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MAIRES CONSORTIUM

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SUMMARY

The Deliverable D6.1 “Synthesis and Integration” reports on the integrated presentation of the main MAIRES land- and sea ice products in the form of satellite image maps brought together in the all-in-one “Atlas of the Ice Cover Fluctuations in the Eurasian High Arctic”. The Atlas can be readily accessed online at the project webpage http://dib.joanneum.at/MAIRES/index.php?page=atlas.

The Deliverable describes mapping goals and challenges, provides mapping specifications and shows several examples of final maps and map prototypes compiled in the Atlas.

Main methodical limitations are discussed and map quality characteristics are specified. Further perspectives are envisaged as well.

The technical note on the Atlas in *.pdf format can be downloaded from the start page of the issue (Fig. 1, left)

1 Introduction to Synthesis of Ice Cover Products and Change Maps

Precise maps depicting long-term elevation changes of land ice masses and seasonal changes of the sea ice cover represent an important instrument and indispensable basis for assessing Earth's cryosphere and obtaining quantitative data on the extent, accumulation, ablation, movement, calving flux and mass balance of ice bodies in documentary and human perceivable form. In the era of climate change, maps of ice-related trends are in great demand among polar and alpine environmentalists and widely used for studying relationships between the cryosphere and climate, fluctuations in sea level and salinity, estimating melt water availability, planning industrial activities and political argumentation in cold regions. "There is a pressing need for a regional-scale assessment of glacier and sea ice change based upon remote sensing observations and numerical modelling" (SWIPA 2011). However, precise and elaborate maps for the computer analysis of glacier state variables and volume changes in entire polar regions are still very small in number. These are rather scarce even in internet publications, not to speak of glacier atlases and inventories pretending to be the most comprehensive glacioclimatic compilations. Satellite maps of ice changes produced so far provide very heterogeneous, approximate and patchy information on mass balance characteristics, such as elevation change rates, equilibrium line altitude (ELA) and accumulation area ratio (AAR), subject to data availability and quality, and processing imperfections. The most surprising and probably the largest gap in the factual cartographic knowledge about glacier changes outside Greenland and Antarctica is observed in the Eurasian High Arctic representing the largest cluster of insular ice caps in the Old World. The mass balance of the northernmost insular ice caps in the Svalbard, Franz Josef Land, Novaya Zemlya, Severnaya Zemlya and De Long archipelagos is poorly known and these regions are scarcely mapped.

New extensive, albeit detailed remote sensing studies devoted to overall glacier change mapping and regional estimates of geodetic mass balance in the Eurasian Insular Arctic were carried out in the MAIRES frameworks using a synergetic combination of satellite altimetry and interferometry. Apart from high sensitivity to changes in glacier topography and independence of natural illumination, the major advantage of combining radar interferometry and altimetry, referred to as dual-sensor INSARAL technique, is the enhanced glacier-wide coverage with elevation change data and the high precision of elevation measurements achieved even in the case of insufficient ground control typical of glacial areas. This is important for the reliable modelling of topographic changes in glacier accumulation areas characterized by relatively sparse coverage with altimetric transects and corresponding underestimation of the accumulation signal by simplified mono-sensor techniques, such as those offered by Moholdt et al. (2010). Our 41 resultant maps of uniform quality cover the entire Eurasian Arctic Basin from Svalbard in the west to Wrangel Island in the east. Web versions of ice change maps accompanied with meta-data are brought together in the all-in-one form of an "Online Atlas of Ice Cover Fluctuations in the Eurasian Arctic".

2 Online Atlas of Ice Cover Fluctuations in the Eurasian High Arctic

The Online Atlas is a systemic collection of forty-one maps compiled in standard cartographic projections, typically UTM or polar stereographic, at multiple divisible scales; these are typically maps of the Eurasian High Arctic as well as several circum-arctic maps, which are thematically connected with each other and entirely cover all glacial areas in the Russian Insular Arctic. The main goal of the atlas is to represent the regime, mass balance and fluctuations of land- and sea ice resources in the Eurasian Arctic Sector as well as to determine and to interpret main forcing agents acting on the ice distribution in the High Arctic. The maps included in the Atlas depict glacier elevation, volume, density and mass changes in the Eurasian High Arctic for the period of 1950-2010s and other relevant glaciological processes, such as glacier calving (iceberg production), sea ice drift and glacial isostatic adjustment derived from satellite ERS and/or TanDEM-X interferometry and ICESat / CryoSat altimetry data in comparison with 60-year old reference elevation models. New map prototypes showing spatial distribution of mass balance characteristics in the heterogeneous field of gravity were generated and interpreted using long-term precipitation records and GOCE gradiometry data. The glacier change maps are combined into several groups depending on glacier dimensions: maps of separate ice caps, maps of large glacier complexes and observational maps of glacier changes in separate archipelagos (meso-regions) and in the entire macro-region. Together they constitute several map/scale series joined in the all-in-one form of an Online Atlas. Atlases have traditionally been bound into book form, while our maps in the atlas are in web-version multimedia formats *.html, *.mpg and *.pdf. The Atlas, its description and the maps constituting the Atlas are available free of charge and can be readily accessed online at our project webpage http://dib.joanneum.at/MAIRES/index.php?page=atlas. A screenshot representing an overview of the Atlas start and end page is given in Figure 1.

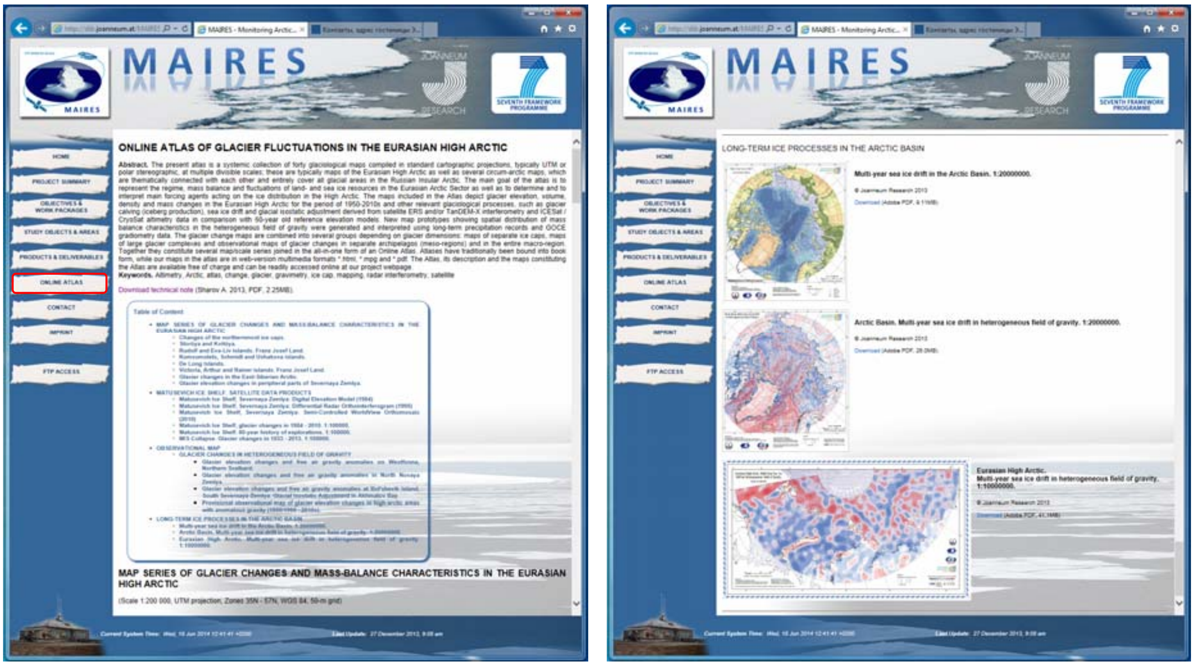


Figure 1. Screenshot of the Atlas start and end page

3 Mapping goals and challenges

The general objective of our mapping activities was to generate a new series of ice cover maps and mass-balance estimates from satellite EO, ground and cartographic data. These are to serve as an active framework for determining, interpreting, validating and inventorying the status and fluctuations of icescapes in the Eurasian High Arctic, and for gaining a better understanding of how ice reserves respond to climatic variations and endogenic forcing. In our practical mapping work the following specific goals were pursued:

- Overall mapping of icescape fluctuations in the Eurasian Arctic at working scales ranging from 1:100,000 to 1:2500,000 attaining a regional overview and high level of detail of change maps.
- Methodological modernization of the dual-sensor INSARAL technique towards the operational mapping and measurement of glacier elevation changes and mass balance characteristics (ELA, AAR, ΔV, etc.) in semi-automatic mode.
- Integral assessment and interpretation of ice volume changes at both local and regional level; verification of several still conjectural hypotheses about gravimetric impacts on glacioclimatic settings in the High Arctic.
- Map validation, web presentation and quality control, also in consultations with users.

The main challenge in completing the cartographic activities was the enormous dimensions of the region to be mapped and the scale of the work load this involved. The procurement of modern EO data and reference elevation models of uniform quality covering all insular ice caps and glacier complexes in the region was a serious effort. The work load related to the production of a single change map depends on the index of glaciation or sea ice extent, elevation range and data availability, and can be roughly estimated as one working day per 200 km² of ice area mapped at 1:100,000 scale. The amount of work involved in the generation of reference elevation models made up approximately a quarter of the total work load. In 3 years an extensive and consistent set of change maps was generated for approx. 45,000 km², or nearly half of the total glacier area on the Eurasian Arctic islands. Four people were directly involved in the mapping work in the period 2011 – 2014.

4 Mapping specifications

Official mapping limits were set so that all the most remote and least studied ice caps in the northern periphery of the Eurasian shelf seas had to be covered by elevation change maps. Thorough information about glacier fluctuations in this marginal area is lacking, but is very much in demand since it may constitute the relevant benchmark for judging and projecting climate change impacts in the entire Arctic. The region extends approx. 2,600 km from Nordaustlandet, Kvitöya and Victoria islands in the west through Rudolph, Eva-Liv, Ushakova, Schmidt and Komsomolets islands in the north to De Long islands in the east (Fig. 2). The situation of insular ice masses close to the edge of summer minimum sea ice proved helpful in analysing spatial asymmetry of the glacier accumulation signal.

At present our new map series includes 37 maps representing glacier elevation, area and volume changes in the Eurasian High Arctic in the period from the 1950s to the 2010s with 50-m grid in the UTM projection (Zones 35N – 57N, WGS 84) at 1:200,000, 1:100,000 or 1:500,000 scales. Besides, 4 small-scale observational maps of sea ice cover fluctuations and 10 map prototypes representing the spatial distribution of glacier elevation changes and mass balance characteristics in the heterogeneous field of gravity as well as the spatial correlation between the annual glacier change rate and the magnitude of geopotential were included into the map series. Several change maps represent the Matusevich Ice Shelf, 241 km² in size (1980), the largest floating glacier in the Old World. Glacier changes in meso-regions with different survey histories were quantified in average annual rate values, i.e. in [m/a]. The maps comply with Russian map accuracy standards.

The reference elevation models (DEM0) with 50-m posting were derived from Russian and Norwegian 1:200,000 and 1:100,000 topographic maps representing the glacier state as surveyed in the 1950s and 1980s, respectively. The reference observation period ranges accordingly from 60 to 30 years. All DEMs in geotiff format have been placed on the MAIRES FTP server. In total, 450 ice caps and glacier complexes, 5 to 5,500 km² in extent, situated in a very cold and dry climate with typically overcast skies and episodic precipitation were mapped with standard vertical accuracy. Numerous separate small-size mountain glaciers with an area less than 5 km² outside glacier complexes were also mapped, albeit with varying levels of accuracy, depending on the available coverage with altimetry data. The geometric and semantic identity of the maps published at different scales was ensured by the methodological uniqueness, systematic tests and adjustments.

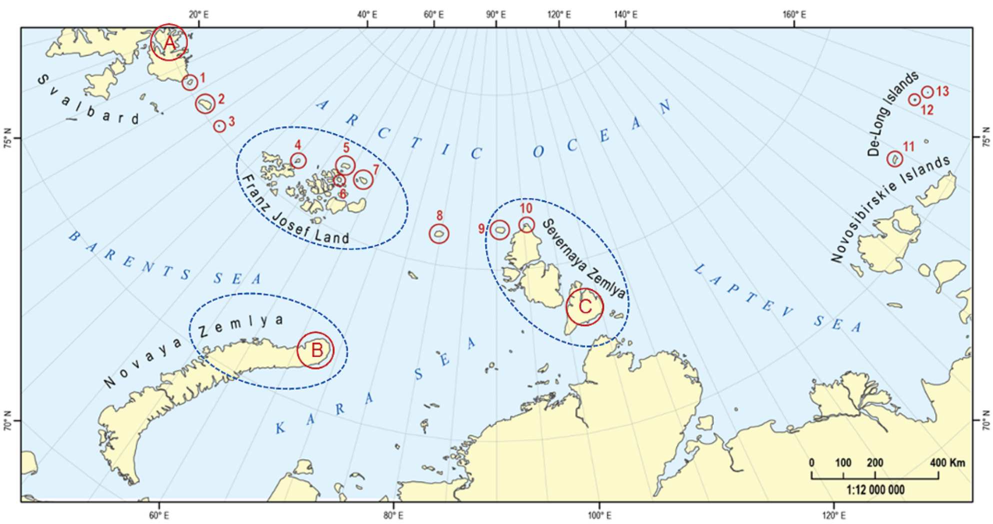


Figure 2. Location of mapped ice caps and glacier complexes

5 Map examples

The systematic application of the INSARAL technique described in D.3.1 to differential processing of multisource satellite data brought consistently good results for glaciers of different sizes, elevation ranges, morphological types and change rates. The elevation change models served as a basic layer for the generation of full-value glacier change maps in accordance with the accuracy and content requirements of traditional glaciological maps. Cartographic styling, drafting, scribing and editing were performed using the ArcInfo 9.3 and Adobe Illustrator CS4 software. All 37 glacier change maps with similar specifications, standardized legends and attractive design were produced relatively quickly and at low cost. The data processing and mapping costs of € 95,000 were a fraction of those incurred by others using alternative survey methods.

Separate map segments representing negative (ablation) and positive (accumulation) elevation changes were coloured in shades of magenta and cyan, respectively. Ten gradations of glacier elevation changes were specified for all maps. The resultant change maps were combined into several groups depending on glacier dimensions: maps of separate ice caps, maps of large glacier complexes and observational maps of glacier changes in separate archipelagos (meso-regions) and in the entire macro-region. Together they constitute the map/scale series, which is readily accessible at http://dib.joanneum.at/MAIRES/. In the following we show several examples of these change maps. For the sake of conciseness we omit map legends and surround details. Some maps are dissected with straight dotted lines representing ICESat differential transects in order to illustrate the spatial distribution of altimetric control in the area.

Figure 3 represents glacier elevation changes in 1950-2010s on the De Long Islands occupied with relatively small ice caps and few outlet glaciers in the far east of the exploration region (Nos. 11, 12, 13 in Fig. 2). To our knowledge, these are the first maps of glacier changes published in the history of exploration in this archipelago. We recognized that the volume of Toll Ice Cap, the largest on De Long Islands, increased by 0.2 km³ over the past 60 years, while the area of glaciation on this island decreased from 72 to 60.3 km². The area of the ice cap at Jeanette Island, the smallest in our study, decreased from 0.4 km² to 0.15 km² (62%).

The satellite image map in Figure 4 demonstrates the recent collapse of the Matusevich Ice Shelf occured in spring 2012. The Matusevich Ice Shelf (MIS), the largest floating glacier in the Old World provides was discovered in 1931 and first mapped by O.v.Gruber in 1933. It is fed by 10 convergent outlet glaciers flowing from Rusanov and Karpinskiy ice caps into the inner part of Matusevich Fjord with water depths reaching 170 meters and more. Both ice caps suffer the negative mass balance since the mid of XXth century. M.Williams and J.Dowdeswell mentioned several MIS breakups and forecasted another breakup for the present time (2001). Our remote sensing studies carried out in 2010s using satellite stereometry, altimetry and radar interferometry data revealed an essential lowering of the ice plug surface up to 40 m, some decrease in the shelf area from 240 to 210 sqkm and ice flow acceleration on several outlet glaciers from 50 to 60 m/year. In the TanDEM-X SAR-interferogram taken over the ice shelf in spring 2011 we detected several new islands in the interior part of the ice shelf. An accidental breakup of the ice shelf pictured in the Quick Bird image of September 2012 happened somewhen in 2012. There was a sequence of severe storms with strong offshore winds recorded at the Golomyanny and Fedorov meteorological stations in April-May 2012 and we suppose that this was the main cause for the disintegration event. Mean annual temperatures didn't reach the climatic limit of -5° C for the viability of ice shelves in the Antarctica, yet the steady increase in the air and water temperature was reported. Our new satellite image map represents the Matusevich Ice Shelf collapse with its total remaining surface of 98 sqkm broken into 3 unequal parts (Fig. 4). Large tabular icebergs, i.e. MIS remnants escaped from the Matusevich Fjord and can be found along the eastern shore of Severnaya Zemlya.

The map fragment in Figure 5 shows elevation changes on the largest glacier complex at Bol'shevik Island, Severnaya Zemlya, a prominent aggregate of 8 ice caps, 16 hanging glaciers, 21 outlet glaciers terminating on the land and 3 tidewater outlets with a total area of 2,600 km² and heterogeneous glacier accumulation–ablation in 1980-2010s. The dashed red line represents the equilibrium line. Bold dashed white lines are gravity anomaly isolines derived from GOCE data, Release 3 TIM, not to be confused with topographic contours.

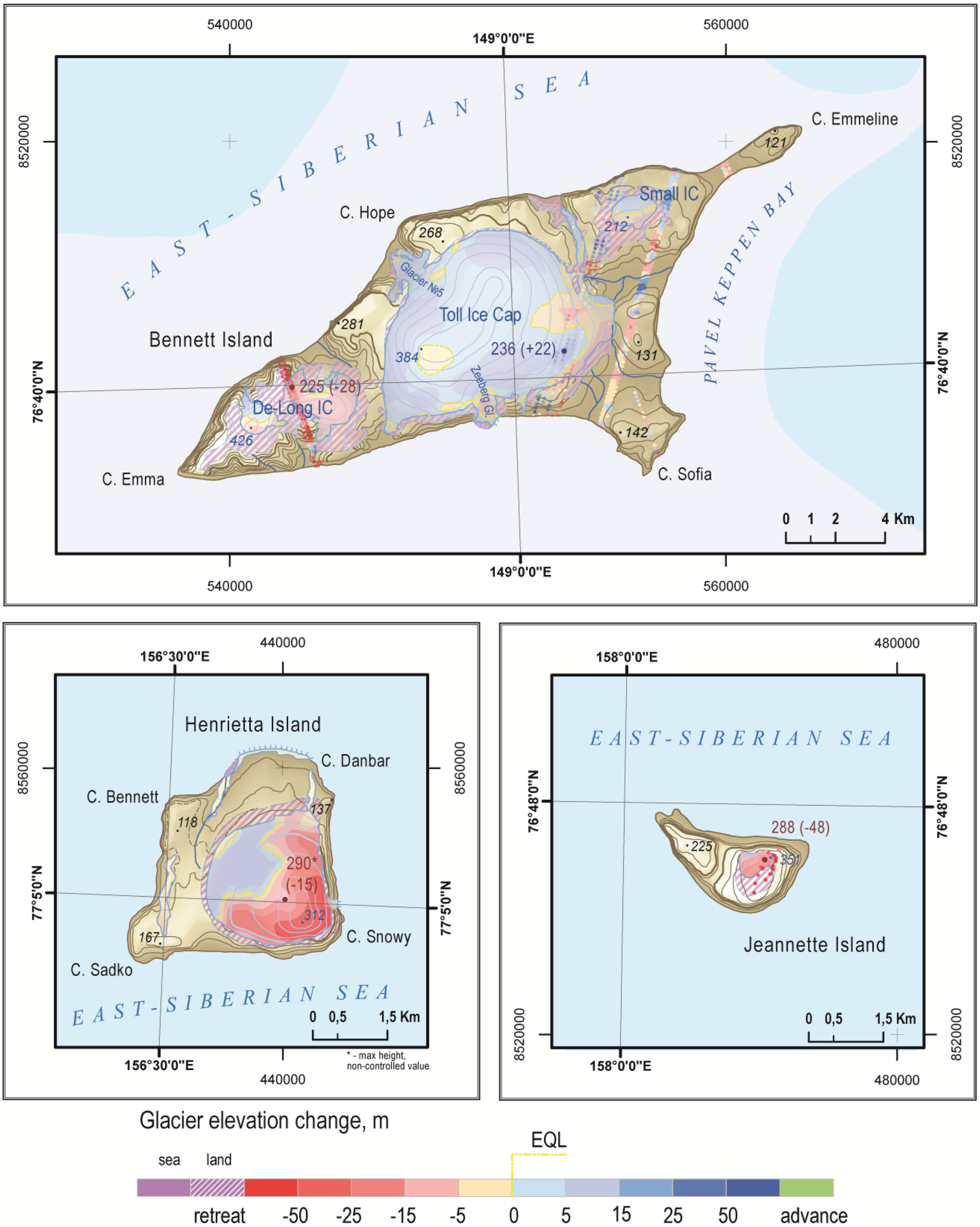


Figure 3. Map examples of glacier elevation changes on separate ice caps on De Long Islands

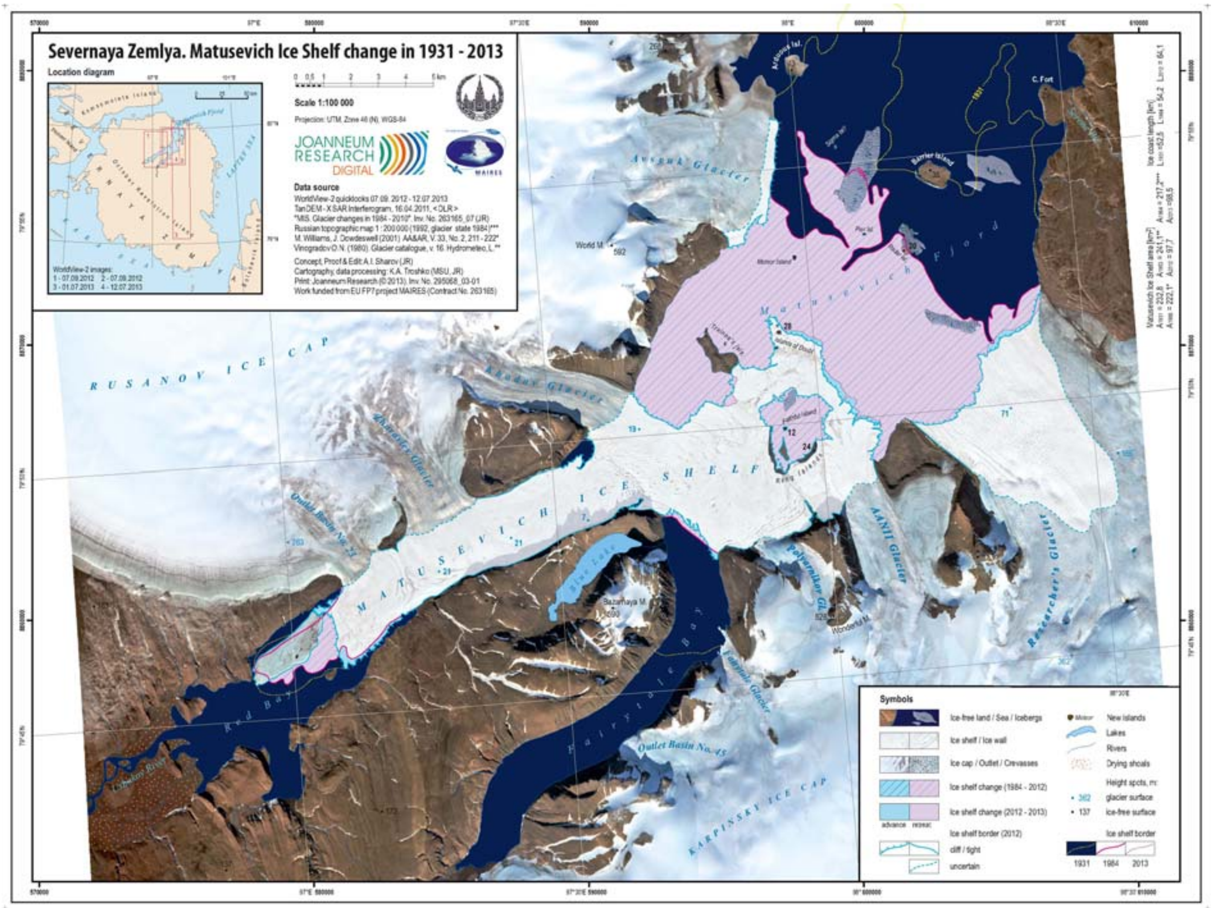


Figure 4. Matusevich Ice Shelf change in 1931 - 2013

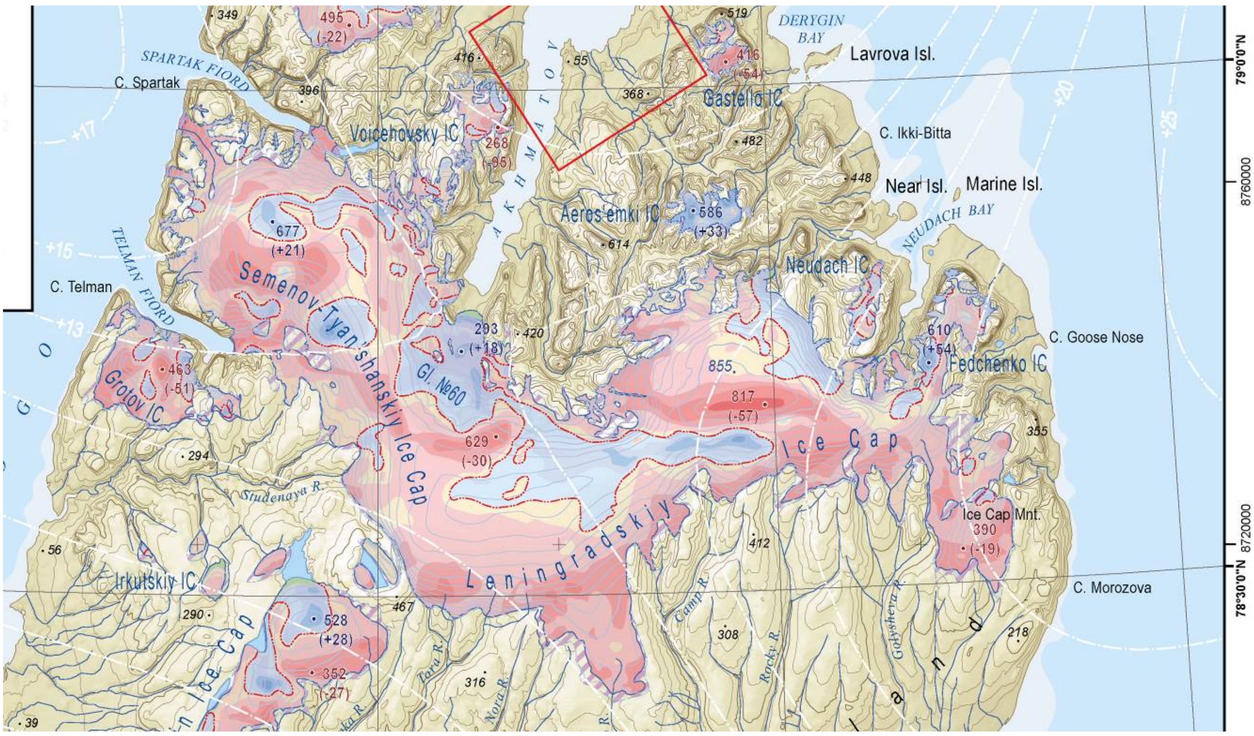


Figure 5. Elevation changes on Semenov-Tyanshanskiy – Leningradskiy Glacier Complex (C in Fig. 2)

Our maps show that ablation processes are strongly manifested on southern slopes, while the accumulation of snow was generally higher on northern slopes. A strong accumulation signal with a magnitude of up to 30 m was detected at the top of slow-moving ice caps at Ushakova, Schmidt and Komsomolets islands.

6 Map prototypes

The idea to combine glacier elevation change maps with the raster grid of free-air gravity anomalies derived from GOCE data arose from the observation that nearly all growing ice caps were situated in the close vicinity of strong positive gravity anomalies. Our natural desire to investigate the relationship between glacioclimatic settings and gravity anomalies led to the generation of several combined products, which showed a strong positive distance-weighted correlation between the magnitude of free-air gravity anomalies and gravity gradients on one hand and glacier elevation changes on the other, while it was noted that the correlation decreases in humid and mountainous areas [8].

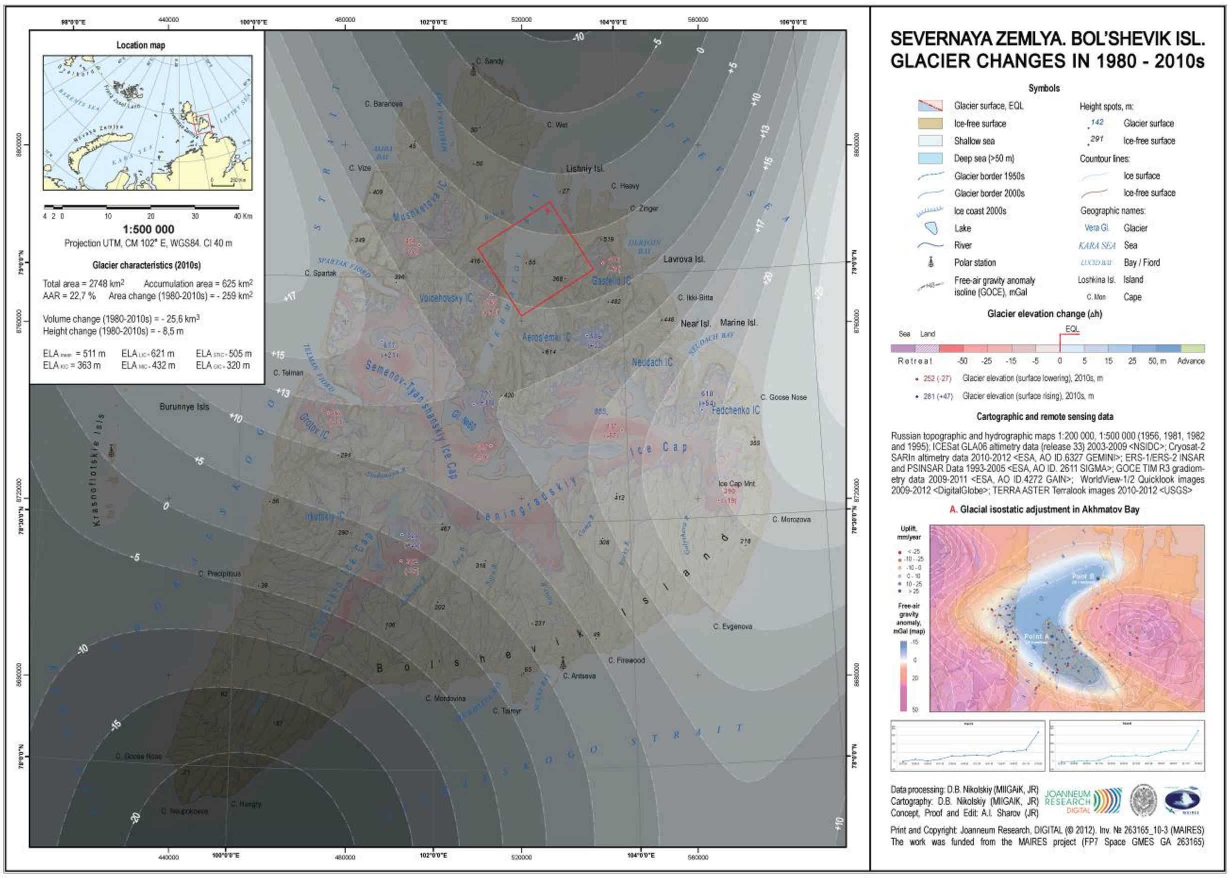
An example in Fig. 6 (top) demonstrates glacier changes in the area of the gravity anomaly over Bol'shevik Island, Severnaya Zemlya, with the anomaly magnitude given in shades of grey. Apart from the calculation of spatial correlation, the dh-dg combination allows glacier density variations to be assessed analytically by calculating the raster grid ratio based on the modification of the Garland formula (1977), under the assumption that all temporal changes of density $\Delta\rho$ occur inside the ice cap, as follows

$$\Delta\rho \cong \frac{\Delta g_{fa}}{2\pi \cdot G \cdot h} - \rho \cdot \frac{\Delta h}{h} \quad \text{or simply} \quad \rho \approx \frac{g_{fa}}{2\pi \cdot G \cdot \Delta h},$$

where Δh denotes glacier elevation change; g_{fa} is the magnitude of free-air gravity anomaly, ρ is the average density of lost / gained glacier material and G is the gravitational constant.

The map prototype shown in Fig. 6 (bottom) suggests the existence of a sub-glacial lake in the area of the extreme density index. The map inset placed in the bottom right corner of Fig. 6 represents the glacio-isostatic adjustment pattern in Akhmatov Bay determined in the sequence of 15 ERS SAR scenes (1993-2005) using the persistent-scatterer INSAR technique. The average rate of glacio-isostatic uplift in the ice-free area of the negative gravity anomaly marked in blue does not exceed 8 mm/a, which makes less than 40 cm for the semi-centennial reference period. We thus neglected this effect in the accuracy control of the glacier change maps.

The results of quantitative comparison and joint interpretation of the resultant map prototypes and long-term precipitation data series obtained at 57 coastal meteorological stations in the study region proved the systematic occurrence of extremely heavy snowfalls in the areas of positive gravity anomalies. Further statistical analysis of long-term precipitation records showed that the precipitation amount, annual number of strong snowfalls and the intensity of snow accumulation are closely dependent on the strength of gravity anomalies nearby. This observation attests to the correctness of the supposition about gravitational forcing on glacioclimatic settings at sub-regional scale.



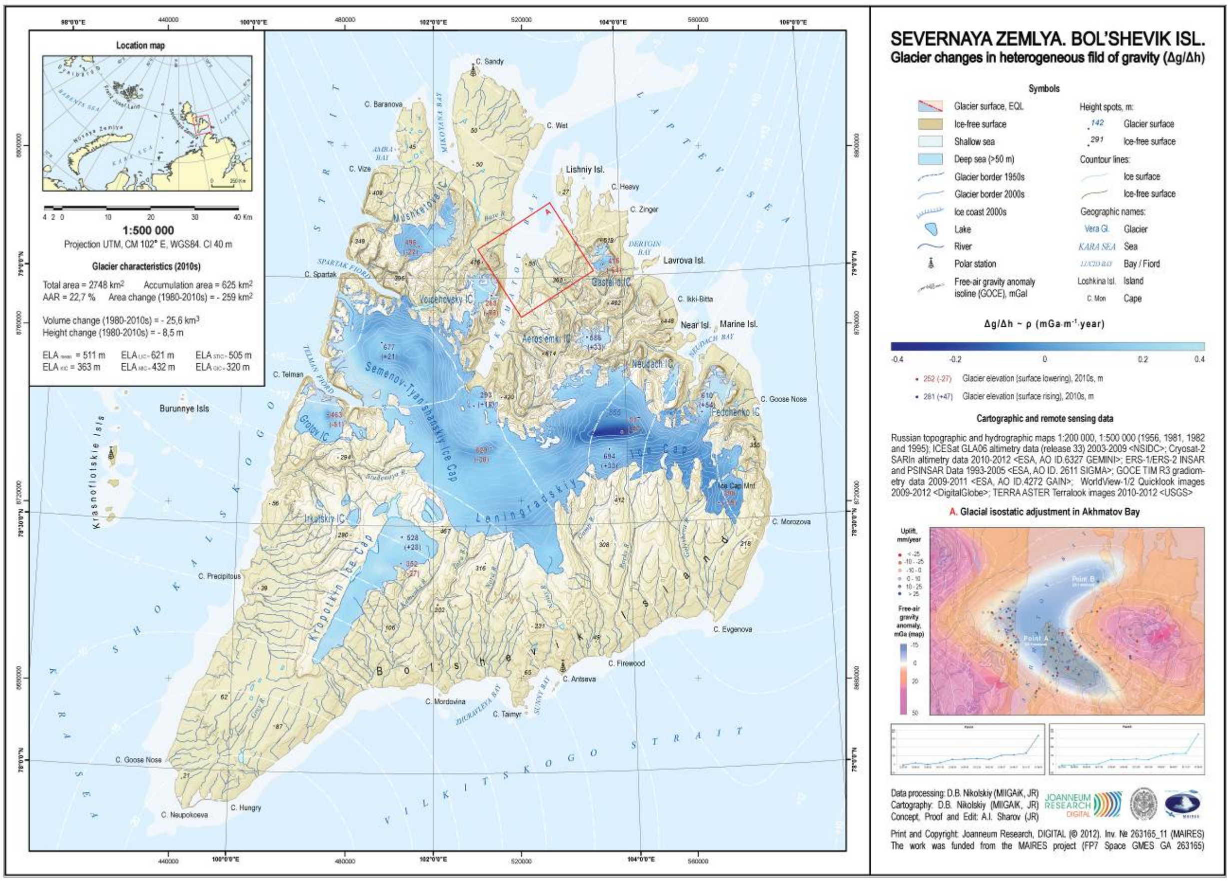


Figure 6. Small-size map prototypes: glacier change in anomalous gravity (top)**;** density parameter (b)

7 Methodical limitations & map quality control

The vertical accuracy of glacier elevation change products is frequently the critical factor limiting the technical feasibility of the entire mapping activity. The dominant contribution to the error budget was from the reference elevation models derived from available topographic maps. In our case the influence of time-dependent errors and inaccuracies of the reference elevation data characterized by rms vertical errors of ± 6 m, i.e. one-fourth of the average contour interval, was reduced due to the 60-year observation period. The magnitude of the change signal on many study ice caps is 10 times larger. The accuracy of glacier change products was controlled with altimetry data and verified during the field campaign in Franz Josef Land using DGPS Novatel DL4 and georadar GSSI SIR-3000. The rms difference between glacier elevations determined in the lab and those measured in the field was ± 3.7 m, while the rms error of height changes was ± 0.3 m/a. The positional accuracy was about 50 m. The existence of positive elevation changes was proved at all check points and the thickness of annual accumulation layers correlated well with glacier changes.

The co-registration accuracy of multi-source satellite data was estimated at ± 1.2 pixel rms. Glacier elevation changes on several study ice caps were repeatedly determined with ICESat GLA06 data releases 28, 29 and 33, and statistically compared. The root mean square difference between test determinations was given as less than 1 m rms and the lidar oversaturation effect was neglected in further work. The residual cumulative influence of random ablation/accumulation processes, snow compaction and radar penetration effects on height measurements due to the “age” difference between available interferometry and altimetry data did not exceed ±1 m. The cumulative volumetric accuracy was estimated at 0.2 km³ and the relative error of the volume change measurement was lower than 5%.

The existence of fast-flowing outlet glaciers at several ice caps renders data processing difficult and complicates the calculation of separate mass-balance components because of generally unknown glacier velocities and ice discharge values for the mid-20th century. Hence only net balance values were determined for those ice caps. Other ice caps belong to the category of slow-moving or passive glaciers with simpler estimation of mass balance characteristics. The lack of bulk density data brings about some difficulties in converting the resultant elevation and volume change products into glacier mass changes. It is believed that our dh-dg map prototypes can assist in tackling this problem. Still, there is some suspicion about the accuracy deviation of satellite measurements over separate small-size steep and crevassed mountain glaciers because of de-correlation effects and phase unwrapping errors, local layover, slope-induced geometric errors and relatively rare spatial coverage by altimetry data.

Map validation and completion activities are still underway. They are planned to be completed after due consultations with users and climate analysts in 2015. Yet, the information content of the resultant ice cover maps has already been found to be superior to that of previously published maps, e.g. in representing top heights, ice divides, equilibrium lines, outlet basins, precipitous ice coasts, hydrographic networks, main shallows offshore, etc. Our online atlas is readily applicable to volumetric estimates and interpretation of glacier changes, here and now, and provides more than just a tool for *later* comparison and *future* variation studies. The atlas proved to be well suitable for estimating multi-year mass balance in the study region, both regionally and locally. We can state that the mapping goals have been achieved.

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