https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

The Cryosphere Discussions

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

Christian Sommer[1], Thorsten Seehaus[1], Andrey Glazovsky[2], Matthias H. Braun[1]

[1]Institut für Geographie, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, 91058, Germany
[2]Institute of Geography RAS, Moscow, 119017, Russia

Correspondence to: Christian Sommer (chris.sommer@fau.de)

Abstract. Glaciers in the Russian High Arctic have been subject to extensive 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±5 Gt a^{-1}, corresponding to a sea level rise contribution of 0.06±0.01 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 increases in temperature and humidity (Box et al., 2019) and an increase in glacier mass loss has been observed in many polar regions (Morris et al., 2020). The Russian 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 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 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.

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

The Cryosphere Discussions

2.1 Glacier elevation & mass change

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 (ΔM/Δt) 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 Uncertainty assessment of glacier mass change

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).

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

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):

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

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

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

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

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

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 DEM acquisition date correction of geodetic mass change

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. 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±0.31 m a^{-1}), mostly due to strong surface thinning close to the termini of the large outlet and tidewater glaciers (Fig. S2). Regional elevation changes of glaciers in Franz Josef Land (-0.48±0.02 m a^{-1}) and Severnaya Zemlya (-0.34±0.03 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. 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 -22.9±4.9 Gt a^{-1} (density

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

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. 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 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 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 autumn 2016 (WA period) do not or only partially capture the amount of precipitation from September to December (Fig. S 1c) which might led to an overestimation of surface elevation change between winter 2010/11 and autumn 2016. 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 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. S4), 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), supporting their observation of increasing mass loss. While the geodetic mass change of Franz Josef Land is very similar to the gravimetric measurements, the geodetic estimate for Severnaya Zemlya is even more negative which might indicate recent acceleration of glacier mass loss also on this archipelago. The strongest local surface lowering is observed at the large outlet

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

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). 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 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 total column water vapor (Fig. S3b) for the Russian Arctic archipelagos. However, the 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 Arctic showed increasingly negative glacier mass change during the 21st century and contributed 0.06 mm a^{-1} to global sea-level rise. 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.

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

The Cryosphere
Discussions

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.

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

References

Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J. and Olsen, M. S.: Key indicators of Arctic climate change: 1971–2017, Environ. Res. Lett., 14(4), 045010, doi:10.1088/1748-9326/aafc1b, 2019.

Braun, M. H., Malz, P., Sommer, C., Farías-Barahona, D., Sauter, T., Casassa, G., Soruco, A., Skvarca, P. and Seehaus, T. C.: Constraining glacier elevation and mass changes in South America, Nat. Clim. Change, 9(2), 130–136, doi:10.1038/s41558-018-0375-7, 2019.

Carr, J. R., Stokes, C. and Vieli, A.: Recent retreat of major outlet glaciers on Novaya Zemlya, Russian Arctic, influenced by fjord geometry and sea-ice conditions, J. Glaciol., 60(219), 155–170, doi:10.3189/2014JoG13J122, 2014.

Ciracì, E., Velicogna, I. and Sutterley, T.: Mass Balance of Novaya Zemlya Archipelago, Russian High Arctic, Using Time-Variable Gravity from GRACE and Altimetry Data from ICESat and CryoSat-2, Remote Sens., 10(11), 1817, doi:10.3390/rs10111817, 2018.

Ciracì, E., Velicogna, I. and Swenson, S.: Continuity of the Mass Loss of the World's Glaciers and Ice Caps From the GRACE and GRACE Follow-On Missions, Geophys. Res. Lett., 47(9), doi:10.1029/2019GL086926, 2020.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., Rabatel, A., Pitte, P. and Ruiz, L.: Two decades of glacier mass loss along the Andes, Nat. Geosci., 12(10), 802–808, doi:10.1038/s41561-019-0432-5, 2019.

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R. and Paul, F.: A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009, Science, 340(6134), 852–857, doi:10.1126/science.1234532, 2013.

German Aerospace Center (DLR): TanDEM-X - Digital Elevation Model (DEM) - Global, 90m, , doi:10.15489/JU28HC7PUI09, 2018.

Huss, M.: Density assumptions for converting geodetic glacier volume change to mass change, The Cryosphere, 7(3), 877–887, doi:10.5194/tc-7-877-2013, 2013.

Jacob, T., Wahr, J., Pfeffer, W. T. and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, Nature, 482(7386), 514–518, doi:10.1038/nature10847, 2012.

Matsuo, K. and Heki, K.: Current Ice Loss in Small Glacier Systems of the Arctic Islands (Iceland, Svalbard, and the Russian High Arctic) from Satellite Gravimetry, Terr. Atmospheric Ocean. Sci., 24(4–1), 657, doi:10.3319/TAO.2013.02.22.01(TibXS), 2013.

Messager, M. L., Lehner, B., Grill, G., Nedeva, I. and Schmitt, O.: Estimating the volume and age of water stored in global lakes using a geo-statistical approach, Nat. Commun., 7(1), 13603, doi:10.1038/ncomms13603, 2016.

Moholdt, G., Wouters, B. and Gardner, A. S.: Recent mass changes of glaciers in the Russian High Arctic: GLACIER MASS CHANGES, RUSSIAN ARCTIC, Geophys. Res. Lett., 39(10), n/a-n/a, doi:10.1029/2012GL051466, 2012.

Morris, A., Moholdt, G. and Gray, L.: Spread of Svalbard Glacier Mass Loss to Barents Sea Margins Revealed by CryoSat-2, J. Geophys. Res. Earth Surf., 125(8), doi:10.1029/2019JF005357, 2020.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., Hagen, J.-O., Hock, R., Kaser, G., Kienholz, C., Miles, E. S., Moholdt, G., Mölg, N., Paul, F., Radić, V., Rastner, P., Raup, B. H., Rich, J., Sharp, M. J., and The Randolph Consortium: The Randolph Glacier Inventory: a globally complete inventory of glaciers, J. Glaciol., 60(221), 537–552, doi:10.3189/2014JoG13J176, 2014.

Rolstad, C., Haug, T. and Denby, B.: Spatially integrated geodetic glacier mass balance and its uncertainty based on geostatistical analysis: application to the western Svartisen ice cap, Norway, J. Glaciol., 55(192), 666–680, doi:10.3189/002214309789470950, 2009.

Rott, H., Floricioiu, D., Wuite, J., Scheiblauer, S., Nagler, T. and Kern, M.: Mass changes of outlet glaciers along the Nordensjköld Coast, northern Antarctic Peninsula, based on TanDEM-X satellite measurements: TanDEM-X Antarctic Peninsula glaciers, Geophys. Res. Lett., 41(22), 8123–8129, doi:10.1002/2014GL061613, 2014.

Sánchez-Gámez, P., Navarro, F. J., Benham, T. J., Glazovsky, A. F., Bassford, R. P. and Dowdeswell, J. A.: Intra- and interannual variability in dynamic discharge from the Academy of Sciences Ice Cap, Severnaya Zemlya, Russian Arctic, and its role in modulating mass balance, J. Glaciol., 65(253), 780–797, doi:10.1017/jog.2019.58, 2019.

Seehaus, T., Malz, P., Sommer, C., Lippl, S., Cochachin, A. and Braun, M.: Changes of the tropical glaciers throughout Peru between 2000 and 2016 – mass balance and area fluctuations, The Cryosphere, 13(10), 2537–2556, doi:10.5194/tc-13-2537-2019, 2019.

Sommer, C., Malz, P., Seehaus, T. C., Lippl, S., Zemp, M. and Braun, M. H.: Rapid glacier retreat and downwasting throughout the European Alps in the early 21st century, Nat. Commun., 11(1), 3209, doi:10.1038/s41467-020-16818-0, 2020.

Strozzi, T., Paul, F., Wiesmann, A., Schellenberger, T. and Kääb, A.: Circum-Arctic Changes in the Flow of Glaciers and Ice Caps from Satellite SAR Data between the 1990s and 2017, Remote Sens., 9(9), 947, doi:10.3390/rs9090947, 2017.

Wouters, B., Gardner, A. S. and Moholdt, G.: Global Glacier Mass Loss During the GRACE Satellite Mission (2002-2016), Front. Earth Sci., 7, 96, doi:10.3389/feart.2019.00096, 2019.

Zheng, W., Pritchard, M. E., Willis, M. J. and Stearns, L. A.: The Possible Transition From Glacial Surge to Ice Stream on Vavilov Ice Cap, Geophys. Res. Lett., 46(23), 13892–13902, doi:10.1029/2019GL084948, 2019.

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

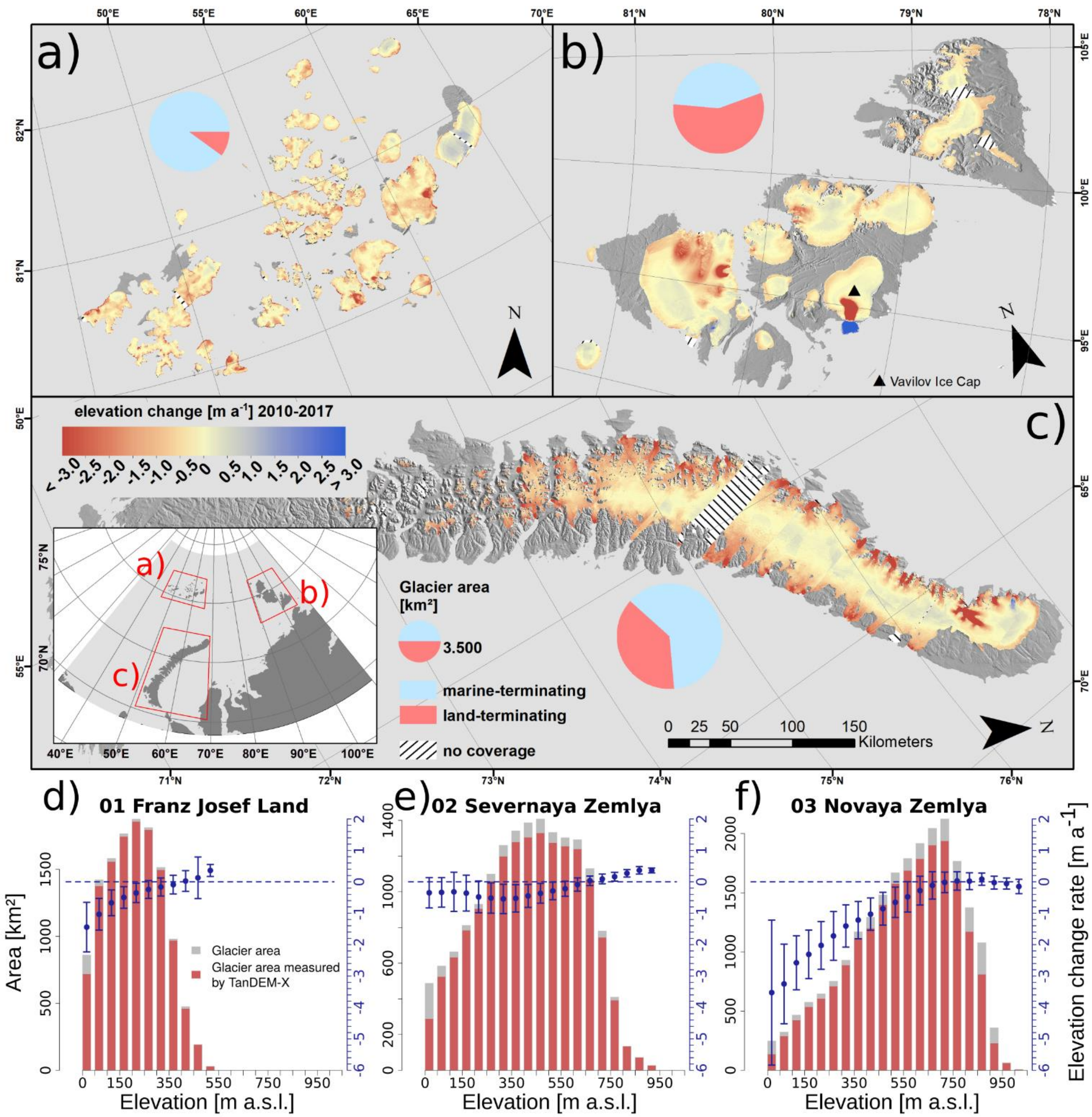

Figure 1: Surface elevation changes of glaciers on Franz Josef Land (a), Severnaya Zemlya (b), and Novaya Zemlya (c) between 2010 and 2017. Hatched areas indicate glaciers without coverage by TanDEM-X. Respective average elevation change rates and total/measured glacier areas within 50m elevation bins 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.

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

Table 1: Overview of glacier elevation and mass change in the Russian Arctic between 2016 and 2017. 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±0.02		-5.14±0.43		-5.45±0.44	
Severnaya Zemlya	16529	97	-0.34±0.03		-4.70±0.54		-4.98±0.56	
Novaya Zemlya	22117	91	-0.53±0.24	-0.68±0.31*	-9.95±4.54	-12.74±4.79	-10.54±4.80	-13.49±5.06*
Russian Arctic	51707	93	-0.46±0.12	-0.52±0.15*	-20.05±4.65	-22.88±4.90	-21.23±4.92	-24.22±5.17*

https://doi.org/10.5194/tc-2020-358
Preprint. Discussion started: 28 December 2020

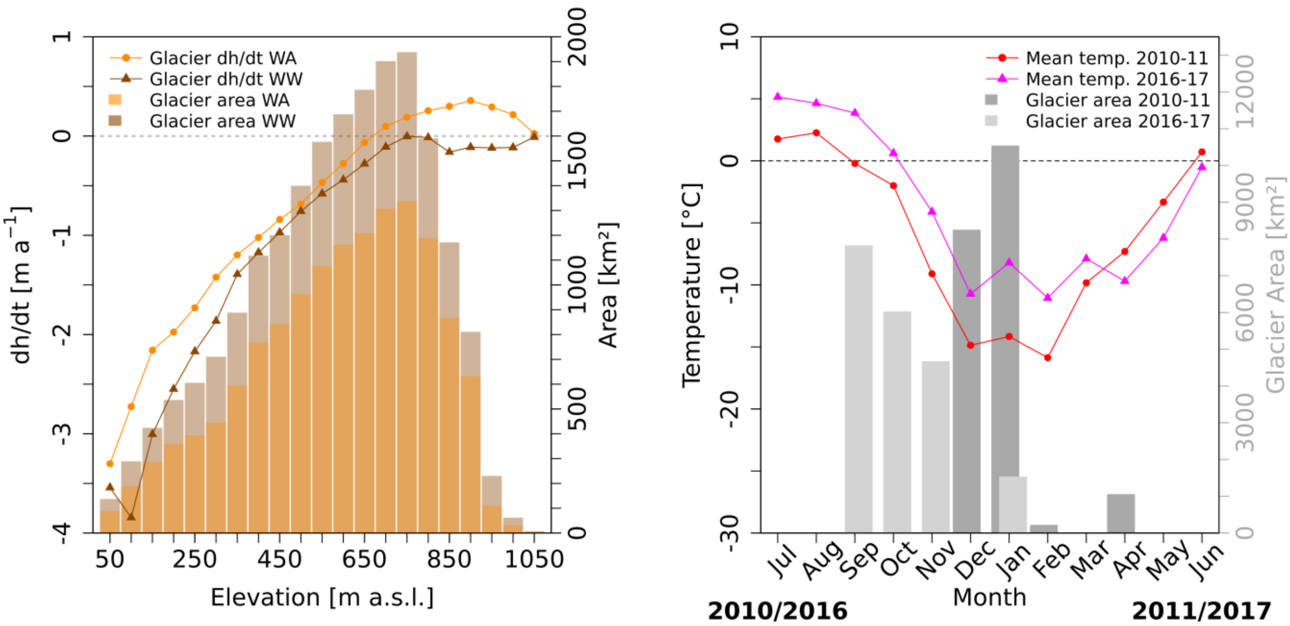

Figure 2: Surface elevation changes of glaciers on Novaya Zemlya (a) which were measured by TanDEM-X from December-April 2010/11 to September-October 2016 (WA, light orange) and December-April 2010/11 to November-January 2016/17 (WW, dark orange). The hypsometric distribution of glacier areas is shown 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.