VARIATIONS OF THE ARCTIC ICE-SNOW COVER IN NONHOMOGENEOUS GEOPOTENTIAL

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ABSTRACT

The overall mapping of glacier elevation changes, the integral geodetic estimation of mass balance and the factor analysis of mutual variations in land and sea ice cover in the Barents-Kara region (BKR), Eurasian Arctic addressed in this paper were performed using a synergetic combination of differential interferometry and altimetry. Careful statistical comparison of the glacier change signal with available maps of gravity anomalies, sea ice charts and long-term rows of glacioclimatic, meteorological and tidal data gave a substantial evidence of cryogravic dependences in the study region. High positive ($\geq +0.91$) spatial correlation between local extremities in glacier change signal, sea ice concentration and gravity anomalies was determined, explained and formulated using the basic concepts of hydrostatic stress and converging precipitation. It was concluded that significant lateral variations of geopotential influence the local intensity of solid precipitation, snow accumulation rate and sea ice grow, glacier regime and character of glacioclimatic changes.

1. INTRODUCTION

Contemporary changes of the Arctic ice-snow cover are frequently referred to as a direct consequence, reactive indicator and important factor of climate change, most notably global warming. The spatial character of changes in arctic glacier dimensions and sea ice concentration is commonly inhomogeneous and the explanation of main causes for this heterogeneity is not so trivial. Atmospheric circulation, winds and oceanic currents are usually mentioned as main factors responsible for the asymmetric distribution of snow and ice resources in the Arctic, with much more ice and snow in some places than others [1]. In addition to these dynamic and variable factors there exist conservative agents tending to oppose and attenuate changes in the cryosphere. Gravity is an example of a conservative force influencing the spatial distribution of ice and snow masses and their sensitivity to weather changes. Different characteristics of land- and sea-ice masses, in fact their very existence, are closely associated with the Earth's gravity. Ice deformation, recrystallization and flow, meltwater runoff, avalanches and sediment transport, icequakes, calving and glacioisostatic processes, tidal oscillations and sea-surface tilts influencing ice drift - are gravity-driven phenomena. Recently, a new hypothesis emerged about gravitational impacts on the local rate of solid precipitation, snow accumulation and ice grow [2]. There is some analogy between this hypothesis and the old astrometeorological theories about weather dependence on the constellation of celestial bodies, which were popular in the XIXth and XXth centuries.

Simple mathematical formulations of gravity impacts on the local weather can be found in the paper published by A.Luiz from the University of Pisa. He demonstrated the dependence between the rainfall onset and the diurnal gravity deviations and explained temporal variations in the partial pressure of water vapour by tidal effects due to the astronomical positions of the earth, sun, and moon [3]. The idea was criticized from rather formal position by W.Jacoby (1969), who pointed out the insufficient magnitude of gravitational tides in the atmosphere. Nevertheless, the practice of applying astronomical data to forecasting unseasonable weather, especially medium and long-range, continued to be the admissible approach also in modern times. New studies focussed on barometric tendencies and characteristic precipitation patterns in time variable gravity field were recently presented in [4, 5]. The regional gravity changes related to anomalous precipitation were derived from GRACE gravity field data and it was concluded that "Precipitation anomalies leave signatures in gravity fields in land area through changes in soil moisture" [6]. We can rephrase this statement as *"Gravity anomalies leave signatures in precipitation fields…"* Such paraphrase may make practical sense because the magnitude of gravity lateral variations is nearly three orders larger than that of temporal deviations.

It is remarkable that most present publications on hydrometeorological processes in the arctic region deal traditionally with temporal and / or vertical variations of gravity, whose typical amplitude does not exceed 0.3 mGal, and ignore the impacts from lateral changes of gravity. All known climatic models describing and forecasting the reaction of Arctic sea- and land-ice cover to global warming treat the Earth's gravity as horizontally constant, but it isn't. The strength of the gravitational field varies considerably across even short distances under the influence of a density gradient. In the Arctic Basin the magnitude of free air gravity anomalies attains 100 mGal and more [7]. The anomaly of +100 mGal or 1/9800th of the acceleration due gravity is small with respect to the globe, but strong enough to be felt at the local level, since it is equivalent to the presence of a hill on the earth's surface with the top

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height of 300 to 900 m depending on the rock density. Yet, anomalous forces arising due to lateral variations of gravity are quite small compared to wind and current forces and are less important over short periods of time. On long-term base, however, instantaneous deviations of gravity can have a noticeable effect on the regime and mass budget of glaciological objects.

At best, the gravity-induced component of ice and snow variations can be determined on topographically smooth, open and steady surfaces, like those of large ice caps, fast sea ice and ice-free planes. At the continental scale, global natural cycles, cyclonic activity and oceanic circulation mask the manifestation of exogenic forces, while local hydrometeorological, aeolian and oceanographic effects distort the relevant signal at the short-space scale. Regional and sub-regional scale seems to be more appropriate for studying cryogravic processes in the Eurasian Arctic with the typical extent of ice fields and gravity anomalies ranging between tens and thousands square kilometres. Since land ice and sea ice are formed from completely different sources, their dynamics are highly dissimilar and it is important to distinguish between these two separate albeit interrelated phenomena. Hence, the present study was focussed on regional and sub-regional features of glacier changes yet without neglecting sea ice processes.

The study was carried out in the frameworks of ICEAGE and SMARAGD national research projects both devoted to determining, mapping and explaining the reaction of large Eurasian ice caps and tidewater glaciers, especially those, which grow, in response to current climate change. As main study area we had chosen the Barents-Kara region representing the biggest cluster of large insular ice caps and strong gravity anomalies in the Old World (Fig. 1). Baseline geometric characteristics of the Barents-Kara glaciation found in the literature for five meso-regions are given in Table 1.

Table 1. Geometric parameters of the Barents-Kara glaciation and their changes in 1950 -2000s

Meso-Region **Parameter Year**	**Svalbard & Kvitoya**	**Franz Josef Land & Victoria**	**Novaya Zemlya**	**Ushakova Island**	**Severnaya Zemlya**	**Totals**
Glacier area, km² (1950s)	36.591[9]	13.746[10]	23.645[11]	326[12]	18.325[12]	92.632
Glacier area, km² (2000s)	35.535	13.463	23.345	324	18.237	90.907
Change *) non-controlled value	-1.056*	-283	-300*	-2.5	-88	-1.726
Glaciation index, % (1950s)	59	85	29	100	50	47
Glaciation index, % (2000s)	57	84	29	100	50	46
Change	-2	-1	0	0	0	-1
Glacier volume, km³ (1950s)	7.567[13]	2.472	6.830	35	5.500	22.404
Glacier volume, km³ (2000s)	7.123	2.258	6.630	38	5.370	21.423
Change	-444	-214	-200	+3	-131	-982
Average thickness, m (1950s)	207	180	289	107	300	242
Average thickness, m (2000s)	200	168	284	118	294	236
Change	-7	-12	-5	+11	-6	-6
Length of ice coasts, km (50s)	1.051	2.666	208	80	501	4.501
Length of ice coasts, km (00s)	894	2.522	192	78	490	4.176
Change	-157	-144	-16	-2	-11	-330
Reference period, years	40	50	50	50	27	43

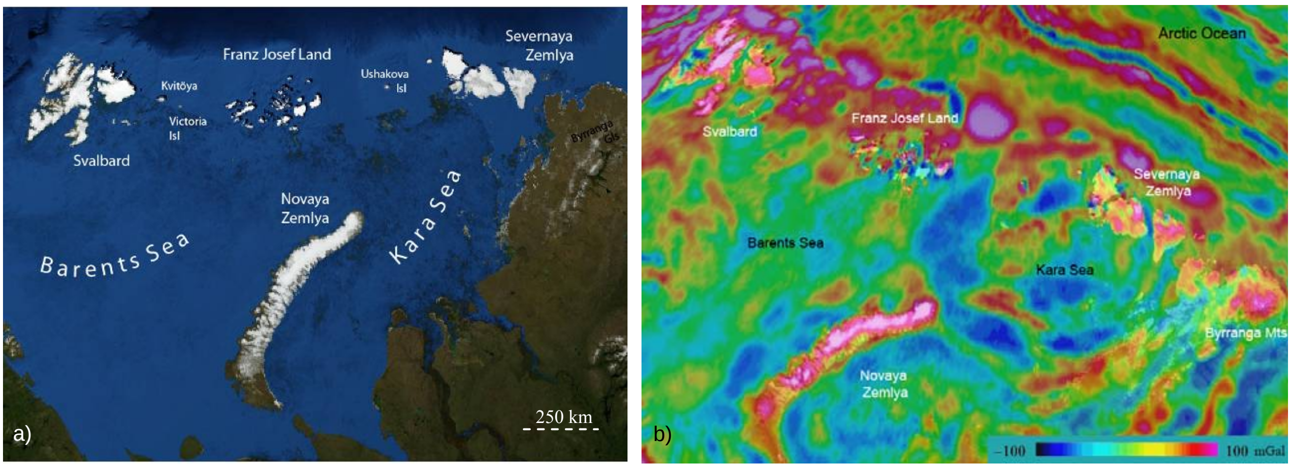

Figure 1. Barents-Kara region: view from space (a); regional map of free-air gravity anomalies (ArcGP grid 2008, b)

In the 1950s, the total area of glaciers occupying separate islands and archipelagos in the study region made approximately 93,000 km² or nearly 14% of the global value. The overall glacier volume reached 22,400 km³ and the average ice thickness was given as 242 m. These values indicate the work load related with glacier change mapping in BKR. The study region is characterized with an essential gradient of climatic conditions, rapidly varying concentration of sea ice, the occurrence of permanent coastal polynyas and the substantial ground-truth and cartographic material on glacier geometric and fluxometric changes collected during our 15-year explorations including 5 field campaigns. The accumulation period in the study region lasts for about 9-10 months, and the snow distribution pattern is fairly stable while the magnitude of winter accumulation can vary from year to year by 100%. The supposition about endogenic gravity-driven forcing on glacioclimatic settings and glacier regime in the study region is based on the results of comparison and joint interpretation of our glacier change maps and existing maps of the Arctic gravity field, e.g. the ArcGP map of free-air gravity anomalies based on the results of ground- and air-borne surveys [2, 7, 8].

2. GEODETIC ESTIMATES OF GLACIER CHANGES IN THE BARENTS-KARA REGION

The geodetic method for glacier mass balance determination based on precise measurements of glacier elevation and volume changes over some known period of time was introduced by R.Finsterwalder approx. 60 years ago [14]. In the course of past 50 years the method practically didn't change and evolved a little from the classical hypsometric technique of map differencing to the comparison of gridded elevation models representing the glacier surface topography of different years. Finsterwalder's basic formulae for calculating cumulative volume changes are still in use. The geodetic method yields usually better agreement with the results obtained by direct glaciological surveys than indirect optical methods and is reputed as the most successful EO approach to measuring glacier mass balance in extensive glacial areas [15]. There exist several simplified methodological variants based on repeated point- and profile-wise surveys of glacier elevations, e.g. by laser altimetry, with subsequent glacier-wide extrapolation of results [16].

In the Barents-Kara region, the most substantial and extensive surveys of glacier mass balance were carried out in the Svalbard archipelago [17]. Yet, reliable mass balance measurements are available only for separate glaciers or the glaciers of small sub-regions. Most regional and sub-regional geodetic determinations were obtained using simplified techniques. In other BKR archipelagos geodetic mass balance measurements were concerned primarily with one or two glaciers and ice caps, such as Shokalskogo Glacier in Novaya Zemlya, Vavilov Ice Cap in Severnaya Zemlya, Sedov Glacier, Jury, Jackson and Windy ice caps in Franz Josef Land. All present regional estimates of mass balance for these archipelagos are derived from local measurements on separate glaciers and extrapolations with long-term meteorological data from several weather stations [18]. Mean values of glacier budget derived from literature data for each meso-region in the Barents-Kara sector indicate that most glacier complexes in the study region have negative net mass balance and their expected contribution to sea-level rise is rather small [17]. Mass balance characteristics of separate isolated ice caps on Kvitoya, Ushakova and Schmidt islands remain practically unknown.

New detailed albeit extensive remote sensing studies devoted to glacier change mapping and regional estimates of geodetic balance in several meso-regions of BKR were recently carried out using satellite altimetry and interferometry as well as reference elevation data [2, 8]. Apart from high sensitivity to changes in glacier topography and independence of natural illumination, the major advantage of combining radar interferometry and lidar altimetry referred to as dual-sensor INSARAL technique is the enhanced glacier-wide coverage with elevation change data and the good 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 accumulation signal by simplified mono-sensor techniques, such as those offered in [16]. Long-term applications of the INSARAL technique brought steadily positive results and demonstrated its good performance on glaciers and ice caps with different extents ranging from tens to thousands square kilometres. The vertical accuracy of glacier change products proved during field surveys on several glaciers and ice caps was given as ± 0.3 m/a rms. The basic reference period for the quantification of glacier elevation changes covered up to 50 years, depending on data availability. This reduced the influence of time-dependent errors and inaccuracies of the reference elevation data ranging from 6 to 13 m rms. The residual cumulative influence of random ablation-accumulation processes on height measurements due to the "age" difference between available interferometry (1990s) and altimetry (2000s) data estimated in cross-over areas did not exceed ±1 m.

In our practical work, 2-pass differential interferograms of study glaciers were processed, geocoded, mosaicked, calibrated and interpreted using tandem ERS-1/2 SAR image pairs, co-located ICESat altimetry data and 50-year-old reference elevation models (DEM_0) derived from topographic maps. The glacier change signal was firstly determined profile-wise by comparing ICESat altimetric heights with the reference elevation data. Each DINSAR mosaic was overlaid and calibrated with the resultant network of differential hypsometric profiles. The co-registration accuracy was given as ±1.2 pixel rms and the elevation change pattern in differential hypsometric profiles matched that in the DINSAR layer. In contrast to other studies of glacier elevation changes, we didn't build a "new" glacier elevation model and didn't compare it with the "old" one, but calculated the glacier change signal between altimetric transects directly from the calibrated differential phase. The big advantage of this algorithm is that it requires no complex process techniques, reduces the computational load, mitigates some problems related to gridding and interpolating errors and enables high level of automation. Optionally, glacier surface topography (DEM_1) can be modelled by summing the elevation change product and DEM_0. The INSARAL data processing was performed using the RSG 6.3 software package.

The data-flow diagram and some results illustrating the INSARAL basic procedures are shown in Fig. 2. Being based on *active* EO methods this end-to-end information circuit represents a sort of early warning system that aids in early detection of extreme glacier changes and recognition of anomalous variations in land ice cover yet without compromising on the complement of glacier state variables to be produced [8]. Some of these variables, e.g. the equilibrium line and glacier accumulation can be derived in a semi-automatic mode from continuous glacier change models even with higher reliability than from optical stereo images.

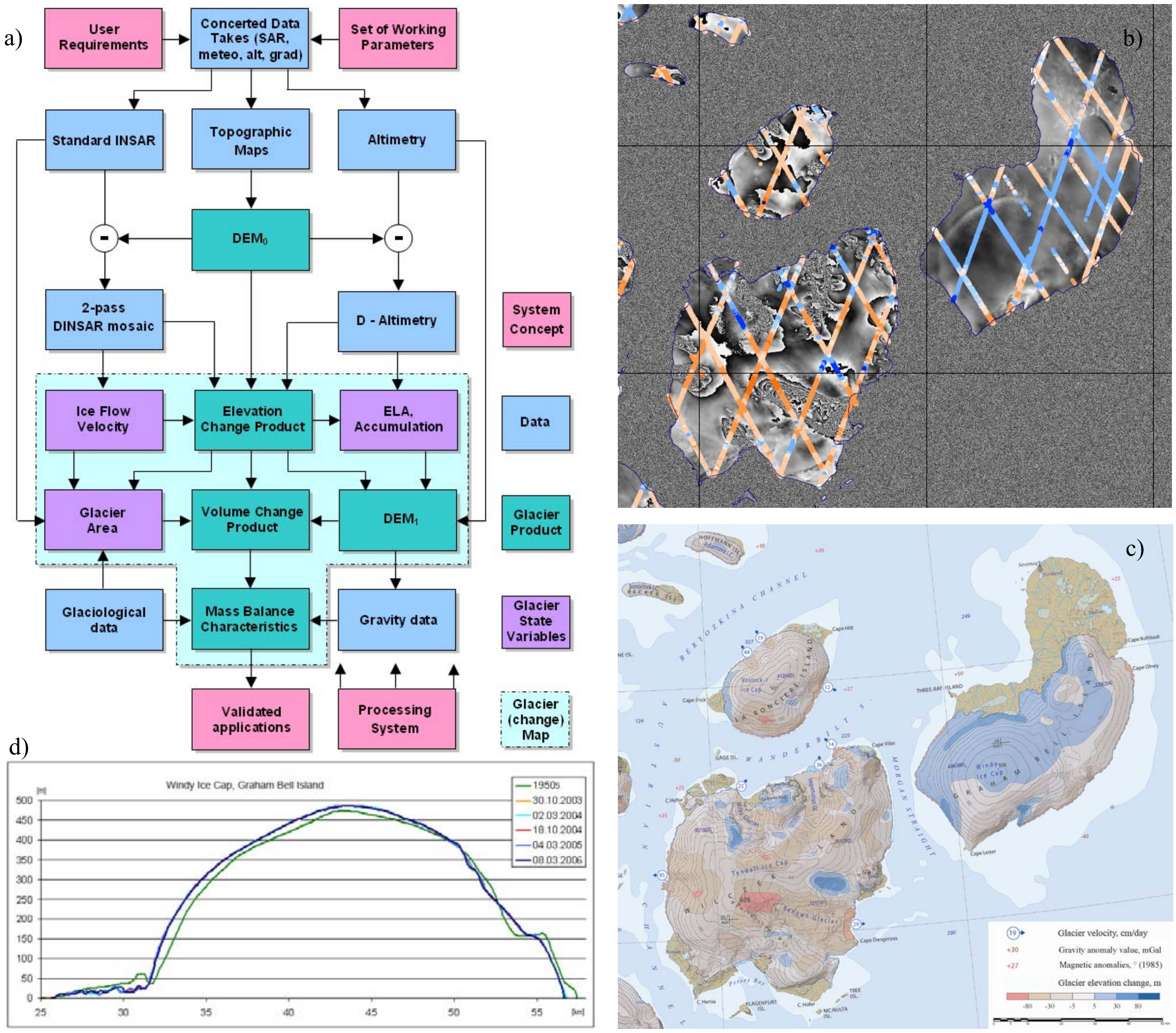

Figure 2. INSARAL data flow (a) and results for the easternmost part of Franz Josef Land: DINSAR mosaic overlaid with differential altimetry profiles (b), glacier elevation change product (c), glacier change signal on Windy Ice Cap, Graham Bell Island (1952-2006, d)

The combined use of radar and lidar data allowed the inter-validation of elevation changes in slow-moving and ice-free areas to be performed and some distortional geophysical effects, e.g. the effect of ionospheric refraction and radar penetration into the snowpack to be compensated. Phase-gradient and coherence-tracking approaches were applied to determining elevation changes in fast-flowing parts of study glaciers mapping glacier outlines, determining main ice divides, and measuring glacier velocities from INSARAL multitemporal data sets [19]. The lack of bulk density data typical of geodetic techniques brought about some difficulties in converting the resultant elevation- and volume change products in glacier mass changes. New space assets for determining the mass redistribution on large- and medium-size glaciers and validating glacier state variables obtained by other methods were expected from the GOCE and GRACE satellite gravimetry missions. Yet, we could not get an advance access to GOCE data, and the spatial resolution of available GRACE data is still too coarse for meso-regional studies in the Eurasian Arctic. Hence, in the present work we used the gravity data obtained from other sources, such as ArcGP and EGM2008 models, state gravimetric maps and terrestrial surveys.

3. REPRESENTATION, ASSESSMENT AND INTERPRETATION OF GLACIER CHANGES

3.1 Composition of glacier change maps

A series of satellite image maps at 1:500,000 scale showing overall glacier elevation changes in the south and north-east Svalbard, Franz Josef Land, Novaya Zemlya and Severnaya Zemlya archipelagos including Kvitoya, Victoria, Ushakova and De Long islands, and in Byrranga Mountains on the Eurasian continent were consecutively generated using the same dual-sensor INSARAL technique (http://dib.joanneum.at/smaragd > results). All maps are presented in UTM projection, WGS84. Elevations of glacier points are given with respect to the multiyear mean level of the Barents and Kara seas. In total eight gradations of glacier elevation changes were set up. Two additional gradations were included in order to account for the advance and retreat of glacier termini. Glacier areas with negative (ablation) and positive (accumulation) changes were coloured in shades of pink-brown and cyan-blue, respectively. In addition to glacier elevation changes, main ice divides, glacier borders, hydrographic network, topographic contours and geographic names, maps also show present heights of ice coasts, frontal velocities of tidewater glaciers, bathymetric and gravimetric marks, and main shallows offshore. The graphical precision of the printed maps is between 0.2 and 0.5 mm at publication scale.

A continuous, complete and measurable picture of glacier changes in the entire BKR was reproduced in the form of two observational maps at 1:5000,000 scale showing glacier mass balance characteristics and changes in the period of 1950-2000s. For comparative estimates of glacier alterations in meso-regions with different history of surveys we calculated average values of elevation changes in [m/a] and “dyed” each glacier complex in different shades of ochre and grey depending on the sign and magnitude of average change value. One of our observational maps was sequentially conflated with several NSIDC maps of sea ice concentration and with the ArcGP map of free-air gravity anomalies in the Arctic for further geophysical analysis of glacier alterations in the Eurasian Arctic. A small-size copy of the resultant combined map including graphs of glacier elevation changes and geopotential variations along several curvilinear profiles is shown in Fig. 3. Gravity anomaly values are represented in different shades of cyan.

The completion of this cartographic work enabled us to quantify glacier state variables at truly regional scale, to study spatial variations of glacier changes and ice flow pattern at macro-level, to determine main causes of anomalous changes and to interpret cryogravic dependences, which are usually masked by local effects. It was much more convenient and, therefore, expedient to perform accurate planimetric and volumetric measurements of glacier changes, and to interpret their causes from the resultant cartographic products than from raw data.

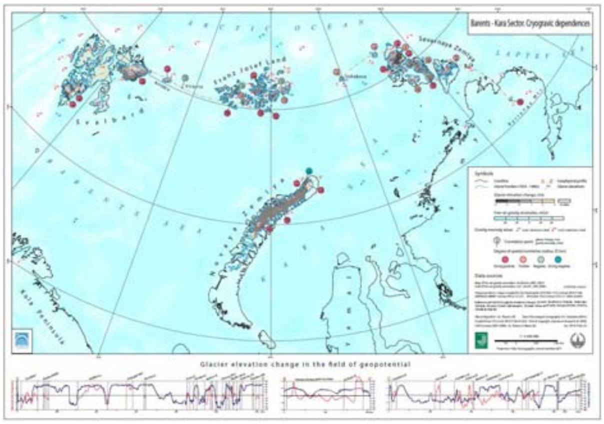

Figure 3. Map of cryogravic dependences in BKR

Several validation campaigns and quality control of the resultant glacier products were carried out in north Novaya Zemlya, south Svalbard and Franz Josef Land using precise geodetic equipment (total station, dGPS) and GSSI SIR-3000 ground-penetrating radar in autumn 2001, spring 2006 and summer 2008 respectively (Fig. 4). The results of field surveys were close to our expectations. The existence of positive elevation changes was proofed at all check points and the thickness of annual accumulation layers correlated well with the magnitude of these changes. The all fieldwork and follow-on activities proved the information content, completeness and high spatial accuracy of glacier change maps. The root mean square difference between glacier elevations measured in the field and determined in the lab from remote sensing data was ± 3.7 m. The overall r.m.s.e. of present volumetric estimations in the Barents-Kara region is assumed to be ± 0.2 km³.

Figure 4. GPS-GPR surveys in Franz Josef Land (2008)

3.2 Regional assessment of glacier changes

Our remote sensing studies and cartometric estimations revealed a significant reduction of approximately 1000 km³ or 4% in the total glacier volume in the past 5 decades, while the total area of the Barents-Kara glaciation reduced by less than 2 %. The annual loss of land ice was determined at approx. 10 km³/a in Svalbard, 4.2 km³/a in Franz Josef Land, 4.0 km³/a in Novaya Zemlya and 4.5 km³/a in Severnaya Zemlya. The average ice thickness of remaining glaciation decreased to 236 m (Table 1). The resultant values of glacier changes correlate well with previous estimations made by other explorers [17, 18, 20, 21, 22] and show that, in the past decades, the rate of land-ice-loss processes in Novaya Zemlya, Franz Josef Land and Severnaya Zemlya accelerated by 10%, 20% and 25% respectively, while it have not changed significantly in Svalbard. Apart from real environmental changes these differences might reflect the different history of explorations in each meso-region, methodical variations and, of course, measurement mistakes. Main geometric parameters of the Barents-Kara glaciation calculated for the first decade of the XXIst century are also specified in Table 1.

The largest negative elevation changes were typically detected in the seaward basins of large and fast-flowing outlet glaciers, both at their fronts and tops. For example, the strongest loss of glacier thickness (-140 m) was discovered in the lower part of Hornbreen-Hambergbreen glacier system in south Svalbard and in upper parts of the outlet glaciers Nos.7 and 8 belonging to the Academy of Sciences Ice Cap in the north-eastern part of Severnaya Zemlya [8]. Ablation processes were stronger manifested on southern slopes of ice caps, while the accumulation of snow was generally higher on northern slopes so that main ice divides "shifted" to the north. The largest positive elevation changes ranging from 75 to 125 m were found in the accumulation areas of the biggest ice caps in the central part of BKR, such as Tyndall and Windy ice domes in Franz Josef Land and Northern Ice Cap in Novaya Zemlya. Significant positive height changes of 25 to 50 m and more were also registered on Austfonna in Svalbard, Schmidt and Vavilov ice caps in Severnaya Zemlya, Kvitoyjokulen at Kvitoya, Ushakova Ice Cap and several other insular ice caps smaller than 400 km² with top heights of about 300 m. Schmidt, Ushakova and Vavilov ice caps gained 2, 3 and 11 km³ of ice respectively. The majority of growing ice caps terminates on land or in shallow waters and don't contain fast-flowing outlets. The sides of these glaciers steepened. Essential accumulation signal was revealed at higher elevations in wind- and sun-protected areas on numerous mountain glaciers of Svalbard, Novaya Zemlya, Severnaya Zemlya and Byrranga Mountains. The surface rise in lower parts of several outlet glaciers was attributed to ice flow and surging processes.

3.3 Geophysical factors of glacier changes

Considering current warming of the Arctic climate, a plausible explanation for the observed long-term grow of several study glaciers can be given with the increased intensity of solid precipitation and deposition of rime or hoarfrost on the glacier surface as well as deceleration of the ice wastage by glacier flow and calving. Indeed, the analysis of differential interferograms showed that several outlet glaciers with long-term records of flow velocities decelerated their motion. For example, the frontal velocity of Sedov Outlet Glacier at Hooker Island in Franz Josef Land decreased from 70 to 40 m/a in the past half-century.

The comparison of our glacier change maps with the NSIDC maps of sea ice concentration corroborated that most ice caps with positive elevation changes situated in a close vicinity of permanent coastal polynyas originating each year at the same place thus providing an additional source of warm and humid air. Besides we revealed that the distribution of land ice, the ice flow pattern and calving characteristics in each meso-region of the Barents-Kara Sector are characterized by abnormal spatial asymmetry. In each archipelago the "centre of ice mass" is clearly displaced towards the north-east. The current glacier activity at the western coasts of Svalbard and Novaya Zemlya is much higher than that at the eastern shore, while the glaciation of Severnaya Zemlya on the other side of BKR exhibits an opposite asymmetry with much faster ice flow towards the Laptev Sea. This is surprising because, on average, the Laptev Sea is approx.1° colder than the Kara Sea [8]

At sub-regional scale the horizontal distribution of glacier elevation changes was not uniform and conformed astonishingly well with the field of geopotential represented in existing maps of gravity anomaly in the Arctic. A relationship between two numerically valued variables was computed in the form of spatial correlation in areas with extreme rates of elevation change, both positive and negative. A strong positive correlation between local extremities in the glacier change signal and gravity anomalies was found in all meso-regions, at all large glacier complexes and in several isolated glacial areas. The overall magnitude of spatial correlation was given as ≥ +0.91 (correlation radius 25 km). The locations of positive glacier changes were usually adjacent to locations of strong positive gravity anomalies. Conversely, the largest negative changes were situated in the close vicinity of negative anomalies. Although an inverse relation associating the emergence of positive gravity anomalies with glacier ice load should not be forgotten, we assume that gravity anomalies have a direct impact on the intensity of solid precipitation, accumulation of snow and evolution of large glacial complexes [8]. Moreover, we recognized that the majority of high-latitudinal albeit glacier-free islands with relatively large surface areas and significant top heights are situated in the areas of "low gravity" or mass deficit. An essential positive correlation was also found between the magnitude of gravity anomalies and snow accumulation on the sea ice, while a strong negative correlation was obtained between the sea ice concentration and the acceleration due to gravity. The thinnest snow cover and the most consolidated one-year sea ice are observed in areas of negative gravity anomalies, e.g. in the north-eastern part of the Kara Sea, known by sailors as "ice sack".

Our first explanation for the different signs of spatial correlation between glacier change and sea ice concentration on one side and the magnitude of Earth's gravity on the other was based on the idea of converging precipitation and diverging ice growth in the areas of mass excess (Fig. 5). The snowfall and ice growth processes involve movements of ice crystals along the local vertical in opposite, i.e. descending and ascending directions. Under common and steady conditions close to the Earth's surface this can lead to increased concentration of snow and dispersion of sea ice in the areas of positive gravity anomalies. Snow cover on sea ice insulates the latter from upward heat loss during winter and reduces sea ice growth. Sea ice is thinner where snow cover is thicker, and thinner ice is more susceptible to break-ups. Further reasonable explanation for the closest and thickest sea ice found in the aquatories with negative gravity anomalies would be that the concave facet of sea surface induces the centripetal ice drift thus making a "trap" for sea ice. In some instances and places, the impact of ice-surface-tilt can exceed those by winds and currents and is thus important even over relatively short periods of time [19].

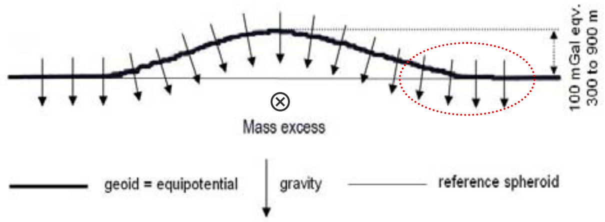

Figure 5. Converging precipitation in high-gravity area

Following the ideas explaining possible causes of anomalous growth of Austfonna in Svalbard [22], we have asserted that there is a reciprocal relationship between snow accumulation on maritime glaciers and the sea ice concentration in their close vicinity. Furthermore, we concluded that significant lateral geopotential variations influence the local intensity of sea ice growth, solid precipitation, snow accumulation and the local character of current glacier changes. The high asymmetry in the ice flow pattern and calving characteristics with much faster ice flow (up to 200 m/a) towards strong positive (+ 70 mGal) gravity anomalies offshore along western coasts of Spitsbergen and northern Novaya Zemlya, the north-eastern shore of Nordaustlandet and the eastern coast of Severnaya Zemlya can also be attributed to gravity-driven impacts on glacier dynamics.

3.4 Analytical explanation of cryogravic interactions

In order to formulate and to clarify the interplay between basic glacioclimatic parameters and gravity anomalies we compiled a basic set of simple differential equations describing meteorological and hydrological settings in the heterogeneous field of gravity. In this analytical consideration, we assume both atmosphere and hydrosphere to be isostatic and use the well-known equation relating the change in hydrostatic pressure P to the change in height or depth

$$P \cong \rho \cdot g \cdot z \,. \tag{1}$$

In equation (1) ρ is the medium density; g is the acceleration due to gravity and z is the height of the air or water column given as

$$z = z_0 \pm h \,, \tag{2}$$

where z_0 denotes the reference surface with constant, e.g. zero, depth or height, and h is a spatially varying depth or height function representing sea surface or glacier topography. In most applications g is considered as constant and the hydrostatic equation is usually written in differential form as

$$\frac{dP}{dz} = \pm \rho \cdot g \,, \tag{3}$$

where the positive sign indicates that water pressure increases with depth, and the negative sign denotes that air pressure decreases with height. In a heterogeneous field of gravity g varies, and equation (3) can be transformed into

$$\frac{dP}{dg} = \rho \cdot z \, . \tag{4}$$

The change in pressure with gravity dP/dg is large in denser and colder mediums and should be more noticeable in cold regions at larger heights and depths.

Differentiation of equation (1) along the horizontal coordinate x under the assumption of constant density and temperature gives the next formula relating the horizontal gradient of water vapour (partial) pressure to the gravity gradient and glacier topography

$$\frac{dP_v}{dx} \cong \rho_v \cdot \left(\bar{z} \cdot \frac{dg}{dx} - \bar{g} \cdot \frac{dh}{dx} \right), \tag{5}$$

where the subscript v stands for water vapour and the overbar means spatial averaging. The term dh/dx represents glacier topography and dg/dx describes spatial variations of gravity in the direction of moist air advection. An identical equation with the positive sign on the right hand side can be obtained for the horizontal gradient of hydrostatic pressure in the water.

In stratiform precipitating clouds the growth of droplets and the intensity of ice nucleation are proportional to the partial pressure of water vapour. The insertion of formula (5) in the Hertz-Knudsen equation for the intensity of ice nucleation, a determining factor for the onset of snowfall, gives the following expression describing the probability of snowfall as a function of gravity gradient:

$$\frac{dW_{net,i}}{dx} = \frac{a_d \cdot \rho_v}{\sqrt{2\pi \cdot m_v \cdot k_B \cdot T}} \cdot \left(\bar{z} \cdot \frac{dg}{dx} - \bar{g} \cdot \frac{dh}{dx} \right). \tag{6}$$

In equation (8) $\alpha_d = 0.01_{-2°C} \div 1.0_{-85°C}$ is the deposition coefficient depending on the air temperature T; m_v is the molar mass of vapour, and k_B is the Boltzmann constant. Similar interrelations can be derived from the ice nuclei parameterizations offered by Fletcher (1962) and Meyers et al. (1992).

By analogy with the biological phenomenon of geotropism our formulae describing glacioclimatic settings in the heterogeneous field of gravity were called as geotropic equations. Equations describing glacier mechanics can also be presented in differential form involving gravity gradients and spatial variations of glacier thickness. However, this is beyond the scope of the present paper as are several important but specific questions concerning the wind transport of snow and the influence of oceanic currents, which are also governed by gravity. Those interested in details are referred to other publications [e.g. 8, 20].

4. FURTHER SUBSTANTIATION OF THE WORKING HYPOTHESIS

At first glance, our hypothesis about glacioclimatic variations in the heterogeneous field of gravity seems to be a little too one-sided or far-fetched, and we try to provide more substantial evidence to justify it. First of all we wish to stress that the research of glacioclimatic variations and feedbacks in the heterogeneous field of gravity became possible only after new series of satellite image maps showing overall glacier elevation changes in the Barents-Kara region were generated using spaceborne altimetry and interferometry data [8]. All resultant inferences rely on long-term observations on statistically large sample of well-mapped glaciers and ice caps. Even the poor and scarce map material available before the First World War permitted F.Enquist to write his comprehensive study on “Wind influence upon the distribution of glaciers” [23]. Some additional evidence on the correctness of our hypothesis was gained during ongoing studies of land- and sea-ice regime in other arctic regions, such as Canadian and East Russian Arctic. Further comparative analysis of multi-source EO data, meteorological and oceanographic data series, and thematic maps revealed that the spatial distribution of steady polynyas and extreme annual values of snow thickness on the fast ice and in low-land tundra also correlate well with the field of geopotential [8]. Error balance estimates and specific glaciological surveys demonstrated major spatiotemporal singularities, methodological advantages and better feasibility of the proposed hypothesis compared to similar empirical-theoretical concepts developed by astrometeorologists.

Initial simulations of ice mass changes indicate that the strongest gradient of glacioclimatic conditions is observed in the vertical direction, and the glacier budget increases rapidly with elevation. Our numerical estimates of glacier mass balance versus glacier elevation vary from -0.2 mwe/a at sea level to +0.18 mwe/a and more at an elevation of 250 m. Other investigators reported on even stronger growth of mass balance with height [18, 20, 21, 24]. Depending on annual precipitation, the altitudinal gradient of mass balance on the Arctic ice caps varies between 0.001 and 0.003 a^{-1}, i.e. from 0.1 m/a to 0.3 m/a per 100 m [24]. In this context we wish to refer to the earlier statement that the existence of a strong gravity anomaly is equivalent to an elevation change in the equipotential surface of several hundred meters. The large magnitude of the gravity anomalies and the spatiotemporal character of their distribution in the Arctic Basin in general and in the Barents-Kara region in particular do not allow them to be interpreted as solely false anomalies caused, e.g. by the impact of currents in shallow waters or geometric errors in glacier mapping. Hence, we believe that the gravity-driven impact on glacier topography and dynamics is quite probable.

5. CONCLUDING REMARKS

Numerous discussions with people working on theoretical problems of glacier behaviour in a changing climate have strengthened our scientific interest and confidence in special practical importance of cryogravic research. A strong encouragement for continuing the study was provided by Prof. Kotlyakov from the Institute of Geography in Moscow, who stated that *glaciers arise in the zones of maximum precipitation, which cannot be explained from solely meteorological data.* A more detailed interpretation of the ice index and glacier changes must still be performed to gain a thorough understanding of all driving forces that contribute to the present land- and sea ice regime in the Arctic Basin. This work will be carried out together with colleagues from the Nansen Environmental and Remote Sensing Center in Bergen as part of the MAIRES FP7 GMES project thus ensuring the continuity of research. New validated data products from GRACE, GOCE and CryoSat-2 satellites may make an essential contribution to the theory and practice of glaciological observations and to a better prediction of fluctuations in snow and ice resources in the Arctic and other regions. Finally, we wish to conclude with a thought-provoking quotation, which would be equally well-placed at the beginning of the paper: "Although glacier variations have been observed for more than four centuries, no quantitative theory linking glacier variations to climatic changes emerged …" [23].

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