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Recent mass changes of glaciers in the Russian High Arctic

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[1] Glaciers and ice caps are known to contribute significantly to present-day sea level rise, but there are still glaciated regions where little is known about modern changes in glacier mass. One of these regions is the Russian High Arctic archipelagos which has a total glaciated area of 51,500 km^2. We have assessed the glacier mass budget of this region for a 6-year period between October 2003 and October 2009 using independent ICESat laser altimetry and GRACE gravimetry. Over this period we found that the archipelagos have lost ice at a rate of -9.1 ± 2.0 Gt a^{-1}, which corresponds to a sea level contribution of 0.025 mm a^{-1}. Approximately 80% of the ice loss came from Novaya Zemlya with the remaining 20% coming from Franz Josef Land and Severnaya Zemlya. Meteorological records of temperature and precipitation for the period 1980–2009 suggest that the recent climatic mass budget is not substantially different from the longer-term trend. **Citation:** Moholdt, G., B. Wouters, and A. S. Gardner (2012), Recent mass changes of glaciers in the Russian High Arctic, *Geophys. Res. Lett.*, *39*, L10502, doi:10.1029/2012GL051466.

1. Introduction

[2] The high Arctic has warmed almost twice as fast as the global average over the last few decades, mainly due to feedback mechanisms from diminishing sea ice cover [*Screen and Simmonds*, 2010]. Glaciers in this region contain about half of all glacier ice outside of Greenland and Antarctica [*Radic and Hock*, 2010], and they will likely play a significant role in the sea-level budget over the next century and beyond [*Gardner et al.*, 2011]. Recent studies have shown that glaciers in the Canadian and Norwegian Arctic have lost mass at considerable rates [*Gardner et al.*, 2011; *Moholdt et al.*, 2010; *Nuth et al.*, 2010]. Less is known about the heavily glaciated islands around the Kara Sea in the Russian Arctic, a region that contains a total ice volume of 15,000–18,000 km^3 [*Kotlyakov et al.*, 2010; *Radic and Hock*, 2010].

[3] The Russian Arctic islands are classified as polar deserts with mean annual temperatures near sea level of $-5°$C to $-15°$C and annual precipitation of 200–800 kg m^{-2} a^{-1}. Climate conditions are warmest and wettest in the southwest and become progressively colder and dryer to the northeast. There have not been any *in situ* mass budget programs in the Russian High Arctic since 1988, and historical records are spatially and temporally limited. All published estimates of decadal-scale climatic mass budget from within 1930–1988 are slightly negative, with values typically ranging from 0 to -200 kg m^{-2} a^{-1} [*Bassford et al.*, 2006; *Dowdeswell et al.*, 1997; *Zeeberg and Forman*, 2001]. The total regional iceberg calving has been estimated to be 4–6 Gt a^{-1} over the period 1930–2000 [*Glazovsky and Macheret*, 2006; *Govorukha*, 1989]. Altogether, these studies suggest an average long-term mass budget between -5 Gt a^{-1} and -15 Gt a^{-1} for the period between 1930 and 1990. A recent global analysis of gravity anomalies from the Gravity Recovery and Climate Experiment (GRACE) indicates a regional glacier mass budget of -5 ± 3 Gt a^{-1} between January 2003 and December 2010 [*Jacob et al.*, 2012].

[4] We have used data from the Ice, Cloud and land Elevation Satellite (ICESat) and the GRACE gravity satellites to assess the glacier mass budget between October 2003 and October 2009 for the three main archipelagos in the Russian Arctic; Franz Josef Land, Severnaya Zemlya (including Ushakov Island) and Novaya Zemlya (Figure 1). We have also analyzed meteorological data from 1980 to 2009 in order to place the recent mass budget estimates into a longer-term climatic perspective.

2. Data and Methods

2.1. Glacier Outlines From Satellite Imagery

[5] Existing glacier inventories of the Russian Arctic are based on aerial photography from the 1950s [*Kotlyakov et al.*, 2010]. We digitized new glacier outlines from orthorectified SPOT-5 [*Korona et al.*, 2009] and Landsat imagery acquired between 2000 and 2010, during summer. We excluded the 200 km^2 Matusevich Ice Shelf in Severnaya Zemlya [*Williams and Dowdeswell*, 2001], but retained ice shelves in Franz Josef Land since they are small (<50 km^2) and cannot be easily distinguished from grounded ice [*Dowdeswell et al.*, 1994]. We estimated that the current glaciated area of the Kara Sea region is 51,500 km^2 (Table 1), which is 9% smaller than that of the World Glacier Inventory [*Ohmura*, 2010]. This large deviation is likely due to a combination of long-term glacier retreat [*Glazovsky and Macheret*, 2006; *Zeeberg and Forman*, 2001] and methodological differences in glacier delineation, e.g., the treatment of ice shelves, nunataks and seasonal/perennial snow cover.

2.2. Mass Budget From ICESat Laser Altimetry

[6] The Geoscience Laser Altimeter System (GLAS) onboard ICESat [*Zwally et al.*, 2002] was operated in campaign mode, acquiring data along the same ground tracks during 17 separate periods of ~33 days between October

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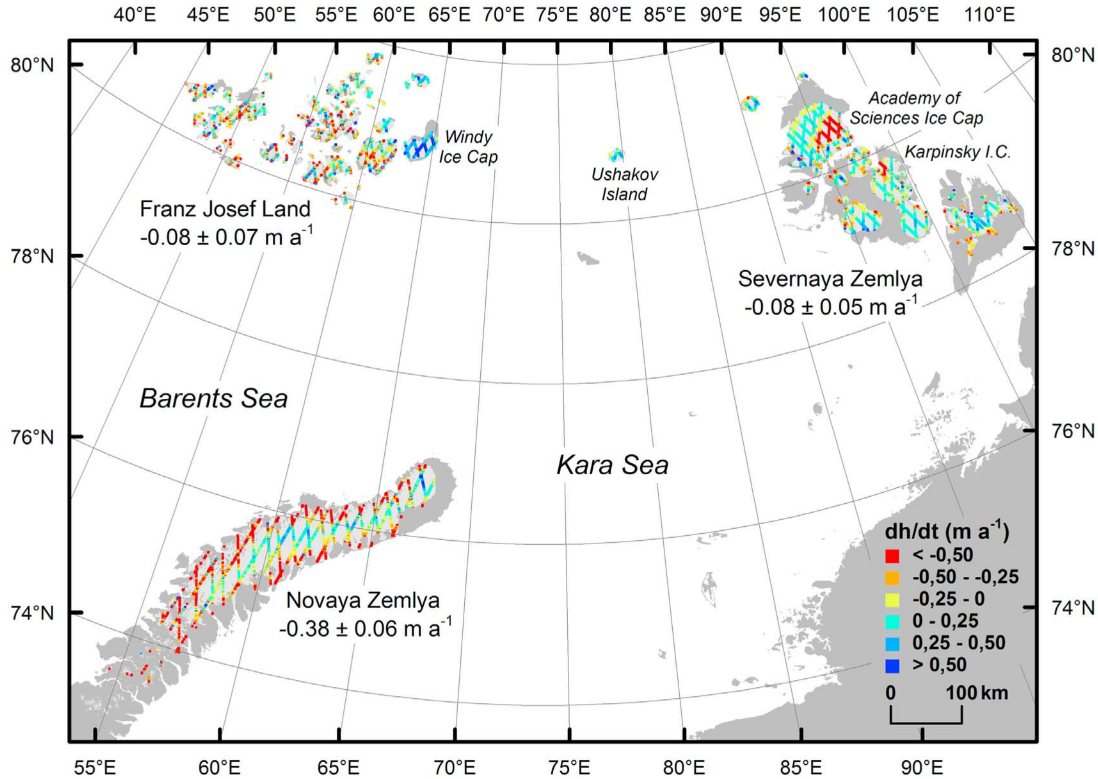

Figure 1. ICESat repeat-tracks with average elevation change rates (*dh/dt*) between October 2003 and October 2009 for glaciers in the Russian High Arctic. Glacier-wide elevation changes are given under each of the three region names.

2003 and October 2009. We used all elevation data from Release 531 of the GLA06 altimetry product [*Zwally et al.*, 2010]. We estimated glacier elevation changes using a well-established regression technique that determines surface slope and average elevation change (*dh/dt*) for planar surfaces that are fitted to 700 m long segments of near-repeat tracks [*Gardner et al.*, 2011; *Moholdt et al.*, 2010; *Smith et al.*, 2009]. The elevation residuals with respect to the least-squares plane solution were used to estimate quasi-seasonal elevation changes (dh_{seas}) between the February/March and October/November observation campaigns.

[7] We parameterized the relation between elevation change (*dh/dt* or dh_{seas}) and elevation using third order polynomial fits for each of the three archipelagos. We then estimated glacier volume changes (*dV/dt* or dV_{seas}) by multiplying the polynomial functions with the hypsometric areas within 50 m elevation bins derived from topographic maps which are based on aerial imagery from 1950–1988 [*Moholdt et al.*, 2010]. This extrapolation scheme yields similar regional *dV/dt* estimates as if the overall or hypsometric mean *dh/dt* values were used instead. Finally, we converted regional volume change rates (*dV/dt*) into mass-change rates (*dM/dt*) using an ice density of 0.9 Gt km^{-3} (Table 1), assuming that changes in the average firn density and thickness were small. Although there are no firn pack data to confirm this, meteorological records do not suggest any major changes in the recent climatic forcing. More details about the methodology and error analysis can be found in the auxiliary material.[1]

2.3. Mass Budget From GRACE Gravimetry

[8] The GRACE satellite system makes repeat observation of the Earth's gravity field allowing for the detection of mass redistribution near the Earth's surface [*Wahr et al.*, 1998]. We used Release 04 GRACE data from the Center for Space Research (CSR RL04) covering the period April 2003 to March 2011. We further processed the data following *Gardner et al.* [2011]; see more details in the auxiliary material. We estimated monthly glacier mass anomalies for

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051466.

Table 1. Regional Mass Budget Estimates From ICESat/GRACE, and Climatic Anomalies[a]

Glacier Region	Glacier Area (km^2)	ICESat 2004–09 (Gt a^{-1})	GRACE 2004–09 (Gt a^{-1})	GRACE 2003–10 (Gt a^{-1})	Temperature Anomaly (°C)	Precipitation Anomaly (kg m^{-2} a^{-1})
Franz Josef Land	12,700	−0.9 ± 0.7	0.7 ± 3.5	0.1 ± 3.4	0.03 ± 0.19	42 ± 28
Severnaya Zemlya	16,700	−1.3 ± 0.8	−2.0 ± 3.0	−0.6 ± 2.9	0.13 ± 0.10	8 ± 16
Novaya Zemlya	22,100	−7.6 ± 1.2	−5.8 ± 3.0	−4.1 ± 2.9	0.50 ± 0.28	89 ± 71
Russian High Arctic	51,500	−9.8 ± 1.9	−7.1 ± 5.5	−4.6 ± 5.4	0.26 ± 0.19	51 ± 42

[a]Climatic anomalies refer to the 2004–2009 period with respect to 1980–2009. Summer (JJA) temperature anomalies are from one meteorological station in each region, while precipitation anomalies are glacier-wide means from three global precipitation products.

each region by an iterative optimization method that fits synthetic surface mass anomalies to the GRACE data in predefined basins, in this case based on the glacier outlines [e.g., *Gardner et al.*, 2011; *Wouters et al.*, 2008]. No *a-priori* information on the mass changes was used, making the GRACE and ICESat results independent of each other. Glacial isostatic adjustment (GIA) was corrected by means of a modified version of the ICE-5 G (VM2) ice loading history and Earth viscosity model [*Peltier*, 2004]. The total GIA mass correction for the three archipelagos was -3.2 Gt a^{-1}. We corrected leakage effects from non-glacial signals in adjacent areas using the GLDAS-NOAH model for terrestrial water storage [*Rodell et al.*, 2004] and by simultaneously estimating terrestrial water storage anomalies in the major river catchments on the mainland of the Russian Arctic. No significant correlations were found between mass anomaly time series in glacier regions and neighboring regions, indicating that the signals in the glacier systems are properly resolved.

[9] The high noise-to-signal ratio in the monthly data precludes accurate estimates of single-year mass budgets. The seasonal cycle in glacier mass is only visible after temporal smoothing (Figure 3). We estimated multi-year mass change rates for each region (Table 1) by fitting linear curves to the monthly GRACE mass anomalies for the ICESat period (October 2003–October 2009) and the longest possible GRACE period (April 2003–March 2011). Uncertainties in the GRACE mass budgets were estimated by comparisons with alternative data products and models (auxiliary material).

2.4. Recent Climatic Anomalies

[10] In order to put the ICESat and GRACE mass budgets into a climatic perspective, we determined climatic anomalies for the period 2004–2009 with respect to a reference period 1980–2009. There are only a few meteorological stations with long-term records in the study regions; namely Heiss Island (central Franz Josef Land: 80.6°N, 58.0°E), Golomjannyj Island (western Severnaya Zemlya: 79.6°N, 90.6°E) and Malye Karmakuly (southwestern Novaya Zemlya: 72.4°N, 52.7°E). We used the three temperature time series to estimate anomalies in summer (JJA) temperature for each glacier region (Table 1). The station-derived anomalies are consistent with glacier area-averaged 700 mb temperature anomalies from climate reanalysis data (auxiliary material).

[11] Precipitation records are sparse and likely contain large biases from gauge undercatch of solid precipitation. Therefore, we determined precipitation anomalies from the average and standard deviation of three global precipitation products: the Global Precipitation Climatology Project Version 2.2 [*Adler et al.*, 2003; *Huffman et al.*, 2009], the NCEP Climate Forecast System Reanalysis [*Saha et al.*, 2010], and the ERM-Interim reanalysis [*Dee et al.*, 2011]. The anomalies were spatially averaged over all glacier area in each region.

3. Results and Discussion

[12] The temperature record from southwestern Novaya Zemlya indicates that the recent summers have been warmer than usual in this region, with a mean 2004–2009 summer (JJA) 2 m air temperature anomaly of 0.50 ± 0.28°C relative to the 1980–2009 mean (Table 1). The recent summer temperatures in Severnaya Zemlya and Franz Josef Land, however, show little deviation from their long-term averages. The glacier area-averaged precipitation anomalies are positive for all regions, indicating a slightly higher precipitation rate in 2004–2009 relative to the 1980–2009 mean, especially in Novaya Zemlya (89 ± 71 kg m^{-2} a^{-1}). *Zeeberg and Forman* [2001] found a strong linear relationship (r = 0.98, N = 7) between summer ablation and mean summer temperature for the Shokal'ski Glacier in northwestern Novaya Zemlya. Assuming that this relation is still valid and that the 0.5°C anomaly is representative for Novaya Zemlya's glaciers, we get an additional ablation of -120 kg m^{-2} a^{-1} which is roughly in balance with the 89 kg m^{-2} a^{-1} increase in precipitation. The two other regions experienced smaller anomalies in both temperature and precipitation. From this we surmise that the 2004–2009 climatic mass budget of the regions did not deviate substantially form their 1980–2009 means.

[13] Elevation changes from ICESat show a general pattern of low-elevation thinning and high-elevation balance or thickening between 2003 and 2009 (Figure 1). This elevation-dependent trend is particularly strong in Novaya Zemlya where the main icefield divide has thickened by an average of 0.09 m a^{-1} (within a 5 km buffer) at the same time as the frontal areas below 500 m a.s.l. have thinned by an average of -0.92 m a^{-1}. There is no significant difference between the frontal thinning of marine- and land-terminating glaciers (-0.94 m a^{-1} vs. -0.89 m a^{-1}), which suggests that climatic influences are more important than marine glacier dynamics. This is similar to the Canadian Arctic [*Gardner et al.*, 2011], but different from the outlet glaciers of the Greenland Ice Sheet where dynamic thinning dominates [*Sole et al.*, 2008]. The northwestern side of the icefield divide, facing the Barents Sea, has thinned more rapidly than the southeastern side that faces the Kara Sea (-0.46 m a^{-1} vs. -0.25 m a^{-1}). Almost all of this difference occurs in the summer seasons, probably due to warmer temperatures on the side of the Barents Sea.

[14] Franz Josef Land's many ice caps show a complex pattern of apparent elevation change (Figure 1), which can be related to meteorological and dynamical factors, as well as steeper surface slopes (average of 3.2° as compared to 2.1° in the two other regions) that degrade the ICESat performance. The Windy Ice Cap on Graham Bell Island in the far east of Franz Josef Land stands out from the rest of the region with a widespread thickening (Figure 1), a pattern that has also been recognized over the previous 50 years as compared to topographic maps [*Sharov*, 2010].

[15] In Severnaya Zemlya, the largest changes have occurred in the eastern basins of the Academy of Sciences Ice Cap, which have thinned by more than -1 m a^{-1} at average (Figure 1). This extensive drawdown is caused by three ice streams that have been in fast-flowing modes since at least 1995 [*Dowdeswell et al.*, 2002; *Moholdt et al.*, 2012]. The total iceberg calving flux from these three ice streams has been estimated to 1.3 Gt a^{-1} between 2003 and 2009 [*Moholdt et al.*, 2012], which is as much as the entire mass loss rate from the archipelago (Table 1). Another example of likely dynamic thinning is the northern basin of the Karpinsky Ice Cap, where the main outlet glacier feeds the Matusevich Ice Shelf over a heavily crevassed grounding zone.

[16] The time series of glacier-wide cumulative elevation changes (Figure 2) show that the seasonal amplitudes (mass

turnover) are largest in Novaya Zemlya, which is expected from the more southerly location in a warmer and more humid climate. The 2004 mass budget year was more negative than the subsequent years in all three regions. This is similar to what was found in Svalbard in the Norwegian Arctic [*Moholdt et al.*, 2010], but opposite of the Canadian Arctic where mass losses were largest in 2006–2009 [*Gardner et al.*, 2011]. The positive correlation in mass budget within the Barents-Kara Sea region (Norwegian and Russian Arctic) and the apparent negative correlation with the Canadian Arctic are likely related to the position of the summer Arctic circumpolar vortex [*Gardner and Sharp*, 2007]. In July 2004, the vortex was located in the Western Hemisphere with a low-pressure trough (cold polar air) over the Canadian Arctic and an anomalously strong high-pressure ridge (warm air) over the Barents-Kara Sea. The smoothed GRACE time series also show largest mass losses in 2004 (Figure 3). The estimated mass budget rate for the full 8-year GRACE time series (April 2003–March 2011) is less negative than for the 6-year period (October 2003–October 2009), indicating that the residual periods have likely been closer to balance than the overlapping 6 years in which a large fraction of the mass loss occurred in 2004 (Table 1).

[17] Our 8-year mass budgets from GRACE agree to within 0.5 Gt a^{-1} of those from *Jacob et al.* [2012] despite different methodologies and a 3-month shift in data coverage. The differences between our independent mass budgets from ICESat and GRACE are larger, but well within each other's error bounds for the coincident 6-year period (Table 1). Both data sets indicate a slightly negative mass budget in Severnaya Zemlya (-1.3 vs. -2.0 Gt a^{-1}) and a strongly negative mass budget in Novaya Zemlya (-7.6 vs. -5.8 Gt a^{-1}), while the mass budget in Franz Josef Land seems to be close to zero (-0.9 vs. 0.7 Gt a^{-1}). ICESat yields a more negative total mass budget than GRACE (-9.8 Gt a^{-1} vs. -7.1 Gt a^{-1}), although the difference is not significant. The more negative mass budget from ICESat can be due to unaccounted internal densification and/or biases in the GRACE analysis caused by inaccurate removal of gravitational signals from atmosphere, ocean, terrestrial water storage and in particular GIA, which is relatively poorly constrained in the region [e.g., *Svendsen et al.*, 2004]. For the final 2004–2009 mass budget estimate, we use the error-weighted mean of the ICESat and GRACE values, giving a Russian High Arctic mass budget of -9.1 ± 2.0 Gt a^{-1}, or -180 ± 40 kg m^{-2} a^{-1} when averaged over the total glacier area. Both numbers are much less negative than in the Canadian Arctic [*Gardner et al.*, 2011], but more negative than in Svalbard [*Moholdt et al.*, 2010].

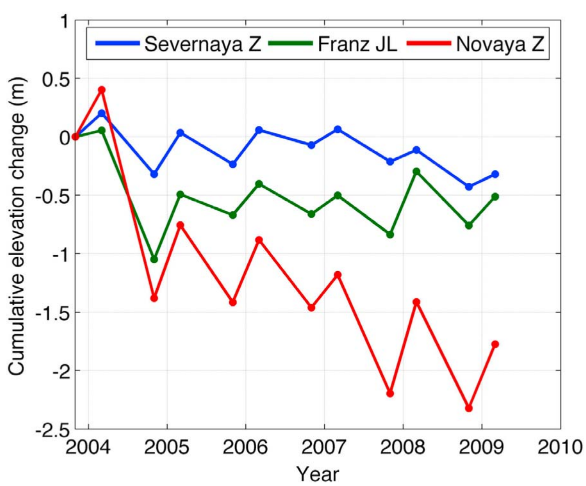

Figure 2. Regional time series of glacier-wide elevation changes between annual ICESat campaigns in October/November and February/March. Elevation changes over summer 2009 are not included due to ICESat's early failure in October 2009.

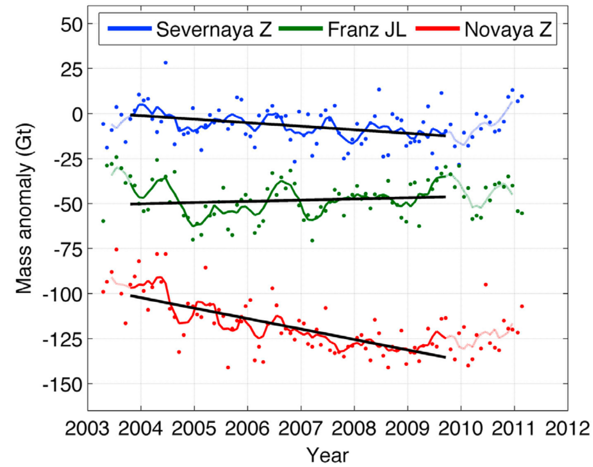

Figure 3. Monthly glacier mass anomalies (dots) as determined from GRACE over the three regions. Colored curves are 5-month running means of the monthly data, while black lines are linear fits to the monthly data within the ICESat period (October 2003–October 2009). Linear fits for the entire GRACE period (April 2003–March 2011) are not shown. Only linear fits were used to estimate mass budgets from GRACE (Table 1).

4. Conclusions

[18] ICESat laser altimetry shows that most glaciers in the Russian High Arctic have recently experienced peripheral thinning and interior balance or thickening (Figure 1), a pattern that has also been observed in the Canadian and Norwegian Arctic. There are however also examples of glaciers with widespread thickening (Windy Ice Cap, Franz Josef Land) and widespread thinning (Academy of Sciences Ice Cap, Severnaya Zemlya), which are probably more related to local anomalies in surface morphology and glacier dynamics than to recent changes in climate. Regional mass budgets derived from ICESat are consistent with independent estimates from GRACE gravimetry for the 2004–2009 mass budget years. Most glacier mass loss has occurred in Novaya Zemlya (-7.1 ± 1.2 Gt a^{-1}) due to a widespread thinning at low elevations. The mass budgets in Franz Josef Land (-0.6 ± 0.9 Gt a^{-1}) and Severnaya Zemlya (-1.4 ± 0.9 Gt a^{-1}) are only slightly negative, which implies a climatic mass budget close to zero or even positive when iceberg calving is considered. The total error-weighted mass budget is -9.1 ± 2.0 Gt a^{-1}, equivalent to a sea level contribution of 0.025 mm a^{-1}. The longer-term mass budget is not known, but meteorological records of temperature and precipitation suggest that the climatic mass budget rate in

2004–2009 was not substantially different from the 1980–2009 period. New and future satellite missions like CryoSat-2 (launched 2010), ICESat-2 (~2016) and GRACE Follow-On (~2016) will be essential for determining possible trends in the longer-term mass budgets of Arctic glaciers.

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References

Adler, R. F., et al. (2003), The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–present), *J. Hydrometeorol.*, *4*(6), 1147–1167, doi:10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2.

Bassford, R. P., M. J. Siegert, J. A. Dowdeswell, J. Oerlemans, A. F. Glazovsky, and Y. Y. Macheret (2006), Quantifying the mass balance of ice caps on Severnaya Zemlya, Russian High Arctic. I: Climate and mass balance of the Vavilov Ice Cap, *Arct. Antarct. Alp. Res.*, *38*(1), 1–12, doi:10.1657/1523-0430(2006)038[0001:QTMBOI]2.0.CO;2.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*(656), 553–597, doi:10.1002/qj.828.

Dowdeswell, J. A., M. R. Gorman, A. F. Glazovsky, and Y. Y. Macheret (1994), Evidence for floating ice shelves in Franz Josef Land, Russian High Arctic, *Arct. Alp. Res.*, *26*(1), 86–92, doi:10.2307/1551882.

Dowdeswell, J. A., et al. (1997), The mass balance of circum-Arctic glaciers and recent climate change, *Quat. Res.*, *48*(1), 1–14, doi:10.1006/qres.1997.1900.

Dowdeswell, J. A., et al. (2002), Form and flow of the Academy of Sciences Ice Cap, Severnaya Zemlya, Russian High Arctic, *J. Geophys. Res.*, *107*(B4), 2076, doi:10.1029/2000JB000129.

Gardner, A. S., and M. Sharp (2007), Influence of the Arctic circumpolar vortex on the mass balance of Canadian High Arctic glaciers, *J. Clim.*, *20*(18), 4586–4598, doi:10.1175/JCLI4268.1.

Gardner, A. S., G. Moholdt, B. Wouters, G. J. Wolken, D. O. Burgess, M. J. Sharp, J. G. Cogley, C. Braun, and C. Labine (2011), Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago, *Nature*, *473*(7347), 357–360, doi:10.1038/nature10089.

Glazovsky, A. F., and Y. Y. Macheret (2006), Eurasian Arctic, in *Glaciation in North and Central Eurasia in Present Time* [in Russian], edited by V. M. Kotlyakov, pp. 97–114, Nauka, Moscow.

Govorukha, L. S. (1989), *Modern Glaciation of the Soviet Arctic* [in Russian], Gidrometeoizdat, St. Petersburg, Russia.

Huffman, G. J., R. F. Adler, D. T. Bolvin, and G. Gu (2009), Improving the global precipitation record: GPCP Version 2.1, *Geophys. Res. Lett.*, *36*, L17808, doi:10.1029/2009GL040000.

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

Korona, J., E. Berthier, M. Bernard, F. Remy, and E. Thouvenot (2009), SPIRIT. SPOT 5 stereoscopic survey of Polar Ice: Reference images and topographies during the fourth International Polar Year (2007–2009), *ISPRS J. Photogramm.*, *64*(2), 204–212, doi:10.1016/j.isprsjprs.2008.10.005.

Kotlyakov, V. M., A. M. Dyakova, V. S. Koryakin, V. I. Kravtsova, G. B. Osipova, G. M. Varnakova, V. N. Vinogradov, O. N. Vinogradov, and N. M. Zverkova (2010), Glaciers of the former Soviet Union, in *Glaciers of Asia*, edited by R. S. Williams Jr. and J. G. Ferrigno, *U.S. Geol. Surv. Prof. Pap.*, *1386-F*, F1–F58.

Moholdt, G., C. Nuth, J. O. Hagen, and J. Kohler (2010), Recent elevation changes of Svalbard glaciers derived from ICESat laser altimetry, *Remote Sens. Environ.*, *114*(11), 2756–2767, doi:10.1016/j.rse.2010.06.008.

Moholdt, G., T. Heid, T. Benham, and J. A. Dowdeswell (2012), Dynamic instability of marine glacier basins of the Academy of Sciences Ice Cap, Russian High Arctic, *Ann. Glaciol.*, in press.

Nuth, C., G. Moholdt, J. Kohler, J. O. Hagen, and A. Kääb (2010), Svalbard glacier elevation changes and contribution to sea level rise, *J. Geophys. Res.*, *115*, F01008, doi:10.1029/2008JF001223.

Ohmura, A. (2010), Completing the World Glacier Inventory, *Ann. Glaciol.*, *50*(53), 144–148, doi:10.3189/172756410790595840.

Peltier, W. R. (2004), Global glacial isostasy and the surface of the ice-age Earth: The ICE-5 G (VM2) model and GRACE, *Annu. Rev. Earth Planet. Sci.*, *32*, 111–149, doi:10.1146/annurev.earth.32.082503.144359.

Radic, V., and R. Hock (2010), Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data, *J. Geophys. Res.*, *115*, F01010, doi:10.1029/2009JF001373.

Rodell, M., et al. (2004), The global land data assimilation system, *Bull. Am. Meteorol. Soc.*, *85*(3), 381–394, doi:10.1175/BAMS-85-3-381.

Saha, S., et al. (2010), The NCEP Climate Forecast System Reanalysis, *Bull. Am. Meteorol. Soc.*, *91*(8), 1015–1057, doi:10.1175/2010BAMS3001.1.

Screen, J. A., and I. Simmonds (2010), The central role of diminishing sea ice in recent Arctic temperature amplification, *Nature*, *464*(7293), 1334–1337, doi:10.1038/nature09051.

Sharov, A. (2010), *Satellite Monitoring and Regional Analysis of Glacier Dynamics in the Barents-Kara Region (SMARAGD)*, Joanneum Res. Forschungsges. mbH, Graz, Austria.

Smith, B. E., H. A. Fricker, I. R. Joughin, and S. Tulaczyk (2009), An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008), *J. Glaciol.*, *55*(192), 573–595, doi:10.3189/002214309789470879.

Sole, A., T. Payne, J. Bamber, P. Nienow, and W. Krabill (2008), Testing hypotheses of the cause of peripheral thinning of the Greenland Ice Sheet: Is land-terminating ice thinning at anomalously high rates?, *Cryosphere*, *2*, 205–218, doi:10.5194/tc-2-205-2008.

Svendsen, J. I., V. Gataullin, J. Mangerud, and L. Polyak (2004), The glacial history of the Barents and Kara sea region, in *Quaternary Glaciations: Extent and Chronology—Part 1: Europe*, *Dev. Quat. Sci.*, vol. 2, edited by J. Ehlers and P. Gibbard, pp. 369–378, Elsevier, Amsterdam.

Wahr, J., M. Molenaar, and F. Bryan (1998), Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, *103*(B12), 30,205–30,229, doi:10.1029/98JB02844.

Williams, M., and J. A. Dowdeswell (2001), Historical fluctuations of the Matusevich Ice Shelf, Severnaya Zemlya, Russian High Arctic, *Arct. Antarct. Alp. Res.*, *33*(2), 211–222, doi:10.2307/1552222.

Wouters, B., D. Chambers, and E. J. O. Schrama (2008), GRACE observes small-scale mass loss in Greenland, *Geophys. Res. Lett.*, *35*, L20501, doi:10.1029/2008GL034816.

Zeeberg, J., and S. L. Forman (2001), Changes in glacier extent on north Novaya Zemlya in the twentieth century, *Holocene*, *11*(2), 161–175, doi:10.1191/095968301676173261.

Zwally, H. J., et al. (2002), ICESat's laser measurements of polar ice, atmosphere, ocean, and land, *J. Geodyn.*, *34*(3–4), 405–445, doi:10.1016/S0264-3707(02)00042-X.

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, T. Herring, B. Minster, J. Spinhirne, and R. Thomas (2010), GLAS/ICESat L1B Global Elevation Data V031, 20 February 2003 to 11 October 2009, digital media, Natl. Snow and Ice Data Cent., Boulder, Colo.