencing ($\delta_{\Delta h/\Delta t}$, including spatial autocorrelation, hypsometric gap-filling & SAR signal penetration), glacier outline errors (δ_S) and the volume to mass conversion with a constant density assumption (δ_p).

$$\delta_{\Delta M/\Delta t} = \sqrt{\left(\frac{\Delta M}{\Delta t}\right)^2 \times \left\{\left(\frac{\delta_{\Delta h/\Delta t}}{\frac{\Delta h}{\Delta t}}\right)^2 + \left(\frac{\delta_S}{S}\right)^2 + \left(\frac{\delta_p}{p}\right)^2\right\}} \quad (1)$$

To derive the relative vertical precision of the DEM difference ($\delta_{\Delta h/\Delta t}$), elevation changes outside glacier areas are aggregated to calculate glacier slope-weighted standard deviations based on 5° slope bins ($\sigma_{\Delta h/\Delta t\ AW}$, Table S 1). To account for spatial autocorrelation, we use an average lag distance (d_l) of 318 m, derived from semivariograms, and Eq. (2) following (Rolstad et al., 2009):

$$S_{cor} = d_l^2 \times \pi$$

$$\delta_{\Delta h/\Delta t} = \sqrt{\frac{S_{cor}}{5 \times S_G} \times \sigma_{\Delta h/\Delta t\ AW}} + s_{pen} \quad for\ S_G > S_{cor} \quad (2)$$

$$\delta_{\Delta h/\Delta t} = \sigma_{\Delta h/\Delta t\ AW} + s_{pen} \quad for\ S_G < S_{cor}$$

Scor is the correlation area and *SG* the glacier area multiplied by an empirical weighting factor of 5 (Rolstad et al., 2009).

To consistently account for a potential bias in glacier surface elevation due to SAR signal penetration on each archipelago, we integrate an approximate difference in penetration depth of 2 m over all glacier areas which were acquired during autumn 2016 (s_{pen}), based on an average penetration difference of 1.45 m which was found on Novaya Zemlya (see 2.3). Biases due to erroneous glacier areas (δS) are calculated with a scaling approach (Braun et al., 2019). The mass change uncertainty of the entire Russian Arctic is estimated as the quadratic sum of the regional errors (Dussaillant et al., 2019).

2.3 SAR backscatter intensity analysisDEM acquisition date correction of geodetic mass change

The SAR backscatter intensity depends on physical properties of the glacier ice, such as grain size and density, roughness and water content (Wessel et al., 2016), and has been used to estimate penetration depths by a number of studies (e.g. Abdullahi et al., 2018, 2019; Li et al., 2021). Fig. 1a shows the hypsometric backscatter distribution of TanDEM-X acquisitions between September 2016 and January 2017 on Novaya Zemlya. While average backscatter intensity of the October-January acquisitions shows similar patterns, a clear difference is observed for the September DEMs. At altitudes above ~400 m a.s.l., the September data show much higher backscatter values than the respective winter scenes, indicating different surface conditions at the acquisition times. To estimate the difference in penetration depth between the September 2016 and winter 2016/17 DEMs, we derive the measured elevation difference and respective backscatter intensity from overlapping glacier areas which were covered by the September as well as winter acquisitions. Those reference areas cover a total glacier area of ~2,500 km² and are equally distributed across the Novaya Zemlya ice cap (Fig. S2a). Using the local incidence angle and surface slope, the measured absolute vertical offsets between September and winter 2016/17 are converted to surface penetration depths according to EQ. 1.

$$d_p = \Delta h_{W-A} \times \frac{\cos\alpha}{\cos\varphi} \quad \text{EQ. 1}$$

Where d_p is the depth of surface penetration, Δh_{W-A} the height difference between Winter and Autumn (September) acquisition, α the glacier surface slope and φ the local incidence angle. Thereafter, d_p is aggregated and compared to altitude and backscatter intensity of the September acquisitions, respectively. As shown in Fig. 1c and Fig. 1d, the offset between the September and winter 2016/17 backscatter intensity increases above elevations of ~400 m a.s.l. while the difference in estimated signal penetration depth increases with higher backscatter intensities of the September acquisitions. Based on this relationship between penetration difference, backscatter intensity and altitude, a linear regression model can be created to estimate the penetration bias d_p (EQ. 2):

$$d_P = \beta_0 + \beta_1 \times Int \quad \text{EQ. 2}$$

Int is the backscatter intensity in decibel and β_0 and $\beta 1$ the regression coefficients. To fit d_p and *Int*, the difference between the autumn and winter TanDEM-X acquisitions and backscatter intensity of all overlapping DEM pixels is used. To predict the bias in surface penetration depth between the autumn and winter acquisitions 2016/17, the model is then applied to all glacier areas above 400 m a.s.l. on Novaya Zemlya which were only covered by September 2016 SAR (~7,800 km², Fig. S2a). Eventually, the estimated surface penetration depths are converted back to vertical differences in elevation by rearranging EQ. 1. The predicted vertical correction values (Fig. S2b) are then added to the September 2016 elevations and the adjusted elevation change rate is calculated.

For Franz Josef Land and Severnaya Zemlya, the elevation change rate is not adjusted, as on both archipelagos the temporal offset between DEM acquisitions is much smaller as on Novaya Zemlya. Average backscatter intensity is relatively homogeneous for all 2016/17 acquisitions on Severnaya Zemlya (Fig. S1c) while on Franz Josef Land only a very small fraction of September TanDEM-X acquisitions (6%) shows significant differences in backscatter intensity (Fig. S1e). Therefore, transferring the empirical relationship between differences in surface penetration depth and autumn backscatter intensities on Novaya Zemlya to those archipelagos would rather increase the uncertainty of the elevation change measurement.

~~To account for uncertainties of the measured elevation change due to different acquisition dates and glacier surface conditions, elevation changes between DEMs which were acquired at temperatures below and above the melting point are compared. During 2010/11, almost all TanDEM-X images were acquired in December and January (94% of glacier area) with temperatures well below zero degrees Celsius and frozen ice surfaces. During 2016, some glacier areas were acquired earlier between September and October. Particularly large parts of Novaya Zemlya (70%) were measured during September and October 2016 at temperatures partly above the melting point (Fig. S1). For those acquisitions, the depth of signal penetration into the glacier surface was probably smaller than for the midwinter acquisitions due to the presence of surface melt. Therefore, we calculate elevation changes on Novaya Zemlya for glacier areas which were measured from winter 2010/11 (Dec-Jan) to winter 2016/17 (Nov-Jan, WW period) and winter 2010/11 to autumn 2016/17 (Sep-Oct, WA period), respectively. 3rd order polynomial functions are then used to estimate the approximate deviation between the periods and correct respective glacier areas of the WA period. Eventually, we use the corrected elevation change rate to adjust the regionwide mean elevation change of glaciers on Novaya Zemlya. For Franz Josef Land and Severnaya Zemlya, the elevation change rate is not adjusted, as on both archipelagos the acquisition dates of most 2016/17 DEMs were similar to the 2010/11 acquisitions. Also, on Severnaya Zemlya no images were acquired at temperatures close to the melting point and on Franz Josef Land there were only a very small fraction of images at these temperatures (< 7%). For the adjusted elevation change rate on Novaya Zemlya we also include half of the area-weighted correction values in the uncertainty of the elevation change rate ($\delta_{\Delta h/\Delta t}$).~~

3. Results

Glacier surface elevation changes of the Russian Archipelagos are shown in Fig. 2~~1~~. High thinning rates are measured at elevations below 600 m a.s.l., while surface change rates in the upper accumulation areas are close to zero or slightly positive. Average elevation change rates are highest on Novaya Zemlya (signal-penetration corrected: -0.68±0.46~~31~~ m a^{-1}), mostly due to strong surface thinning close to the termini of the large outlet and tidewater glaciers (Fig. S3c~~2~~). Regional elevation changes of glaciers in Franz Josef Land (-0.48±0.04~~2~~ m a^{-1}) and Severnaya Zemlya (-0.34±0.12~~03~~ m a^{-1}) are in general less negative and confined to a smaller number of glaciers. Average elevation changes on Severnaya Zemlya are strongly positive below 50 m a.s.l. (Fig. S3b) due to a surge event within the observation period at the Vavilov Ice Cap (Zheng et al., 2019). Slight thickening is also observed at the highest glacierized altitudes and the Academy of Sciences Ice Cap (Severnaya Zemlya), similar to the observations of (Sánchez-Gámez et al., 2019). The overall adjusted mass change of the Russian Arctic is -23.06~~2.9~~±6.41~~4.9~~ Gt a^{-1} (density conversion factor: 850 kg m^{-3}). Approximately 50% of the total mass loss are caused by glaciers on Novaya Zemlya, while mass changes of Severnaya Zemlya and Franz Josef Land account for about a quarter each. Table 1 summarises the measured and adjusted change rates for the Russian Arctic.

For the DEM acquisitions of 2016/17 on Novaya Zemlya, a distinct difference in backscatter intensity is visible between SAR data acquired in September 2016 and October-January 2016/17 (Fig. 1a). The average vertical difference in surface elevation on the respective overlapping glacier areas (Fig. S2a) is 2.13 m while the elevation change rates derived from all glacier areas which were acquired in September 2016 (Fig. 1b), show an average difference of 0.4 m a^{-1} in surface lowering compared to the winter 2016/17 DEMs. Furthermore, the elevation change rate of the period winter 2010/11 to winter 2016/17 is consistently more negative at all altitudes while the change rate between winter 2010/11 and September 2016 indicates elevation gains at the highest glacierized altitudes. The analysed vertical elevation differences of the overlapping glacier areas (Fig. S2a) and the respective backscatter intensity of the September datasets (Fig. 1a) indicate altitudinal differences in signal penetration depth between the autumn and winter SAR data.

When transferred to all areas on Novaya Zemlya, the glacier surface acquired by TanDEM-X in September 2016 was approximately 2.3 m higher than the surface elevations measured during the winter months 2016/17. The measured glacier mass change rate of Novaya Zemlya is therefore ~20% lower than the adjusted mass change because the elevation changes derived from DEM acquisitions of September 2016 is consistently less negative than those from the winter months.

The adjusted glacier mass change rate of the Russian Arctic is ~10% higher than the measured mass change due to the different observation periods on Novaya Zemlya. The differences in glacier elevation change rates on Novaya Zemlya and average temperatures of the acquisition months are shown in Fig. 2. Elevation changes derived from DEM acquisitions during months with average temperatures above the melting point (September-October, WA period) are consistently less negative than those from months with lower temperatures (November-January, WW period). Also, change rates of the WW period are negative or close to zero at almost all altitudes while rates of the WA period indicate positive elevation gains at the highest altitudes.

4. Discussion

Differences in the SAR derived elevation change rates (Fig. 1b) can be related either to surface penetration of the X-Band radar or physical changes of the surface height due to accumulation or ablation of snow and ice. The TanDEM-X DEM difference on Novaya Zemlya does not fully cover the accumulation period of the last year of the observation period as the acquisitions of Septemberautumn 2016 (WA period) do not or only partially capture the amount of winter accumulationprecipitation from OctoberSeptember to December. (Fig. S 1c) which might led to an overestimation of surface elevation change between winter 2010/11 and autumn 2016. This potential bias in measured winter accumulation would lead to an overestimation of surface elevation loss between winter 2010/11 and September 2016-. However, the analysis of surface elevation changes derived from autumn and winter DEMs indicate, that the surface measured by TanDEM-X in winter 2016/17 was below the surface heights acquired in September 2016. As the occurrence of major surface melt within the Arctic winter months is unlikely, the observed elevation offset is most likely related to differences in the relative depth of signal penetration of the X-band SAR. The analysis of backscatter intensities of different acquisition months (Fig. 1a) indicates a change in glacier surface properties between the acquisitions from September 2016 and winter 2016/17. The observed differences in backscatter could be related either to the presence of melt or fresh snow at the glacier surface which would decrease the depth of signal penetration as the amount of penetration depends on the condition of the glacier surface and is close to zero for melting snow surfaces and bare glacier ice. The majority of SAR data of the 2016/17 timestep was acquired at months with temperatures well below 0°C while average temperatures on Novaya Zemlya in September 2016 were close to the melting point (Fig. S1f). Thus, the differences in backscatter intensity could be caused by either accumulation of fresh snow at the glacier surface or days with snow melt during September 2016. It is likely that the depth of signal penetration in the winter seasons 2010/11 and 2016/17 was relatively large but similar due to comparable dry and frozen surface conditions. A similar observation was reported for Antarctic Peninsula glaciers where the measured TanDEM-X cold-season heights rather referred to the refrozen firn of the previous summer than to the actual glacier surface (Rott et al., 2014). During the September 2016 acquisitions on Novaya Zemlya, the absolute depth of signal penetration was probably smaller and the measured surface closer to the glacier surface. However, due to the change in surface conditions, the relative difference between penetration depths of the winter season 2010/11 and autumn 2016 increased. The adjusted glacier change rate of Novaya Zemlya is therefore more negative than the measured rate because the effects of different signal penetration depths probably outweigh the winter accumulation.

However, as the mean elevation change of the WA period is less negative than the WW period, the observed spatial differences in elevation change on Novaya Zemlya can most likely be attributed to differences in penetration depth of SAR measurements from months with surface melt. The SAR penetration depth depends on the condition of the glacier surface and decreases during melting conditions. Almost all DEMs at the beginning of the observation period were acquired during winter 2010/11, with temperatures well below 0°C, while a number of images of the 2016/17 acquisitions are from autumn 2016, with temperatures above the melting point (Fig. 2b & Fig. S 1). It is likely that the surface heights measured in autumn 2016 were close to the actual glacier surface while the penetration depths of the TanDEM-X SAR during midwinter 2010/11 and 2016/17 were similar and might refer to the refrozen firn of the previous summer as observed for cold-season TanDEM-X measurements of Antarctic glaciers (Rott et al., 2014). The adjusted glacier change rate of Novaya Zemlya is therefore more negative than the measured rate because the effects of different signal penetration depths probably outweigh the winter accumulation. Yet, due to this effect it is not possible to quantify the actual amount of accumulation between September and December 2016.

Over the last decades, the High Arctic has been subject to ongoing warming (Jansen et al., 2020) and glacier mass budgets have become more negative. Particularly, average temperatures on the southern islands of the Russian Arctic have become warmer (Fig. S3a). Compared to previous studies (Fig. S54), glacier mass loss has increased in the Russian Arctic since 2010. The glacier mass changes measured by TanDEM-X are similar or slightly more negative than recent gravimetric records (Ciracì et al., 2020; Wouters et al., 2019(Ciracì et al., 2020), supporting their observation of increasing mass loss. A recent global study based on optical elevation models (Hugonnet et al., 2021) reported a less negative mass change (-10.4±1.9 Gt a^{-1}) since 2000, yet their measurements also indicate a distinct acceleration in mass loss over the course of the 21^{st} century.

-While the regional geodetic mass change derived from TanDEM-X of Franz Josef Land is very similar to recentthe gravimetric (Ciracì et al., 2020) and altimetric (Zheng et al., 2018) measurements, the geodetic estimate for Severnaya Zemlya is even more negative which might indicate recent acceleration of glacier mass loss also on this archipelago. However, the highest mass changes are mostly confined to a small number of outlet glaciers of the Vavilov and Academy of Sciences Ice Caps (RGI60-09.00915,919,920,971). For the remaining glacierized areas of the Severnaya Zemlya Archipelago, the average elevation change rate is much smaller (-0.20 m a^{-1}). The strongest local surface lowering is observed at the large outlet glaciers, most notably on Novaya Zemlya. For those glaciers, an increasing retreat in the early 21st century was attributed to fjord geometries and changes in sea-ice concentrations (Carr et al., 2014). Long-term observations also indicate a more rapid thinning during recent years, particularly at the termini of marine-terminating glaciers (Melkonian et al., 2016). Using a combination of gravimetric and altimetric measurements, (Ciracì et al., 2018) reported a similar mass change of -14±4 Gt a^{-1} for Novaya Zemlya (2010-2016) to the signal penetration adjusted mass change rate derived by TanDEM-X. An acceleration in flow velocities for the major tidewater glaciers in the Russian Arctic was also measured by (Strozzi et al., 2017) over the course of the last decades. In contrast to the lower ablation areas, elevation gains of up to 0.4 m a^{-1} are measured for the highest altitudes of the Russian Arctic, which does not seem to be~~are not always~~ related to potential SAR penetration because the respective measurements were acquired under similar surface conditions. This is particularly noticeable at some parts of the large accumulation areas of Novaya Zemlya, Severnaya Zemlya and Graham Bell Island (Franz Josef Land). Similar patterns can be also observed in the elevation change maps of altimetry measurements (Ciracì et al., 2018; Moholdt et al., 2012; Sánchez-Gámez et al., 2019) and might be related to increased moisture transport and accumulation (Box et al., 2019). The ERA5 datasets also indicates a positive trend in temperature and total column water vapor (Fig. S4a & b~~3b~~) for the Russian Arctic archipelagos. However, the latter trend is not statistically significant in most regions and less pronounced than the increase in temperature, supporting our observations of an overall amplification of glacier mass loss.

5. Conclusion

Glaciers in the Russian High Arctic have shown ~~showed~~ increasingly negative glacier mass change during the 21st century and contributed 0.06 mm a^{-1} to global sea-level rise between 2010 and 2017. This observation is in line with glacier changes of other Arctic regions, showing an increasing contribution to sea-level rise in recent years compared to glacierized areas outside of the polar regions. ~~Within the Arctic, the Russian Arctic archipelagos are currently one of the largest contributors to sea-level rise, alongside glaciers in Alaska, the Canadian Arctic, Greenland and, of course, the Greenland ice sheet.~~

The acquisition date related differences in elevation change on Novaya Zemlya highlight the relevance of similar surface conditions between SAR acquisitions when using DEM-differencing. Particularly for shorter observation periods, corrections for temporal offsets between acquisitions are crucial as the measured elevation change rate can be biased by changes in surface conditions. However, acquisitions from the same season should be used whenever possible, as the measurement uncertainty increases depending on the corrected glacier area. Regarding upcoming TanDEM-X acquisitions, combined measurements with the new ICESat-2 laser altimeter have the potential to much better constrain offsets between different acquisition dates.

Data availability. Elevation change maps and raster masks with the specific observation period of each cell are provided via the World Data Center PANGAEA (https://www.pangaea.de/) at #link#.

Author contributions. C.S. processed the glacier elevation and mass change data, created the graphs and wrote the manuscript. The analysis code of the DEM creation and coregistration was jointly developed by C.S. and T.C.S. A.G. contributed to the comparison and interpretation of measured glacier changes. M.H.B. initiated and led the study. All authors revised the paper.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This study was financially supported by the grant BR2105/14-2 within the DFG Priority Program "Regional Sea Level Change and Society". We thank the Copernicus Climate Change Service (C3S) which is implemented by the European Centre for Medium-range Weather Forecasts (ECMWF) on behalf of the European Commission for free and open data access. TanDEM-X data was kindly provided free of charge by the German Aerospace Center (DLR) under AO mabra_XTI_GLAC0264.

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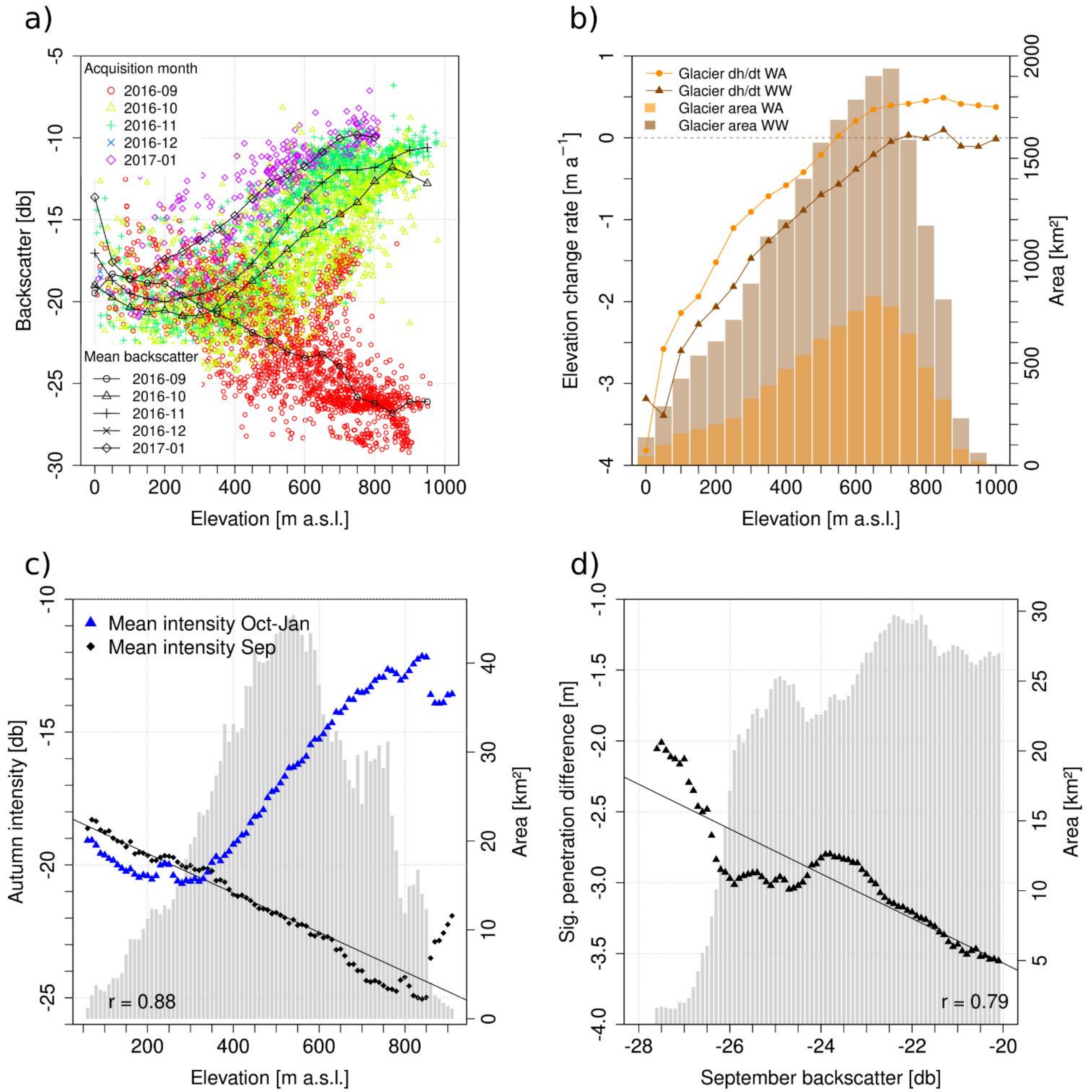


Figure 1 a) Backscatter intensity of different TanDEM-X DEM acquisition months versus elevation on Novaya Zemlya. Black lines indicate average backscatter aggregated within 50m elevation bins. b) Mean elevation change rates of DEM differences between winter 2010/11 and winter 2016/17 (WW, triangles) and winter 2010/11 and September 2016 (WA, dots). c) Altitudinal distribution of mean backscatter intensity (aggregated in 10m elevation bins) of September and winter 2016/17 SAR data on overlapping glacier areas (i.e. areas which were acquired in September and winter 2016/17). d) Differences in estimated signal penetration between September and winter 2016/17 versus mean backscatter intensity of September 2016 acquisitions on overlapping glacier areas (aggregated within 0.1 db backscatter intervals between -20 to -28 db).

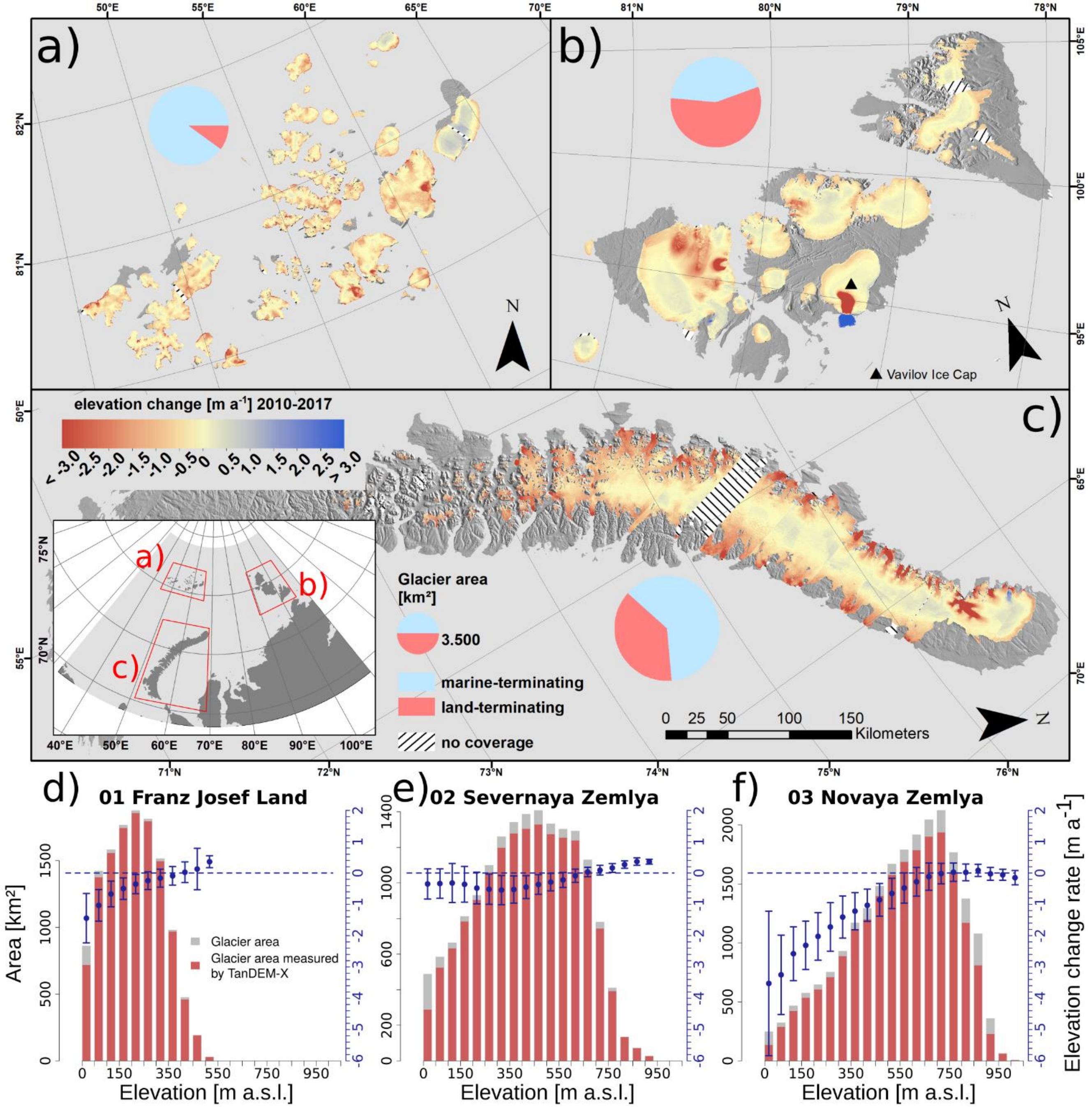
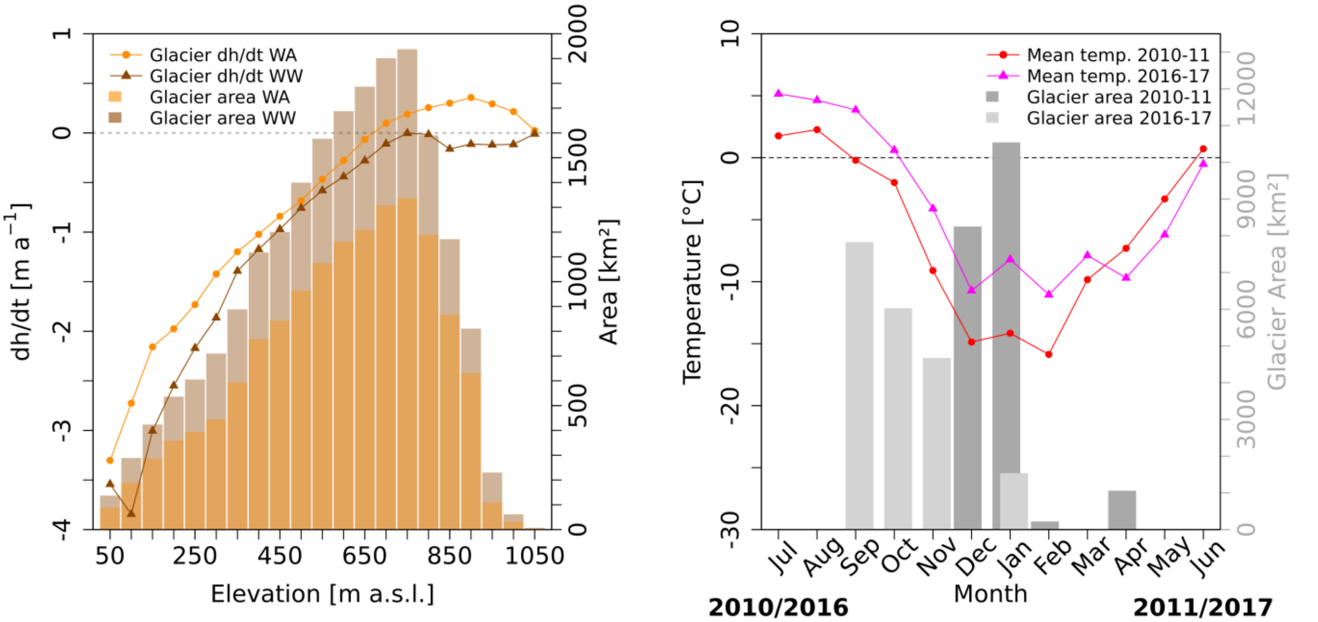


Figure2-21: Surface elevation changes of glaciers on Franz Josef Land (a), Severnaya Zemlya (b), and Novaya Zemlya (c) between 2010 and 2017. Hatched areas indicate glaciers without coverage by TanDEM-X. Respective average elevation change rates and total/measured glacier areas within 50m elevation bins are shown in Figures 1 (d)-(f). The hypsometric distribution of Severnaya Zemlya does not include the surge of the Vavilov ice cap (RGI60-09.00971). Elevation changes of Novaya Zemlya were corrected for SAR-signal penetration.

Table 1: Overview of glacier elevation and mass change in the Russian Arctic between 2010/11~~16~~ and 2016/17~~7~~. Glacier areas (*S*) are derived from the Randolph Glacier Inventory 6.0. Its spatial coverage by elevation change measurements (*S mea.*) is stated in percent. *Dh/dt* shows elevation change rates as measured by TanDEM-X while *dh/dt adj.* includes the SAR signal-penetration corrected elevation change rate of Novaya Zemlya. *dM/dt* and *dM/dt adj.* are the respective glacier mass change rates using a volume-to-mass conversion factor of 850 kg m^{-3} (a) and 900 kg m^{-3} (b).
***Acquisition date offsets adjusted for Novaya Zemlya.**

Region	S [km²]	S mea. [%]	dh/dt [m a^{-1}]	dh/dt adj. [m a^{-1}]	dM/dt [Gt a^{-1}]a	dM/dt adj. [Gt a^{-1}]a	dM/dt [Gt a^{-1}]b	dM/dt adj. [Gt a^{-1}]b
Franz Josef Land	12750	96	-0.48±0.04~~2~~		-5.14±0.43		-5.45±0.45~~4~~	
Severnaya Zemlya	16529	97	-0.34±0.12~~03~~		-4.70±1.31~~0.54~~		-4.98±1.38~~0.56~~	
Novaya Zemlya	22117	91	-0.53±0.23~~4~~	-0.68±0.46~~31~~*	-9.95±3.14~~4.54~~	-12.92~~74~~±6.18~~4.79~~	-10.54±3.31~~4.80~~	-13.68~~49~~±6.54~~5.06~~*
Russian Arctic	51707	93	-0.46±0.15~~2~~	-0.52±0.24~~15~~*	-20.05±3.47~~4.65~~	-23~~2~~.06~~88~~±6.41~~4.90~~	-21.23±3.66~~4.92~~	-24.4~~2~~2±6.79~~5.17~~*



~~**Figure 2: Surface elevation changes of glaciers on Novaya Zemlya (a) which were measured by TanDEM-X from December-April 2010/11 to September-October 2016 (WA, light orange) and December-April 2010/11 to November-January 2016/17 (WW, dark orange). The hypsometric distribution of glacier areas is shown as orange bars. Monthly average skintemperatures of Novaya Zemlya (b) during the TanDEM-X acquisition months in 2010/11 (red dots) and 2016/17 (magenta triangles) are derived from ERA5. The gray bars show the glacier area covered by TanDEM-X acquisitions per month.**~~