Mass Balance of the Russian High Arctic Archipelagoes Between 2002 and 2017

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Abstract:

We evaluate the mass balance of the Russian High Arctic Archipelagoes (RHA) between April 2002 and August 2016 employing independent estimates obtained using time-variable gravity from the NASA/DLR GRACE mission and satellite altimetry data from the NASA ICESat and the ESA CryoSat-2 missions. Gravimetric and altimetric observations provide consistent results and show that over the period under analysis, glaciers in the region have lost mass at a rate of 15.7 ± 7 Gt/yr corresponding to a sea level contribution of 0.039 mm/yr. The mass loss increased after 2010, reaching a maximum rate of 24.6 ± 7 Gt/yr between 2010 and 2016. The increased mass loss was associated with high thinning rates at low elevations (below 500 m), with marine-terminating glaciers thinning significantly faster than those terminating on land. The mass loss process was associated with a shift in climatic conditions in the region due to enhanced atmospheric and ocean temperatures. These results indicate that glaciers in the region are sensitive to variations of both climatic mass balance and ice discharge.

Data and Methodology:

GRACE:
We use 156 (April 2002 – August 2016) monthly GRACE Level-2 RL05 gravity solutions provided by the Center for Space Research (CSR) at the University of Texas at Austin [2]. We replaced the C_{20} coefficients with values derived from Satellite Laser Ranging missions and account for the *l=1* omission by GRACE using coefficients calculated from a combination of GRACE and ocean model outputs.
We evaluate the GIA correction using outputs by a model reproducing the response of a compressible solid Earth to surface loads forced by the ICE-5G ice loading history [1].
Variations of Terrestrial Water Storage (TWS) are removed from the GRACE signal using the average of the **o**utputs **from** two land surface models: the Community Land Surface Model v4.5 and GLDAS/NOAH Land Surface Model v2 [9].

Altimetry:
We use ICESat data release 534 of the GLAS/ICESat L2 Global Land Surface Altimetry Data (GLA14) from the GLAS Science Computing Facility at NASA/GSFC and Cryosat-2 level2 (L2) baseline-C elevation data available in SAR interferometry mode (SARIn) [10-11].

Mascon Inversion:
We obtain ice mass change time series by applying the mascon inversion presented in [4]. We express the uncertainty associated to our estimates as a 95% confidence interval calculated considering the different components affecting our observations. In this case, the error of the regional ice mass estimates is due to the GRACE measurement error, GIA error, leakage error, ocean leakage error, and the statistical uncertainty of the fit.

Elevation Change Calculation:
Elevation change estimates are obtained employing a generalization of the plane-fit presented in [5]. This approach measures ice elevation change rates by fitting a time variable plane model function to elevation data available within a selected spatial range (see eq. 1).

$$F(x, y, t) = a_0 + a_x x + a_y y + a_t t \qquad (1)$$

ICESat: The plane fit is applied at multiple locations considering planes with centroids equally spaced along each satellite track. The spacing is chosen equal to one half the size of the plane radius (350 m), consecutive planes are therefore partially overlapping [5].

Cryosat-2: We map elevation changes over ice covered regions using the plane fit employing all available elevation measurement locations as plane centroids as in [12]. Given a single centroid, we locate all elevation data within 1,000 m from the plane centroid. We least-squares fit the time-variable plane function of the elevation observations.

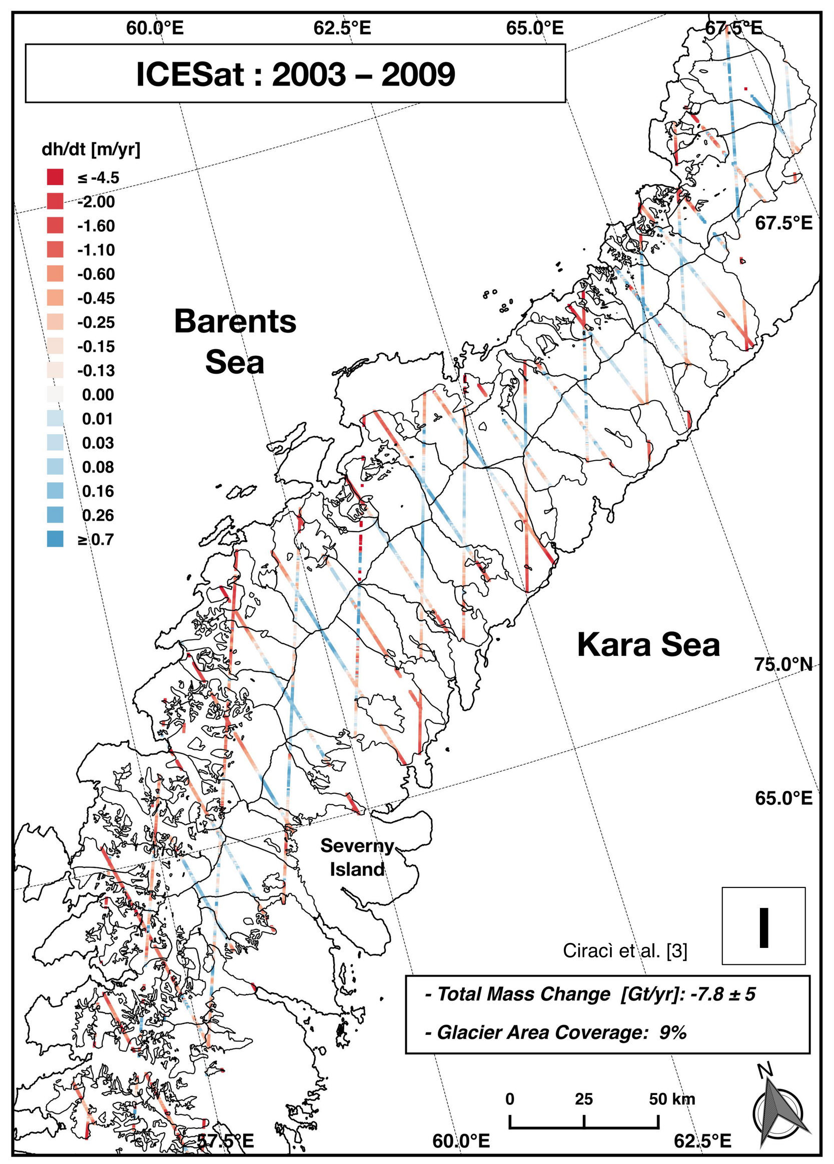
In Both Cases: To reduce the effect of erroneous elevation measurements, the least squares inversion is applied iteratively at each centroid location discarding all measurements with a residual value larger than 3 times the standard deviation of all residuals. In addition, we consider only measurements containing at least 15 observations, from more than 4 different sub-tracks (only for ICESat), and distributed on a temporal interval of at least 2 years. We reject elevation changes derived from planes with an estimated slope greater than 10°.

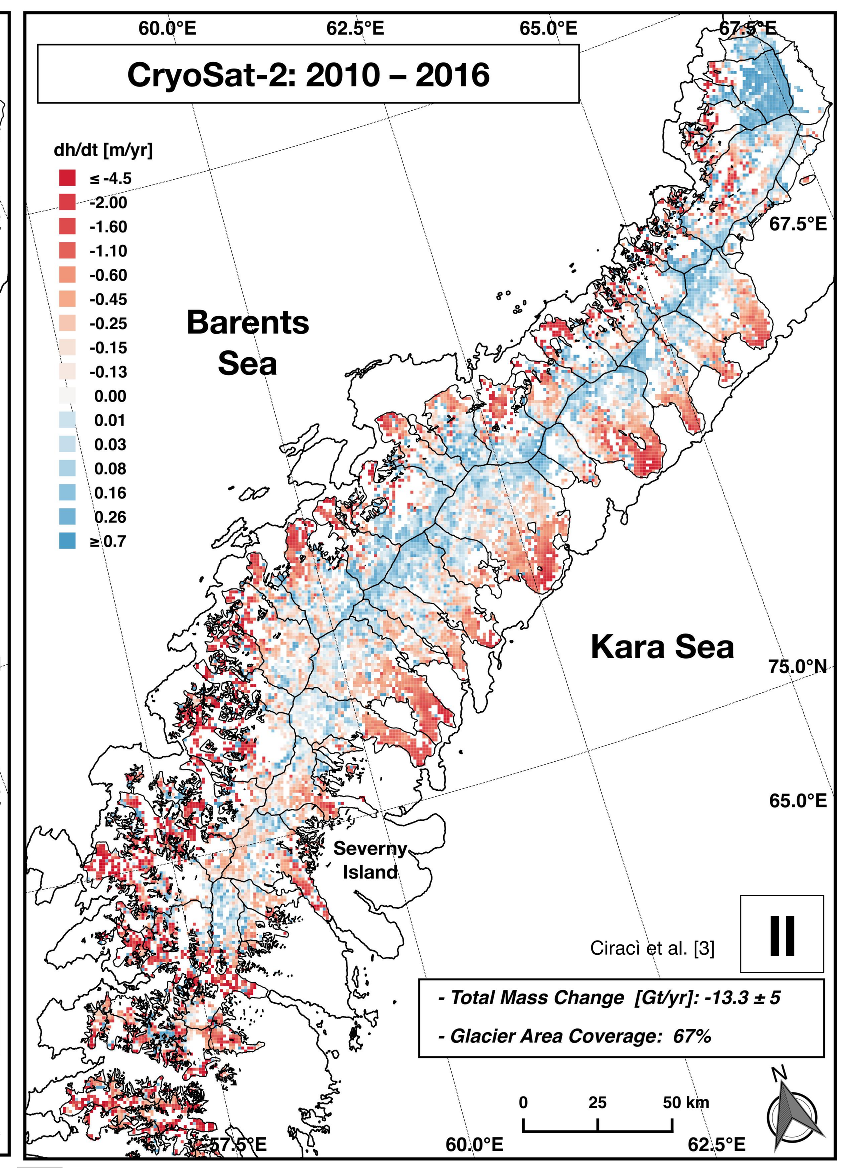
Averaging Procedure: We average the elevation change measurements obtained with ICESat and in CryoSat-2 on a 1km grid. The grid is defined on the standard NSIDC/North Polar Stereographic Projection (EPSG:~3413).

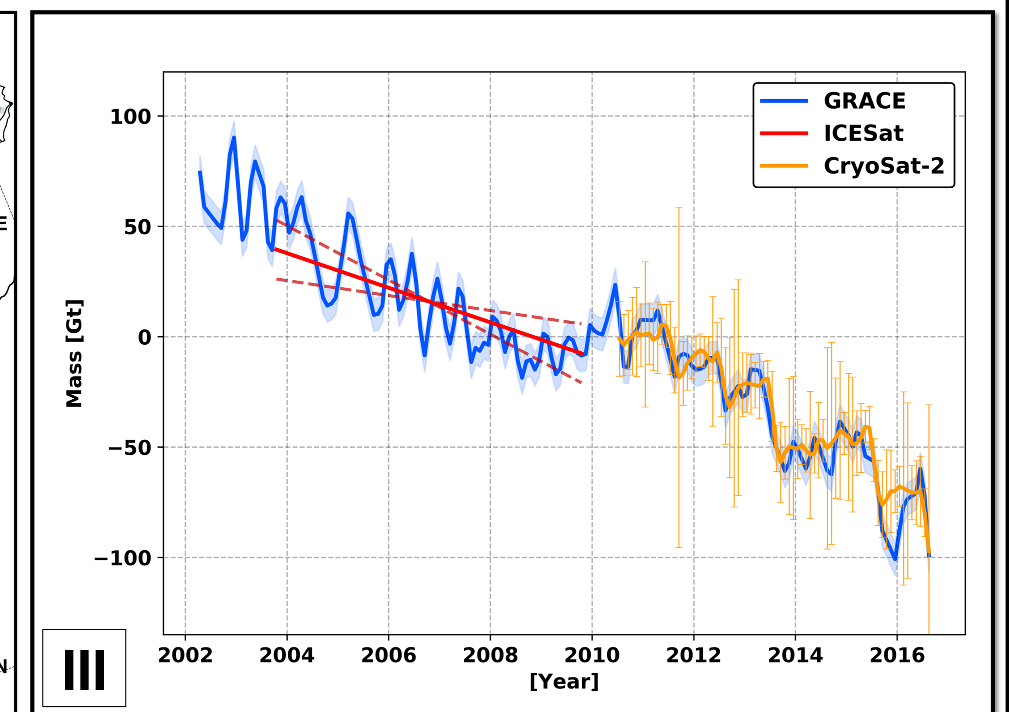
Volume to Mass Conversion: The ice volume change for each grid point is calculated by multiplying the relative mean elevation change value with the grid cell area. The total ice volume change is calculated by summing the contributions from all grid cells. We calculate the total ice mass change by multiplying the total volume change with the density of ice (0.917 g/cm^3) and consider the effect of this assumption in our error budget. We provide our final estimates considering uncertainty terms related to: elevation change measurement and extrapolation error; error in the considered glacier area; error associated with the non-uniform distribution of the elevation change measurements on the glacier surface; error associated with the volume to mass conversion.

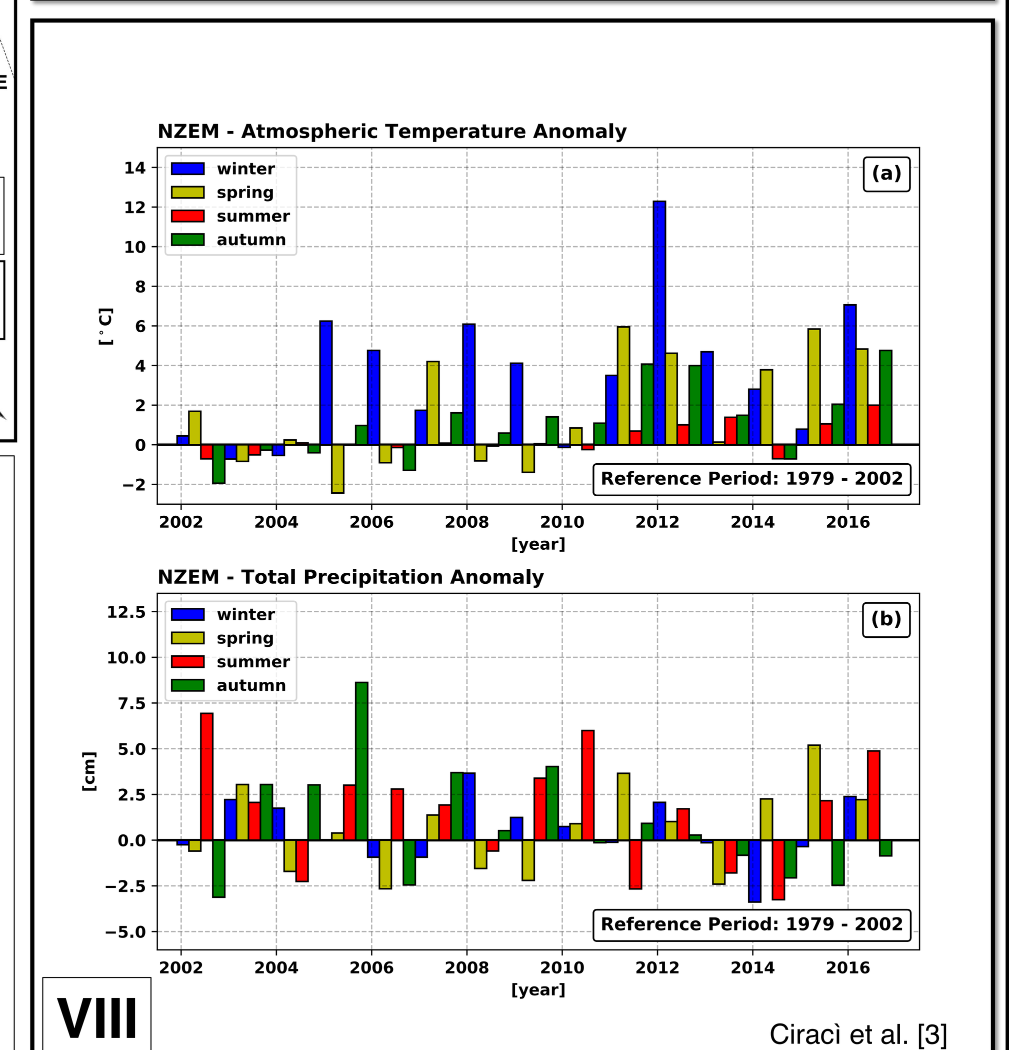
Atmospheric Temperatures and Total Precipitation:
We analyze surface temperatures using ERA-Interim reanalysis data [13]. We employ ``*monthly means of daily means*'' of 2-m temperature. We evaluate the seasonal mean temperatures and temporal anomalies with respect to the reference ~~the~~ time period 1979--2002 in order to investigate climate variability in the region. We also use *Synoptic Monthly Means* of Total Precipitation to evaluate accumulation variability during the period under analysis. We do not employ data from meteorological station in this case since these data are considered biased and underestimate solid precipitation [5].

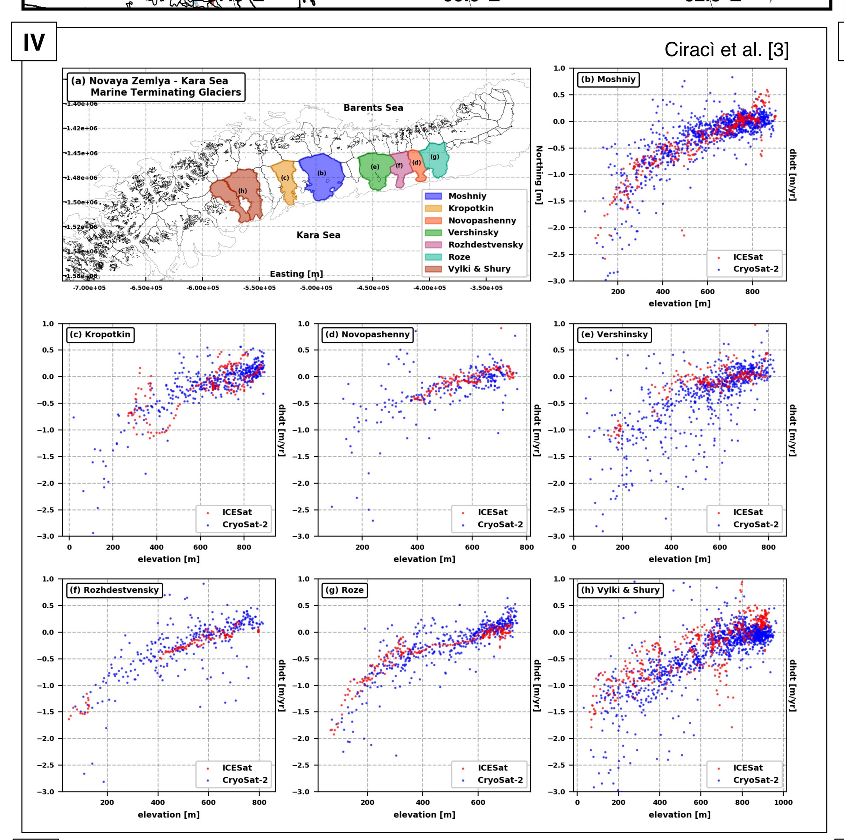
Novaya Zemlya (NZEM)

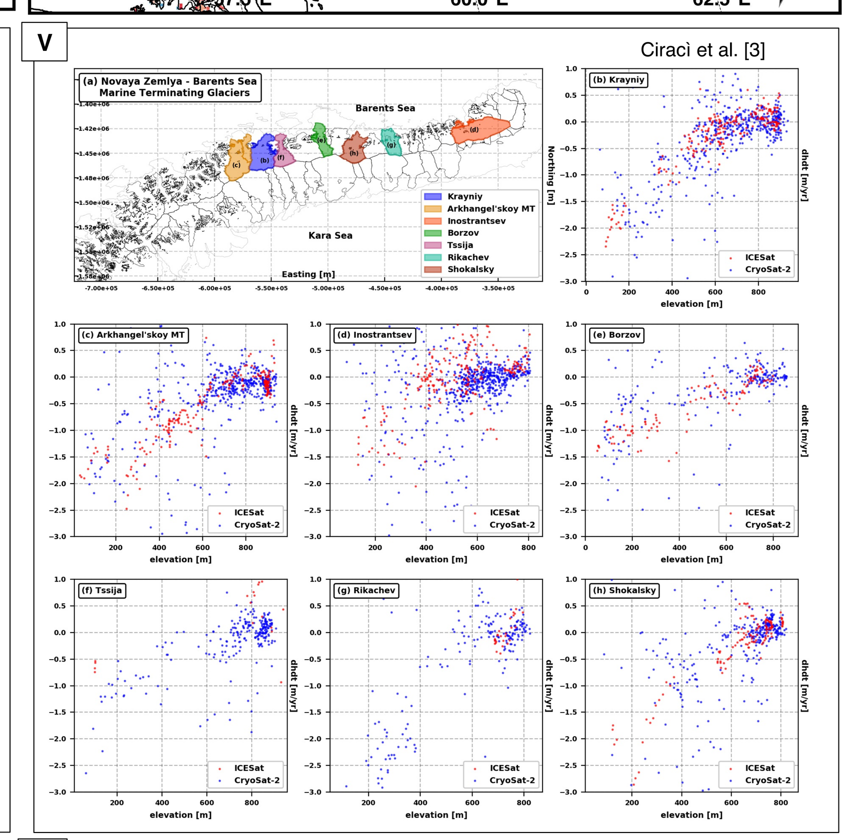


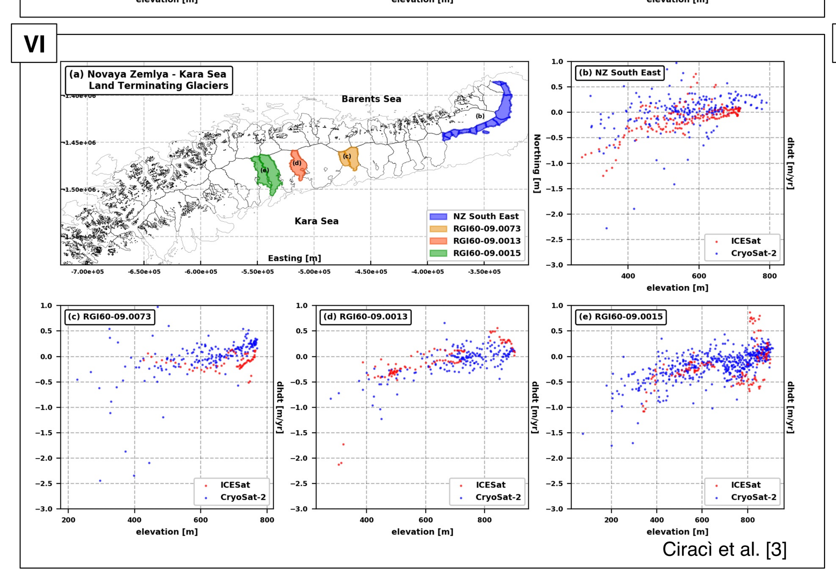












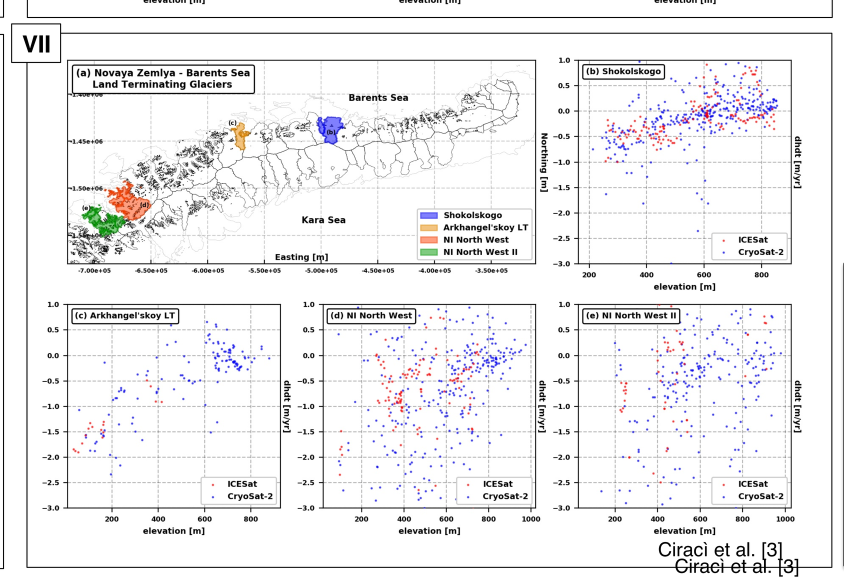


Figure I: Map of ice elevation change for NZEM glaciers estimated using ICESat for October 2003 to October 2009. Regional glaciers outlines are extracted from the sixth release of the Randolph Glacier Inventory [8].
Figure II: Map of ice elevation change for NZEM glaciers estimated using CryoSat-2 data for the time period July 2010 – July 2016. Regional glacier outlines are extracted from the glacier inventory by [9].
Figure III: In blue, NZEM glacier mass change time series derived from GRACE using a mascon inversion for the time period between April 2002 and August 2016 (monthly measurement error is blue shade). In red, regional glacier mass change using ICESat between October 2003 and October 2009 (range of variability in mass change is red dash). In orange, regional mass change time series calculated using CryoSat-2 between July 2010 and July 2016 with vertical error bars.
Figure IV–VI: Elevation vs. Elevation Changes calculated calculated using ICESat and CryoSat-2 for: (IV) marine-terminating glaciers facing the Barents Sea; (V) marine-terminating glaciers facing the Kara Sea; (VI) land-terminating glaciers facing the Barents sea; land-terminating glaciers facing the Barents Sea; (VII) land-terminating glaciers facing the Barents sea; land-terminating glaciers facing the Kara Sea.
Figure VIII: (a) Seasonal atmospheric Temperature Anomaly (ERA-Interim – monthly mean 2 m temperature) calculated using the interval between 1979 and 2002 as a reference period. **(b)** Total seasonal precipitation (ERA-Interim – Total Precipitation Synoptic Monthly Means) anomaly calculated using the time period 1979--2002 as a reference period.

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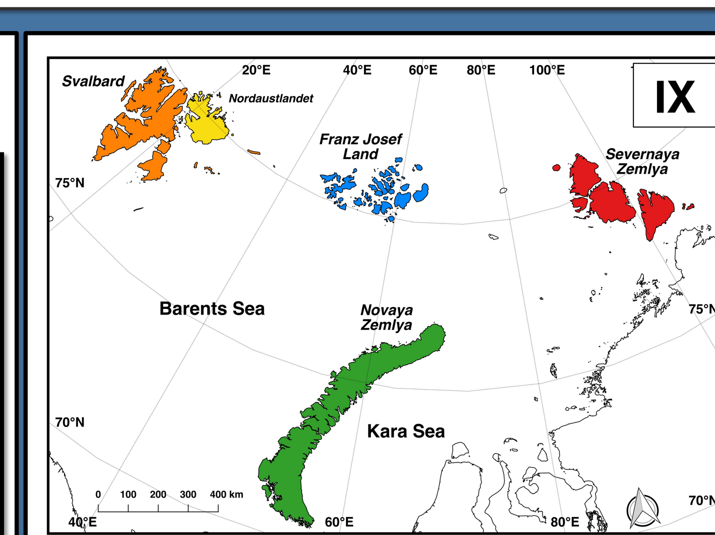

	2003–2009	2010–2016	2002–2016
NZEM	-10 ± 5	-14 ± 4	-8.7 ± 4
SZEM	-2.6 ± 3	-3.6 ± 3	-3.2 ± 3
FJL	-4.3 ± 4	-7 ± 3	-3.8 ±3
Nordaustlandet	–	–	–

Figure IX: Location Map. In green, the Novaya Zemlya; in red, Severnaya Zemlya, in blue Franz Josef Land; in orange, the Svalbard Archipelago; in yellow, Nordaustlandet Island.
Table 1: Regional Annual Mass Change Trends from GRACE expressed in Gigatonnes/ year [Gt/yr].

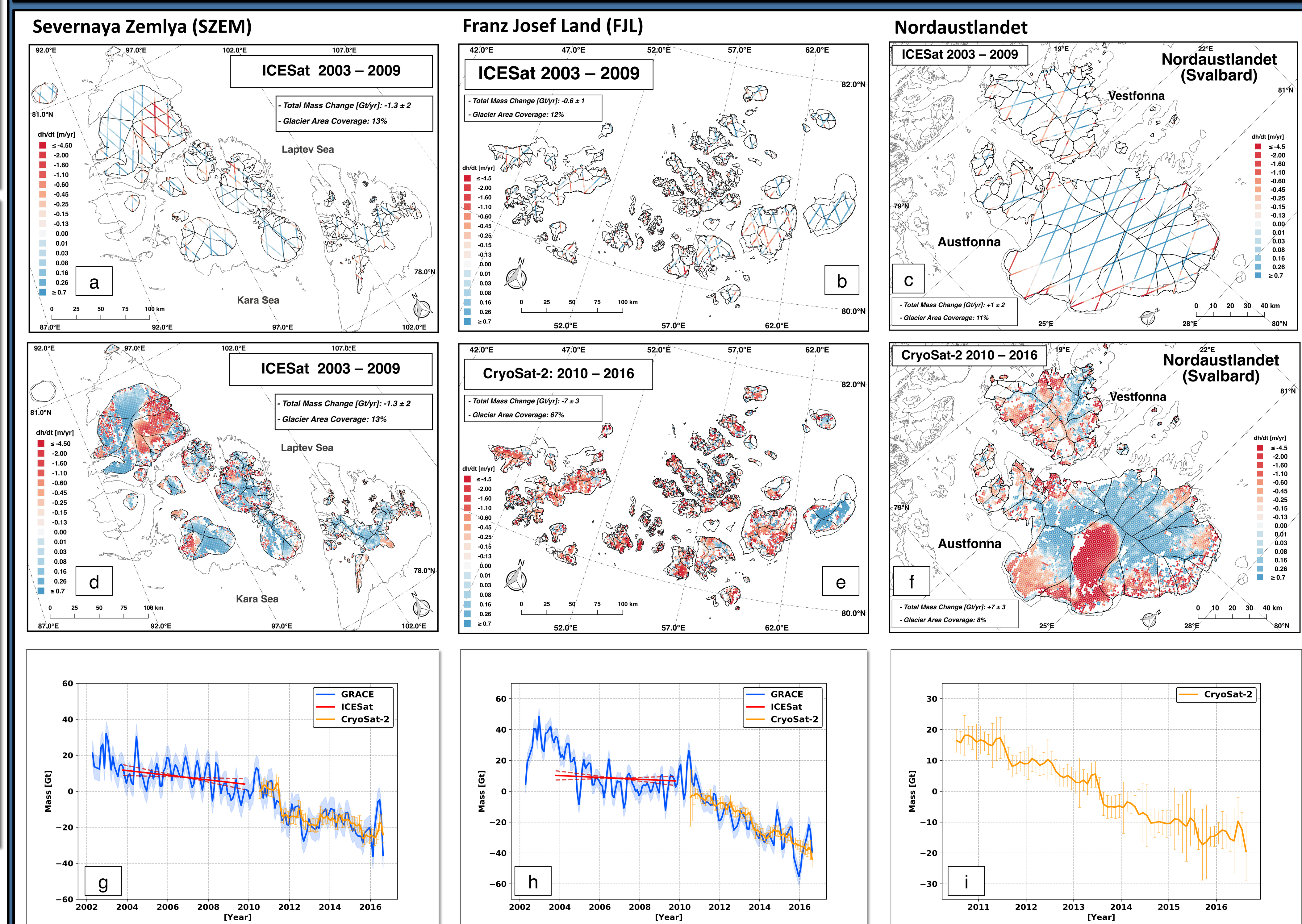

Figure X: (a – c) Map of ice elevation change for SZEM **(a)**, FJL **(b)**, and Noraustandlet **(c)** estimated using ICESat for October 2003 to October 2009. **(d — f)** Map of ice elevation change for SZEM **(d)**, FJL **(e)**, and Noraustandlet **(f)** estimated using CryoSat-2 the time period between July 2010 —July 2016. (g — i) **:**glacier In blue, mass change time series derived from GRACE between April 2002 and August 2016 (monthly measurement error is blue shade). In red, regional glacier mass change using ICESat between October 2003 and October 2009 (range of variability in mass change is red dash). In orange, regional mass change time series calculated using CryoSat-2 between July 2010 and July 2016 with vertical error bars.

Conclusions:

We present a combined analysis of multi-sensor data, using GRACE time-variable gravity for the entire mission, ICESat altimetry for the entire mission and CryoSat-2 altimetry until present to document the mass loss from the glaciers of the Russian High Arctic. We find that the mass loss in the western regions has been increasing over the entire period, with two brief pauses, and with a marked increase after 2010. This long-term trend and interannual variability are consistent with a sustained warming of the region, modulated by alternative phases of negative and positive North Atlantic Oscillation (NAO), which pause or reinforce the mass loss from RHA glaciers. With NAO remaining positive after 2010, the mass loss is now increasing faster than in the previous decade.
We find excellent agreement between the remote sensing techniques. Our altimetry estimate suggests the present-day mass loss is dominated by marine-terminating glaciers. In addition, the overall ice mass loss from the RHA glaciers is well above the estimated SMB change. Finally, our results indicate that the ocean plays a major role in the evolution of the RHA glaciers.

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