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SMARAGD is a research project funded by the Austrian Federal Ministry of Science and Research

SMARAGD – Satellite Monitoring and Regional Analysis of Glacier Dynamics in the Barents-Kara Region
Graz 2010
Aleksey I. Sharov (Ed)

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ISBN 978-3-200-01618-7
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PREFACE

Dear readers, friends and colleagues, the booklet you hold in your hands is the result of long-term efforts, thoughts and aspirations. It is the combined work of a group of nine scientists, six Austrians and three Russians, some young and some older, men and women, all engaged in the study of glacioclimatic variations and their influence on mankind. In brief, the book is about remote sensing, mapping, analysis and prognosis of ice mass changes occurring on the largest Eurasian glaciers and ice caps today plus-minus 50 years. This is a firsthand record of our research and includes the results of our fieldwork carried out in the Arctic during the 4th International Polar Year (IPY) in 2007 – 2009. It also includes some interesting results from prior and complementary work that extend beyond the IPY timeframe and reflect longstanding Austrian-Russian cooperation in the area of polar research and education. The events and activities described in the book took place in the Barents-Kara region, High Eurasian Arctic, representing the largest cluster of tidewater glaciers in the north-eastern quarter of the globe.

The ultimate aim of the publication was to highlight the modern potential of satellite remote sensing for glacier change mapping, analysis and prognosis. A further aim was to demonstrate and generalize the results and experience gained as a result of work on the SMARAGD research project. The SMARAGD project was devoted to the integral assessment of dynamic ice loss and gain processes in the largest glacial areas of Eurasia in response to climatic changes. It represented a constituent part of the Austrian–Russian IPY initiative FERMAP, which was funded by the Austrian Federal Ministry of Science and Research. The SMARAGD consortium was coordinated by Joanneum Research, one of the largest research organisations in Austria, and included the Central Institute of Meteorology and Geodynamics in Vienna, Environmental Education Forum in Vienna, the Moscow State University of Geodesy and Cartography, and the Geographic Faculty at the Lomonosov State University in Moscow. The SMARAGD project lasted nearly 3 years and was successfully concluded in September 2009. All project reports were well received by the funding organisation and this inspired us to publish the most interesting results in a more vivid and accessible form as a textbook. All consortium members welcomed the idea of converting the research report into a textbook and agreed to provide their contributions to the current issue at no charge. This was the turning point and we immediately started work on writing and illustrating the book.

It is worth noting that the idea of writing a small albeit comprehensive book about satellite monitoring of glacier changes in the extreme North Arctic first occurred during our somewhat tedious field study in Hornsund, south Spitsbergen in March-April 2006 and was then put on hold due to a lack of human, financial and time resources for its realization. The idea was rekindled after the subsequent joint glaciological expedition to the Franz Josef Land archipelago in July-August 2008. By then we had obtained sufficient proof to crystallize our pet theory and to substantiate several working hypotheses about glacioclimatic variations in the heterogeneous field of gravity. This time, the idea of publishing a book found strong support among sponsors and potential authors. We wish to warmly thank Dr. Christian Smoliner and Doris Zabsky from the Austrian Ministry of Science and Research for their guidance, encouragement and systematic support generously given to us within the framework of the SMARAGD project.

1 Tidewater glaciers (TWGs) are those extending into the sea and producing icebergs.
2 The acronym SMARAGD stands for “Satellite Monitoring And Regional Analysis of Glacier Dynamics”.
3 The acronym FERMAP stands for “Franz Josef Land Environmental Research, Monitoring and Assessment Project”.

Page 1
Preface

All contributing authors - experienced scientists and well known experts in their fields - glaciologists, meteorologists, remote sensing experts, cartographers and educationalists - have worked on various research projects over many years and have developed their own varying opinions on the main causes, modes and consequences of glacial changes in polar and alpine regions. The variety of scientific interests and natural desire to find a consensus on common priorities paved the way for the definition / identification and thorough review of the key topic, filtered out one-sided and conjectural concepts, and provided the book with noteworthy and complementary content. Numerous discussions, deliberations and cross-examinations, critical comments and valuable recommendations we received from external reviewers, advisors and publishers further enhanced the book's quality, although at the price of somewhat delayed publication. Graphic design provided by Elmar Veitmeier (Joanneum Research) and proofreading performed by Angelika Prohammer contributed essentially to the attractive overall appearance and readability of the booklet.

Memorable discussion sessions and multi-media presentations involving the participation of teachers and pupils at joint interdisciplinary workshops held in Vienna and Graz during the 4th IPY gave us useful critical feedback, furnished us with tips on how to write for pupils and very young researchers, and made our work all the more interesting. In line with the directive from the Ministry on research-education cooperation and bearing in mind that our work was supported by public funds, we decided to include a short chapter in this book describing the reaction of the younger generation to present climate change and polar research. It was highly interesting and instructive for all participants to take part in such a literary pursuit.

The resultant booklet is well illustrated and very readable. It provides all relevant references and links for further reading and research. Most of the map products mentioned in the booklet are directly accessible as full-size copies on the project homepage http://dib.joanneum.at/smaragd > results.4 In accordance with our new financial policy, the booklet will now be available free of charge. We recommend this booklet for anyone studying glaciers and climate change in polar regions.

Polar geographers and people interested in arctic geodynamics will find much detail about glacioclimatic interrelations and variations, which have occurred in the Barents-Kara region in the course of the past 50 years. Our integral estimates of glacier changes given in linear, areal, volumetric and fluxometric terms for each ice cap, island, archipelago and for the whole study region can be further used by climate modellers for validating and forecasting actual or potential fluctuations of snow and ice resources in the Arctic at regional and circumpolar scales. People studying cartography will find useful examples of original glaciological and analytical maps.

If you are a student of the subject or are preparing your project proposal, PhD or diploma thesis about land ice, this book will allow you to access state-of-the-art research and to list the main natural agents controlling glacier dynamics, both exogenic and endogenic. Please don’t be in a hurry to get through the first few pages which were written at the initial stages of our work. They cover background topics and contain basic definitions that are essential to the understanding of the problems of satellite monitoring in the High Arctic. It was something of a challenge to explain these well in writing.

Experts in Earth observation will recognize that the data processing methods and their application to glacier change mapping described in the book are at the cutting-edge of modern

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4 At the same website you can get a digital copy of the book in *.pdf format.
Preface

developments in polar remote sensing. Anyone considering implementing satellite interferometry and altimetry, either independently or jointly, for glaciological studies will be pleased by the depth of detail found in this booklet. The research concept described in the first chapter, the stratagem of research-education cooperation from the last but one chapter and some detail on the organisation of field studies and coordination with relevant ongoing projects may be useful for persons currently managing so called CalVal\(^5\) activities in the Arctic and GMES-like\(^6\) research initiatives.

Critics too will find something to consider and discuss. The discovery of several growing glaciers in the study region seems to be improbable in the view of common glacial retreat, and there are some uncertainties in our analysis of such glacier behaviour. Analytical explanations of high spatial correlation between local extremities in the glacier change signal and those in the field of geopotential involve several simplified and even intuitive assumptions whose adequacy has yet to be verified both in the field and in the lab. Several important but specialized questions related to geophysics, glacier mechanics and periglacial processes remained open due to the lack of data and expertise within the working group. The book is, however, not intended to be abstruse. Should you require further clarification on a particular section, please feel free to contact the responsible author. Our contact details and writing responsibilities are as follows:

DDr. Aleksey I. Sharov (JR_DIB\(^*\)) wrote the Preface, Chapters 1, 2, 3 and Conclusions. Dr. Wolfgang Schöner and Di Bernhard Hynek (both from ZAMG\(^*\)) were responsible for Chapters 4 and 5. Dr. Markus Langer (UMBF\(^*\)) compiled Chapter 6.

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We do hope that the book will live up to your expectations. All authors will be pleased to receive your comments and suggestions regarding the book’s contents and quality, comments on possible improvements and, of course, incentives to greater efforts. So far we have received positive remarks from many of the collaborators at institutions assisting us in this work. And finally, the last line of this preface is dedicated to all members of our families for their invaluable help, patience, understanding and general support. ☺

Aleksey I. Sharov

Graz, December 2009

\(^5\) CalVal means calibration and validation of Earth Observation data.

\(^6\) GMES (Global Monitoring for Environment and Security) is the European Initiative for Earth Observation.
1. INTRODUCTION TO GLACIER MONITORING

by Aleksey I. Sharov

1.1 Study objects & Study region

Glaciers and ice caps other than ice sheets\(^7\) have recently been receiving closer scientific attention since their dynamic environment is proving highly sensitive to climatic changes and influences with respect to sea-level changes (Dowdeswell et al., 1997). Several recent publications including the 4th IPCC report demonstrate that melting of glaciers and ice caps, and not that of ice sheets, dominates the eustatic sea-level rise in the 21st century (e.g. Meier et al. 2007). The character of variations in the physical characteristics of land ice cover can serve as an important and reactive indicator of present environmental trends on the globe, which responds relatively quickly to climatic changes and might help in forecasting the short-term consequences of those changes. In other words, by their presence in a given area, glaciers indicate the existence of certain climatic conditions, while glacier changes indicate an alteration of these conditions. An increased socio-economic interest in climate change today reveals an essential lack of reliable information on glacier changes worldwide, demanding immediate attention. In this context, the Arctic Region represents the largest information gap in world glacier inventories.

Arctic glaciers are among the most varied objects on the earth’s surface as a result of changes in solar radiation, fluctuations in the Arctic Oscillation, enhanced oceanic forcing, variability of freshwater inflow and thermohaline circulation, sea ice concentration, emission of sea-salt aerosols and solid precipitation in the Arctic Basin. The older generation of glaciologists said that in the High Arctic “the changes of a glacier’s shape and of its surface structures are usually of such a magnitude that they require map revision almost as frequently as do the heavily populated areas, where civic activities rapidly change the surface of the earth” (Blachut & Müller 1965). Tidewater glaciers (TWGs) terminating in the sea and producing icebergs are considered as especially dynamic and changeable types of land ice in the Arctic. Publications periodically announce drastic changes in the position of tidewater glacier termini ranging from several hundred to several thousand meters (cf. Dowdeswell 1989, Zeeberg & Forman 2001, Sharov 2005). Apart from Antarctica and Greenland, glaciers entering the sea are well developed in the Canadian High Arctic, and can also be seen in Alaska and Patagonia. They are widely distributed in the Eurasian arctic archipelagos of Franz Josef Land, Svalbard, Novaya Zemlya and Severnaya Zemlya, and persist at Jan Mayen, Kvitoya, Victoria, Ushakova and De Long islands. With the exclusion of Jan Mayen and De Long islands, nearly all Eurasian TWGs are situated in the Barents-Kara region (Fig. 1, a). This is why we selected this northernmost part of the Eurasian Arctic terra firma for our studies.

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\(^7\) An ice sheet is a mass of glacier ice that covers surrounding terrain and is greater than 50,000 km\(^2\). The only current ice sheets are in Antarctica and Greenland.
The present total area of the Barents-Kara glaciation\(^8\) including glaciers of Svalbard and Kvitoya, Franz Josef Land and Victoria Island, Novaya Zemlya, Severnaya Zemlya and Ushakova Island is approximately 93,000 km\(^2\) or nearly 14% of global glaciation\(^9\). After the

\(^8\) Maximal estimate; reference period 1950s -1960s.
\(^9\) The total area presently covered by glaciers and ice caps is given as 685,000 km\(^2\), which is unequally shared between the Northern (approx. 581,000 km\(^2\) or 85%) and Southern (approx. 104,000 km\(^2\) or 15%)
Generation of glacier data products

Greenland Ice Sheet, this macro-region has the highest index of glaciation of all arctic regions: nearly 50% of its terrain is covered by glaciers. In terms of its present size the Barents-Kara glaciation occupies an intermediate position between the Canadian Arctic glaciation (148,800 km²) and separate glaciers of Greenland with a total area close to 76,000 km². Further geometric characteristics of the Barents-Kara glaciation determined for five meso-regions are given in Table 1. These values indicate the potential work load related to glacier change mapping in the study region.

The study region covers several climatic zones and comprises glaciers of different size, elevation range (0 – 1,500 m asl), morphological type and dynamics. In many places, separate ice masses form large glacier complexes. All of them fall in the category of maritime or insular glaciers including small (< 50 km²), medium (< 1,000 km²) and large-size Arctic ice caps with slow moving or stagnant margins and faster flowing outlet glaciers draining the surplus ice from the accumulation areas of ice caps into the ablation zone. Many outlet glaciers reach the sea and constitute the group of tidewater glaciers. Fast-flowing tidewater outlet glaciers with frontal velocities of up to 1-2 m/day were detected in the Svalbard (e.g. Kronebreen), Franz Josef Land (Karo and Impetuous glaciers) and Severnaya Zemlya (outlet glaciers No. 7 and 8) archipelagos. Mountain, plateau and apron glaciers move more slowly.

According to geophysical classification by Lagally (1933), Ahlman (1948) and Baranowski (1973), almost all glaciers in the Barents-Kara region belong to the sub-polar type, i.e. to the group of glaciers with surface summer melting. Most of them are characterized by slightly negative ice temperatures (cold glaciers), but some glaciers are polynymetal and contain both cold and temperate ice. Many glaciers are two-layered, with an upper layer of cold ice and a basal layer of temperate water-saturated ice. In Svalbard, some of these two-layered tidewater glaciers are known as surging glaciers, which periodically demonstrate a dramatic increase in motion velocity usually accompanied with an essential, albeit transient advance of the glacier front. Glacier surges in other archipelagos are seldom, but not improbable (Sharov 1997, Sharov & Tyukavina 2009).

Table 1. Geometric parameters of the Barents-Kara glaciation (second half of the 20th century)

<table>
<thead>
<tr>
<th>Meso-Region</th>
<th>Parameter</th>
<th>Franz Josef Land &amp; Victoria</th>
<th>Novaya Zemlya</th>
<th>Svalbard &amp; Kvitoya</th>
<th>Severnaya Zemlya</th>
<th>Ushakova Island</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Glacier area, km²</td>
<td>13,746¹⁰</td>
<td>23,645¹¹</td>
<td>36,591¹²</td>
<td>18,325¹³</td>
<td>326¹²</td>
<td>92,632</td>
</tr>
<tr>
<td></td>
<td>Glaciation index, %</td>
<td>85</td>
<td>29</td>
<td>59</td>
<td>50</td>
<td>100</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>Glacier volume, km³</td>
<td>2,472</td>
<td>6,830</td>
<td>7,567¹⁴</td>
<td>5,500</td>
<td>35</td>
<td>22,404</td>
</tr>
<tr>
<td></td>
<td>Average thickness, m</td>
<td>180</td>
<td>269</td>
<td>207</td>
<td>300</td>
<td>107</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>Length of ice coasts, km</td>
<td>2,666</td>
<td>208</td>
<td>1,051</td>
<td>501</td>
<td>80</td>
<td>4,501</td>
</tr>
</tbody>
</table>

Seaward margins of tidewater glaciers form precipitous ice coasts rising 2 to 50 m, and sometimes even 100 m above sea level, which are destroyed relatively fast in moving water

¹⁰ Catalogue of Glaciers in the USSR v. 3.1 (1965)
¹¹ Catalogue of Glaciers in the USSR v. 3.2 (1978)
¹² Liestøl O. (1993)
¹³ Catalogue of Glaciers in the USSR v. 16 (1980)
¹⁴ Kotlyakov V. (1985)
and rebuilt by the ice influx (Fig. 1, b - f). The total length of the ice coasts in the study region can be estimated at approximately 4,500 km (1950s, Table 1), which accounts for about 4% of the Eurasian coastline. Three basic types of ice coasts can be distinguished, depending on the position of the glacier face with respect to the sea level and sea bottom: ice cliff, ice wall and ice front. Cross-sections of ice coasts typical of the Eurasian Arctic are shown in Figure 2. In contrast to ice cliffs (Fig. 2, a), which form at the slow moving or stagnant seaward margin of an ice cap or glacier tongue, ice walls and ice fronts are normally formed by fast moving tidewater glaciers where the frontal velocity of ice flow exceeds the velocity of marine abrasion. Ice walls and fronts produce icebergs (Fig. 2, b, c) and undergo large spatial changes amounting to several hundred meters across the shore each year.

Figure 2. Seaward margins of large TWGs: ice cliff (a), ice wall (b), ice front (c), “raising” ice coast (d), ice toe (e)

The dominance of ice-loss processes at glacier fronts over the ice influx leads to the retreat of glacier termini and vice versa. The rate of retreat \( \frac{dL}{dt} \) can be defined as a negative difference between the mean ice speed at the glacier front \( u \) and the rate of frontal ablation \( u_c \), i.e.

\[ \frac{dL}{dt} = u - u_c , \]

where \( L \) is the glacier length, \( t \) is the time interval, and \( u_c \) is sometimes called “mean calving speed” because the effect of both melting and sublimation is small compared with that of iceberg calving (Hanson & Hooke 2000). The current retreat of TWG fronts \( dL \) and rapid disintegration of thinner glacier margins lead to a corresponding increase in the subaerial part of the glacier face, thus raising actual ice coast heights \( h_a \) (Fig. 2, d). Previous field observations and remote sensing surveys in the Barents-Kara region revealed that most TWG fronts have “risen” 10 to 40 m above sea level in the past 50 years (Sharov & Etzold 2005).
Generation of glacier data products

This fact does not contradict the general lowering of glacier surfaces in the ablation area $dh$ as a result of increased melting and, probably, accelerated ice flow at seaward glacier margins.

Some parts of the glacier bed of large ice caps and domes are situated 50 to 200 m below sea level (Dowdeswell et al. 1996). The occurrence of bottom ice is not unusual; its melting can offset the sea level rise. The locations of bottom ice are visible as light green areas along calving faces at Cape Arctic, Severnaya Zemlya (Fig. 1, f). Underwater ice toes can also produce icebergs (Fig. 2, e). Partially or transiently floating ice tongues and ice bridges undergoing vertical oscillations were observed in Franz Josef Land, Svalbard and Novaya Zemlya (Fig. 3, Sharov et al. 2003, Sharov & Wack 2007). Severnaya Zemlya holds the Matusevich Ice Shelf, 241 km² in size (1980), the largest floating glacier in the Old World.

According to present notions, glaciers of the Barents-Kara region are in the regressive stage. The total mass balance of the Barents-Kara glaciation has remained negative over the past 70 years due to climate warming and considerable calving (Jania & Hagen 1996). Mass balance measurements are still only available for few glaciers in the study region; they do not show any particular trend. There is very little factual knowledge about glacier elevation changes, and quantitative information on calving processes is extremely scarce.

1.2 Glaciological data sources

Standardized glaciological information about most glaciers and ice caps in the study region is provided by world glacier inventories and regional databases, such as World Glacier Inventory (WGI, Häberli 1998), LANDSAT-7 Glacier Inventory (Aber & Klein 2001), GLIMS Glacier Database (Raup et al. 2007), WGI-XF (Cogley 2009), GISICE Glaciological Database of the Eurasian High Arctic (Dowdeswell 2001), which are readily accessible to the scientific community. A good example of a worldwide glacier inventory comprising / integrating several former inventories and containing glacier topography parameters, glacier outlines and metadata compiled over the past few decades is that managed by the World Glacier Monitoring Service (WGMS) at the University of Zurich.

None of these inventories are complete, however, and the largest gap in glaciological data is observed in the Eurasian Arctic. Moreover, current glacier inventories provide data in tabular form as point information with limited use for detailed spatial analysis, change assessment and cartographic applications. For example, the GLIMS inventory intends to provide the community with data for later comparison and cannot be considered as an “early warning system” for glacioclimatic change monitoring.

Since 1959, worldwide changes in glacier geometry have been periodically reported for five-year periods in a series of volumes on “Fluctuations of Glaciers” (FoG) issued by the International Commission on Snow and Ice of the International Association of Hydrological Sciences and the International Association of Cryospheric Sciences of the International Union of Geodesy and Geophysics. The last volume, No. IX, issued by the WGMS relates to the period 2000 to 2005 and provides general information on 723 separate glaciers, variations in the positions of glacier fronts for 712 glaciers, a mass balance summary (58 glaciers) and changes in area, thickness and/or volume observed on 49 glaciers (Haeberli et al. 2008).

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15 Calving of icebergs.
16 http://www.glims.org/
17 Out of 160,000 glaciers worldwide
18 Africa (12), Bolivia (3), CIS (1), India (1), USA (1), rest in Europe.
This clearly indicates that changes in glacier area, thickness and volume are poorly observed. The No IX volume includes some change data for only 4 glaciers situated north of latitude 70°N, which allows the whole Eurasian High Arctic to be qualified as a data-poor region.19

A joint UNEP-WGMS illustrative report on “Global Glacier Changes: Facts and Figures” released in September 2008 provides an overview of worldwide glacier fluctuations illustrated with snapshots of glacier surges, calving instability, flood, ice avalanche and tectonic events, and gives glacier front variation data and mass balance estimates for a number of reference glaciers from 10 macro-regions worldwide (Zemp et al. 2008). Cumulative values of specific mass balance are provided for the past decades showing a steadily increasing difference between the mean estimate for all glaciers and the mean estimate for reference glaciers. The data gaps observed in this report are similar to those in volume No. IX.

The most consistent, thorough and condensed knowledge on the state of glaciers in the Barents-Kara region is compiled in national glacier inventories, catalogues of glaciers, and topographic and thematic maps, both in sheet and atlas form, which were mostly created from materials of extensive aerial and hydrographic-geodetic surveys carried out in the 1950s to 1960s. Yet, even comprehensive atlases containing large numbers of glaciological and climatic maps, such as the “Atlas of the Arctic Ocean” (1980), “Atlas of the Arctic” (1985) and “World Atlas of Snow and Ice Resources” (1997) produced in the Russian Federation and the “Glacier Atlas of Svalbard and Jan Mayen” (1993) issued in Norway, include very few maps showing glacier changes in the study region. None of these maps represent glacier changes at regional scale.

The whole territory of the Eurasian High Arctic is covered by topographic map series down to a scale of 1:100,000, the contour interval (CI) being 20 or 40 meters in Russian and 25 or 50 meters in Norwegian maps. There are also map series at 1:50,000 and 1:25,000 scales covering individual areas and a few sheets at 1:10,000 scale (e.g. Parry & Perkins 1987). The rms vertical accuracy of standard topographic maps is typically given as one fifth to one third of the contour interval on glaciers, i.e. 4 to 16 m rms. These cartographic materials represent the most accurate and detailed means available for the analysis of glacier state variables and changes in the study region, but their use for precise topographic determination is only possible by taking into account the positional accuracy of the maps as well as any natural changes having occurred since the reference surveys. A special effort is still required to generate digital elevation models (DEMs) from these maps and to adjust them to a modern terrestrial reference frame. All Norwegian and Russian topographic and thematic maps (1950s and younger) for the generation of reference elevation models of study glaciers were provided by participating institutions and obtained from relevant on-line archives, e.g. that on http://poehai.org/maps, at low cost.

Controlled reference elevation models with 50 m posting covering the Franz Josef Land, Novaya Zemlya and Severnaya Zemlya archipelagos including Kvitoya, Victoria and Ushakova islands were derived at Joanneum Research (JR) in Graz from Russian topographic maps 1:200,000 (CI = 20 or 40 m) representing the glacier state in the 1950s to 1960s (Fig. 3, a, b, d). All available topographic maps were vectorized in 45 working days using the “Easy Trace 8.6 Pro” software package. The 20-m DEM of Svalbard was created by the Norwegian Polar Institute (NPI) using updated 1:100,000 map sheets and vertical air photographs taken in 1977 and 1990. The horizontal accuracy was given as ± 2 – 3 m (Nuth et al. 2007). The Svalbard

19 General information is provided for 7 glaciers in this macro-region.
20 For low-lying areas
DEM was still incomplete at the beginning of the present work in 2007 and some missing parts were generated with 50-m posting at Joanneum Research using older elevation data (Fig. 3, c). Figure 3 shows several fragments from the 50-m reference elevation models in a Universal Transverse Mercator (UTM) projection representing the glacier state in the 1950s to 1960s. The amount of work related to the digitization / vectorization of the topographic maps and the generation and adjustment of reference elevation models using the EasyTrace or RSG software packages accounted for approximately one fourth of the total workload.

Figure 3. Fragments of 50-m reference elevation models for Severnaya Zemlya (a), Franz Josef Land (b), Svalbard (c) and Novaya Zemlya (d)

Apart from positional accuracy and spatial resolution, the applicability of reference elevation models to glacier change mapping and geodetic mass balance measurements depends on the magnitude of the glacier change signal. The 50-year change signal on many study glaciers ranges from several tens of meters to one hundred meters or is ten times larger than the reference data inaccuracies. In some areas, such as parts of eastern Svalbard, the quality of older topographic data is compromised by highly inaccurate geolocation and difficulties with photogrammetric methods of stereoplotting over large expanses of ice and snow. In such cases we applied younger topographic maps with higher accuracy and level of detail.

Other "global" elevation models, e.g. GTOPO30 (30 arc seconds or 1000 m posting interval, released in 1996), SRTM3 (3 arc seconds / 90 m, 2003) and ASTER GDEM (1 arc second / 10
Generation of glacier data products

m, 2009) are available free of charge, but are not suitable to serve as a reference model for glacier elevation change mapping in the Barents-Kara region because of their poor spatiotemporal coverage (SRTM3\textsuperscript{21} and ASTER GDEM\textsuperscript{22}) and limited vertical accuracy (±15 m rms and worse for the ASTER GDEM; ±30 m rms and worse for the GTOPO30). These models are too "young, narrow and rough".

When merging and adjusting separate elevation models one should account for the reference period or data age and the actual datum plane to which all height and depth measurements are referred. In our case, the basic reference period for the quantification of glacier elevation changes covers up to 50 years, depending on data availability\textsuperscript{23}.

The 50-year period of the present study is sufficiently long to compensate for the influence of global natural cycles and to ensure accurate temporal extrapolations as well as to allow adequate conclusions on the character and origin of glacier changes to be drawn and subsequent glacioclimatic forecasts to be made. Glacier changes in regions with different history of surveys were quantified in average annual rate values, e.g. in [m/a]. The regional variations in the multi-year mean sea level, i.e. the actual datum plane, did not exceed 0.7 m during the past 50 years, which was evidenced from repeated spirit levelling surveys performed in Franz Josef Land, Novaya Zemlya and South Spitsbergen (Kostka & Sharov 1996, Sharov & Wack 2007). The WGS 84 ellipsoid was chosen as the horizontal reference datum. The UTM projection was used for producing glacier maps and value-added products. Additional quality control, particularly in ice free areas, was performed using lidar altimetry data.

Still, our reference elevation models alone could not provide glacier change data; they had to be quantitatively compared with modern elevation data obtained from remote sensing and recent terrestrial surveys.

1.3 Glacier monitoring strategy

The dynamic environment and high rates of natural change, the remoteness from economically developed regions and harsh environment impeding both aerial surveying and extensive field work are the principal reasons for applying satellite monitoring in extensive glacial areas of the Arctic, where natural features are predominant, complicated socio-economic objects are scarce, the glaciated relief is mostly homogeneous and vegetation cover is negligible. Techniques making use of artificial polar-orbiting satellites and multi-sensor, multi-temporal data fusion are believed to be the most effective tools for monitoring glacier changes in the Arctic. The most important impact of satellite glacier products on climate data records is anticipated for the High Arctic, where reliable long-term climatological and glaciological data records are scarce and sometimes inaccessible due to a certain geographic isolation, relatively short history of explorations, data dispersion among national databases and massive closure of polar stations in the period from the 1990s to 2000s. It is worth noting that the meteorological satellites in geo-stationary orbits lack coverage of the High Arctic,

\textsuperscript{21} Data acquisition period: 11 days in 2000; data is missing in topographically steep areas and outside of the zone 60°N – 56°S.
\textsuperscript{22} Data acquisition period from 2000 onwards, areas of missing data due to constant cloud cover.
\textsuperscript{23} The period for which air photography is available. In several glacial areas reference elevation data were derived from younger topographic maps representing the glacier state in the 1970s to 1990s.
which limits information on climate change and highlights the importance of applying polar-orbiting satellites to glacier monitoring in this macro-region.

Special emphasis was given to estimating the impact and scientific contribution of ESA Earth Observation (EO) missions to further understanding and forecasting recent and potential glacioclimatic changes in the study region with the highest index of glaciation, relatively rapid response to climate fluctuations, high rates of environmental changes and few meteorological stations. ESA polar orbiting satellites ERS-1/2, ENVISAT and GOCE, replaced and complemented by the CryoSat-2 and Sentinel missions, ensure continuity of observations and contribute to an increased coverage of this macro-region with a view to expand the scope and improve the coordination of observation and monitoring throughout the circumpolar Arctic as was requested in the EU Council conclusions on Arctic issues (08.12.2009).

A regional approach to estimating changes in a large population of glaciers with significant size variations and often different reactions to climatological forcing as offered in the 2007 IPCC report will be a distinct improvement to the current status of glaciological research. The overall regional mapping of glacier topography and change characteristics will allow the combined effect of variations in air temperature, pressure and precipitation on glaciers to be extracted, thus providing an estimate of climatological heterogeneity and delivering inputs to regional and global climate models. Furthermore, we wish to cite the following finding summarized by SWIPA, the Arctic Council’s assessment of “Snow, Water, Ice and Permafrost in the Arctic” (2009): “Direct measurements of changes in Arctic mountain glaciers and ice caps are limited to a small number of glaciers across the Arctic and there is a pressing need for a regional scale assessment of glacier and ice cap change based upon remote sensing observations and numerical modelling”.

The systemic top-down approach to studying, monitoring and mapping glacier complexes with EO data is our main strategy and concept of information processing in the SMARAGD project. The entire specification of base elements and relevant processes under investigation, including main agents of exogenic (climate change, extra-terrestrial factors and socio-economic activities) and endogenic (seismic, tectonic and gravity-induced impacts) forcing on study glaciers, has to be determined at the very beginning of monitoring work. The main glacier state variables studied and recorded as satellite data products are schematically represented in Fig. 4. Figure 4 also depicts other components of the Earth’s cryosphere and related processes of different relevance accounting for the requirements of the climate modelling community, data availability and modern opportunities of EO systems.

In general, the set of glacier variables under observation and technical requirements for their determination depend on the scale of monitoring and can be defined by analogy with the information requirements for both topographic charts and thematic maps of glacial areas at a particular scale (Sharov 1997). In our work, all product requirements are based on the leading principle of meaningful performance with regard to costs and time planning, and may slightly vary depending on the study area, data availability and quality, and the resources available to the working group.

24 The distribution density can be as low as 1 station at the sea level per 20,000 km² of land ice with elevations ranging from 0 to 1000 m.
25 http://earth.esa.int/workshops/spaceandthearctic09/
26 Intergovernmental Panel on Climate Change (http://www.ipcc.ch/)
27 http://www.amap.no/swipa
Modern satellite remote sensing usually does not allow for the investigation of submarine and subterranean objects, and the main object of complex satellite monitoring is related to a particular locality, i.e. glacier surface with all its features accessible to direct remote observations. Moreover, spaceborne surveying does not immediately enable a comprehensive analysis of functional interdependencies in the High Arctic environment. One barrier to such investigations is the manifold increase in the number of thematic studies requiring field research in situ which can be very problematic if it has to be carried out under severe Arctic conditions. This is why the present study concentrates on spatial or lateral relationships rather than temporal interrelations between glaciological objects.

This strategy helped to avoid any misunderstanding within the research group, to clearly formulate our research goals and to interpret the main results, to control the systemic complement of output products and to ensure the glacioclimatic products developed are compatible with the needs of the climate modelling community. Presently, glaciers and ice caps are only treated in regional climate models (c.f. Radic & Hock 2006, Huss et al. 2008a), while our developments were designed to extend spatiotemporal coverage of glacier change models and provide reasonably accurate spatial representations of glacier state and change at regional scales yet without compromising on the detail and completeness of these models. New map series representing glacier changes at meso- and macro-level might mitigate some scaling problems in studying interrelations between atmosphere, ocean and glacier state variables.
Generation of glacier data products

Historically, most input data sets for mapping and inventorying glaciers and ice caps were derived from image data obtained by optical air- or space-borne sensors, such as LANDSAT-(E)TM, SPOT-HRV/G and TERRA-ASTER. Hence, longer periods of time were required for the acquisition of optical imagery covering extensive glacial areas in regions with frequent cloud cover and snowfall. As a result, the entries in satellite glacier inventories are typically of different age and quality and are not characterized by regularity, homogeneity and consistency, all of which are basic requirements for reliable change detection. The scantiness of new optical images of glaciers is becoming a relatively problematic issue, since the present LANDSAT and ASTER sensors are approaching the end of their service life. Their spaceborne successors, such as ALOS-PRISM and METEOR-M, have problems of their own and their autonomous applicability to worldwide mapping of glacier changes is still conjectural.

Besides, the limited possibilities of optical image remote sensing, e.g. its relatively low sensitivity to height changes in accumulation areas of large glaciers, do not allow for the overall mapping of glacier elevation and volume change from space. Volumetric studies are easy to advocate, but difficult to realize, and most reports on glacier changes in the study region have been based on linear or areal measurements. The geodetic method of mass balance measurements based on precise determination of glacier volume changes (dh/dt) by differencing stereophotogrammetric maps or elevation models representing the glacier surface topography of different years was infrequently used in satellite-based models of study glaciers.

Indirect remote sensing estimates of glacier mass balance from the accumulation area ratio (AAR) and equilibrium-line altitude (ELA), which can be determined within certain limits from spaceborne optical imagery, considerably reduce the field work in comparison with the direct glaciological method, but are error prone especially in extensive poorly studied regions and under anomalous meteorological conditions (Kuhn et al. 1999). The use of correlation between changes in the equilibrium-line altitude (ELA) and glacier terminus levels also cannot provide a reliable estimate of mass balance variations for each glacier type on an operational basis. It has to be stressed that the glacier terminus position or the glacier length cannot be used, on its own, for mass balance estimation since the total ice volume can decrease while glacier length increases or remains stable. Mass balance models based on climate data cannot be considered as an independent product for climate analysis and will not be treated in this publication.

Satellite-based altimetry and synthetic aperture radar (SAR) sensors operate independent of natural illumination and can provide homogeneous data on glacier topography on a diurnal basis in both cold and warm seasons. In contrast to the passive remote sensing method of classical stereo-photogrammetry, which is widely used for topographic modelling of large and small glaciers with appropriate ground control, such a combination of active ranging systems is particularly suited to repeated measurements of glacier state variables with high temporal and spatial resolution in cases of insufficient ground, especially vertical control. The compatibility and complementarity of radar imaging and altimetric profiling systems has already been demonstrated by several extraterrestrial missions (c.f. Slama 1980), evidenced by the combined operation of the SAR imager and radio altimeter on board ERS and ENVISAT satellites, and emphasized in our previous studies (Sharov & Jackson 2007).

Both methods are sensitive to changes in glacier topography and, up to now, there is no reasonable alternative to radar systems for the periodical acquisition of spatially homogeneous...
data in high-latitude glacier regions. For example, multitemporal high-resolution data takes over Severnaya Zemlya and De Long Islands situated half way between the ground receiving stations in Kiruna, Sweden, and Anchorage, Alaska, were possible only from ascending (night) orbits of ERS and ENVISAT. Precise orbital data provided for ERS, ENVISAT and other satellites enables straightforward geometric processing of SAR imagery and stimulates inverse radargrammetric solutions. New opportunities for determining the ice bulk density and validating mass changes on large and medium size glaciers are expected from the GOCE and GRACE satellite gravimetry missions.

Even with active dual-sensor EO methods one cannot cover all glaciers in the Eurasian Arctic, or even one large macro-region with detailed large-scale maps of state variables within a single remote sensing study. Hence a scientific consensus is needed between the requirements of detail or working scale and spatial coverage of the glacier maps to be produced from satellite data. In the SMARAGD project such consensus has been achieved by producing several map series of glacier changes at large (1:50,000), medium (1:500,000) and small (1:5,000,000) scales for separate glacier complexes, meso-regions and the entire Barents-Kara region respectively. A limited number of 20 glacier complexes was selected for detailed remote sensing studies and full-value mapping of glacier state and changes. The list of SMARAGD study areas is given in Table 2. The first 20 study glaciers belong to the Barents-Kara region. Four mountain glaciers and ice caps from other parts of the Eurasian Arctic are shown as a “reference” and optional development for further CryoSat-2, Sentinel-1 and GOCE-related studies. Six glaciers specified in the list are included in “Fluctuations of Glaciers”, v. IX and three of them in its change part.

The SMARAGD study glaciers were selected so as

- to map the glacier state and changes in the entire Barents-Kara region, wherever possible without gaps, and to fill the largest gaps in existing world glacier inventories and international databases,
- to ensure full coverage of the study glaciers with ESA archival and new mission data and the technical feasibility of spaceborne interferometric, altimetric and gravimetric observations,
- to include glaciers of different size, elevation range, morphological type and dynamics, with different sensitivity to climate change and different history of surveys,
- to cover different climatic zones with different rates of environmental changes and socio-economic activities,
- to determine the glacier change signal along the extensive latitudinal transect characterized by the largest gradient of solid precipitation and glaciation index,
- to coordinate the available expertise and to ensure the availability of external validation data and the homogeneous distribution of validation activities,
- to re-use existing databases, cartographic materials, documentation and infrastructure from previous glacier-related EO projects, including the network capabilities of European glaciological stations,
- to cover the main Cal/Val glacial areas related to the launch and operation of the GOCE, CryoSat-2 and Sentinel-1 missions,
- to complement and not duplicate the efforts undertaken by other ongoing EO activities,
- to stimulate further studies of mutual variations in land and sea ice,

30 E.g. those related to glacioisostatic compensation.
Generation of glacier data products

- to stay within the constraints of time schedule and cost.

Table 2. List of SMARAGD study glaciers / areas

<table>
<thead>
<tr>
<th>N</th>
<th>Sub-Region</th>
<th>Name of Glacier Complex</th>
<th>Glacier Area, km²</th>
<th>Priority*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S Spitsbergen</td>
<td>Hombreen-Hambergbreen etc.</td>
<td>179 + 144</td>
<td>high</td>
</tr>
<tr>
<td>2</td>
<td>S Spitsbergen</td>
<td>Hansbreen and Torelbreen</td>
<td>60 *</td>
<td>high / ref</td>
</tr>
<tr>
<td>3</td>
<td>Spitsbergen</td>
<td>Lomonosovfonna etc.</td>
<td>600</td>
<td>medium</td>
</tr>
<tr>
<td>4</td>
<td>W Spitsbergen</td>
<td>Kronebreen, Kongsvegen</td>
<td>700 + 102</td>
<td>medium</td>
</tr>
<tr>
<td>5</td>
<td>NE Svalbard</td>
<td>Austfonna &amp; Vestfonna</td>
<td>8,100 + 2,500</td>
<td>high</td>
</tr>
<tr>
<td>6</td>
<td>NE Svalbard</td>
<td>Kvitloyokulen</td>
<td>690</td>
<td>high</td>
</tr>
<tr>
<td>7</td>
<td>Victoria Island</td>
<td>Victoria Ice Cap</td>
<td>10</td>
<td>high</td>
</tr>
<tr>
<td>8</td>
<td>W Franz Josef Land</td>
<td>Southern, Moscow, Broussilov, Moon caps</td>
<td>2,150 + 980 +</td>
<td>high</td>
</tr>
<tr>
<td>9</td>
<td>Franz Josef Land</td>
<td>Glaciers of Ziegler Island, Sedov Glacier</td>
<td>364 + 7 +</td>
<td>high / ref</td>
</tr>
<tr>
<td>10</td>
<td>E Franz Josef Land</td>
<td>Tyndall, Windy ice caps etc.</td>
<td>1,890 + 727+</td>
<td>high / ref</td>
</tr>
<tr>
<td>11</td>
<td>N Novaya Zemlya</td>
<td>Northern Ice Cap</td>
<td>2,250</td>
<td>high</td>
</tr>
<tr>
<td>12</td>
<td>Novaya Zemlya</td>
<td>Main Glacier Complex</td>
<td>approx. 20,000</td>
<td>high</td>
</tr>
<tr>
<td>13</td>
<td>Novaya Zemlya</td>
<td>Shokalstskogo Glacier</td>
<td>280</td>
<td>high / ref</td>
</tr>
<tr>
<td>14</td>
<td>S Novaya Zemlya</td>
<td>Southern glaciers</td>
<td>600</td>
<td>medium</td>
</tr>
<tr>
<td>15</td>
<td>Ushakova Island</td>
<td>Ushakova Ice Cap</td>
<td>325</td>
<td>high</td>
</tr>
<tr>
<td>16</td>
<td>NW Severn. Zemlya</td>
<td>Schmidt Ice Cap</td>
<td>438</td>
<td>high</td>
</tr>
<tr>
<td>17</td>
<td>N Severn. Zemlya</td>
<td>Academy of Sciences Ice Cap etc.</td>
<td>5,863 + 290</td>
<td>high / ref</td>
</tr>
<tr>
<td>18</td>
<td>Severnaya Zemlya</td>
<td>Karpinsky, Vavilov, University ice caps etc.</td>
<td>2,561 + 1,805 +</td>
<td>high</td>
</tr>
<tr>
<td>19</td>
<td>Severnaya Zemlya</td>
<td>Matusevich Ice Shelf</td>
<td>241</td>
<td>high</td>
</tr>
<tr>
<td>20</td>
<td>S Severnaya Zemlya</td>
<td>Leningradsky Ice Cap etc.</td>
<td>1,704 +</td>
<td>high</td>
</tr>
<tr>
<td>A</td>
<td>Scandinavia</td>
<td>W. &amp; E. Svertsen Ice Caps</td>
<td>221 + 148</td>
<td>reference</td>
</tr>
<tr>
<td>B</td>
<td>Polar Ural</td>
<td>IGAN, Obruchev, MGU glaciers etc.</td>
<td>1 +</td>
<td>reference</td>
</tr>
<tr>
<td>C</td>
<td>Byrranga Mts</td>
<td>Toll Glacier etc.</td>
<td>29</td>
<td>reference</td>
</tr>
<tr>
<td>D</td>
<td>De Long Islands</td>
<td>Toll Ice Cap etc.</td>
<td>82</td>
<td>reference</td>
</tr>
</tbody>
</table>

*) Glacial areas with essential validation data are specified as reference. The six largest ice caps selected for further GOCE applications are marked in blue.

The six largest ice caps selected for further GOCE applications are marked in blue.

The study glaciers constitute 3 distinct groups:

1) large and medium-size maritime ice caps of the insular Arctic with a mostly homogeneous topography, slow motion and essential accumulation at glacier tops (main macro-group),
2) small- and medium-size fast-flowing tidewater outlet glaciers draining ice from larger ice caps into the sea with strong ablation at glacier fronts (transitional meso-group),
3) small- and medium-size mountain / valley glaciers terminating on land, including four reference glacial areas on the Eurasian continent with a strong change signal and comprehensive series of observational data (validation group).

Glaciers with homogeneous topography were preferred. Approximately 20% of study glaciers are considered as “difficult” for satellite observations due to their small size, complex topography and/or irregular dynamics. Nearly every large glacier contains “difficult” parts, which were pre-defined by analyzing reference elevation models, detecting low-coherence sections in quick-look INSAR data and spike changes in multi-pass altimetry data.
In the practical work we applied the region growing approach to each meso-region (archipelago) starting from one central, usually large- or medium-size glacier and extending / detailing the research outwards. The bottom-up approach was applied to elevation (change) modelling in that we started from the coastline or 0-m contour as the most extended topographic feature in the region requiring utmost geometric accuracy and successively drew all other contours / isolines in one direction, working from a lower elevation upward. Glacier borders were mostly delineated in a clockwise direction. It was always possible to indicate the location of the highest positions in relatively flat and homogeneous terrain at glacier tops (Sharov & Jackson 2007). Hydrological networks and drainage channels were modelled upstream, beginning at the lowest point of the main stream / valley in the region. Glacier topographic models were checked for anomalies such as gross recording errors, angularity, missing lines, etc. and were subsequently corrected. Validation and quality control of glacier products are described in Chapter 5.

1.4 Method of glacier monitoring

The advance of satellite radar interferometry (INSAR) and, especially, differential interferometry (DINSAR) provided new and unique opportunities for glacier change mapping with spaceborne SAR data (Gabriel et al. 1989, Dowdeswell et al. 1999). The whole Barents-Kara region has been repeatedly covered by ERS-1/2 SAR scenes suitable for interferometric analysis. Still the interferometric method requires basic, especially vertical control data for geocoding and calibrating SAR interferograms, and for compensating distorsional geophysical effects, e.g. ionospheric refraction or radar penetration into the snow pack. Combined with satellite altimetry this imaging technique is regarded as a highly informative remote sensing method for continuous glacier surveys, systematic mapping of glacier topography, determining glacier elevation changes and geodetic mass balance measurements (e.g. Robin 1966, Nielsen et al. 1997, Sharov & Etzold 2004). The combined use of precise-orbit interferometry and altimetry referred to as the INSARAL method allows parametric scaling, geocoding, mosaicking and interpreting of differential interferograms to be performed with fewer or even without traditional ground control points (GCPs) and reference information. It is at all events worth noting that the combination of lidar altimetry with radar interferometry essentially moderates the requirement of glacier-wide coverage with optical data and is thus applicable to precise mapping of elevation changes on both large and medium ice caps and separate valley glaciers (Fig. 5).3

Figure 5 exemplifies the INSARAL dataset for the central part of Franz Josef Land including typical fragments from ERS-1/2 INSAR (09/10.10.1995, a) and 2-pass DINSAR (1952-1995, b) fringe images showing glacier topography and elevation changes / ice flow respectively. The differential interferogram in Fig. 5, b represents both the ice flow pattern in outlet basins and glacier elevation changes in slow-moving parts of ice caps for the period of the 1950s to 1990s; one can see four large and three smaller tidewater outlets draining ice from the large (920 km²) Moscow Ice Cap at Hall Island into the Barents Sea. The differential interferogram is overlaid with two arbitrarily chosen differential hypsometric profiles showing glacier elevation changes along the ICESat altimetric transects of 2005 on the Moscow Ice Cap at Hall Island and on the relatively small (21 km²) Hydrographer’s Ice Cap in the northern part of Hayes Island. Negative elevation changes (surface lowering) are given in shades of ochre while

31 In glacier accumulation areas, radar “observes” some backscattering layers below the true glacier surface.
32 As an autonomous method, satellite altimetry is applied to glacier change mapping only on ice sheets and large glaciers due to its relatively large (approx. 10 km at high latitudes) track spacing.
positive changes are marked in blue. The rms error of height differences is given as ± 5 m. Such profiles are used for the calibration of glacier differential interferograms and for the glacier-wide quantification of elevation changes. Typical hypsometric profiles of Hydrographer’s and Moscow ice caps derived from topographic maps (green) and ICESat altimetry data (blue) are given in the lower part of Fig. 5. The comparison of ICESat altimetric transects with the hypsometric profiles derived from existing topographic maps corroborates the significant (up to 60 m) lowering of the glacier surface on both ice caps in the past 50 years.

Figure 5. Illustration of the INSARAL dual-sensor technique for glacier elevation change mapping with the aid of differential interferometry and altimetry

Five years of application in different glacial areas brought good results and demonstrated the feasibility and high reliability of the INSARAL technique for mapping elevation changes on large (1000 km²) and medium-size (100 km²) glaciers and ice caps. Recent studies in the Arctic, the Alps and in Scandinavia have also demonstrated the applicability of INSARAL to mapping changes on small (10 km²) glaciers (Sharov & Etzold 2004, Sharov & Jackson 2007). Several attempts were made, with varying success, to study the dynamics of glacierrts (1 km²), debris-covered and rock glaciers with the aid of spaceborne interferometry (Nagler et al. 2002, Sharov & Etzold 2004). The combined INSARAL method is still not suitable for separate small-size steep and crevassed mountain glaciers of temperate latitudes because of relatively scarce coverage by altimetry data, local layover and de-correlation (melting) effects, and
Generation of glacier data products

Slope-induced geometric errors. In high-latitude glacial areas this problem vanishes due to the convergence of polar orbits\(^{33}\), permanently cold weather, seasonal snow cover and the inclusion of small glaciers into larger glacier complexes.

Elevation change measurements were naturally accompanied with glacier outline mapping (from INSAR amplitude and coherence data), determining main ice divides and outlet glacier basins (from INSAR phase gradients), and measuring glacier velocities in polar Norway, South Spitsbergen, North-East Svalbard, Franz Josef Land, Novaya Zemlya and Severnaya Zemlya (Sharov et al. 2003, Sharov & Nikolskiy 2007, Sharov et al. 2009). Joint analysis of multitemporal amplitude and coherence interferometric data taken in the cold and warm seasons involving coherence ratio images enabled the semi-automatic discrimination between debris- and snow-covered glacier- and non-glacier areas, lakes and fast sea ice. The comparison with stereophotogrammetric maps derived from high-resolution IKONOS imagery and terrestrial surveys on the same glaciers showed that the information contents of traditional optical image maps of mountain glaciers are frequently inferior to those of interferometric radar maps, e.g. in detecting ice deformations and measuring ice-surface velocities in hard-to-reach locations as well as in determining the actual position of glacier termini if the glacier surface is covered with snow or debris (Sharov & Etzold 2004, 2008).

Hence, the INSARAL method can be used as an autonomous technique providing a sound alternative to optical imaging sensors. The methodological variant of combining precise-orbit differential interferometry and altimetry illustrated in Fig. 5 provides a sound solution to:

- geocoding, calibrating, mosaicking and interpreting glacier differential interferograms,
- decomposing the line-of-sight displacement into horizontal and vertical components,
- reconstructing the ice-flow field and strain-rate pattern, and measuring glacier velocities,
- determining glacier borders and delineating the outlet glacier basins belonging to larger ice caps,
- distinguishing between debris- and snow-covered glacier and ice-free areas, lakes and fast sea ice,
- modelling and visualizing the distribution of elevation changes on both stagnant and fast-flowing glaciers

with a minimum number of SAR scenes, a minimal amount of ground referencing and an excellent quality-to-price ratio.

Another advantage of the INSARAL approach is that it requires no complex process techniques, such as phase unwrapping, reduces the computational load, mitigates some problems related to gridding and interpolating errors, and ensures a high level of automation. A useful feature is that it can be realized without essentially compromising on the accuracy, detail and coverage of basic glaciological products, such as glacier topography (outline, area, ice divides), equilibrium-line altitude, flow rate and mass balance. Some of these products, e.g. the equilibrium line and the net mass balance can be derived semi-automatically from continuous glacier change models even with higher reliability than from optical images. The geodetic method of measuring glacier mass balance used in the present work usually provides better agreement with the results obtained by direct glaciological surveys than indirect optical methods (Kuhn et al. 1999).

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\(^{33}\) ICESat-GLAS 70-m footprints are spaced at 170 m; available track spacing in the High Arctic is about 10 km.
Generation of glacier data products

1.5 Problem areas & Technical solutions

It should be stressed that the use of modern developments in satellite remote sensing and mapping technologies for cryospheric monitoring in the extreme conditions of high latitudes and altitudes is still largely unexplored and thus is of special practical importance and scientific interest. Most research in the area presently focuses on designing and validating algorithms for satellite data processing, while comparatively little attention is paid to appropriate cartographic representation of the glaciological information derived from spaceborne radar and lidar surveys. This is quite evident from reviewing the satellite maps of glaciers published so far; most of them fall into the category of “quick and dirty” reproductions or provisional maps at best. Usually the extent of glacier marginal changes is relatively small when compared to the total glacier area, which brings about additional difficulties and makes traditional glacier change maps less informative and unattractive (Figure 6). Precise and elaborate satellite maps representing glacier-wide changes in legible metrical form are still very few in number. This is presumably due to the complexity of the SAR algorithm and some uncertainties in the performance of novel and unaccustomed interferometric and altimetric techniques (Sharov & Etzold 2004). In the present work we produced a new series of full-value34 glacier change maps using satellite interferometry and altimetry data.

The combination of satellite SAR interferometry (INSAR) and lidar altimetry used in this work provides a particularly potent solution to measuring, interpreting and mapping glacier elevation changes both at the margins and in the interior of land ice masses and to estimating glacier mass balance on a regional and continental scale. The combined use of radar and lidar data allows the problem of sparse line-wise altimetric coverage of study glaciers to be solved. Some technological complications and restrictions, however, do still exist.

Figure 6. Cartographic sketches of glacier marginal changes in Franz Josef Land (1950-2000s)

Probably the most serious technical problem is the overall mapping of elevation changes in fast flowing parts of study glaciers, since it commonly involves a complex procedure of differential phase unwrapping. In our case this problem was tackled by using the phase-gradient approach that exploits the idea of proceeding from operations on wrapped SAR interferograms to the analysis of their derivatives or phase gradients (Fig. 7, Sharov & Etzold 2004). The resultant phase gradient images called topograms can be multiplied with a real, not necessarily integer scaling factor derived for each location from the co-registered differential

34 In compliance with the accuracy and content requirements of traditional glacier (change) maps.
altimetry data; the latter is also applied to decomposing the line-of-sight displacement into horizontal and vertical components and for other controlling operations.

The orientation of mountain and outlet glaciers across the radar range direction can bring some additional difficulties in measuring horizontal velocities of glacier flow; the impact becomes irrelevant in the case of elevation change measurements. The orientation problems, as well as the impact of local layover and temporary de-correlation effects were mitigated by combining SAR scenes taken from both ascending and descending orbits at proper seasons and times. We selected only SAR images obtained under cold, steady and cloudless weather conditions for further interferometric processing. Weather conditions during INSAR surveys were evaluated by using meteorological maps and archival optical images simultaneously taken over the same area from NOAA satellites.

Another technical difficulty is the “age” difference between available interferometry (1990s) and altimetry (2000s) data, which may cause errors up to 5 m even on a relatively flat glacier surface. The residual cumulative influence of random ablation-accumulation processes on height measurements estimated in cross-over areas did not usually exceed ±1 m\(^3\). In real data processing, we assumed a spatially homogeneous distribution of glacier elevation changes during the time interval between interferometric and altimetric surveys. Different dates of interferometry (1990s) and reference elevation data (1950s/1980s) can influence the planimetric accuracy of geocoded products but do not influence the vertical accuracy of modelling glacier elevation changes.

The influence of reference elevation errors on the magnitude of the glacier change signal was estimated and partly compensated by analysing and suppressing the change signal in the ice-free terrain. The dominant contribution to the error budget was from the reference elevation models derived from available topographic maps of Eastern Svalbard and Kvitoya. Gridding and interpolation errors were reduced by not using the DEM differencing method for glacier change mapping, but instead generating the elevation change product directly from calibrated differential interferometric phase values determined along the topographic contours from available topographic maps. Some other systematic processing errors brought about, e.g. by simplifying assumptions, were diminished by reducing the map publishing scale from 1:500,000 to 1:1,000,000.

The last, but not least problem is the lack of ice thickness and bulk density data for the direct calculations of mass fluxes / changes and mass balance estimates on study glaciers from space-borne elevation and volume change products. In addition, changes in snow density

\(^{35}\) incremental errors
must be taken into account in order to properly estimate mass balance using the suggested geodetic methods. In some areas the glacier bed topography and ice thickness are known from ice core sites, terrestrial and airborne radio-echo sounding (RES), and indirect geomorphological and geophysical observations (Fig. 8, Dowdeswell et al. 1996, 2004). Some information on the snow density and the thickness of accumulation layers was derived from previous publications and field surveys using ground penetrating radar and densitometry. The ice thickness distribution can be inferred, although sometimes with a considerable and poorly specified error term, from known surface topography and mass flux using principles of flow mechanics. However, factual knowledge about land ice volumes and mass fluxes on most study glaciers is missing.

In this context satellite gravity missions constitute a unique observation system for monitoring ice mass flux and mass redistribution in the Earth system. Satellite gravimetry – in particular the GRACE and GOCE missions – might provide an additional highly accurate gravimetric control for enhancing glacier change models and mass balance estimations on a regional basis. At higher geographical latitudes the GOCE ground track distribution is quite dense, providing comprehensive gravity observations for the study region. On well-mapped large Arctic ice caps GOCE multitemporal observations will provide valuable input for validation with glacier state variables obtained by other methods.

The expected impact of GOCE data on regional glaciological records will be at least twofold. First, the precise knowledge of the static gravity field represents a unique physical reference surface for analysing processes of glacier dynamics, e.g. the spatial correlation between glacier accumulation and evolution of snow ice fields, sea ice concentration and distribution of gravity anomalies (Sharov et al. 2009). Second, valuable data about glacier mass change / flux can be derived from time series of gravimetric observations. Being co-located with the maps of glacier elevation change obtained by other EO methods these data can be used for estimating the bulk density of volume losses or gains, thus providing an important input for glacioclimatic numerical models.

ESA has not provided access to GOCE data until now, even for principal investigators and Cat.1 users, 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, national gravimetric maps and terrestrial surveys.
1.6 SMARAGD Objectives & Setup

The general objective of the SMARAGD research project was to generate a new series of glacier change maps and mass balance estimates from satellite EO, ground and cartographic data. These products are designed to serve as an active framework for determining, interpreting, validating and inventorying the status and fluctuations of ice resources in the main glaciated areas of the Eurasian Arctic, and for developing a deeper understanding of how glaciers respond to climatic variations and endogenic forcing. The underlying concept of the proposed research is to map and interpret glacier state and change in the Barents-Kara region with the aid of differential interferometry and altimetry data obtained by active spaceborne sensors, both radar and lidar. The methodological stratagem is to compensate for the lack of reliable control and reference elevation models, which are needed for precise interferometric modelling of glaciers and their changes, by using spaceborne lidar altimetry data from the operational ICESat-GLAS mission. An additional gravimetric control to glacier mass balance / change models is provided by the regional gravity data available from the ArcGP / EGM 2008 models and from existing maps of free-air gravity anomalies.

The entire project work was carried out preferentially using ESA radar data obtained from post-operational and operational satellites, such as ERS-1/2 and ENVISAT. The SMARAGD project is considered as a coherent continuation of the INTEGRAL FP6 GMES project and ESA EO projects SIGMA, INTERSTEREO, POLARIS, GAIN and GEMINI, which were devoted to joint geometric processing of radar interferometry, lidar and radar altimetry, and gradiometry data taken over Eurasian glacial areas. The research constitutes a part of IPY initiatives and CaVal observations related to the launch and operation of the ESA GOCE (2007) and CryoSat-2 (2010) satellites. In the SMARAGD framework, a comprehensive and consistent set of satellite data products describing glacier surface topography, structural morphology (outlines & termini, ice divides, equilibrium line, total area, etc.), rheology (ice-flow and strain-rate pattern, frontal and max. velocities), mass balance and their changes was generated for approx. 33,000 km² and updated for another 30,000 km² of the earth’s territory occupied by glaciers and ice caps. This is the first time that dynamic changes in glacier topography and rheology over the entire macro-region have been revealed, measured, mapped and explained within a single study.

The main spatiotemporal characteristics of glacier state and change were determined and validated in 5 glaciated meso-regions of the Barents-Kara region (see Table 1) using straightforward and precise geodetic measurements based on satellite EO data and direct glaciological observations in situ, thus filling essential data gaps and meeting the demands of the global climate research community. The SMARAGD satellite data products were represented in the form of glacier elevation models, mass balance measurements and satellite maps of glacier state variables and their changes at scales ranging from 1:50,000 to 1:5,000,000. The basic reference period for the quantification of glacier elevation changes covered 50 years, subject to data availability and quality. The posting interval of raster models was 50 m and 100 m. New series of satellite image maps representing glacier changes and their causes in the Barents-Kara region were compiled, edited and published at 1:500,000 scale. Observational maps of glacier changes in the heterogeneous field of gravity were

36 SMARAGD – Satellite Monitoring And Regional Analysis of Glacier Dynamics
37 ArcGP – Arctic Gravity Project (http://earth-info.nga.mil/GandG/wgs84/agp/hist_agp.html)
39 “Interferometric Evaluation of Glacier Rheology and Alterations” (http://db.joanneum.at/integral/)
40 ESA CryoSat-2, ALOS, IPY and GOCE AO projects (Principal Investigator - A.Sharov).
41 Calibration and Validation
Generation of glacier data products

generated at 1:5,000,000 scale. The resultant glacier change maps are available at the project website http://dbb.joanneum.at/smaragd/> results. All SMARAGD products comply with the GCOS requirements and climate monitoring principles specified in the “Systematic Observation Requirements for Satellite-based Products for Climate.”

An adequate understanding of interrelations between climate change and glacier dynamics in the Arctic, their potential impacts and illustrative scenarios of future glacioclimatic changes as well as concise summaries of validated glacier products were communicated to scholars, students, teachers, scientists and policy makers. The main project ideas and results were presented and discussed at the ACV Colloquium in Graz (2007), the MIIGAiK Jubilee Conference in Moscow (2009), the Polar Symposium in Vienna (2009), the ESA-ISSI Workshop in Bern (2009) and the EGU General Assembly 2009. The SMARAGD team published 9 scientific papers based on the project results (see list of references). First results from the SMARAGD project were represented in the text book: Sharov A. & Jackson M. (Eds) “Interferometric evaluation of glacier rheology and alterations”, Druckhaus Thalerhof, Graz 2007, 155 p. ISBN 978-3200-01123-6. The SMARAGD findings and outcomes were cited in other project proposals and reports. All relevant scientific reports and technical documentation were provided to the Austrian Ministry of Science in due time and form and in compliance with the contractual conditions and reference documents.

1.7 Parent and follow-on projects

The topic of glacier change monitoring from European polar-orbiting satellites carrying SAR instruments was treated in the international AMETHYST FP5 INCO-2 (2000-2002), OMEGA FP5 ESD (2001-2004), and INTEGRAL FP6 GMES (2004-2007) projects and is currently addressed in the Ice2Sea (FP7 Environment), GlobGlacier (ESA DUE) and ICEAGE (Austrian FFG) research initiatives (Sharov & Jackson 2007). The SvalGlac project is in the re-evaluation stage and will probably be carried out in the ESF PolarClimate framework. Joanneum Research and international partners are currently working on five ESA EO projects devoted to enhanced modelling of glacier dynamics and studying mutual variations in land and sea ice cover in the Eurasian Arctic using a combination of satellite interferometry, altimetry and gradiometry.

Previous studies of glacier changes in the Eurasian Arctic from European satellites tended to be of national and local rather than regional and international character, however, and very little is known at present about general modes and driving mechanisms of glacier changes in the Arctic macro-regions. In the SMARAGD project the main emphasis was put on truly regional analysis and small- to medium-scale mapping of glacier dynamics / changes, mostly using multitemporal ESA radar data covering the entire Barents-Kara region. As part of the “Sparkling Science / FERMAP” research-education-cooperation programme the SMARAGD project team collaborated with other project teams involved in this programme, such as BIPOLAR and “Schools on Ice”. Several follow-on EO glaciological projects, such as MAIRES (FP7, GMES EU-Russia), ICEAGE (FFG ASAP-5), SIGMA2 (ESA ID.2611), GEMINI (ESA ID.6327) and PolarVision (Austrian Ministry of Science and Research) were initiated and set up using SMARAGD outputs, thus ensuring research continuity. New project proposals, e.g. GLACIS50 (ESA CCI) and GEOMASTER (FFG) based on the SMARAGD results were submitted to corresponding commissions for evaluation.

42 http://www.wmo.int/pages/prog/gcos/index.php
43 http://www.esf.org/research-areas/european-polar-board-epb/polarclimate.html
2. GENERATION OF GLACIER DATA PRODUCTS

by Aleksey I. Sharov, Alexandra Yu. Tyukavina and Irina S. Bushueva

2.1 Glacier product specifications

In accordance with the GCOS requirements and by analogy with the “Implementation Plan for the Global Observing System for Climate”, the main tasks of glacier monitoring can be formulated as follows: to monitor spatial and physical changes of the glacier surface, glacier motion, mass balance and stream runoff in order to understand glacier impact on sea level change and the Earth’s water cycle and to improve the quantitative prediction of water resources, glacier-related hazards, and the consequences of global change (USGS 2000, GCOS 2009). The GCOS requirements for satellite-based glacier products specify the list of glacier state variables which can be derived from satellite data, including glacier area, topography, velocity, glacier dammed lakes, facies, snowline, accumulation and mass balance. The support of early-detection strategies in global climate change observations is considered the main benefit from using such EO data products.

Similar specifications were offered in the “Operational Monitoring of European Glacial Areas” OMEGA FP5 EESD project (2001-2004) and further detailed in the INTEGRAL FP6 GMES project focusing on glacier observations from European satellites (Sharov & Jackson 2007). In the SMARAGD project we revised the list of glacier state variables under investigation in direct consultation with the relevant climate research community and determined the principal requirements for the glacier monitoring EO system using active spaceborne sensors, both radar and lidar (Table 3). The glacier variables and technical requirements specified in Table 3 were determined in accordance with our collective expertise, precursor prototypes and production experience gained from previous work and parent projects. The list was enhanced several times so that it now reflects the detailed and realistic requirements of our end users. Most values in Table 3 meet GCOS requirements, reflect modern capabilities of satellite EO systems and offer / promise substantial benefits. The glacier products generated in the SMARAGD project cover either longer (e.g. 1950s-2000s) or shorter (e.g. 1980s-2000s) periods depending on data availability and quality.

The SMARAGD project was designed to generate the most requested glacier change products. Several additional products increasing the value of basic outcomes were also compiled. It was still not possible to address all products specified in Table 3. For instance, satellite radar and lidar data were not used for monitoring the glacier surface and supra-glacial and dammed lakes or for determining the elevation of the snowline due to limited resources.

The main products of the SMARAGD project include satellite data sets and digital maps of glacier state variables and changes as well as software tools and complementary data sets for glacier mapping. The greatest advantage of representing glacier products in the integral form of digital maps is that all or several glacier state/change variables are visualized together, thus providing good opportunities for performing joint multi-factor analysis, studying main spatial interrelations, and detecting natural anomalies and processing errors. The integral representation of glacier state variables in the form of digital maps does not mean, however, that separate glacier characteristics cannot be delivered, e.g. line-wise or point-wise. In addition, point-wise data was delivered where data coverage and quality precluded map production. Satellite digital maps of the study glaciers were represented in multi-layer form containing raster, vector and alphanumerical (textual) layers. Each layer represents a single
Generation of glacier data products

variable of glacier state and/or change. Each glacier state variable represented in the resultant maps can be separately printed, viewed and delivered in raster, vector, or point format. Open GIS standards were preferred for formatting SMARAGD cartographic products to make them suitable for dissemination via GoogleEarth / GoogleMaps or similar technologies and incorporation in end user databases. Raster products are usually presented in *.geotiff format, vector products are given in *.shp and point products in *.xls or other formats requested by the user community. The format type of the products delivered can be changed on request, e.g. from raster to vector and from vector to point. All basic maps were issued in the UTM (WGS84) projection.

Table 3. List of glacier state variables and technical requirements

<table>
<thead>
<tr>
<th>Glacier state variables, units</th>
<th>Natural cycle</th>
<th>Resolution, m</th>
<th>Observing cycle, years</th>
<th>Expected accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, km²</td>
<td>annual</td>
<td>50 -</td>
<td>5</td>
<td>5 %</td>
</tr>
<tr>
<td>Area change, km²/a</td>
<td>annual</td>
<td>25 -</td>
<td>5</td>
<td>1 – 2.5 %</td>
</tr>
<tr>
<td>Topography (extent &amp; elevation), m</td>
<td>annual</td>
<td>50 1</td>
<td>2</td>
<td>50 m (horizontal) 2 m (vertical)</td>
</tr>
<tr>
<td>Change in termini pos, m or m/a</td>
<td>annual</td>
<td>25 -</td>
<td>2</td>
<td>10 m/a</td>
</tr>
<tr>
<td>Elevation change, m or m/a</td>
<td>annual</td>
<td>50 -</td>
<td>1 - 5</td>
<td>0.25 m/a</td>
</tr>
<tr>
<td>Velocity, m/a or cm/day</td>
<td>seasonal</td>
<td>250 -</td>
<td>0.5</td>
<td>10 m/a, 2 cm/d</td>
</tr>
<tr>
<td>Calving velocity, cm/day or m/a</td>
<td>diurnal</td>
<td>250 -</td>
<td>0.5</td>
<td>2 cm/day</td>
</tr>
<tr>
<td>Velocity change or strain rate, m/a²</td>
<td>diurnal</td>
<td>500 -</td>
<td>1</td>
<td>1% (1 m²/a²)</td>
</tr>
<tr>
<td>Accumulation, m</td>
<td>seasonal – annual</td>
<td>500 0.25</td>
<td>1</td>
<td>5 – 10 %</td>
</tr>
<tr>
<td>(Specific) Mass balance, m or kg/(m²⋅a)</td>
<td>seasonal – annual</td>
<td>500 0.25</td>
<td>0.5 – 1</td>
<td>0.20 m or 100 kg/(m²⋅a)</td>
</tr>
<tr>
<td>Macro-regional glacier inventory *</td>
<td>decadal</td>
<td>100 -</td>
<td>5</td>
<td>5% omission &amp; commission</td>
</tr>
<tr>
<td>Supra-glacial and dammed lakes *</td>
<td>seasonal – annual</td>
<td>50 -</td>
<td>5</td>
<td>2.5 %</td>
</tr>
<tr>
<td>Glacier surface state, classes / facies *</td>
<td>diurnal</td>
<td>500 -</td>
<td>0.25 - 0.5</td>
<td>5 %</td>
</tr>
</tbody>
</table>

*) Asterisk denotes optional products included in the list for the sake of discussion.

The 11 glacier (change) maps produced (5) and upgraded (6) in the SMARAGD project are listed in Table 4. The internet download system and FTP (file transfer protocol) system are used for delivering SMARAGD data products. Newly generated products were placed on the project website http://dib.joanneum.at/smaragd > results. Upgraded glacier change maps can be found on the INTEGRAL homepage at http://dib.joanneum.at/integral > results. The SMARAGD website will be maintained for at least three years after the project end in 2009.
Table 4. Satellite map series of glacier state variables and changes in the 1950s-2000s

<table>
<thead>
<tr>
<th>Product name</th>
<th>Publishing scale</th>
<th>Region</th>
<th>Status</th>
<th>Quantity (sheets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map of Eurasian ice coasts in 1950s – 2000s</td>
<td>1:10,000,000</td>
<td>Eurasian Arctic</td>
<td>upgrade</td>
<td>1</td>
</tr>
<tr>
<td>Observational map of glacier changes in 1950s -2000s (with insets)</td>
<td>1:5,000,000</td>
<td>Eurasian Arctic</td>
<td>new</td>
<td>1</td>
</tr>
<tr>
<td>Map of cryogravic dependences</td>
<td>1:5,000,000</td>
<td>Barents-Kara region</td>
<td>new</td>
<td>1</td>
</tr>
<tr>
<td>Basic maps of glacier changes in 1950s-2000s (with insets)</td>
<td>1:1,000,000, 1:500,000, 1:200,000</td>
<td>Severnaya Zemlya, Franz Josef Land, Kvitoya &amp; Victoria islands, Novaya Zemlya, Ushakova Island</td>
<td>new, upgrade, new</td>
<td>1, 1, 2</td>
</tr>
<tr>
<td>Glacier changes in 1936-2003</td>
<td>1:300,000</td>
<td>South Svalbard</td>
<td>upgrade</td>
<td>2</td>
</tr>
<tr>
<td>Hornbreen-Hambergreen ice bridge in 1936-1984-2004</td>
<td>1:100,000</td>
<td>South Spitsbergen</td>
<td>upgrade</td>
<td>1</td>
</tr>
<tr>
<td>Map of glacier velocity, strain rate and marginal changes</td>
<td>1:100,000</td>
<td>Svaltisen Ice Caps</td>
<td>parent</td>
<td>2</td>
</tr>
<tr>
<td>Detailed validation map &quot;Hornbreen &amp; Hambergreen in XX-XXI century&quot; with insets</td>
<td>1:50,000</td>
<td>South Spitsbergen</td>
<td>parent</td>
<td>1</td>
</tr>
<tr>
<td>Cartographic sketches of glacier changes</td>
<td>1:200,000, 1:100,000</td>
<td>Byrranga Mountains, Matusevich Ice Shelf</td>
<td>preliminary, preliminary</td>
<td>1, 1</td>
</tr>
<tr>
<td>Map of free-air gravity anomalies</td>
<td>1:20,000,000</td>
<td>Global</td>
<td>parent product</td>
<td>1</td>
</tr>
<tr>
<td>Semi-controlled (D)INSAR mosaic overlaid with ICESat transects</td>
<td>1:500,000, 1:500,000, 1:500,000, 1:200,000</td>
<td>Austfonna, Svalbard, Novaya Zemlya, South Spitsbergen, Franz Josef Land, Kvitoya &amp; Victoria islands, Severnaya Zemlya, Ushakova Island</td>
<td>parent products, new, new, new</td>
<td>8 layers, each</td>
</tr>
<tr>
<td>On-line Atlas of Glacier Changes (1950s-2010s)</td>
<td>-</td>
<td>East &amp; West Arctic</td>
<td>to be produced</td>
<td>1</td>
</tr>
</tbody>
</table>

The following intermediate products needed for further mapping, interpreting and validating glacier state and change variables were produced or adapted from available databases for all study glaciers:

- **Reference elevation models (DEM<sub>0</sub>)** with 50 m posting or 100 m for poorly mapped glaciers;

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**Generation of glacier data products**

- **INSAR mosaics** geocoded and calibrated (overlaid with ICESat altimetric transects);
- **2-pass DInSAR mosaics** calibrated and geocoded (overlaid with differential altimetry profiles);
- **Validation elevation models** (DEM$_2$) independently derived from satellite stereometry with 50 m posting for validation of glacial areas (Table 2, reference glaciers);
- **Combined (ArcGP-EGM2008) maps of static gravity gradients** (GG$_1$ and GG$_2$) for validation studies.

The resultant maps specified in Table 4 contain the following “sub-products”

- **Glacier dimensions** including glacier outlines, inland termini positions, main ice divides, boundaries of outlet basins belonging to larger ice caps, main flow lines, ice coasts (annexed with the value(s) of glacier area in km²);
- **Glacier surface topography** (DEM$_1$) with 50 m posting including top heights and contours on glacier;
- **Glacier elevation change** including equilibrium line and accumulation area, separate legend / scale with 10 gradations of elevation change and two gradations for glacier retreat and advance (annexed with the value(s) of average ELA, accumulation area, accumulation magnitude and volume change);
- **Ice flow field** or (optionally) **strain rate pattern** with 250 m grid size including maximum speed values and frontal velocity values for tidewater glaciers (annexed with velocity change values);
- **Geodetic mass balance estimations for the reference period** (annexed with the values of specific mass balance and mass balance change);
- **Common ancillary information** including map title, legend, geodetic/geographic grid, names, spot heights, contours, hydrography, bathymetric marks, main shallows, supplementary geophysical characteristics, imprint, frames, etc.

Several maps showing interrelations between local intensity of solid precipitation, snow accumulation, sea ice concentration, glacier change and gravity anomalies are still being prepared for further publications and discussions with other research groups. It is planned that the glacier (change) maps produced in the SMARAGD project will be included in the “Satellite Atlas of Glacier Changes in the Arctic”, which will be available online.

An explanation of all output glacier products is provided either in the form of a legend, imprint and ancillary text placed on the map or in the form of textual annotations annexed to the product. The spatial and temporal applicability of glacier (change) products generated in the SMARAGD project ranges from local to global and from momentary to decadal applications. The main impact is expected from retrospective and prospective applications in the Northern Hemisphere and especially in the Arctic Region at the present time ± 50 years. We expect SMARAGD products to be used in a wide range of applications and services, e.g.:

* ice cover change (ICC) monitoring in the Arctic at 1:500,000 working scale using change maps and models as well as periodic upgrades;
* online atlas of ICC and archive of non-cartographic products including web versions of the resultant maps and models, concise description of basic mass balance characteristics and integral estimations of ICC, dataset of calving and surface velocities for glacial areas, etc., updated once a year;
* pan-Arctic inventory of ICC including several regional inventories.

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**Generation of glacier data products**

Furthermore it is believed that the uniform quality of SMARAGD glacier change products, as opposed to the varying quality arising from the present procedure of combining optical imagery from different satellites to compose a regional glacier map, will ensure the comparability of results obtained in different parts of the Eurasian Arctic and contribute to establishing a worldwide glacier monitoring scheme.

### 2.2 Basic procedures for modelling glacier elevation changes

The overall modelling of glacier elevation changes in the Barents-Kara region over the past 50 years was performed by means of joint geometric processing of altimetric, interferometric and reference elevation data. The INSARAL algorithm for mapping glacier state and change at a macro-regional scale with the aid of satellite differential interferometry and altimetry was sufficiently developed to generate the specified glacier products within the constraints of time schedule and cost. A hierarchical approach was applied: First we generated reference elevation and glacier change models. We then delineated fast flowing parts of glaciers with the subsequent production of surface topography (DEM), glacier outlines (area) and mass balance characteristics, thus ensuring additional control and improving the accuracy and detail of the products. In contrast to other studies of glacier elevation changes, we did not build a “new” glacier elevation model and did not compare it with the “old” one, but calculated height changes directly from the calibrated differential INSAR phase.

Our enhanced differential approach to multi-source data processing includes the following basic procedures:

1) generation of the reference elevation model (DEM) covering all study regions;
2) co-registration of ICESat altimetric transects with the reference elevation model, *profile-wise* calculation of glacier elevation changes and graduation of the resultant d-height profiles;
3) generation of standard 2-pass differential SAR interferograms in the slant range geometry (2-pass DINSAR) and isolation of the interferometric phase related to glacier elevation change;
4) geocoding, adjusting and mosaicking differential interferograms in the DEM geometry;
5) overlaying the resultant DINSAR mosaic with differential altimetry transects, calculation of glacier elevation changes in between altimetric transects, e.g. along “old” topographic contours and at specific points, and *surface-wise* generation of a glacier change model using the same constraints and tuning parameters as in procedure 1);
6) generation of basic reference and thematic layers for glacier maps, accuracy control and error correction.

The data flow and the interplay between basic and subsidiary procedures involved in the INSARAL methodology can be seen in Fig. 9, which demonstrates the structural composition and main functions of the SMARAGD information system. The diagram shows the entire system as a single process and explains what kinds of data are input (EO data) to and output (glacier products) from the system. Being based on active EO methods this end-to-end information flow represents a sort of early warning system that aids in early detection of extreme glacier changes and detection of anomalous variations in land ice cover, yet without compromising on the complement of glacier state variables to be produced and delivered.

The following is a concise description of the main procedures and functions involved in the baseline INSARAL methodology. The 2-pass DINSAR interferograms composed of tandem and short-repeat pass (3- and 6-day) ERS-1/2 SAR data covering all study areas were orthorectified, calibrated, de-ramped and mosaicked using the change signal obtained by...
differencing spaceborne altimetric profiles taken in the 2000s and the reference elevation models (DEM0) representing the glacier state as of the 1950s-1960s (Fig. 10). The expected co-registration accuracy was given as ± 1.2 pixel rms. The precision of reference elevation data was characterized by an rms accuracy of ± 6 m. The DEM0 accuracy in ice free areas was controlled with altimetry data. The estimated impact of the different “ages” of interferometry and altimetry data on modelling accuracy in cross-over areas was ≤ 1 m.

Figure 9. SMARAGD data flow diagram
Figure 10. INSARAL results for Severnaya Zemlya: differential altimetry profiles (1956 – 2007, a), ELA and accumulation signal at the top of Vavilov Ice Cap (b), DINSAR mosaic overlaid with differential altimetry profiles (c) and glacier elevation change (d), (fragments, legend not shown).

The region-wide change signal (Elevation Change Model) was derived in a straightforward manner from the calibrated differential phase and mapped at 1:500,000 scale (Fig. 10, d). In addition to simple checks in ice-free areas with “no-changes”, the INSARAL method ensures...
Generation of glacier data products

reliable scaling of glacier differential interferograms with real non-zero change values. Cloudiness\(^45\), topographic shadowing and layover effects were estimated prior to INSAR data processing using ancillary NOAA data and the DEM\(_0\) reference elevation model. Distortional geophysical effects, e.g. the effect of ionospheric refraction and radar penetration into the snowpack were compensated.

An integral assessment of glacier elevation and volume changes was carried out. Glacier outlines (area) were delineated and ice flow velocities were measured using coherence or phase-gradient tracking and the 2-pass DINSAR algorithm respectively. Optionally, glacier surface topography (DEM\(_1\)) was modelled for selected areas by means of summation of DEM\(_0\) and the elevation change model, involving reliable vertical control and \textit{in situ} data. Approximately 15\% of the project time was used for outlining glacier boundaries and determining glacier area, yet without compromising on consistent spatial coverage. Glacier-wide distributive estimations of mass balance characteristics were performed and validated using \textit{in situ} glaciological measurements, satellite optical stereometry and gravimetry. The magnitude of spatial correlation between glacier accumulation, sea ice concentration and geopotential variations was determined and the spatial asymmetry in the distribution of glacier changes and ice flow pattern was explained.

The list of the most expensive and time consuming procedures entailing essential computational and manual efforts includes

- digitization of topographic maps and generation of reference elevation models,
- (D)INSAR data processing,
- cartographic styling, drafting, scribing and editing,
- validation activities.

The cartographic workload involved in the production of a single glacier map depends on the glacier distribution density (index of glaciation, elevation range) and data availability. As a rough estimate, it takes one working day to map 200 km\(^2\) of glacier area at 1:1,000,000 scale. The whole mapping work was completed in approximately 170 working days over a period of 2 years and resulted in 5 new and 6 upgraded map sheets. The data processing and mapping costs were only a fraction of those of other survey methods. Some pictures illustrating the INSARAL basic procedures and the resultant intermediate products for glaciers in Severnaya Zemlya are given in Fig. 10. Glacier change models and other complementary information derived from satellite interferometry, altimetry and reference elevation data were refined, cleaned and framed for subsequent cartographic composition.

2.3 Composition of glacier change maps

Several glacier change maps of Severnaya Zemlya and Franz Josef Land including Kvitoya, Victoria and Ushakova islands were completed, edited and printed during the period of 2007 – 2009. 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. The graphical precision of the printed maps is between 0.2 and 0.5 mm at publication scale. Cartographic styling, drafting, scribing and editing were performed using the ArcInfo 9.3 and Adobe Illustrator CS4 software. The description of cartographic products is given in the following.

---

\(^45\) Heavy clouds reduce the magnitude of interferometric coherence.
A satellite map of glacier changes (UTM, Zone 46N, WGS 84) in the period from the 1980s to the 2000s covering the entire Severnaya Zemlya archipelago with a total land area of 36,800 km² was generated on the basis of the glacier change model shown in Fig. 10, d). A small-size copy of the map is given in Fig. 11. In addition to glacier elevation changes, main ice divides, glacier borders, hydrographic network, topographic contours and geographic names the map also shows present heights of ice coasts, frontal velocities of tidewater glaciers, bathymetric marks and main shallows offshore. The locations of polar meteorological stations, ice core sites and top heights are given as well. Several quality control procedures including a
positional accuracy test and a map content review were performed prior to final map printing at both 1:500,000 and 1:1,000,000 scales.

A satellite map of the Franz Josef Land region with surrounding islands showing glacier changes from the 1950s to 2000s was compiled at 1:500,000 scale in the UTM projection, Zone 40N (Figure 12). The map covers an area of 383 x 242 km² (without insets). It consists of 7 layers including the topographic layer containing contour lines, symbols and text in vector format, several controlled (D)INSAR amplitude and fringe image mosaics overlaid with (differential) altimetry transects, and the change model representing glacier elevation changes in seven gradations. Further to this, we included two additional gradations of glacier changes.
Generation of glacier data products

in order to account for the advance and retreat of glacier termini. Each pixel of the image map corresponds to an area of approximately 5,600 m² on the ground. Two insets represent glacier elevation changes at Kvitoya and Victoria islands.

The precise delineation of ice shorelines and inland glacier borders was performed using coherence tracking and phase-gradient algorithms. Tips of lines representing inland glacial borders were joined with previously drawn ice shorelines. Ice-free areas were rendered in shades of ochre and water surfaces in opaque cyan thus enabling planimetric measurements of glacier area. The list of official Russian names and their English equivalents is attached. The English versions of all geographical names were determined and verified with historical maps and information published by J. Payer, F. Jackson, W. Wellman and A. Fiala. Scientific notation was applied for transliterating toponyms of Russian origin into English. Figure 13 represents two of five interferometric mosaics of Franz Josef Land used for glacier mapping and included in the map set. The frontal velocities of 50 outlet glaciers were newly determined from such (D)INSAR models and placed on the main map. Besides, we discovered that Mesyatseva Peninsula at Eva-Liv Island in Franz Josef Land was detached from the main island and became a separate islet with a total area of 2.7 km² (81°42'N, 62°45'E).

Figure 13. Controlled interferometric mosaics of Franz Josef Land at 1:500,000 scale (glacier state 1995): amplitude image (left), fringe image (right, small-size copies)

A satellite image map showing glacier changes at Ushakova Island situated in the Kara Sea approx. 240 km east of the FJL archipelago is given on the next page (Fig. 14). The island is entirely occupied by an ice cap with a total area of 325.5 km². It was first discovered and charted in 1935 as the last major geographic discovery in the Eurasian Arctic. The map of ice cap changes shown in Fig. 14 is a good example of student cartographic work involving some familiarities and decorative elements, yet without compromising on detail and accuracy. Similar maps were previously produced for south and north-east Svalbard and north Novaya Zemlya; those interested in a detailed description of glacier change mapping in these archipelagos are referred to other publications (Sharov & Osokin 2006, Sharov & Nikolskiy 2007).
Figure 14. Satellite map of glacier changes at Ushakova Island in 1950s-2000s
3. MEASUREMENT AND INTERPRETATION OF GLACIER CHANGES

by Aleksey I. Sharov

3.1 Geometric changes of study glaciers

The resultant glacier maps of the Barents-Kara archipelagos allowed linear, areal and volumetric glacier changes to be measured in semi-automatic mode. Linear changes are expressed as the loss or gain in glacier thickness (elevation change $dh$) and as advance or retreat measured at right angles to the glacier termini or along the main flow line ($dL$, see Eq. 1). Areal changes are expressed as the extent of glacier surface ($dA$) gained or lost in both lower and upper parts of the glacier, e.g. around nunataks, not just at the terminus. Volumetric changes are expressed as the quantity of material (snow and ice) added to, or lost from, the whole glacier. In our case, changes in glacier volume $V$ were calculated for each large glacier separately as an algebraic sum of $n$ products calculated for each change gradation $i$ in accordance with the following equation

$$
\Delta V \approx \sum_{i=1}^{n} A_i \cdot \bar{dh}_i
$$

where $\bar{dh}_i$ denotes the elevation change value averaged over the measured area, $n$ is the number of change gradations and $A_i$ is the measured area. The approximate thickness of the submerged part of glacier faces needed for the estimation of volumetric glacier changes was determined from the available hydrographic charts, RES data and previous publications (e.g. Kotlyakov 1985, Macheret et al. 2000, Dowdeswell & Evans 2004).

The reference periods for the quantification of glacier changes varied from 20 to 55 years depending on the age of the topographic maps / DEMs and the date of ICESat data takes. In general, the reference periods are as follows:

- Franz Josef Land, Novaya Zemlya, Victoria and Ushakova islands - 1950s … 2000s;
- Severnaya Zemlya and Kvitoya - 1980s … 2000s;
- Svalbard - 1960s … 2000s.

For the sake of comparison, the average values of elevation changes were calculated in meters per year [m/a]. The most interesting results are presented in the following.

3.1.1 Severnaya Zemlya

In Severnaya Zemlya (SZ) the distribution of land ice, the ice flow pattern and calving characteristics are characterized by abnormal spatial asymmetry. The “centre of ice mass” is clearly displaced towards the eastern coast of the archipelago. The western slopes of most ice caps appear more uniform in morphology. Only 5 to 6 slow-moving outlet glaciers flow towards the Kara Sea and 26 fast-moving outlets reach the Laptev Sea. Most icebergs are observed along eastern and south-eastern margins of tidewater glaciers, and glacier elevations are most variable on the eastern side of ice caps. This is surprising because, on average, the Laptev Sea is approx. 1° colder than the Kara Sea. Orographic effects were suggested as a plausible explanation for such asymmetry in (Koryakin 1988). In this context it is worth noting that the glaciation of Novaya Zemlya on the other side of the Kara Sea exhibits an opposite asymmetry with much faster ice flow westwards than in the opposite direction (Sharov & Jackson 2007).
The annual rate of ice loss due to calving was given as 0.2 km³/a and 0.4 km³/a in (Jania & Hagen 1996) and (Vinogradov 1980) respectively, which both appear to be underestimated. Recent estimations in (Dowdeswell et al. 2002) have shown that ice flux values at the Academy of Sciences Ice Cap margins exceed 0.6 km³/a. Individual estimates of the annual net balance in Severnaya Zemlya vary from -3/-4.5 km³/a (Govorukha 1970) to -1/-1.5 km³/a (Koryakin 1988), thus indicating the lack of reliable measurements and extrapolation errors.

In the SMARAGD project, the maximum loss of glacier thickness in Severnaya Zemlya (-149 m in 27 years) was discovered in the upper parts of the largest and fastest outlet glaciers Nos.7 and 8 belonging to the Academy of Sciences Ice Cap and flowing towards the Laptev Sea. The largest increase in ice thickness of +46 m was recorded on the opposite western side of the same ice cap in the lower part of outlet glacier No. 17, which might indicate a recent surge event. The northern part of the glacier tongue advanced with the result that it nearly completely dammed up the entire Growing Lake. The total advance of this glacier, which occurred sometime between 1988 and 2007, is given as nearly 23 km². The front of Outlet Glacier No. 12 belonging to Rusanov Ice Cap advanced offshore by 1.2 km, the glacier area increased by approximately 7 km². It is worth noting that there have been no previous reports about present glacier surges in the archipelago.

The present total area of the Matusevich Ice Shelf was measured as 172 km², representing a relative decrease of 29 % in approx. 30 years. The DINSAR data analysis showed that the ice shelf is undergoing vertical oscillations in some parts and is subjected to essential horizontal stress due to the permanent inflow of ice from parent ice caps with flow velocities in main outlets ranging from 45 to 80 cm/d. The thickness of the Matusevich Ice Shelf decreased by 40 meters in some places and the surface roughness of the ice isthmus increased drastically over the past years (Fig. 15). This measurement is consistent with the observations made recently in the Canadian Arctic, where large ice shelves demonstrate similar behaviour. Several small ice caps, such as Maritime (7 km²) and No. 3 (1.4 km²) at Komsomolots Island and Little (3 km²) at Pioneer Island have totally disappeared. The northernmost Arctic and Schmidt ice caps lost approx. 17 km² and 30 km² of their areas respectively.

Figure 15. Hypsometric profiles from topographic maps (green) and ICESat data (blue) across Matusevich Ice Shelf (a); ICESat transect on the 1:1,000,000 map by O.v. Gruber (1933, b)

The total reduction in glacial cover in SZ in the period from the 1980s to 2000s was estimated at 86 km² (~0.5% or ~3.2 km³/a), which means that apart from essential changes on the Matusevich Ice Shelf, the overall area of glaciation remained nearly unchanged, which also applies to the ice coast length. This observation agrees with our previous estimation of glacier
area change on SZ obtained in the AMETHYST FP5 project (Contract No. ICA2-CT-2000-10028). Formerly, the reduction of glacier area in SZ was given as -65 km² for the period of 1953 – 2001, or 1.35 km²/a (Sharov 2002).

The highest point of Severnaya Zemlya on the top of Karpinsky Ice Cap was measured at 965 m asl, which is 2 meters higher than the value given on topographic maps. The measurements revealed a drastic lowering of the glacier surface in the interior part of Leningradsky (-55 m), Semyonov-Tyan-Shansky (-47 m), Rusanov (-27 m) and University (-10 m) glaciers and essential accumulation at the tops of Schmidt (+43 m), Arctic (+27 m), Kropotkin (+23 m), Pioneer (+22 m), Vavilov (+16 m), Albanov (+15 m) and Dezhnev (+13 m) ice caps (Fig. 10, b). The sides of most ice caps have steepened (Sharov & Tyukavina 2009).

Our estimations revealed a significant reduction of 131 km³ or 2.3 % in total glacier volume over the past 25 to 27 years. The Academy of Sciences, Karpinsky, Leningradsky, University and Rusanov ice caps terminating in deep waters and feeding fast tidewater glaciers lost 87 km³, 21 km³, 11 km³, 10 km³ and 8.5 km³ of their volumes respectively. Essential positive changes in glacier volumes were detected at Kropotkin (+0.9 km³), Schmidt (+2.3 km³) and Vavilov (+11.5 km³) ice caps with typically low velocities of ice flow. Due to the good quality of reference elevation data, the overall rmse of the present volumetric estimations for Severnaya Zemlya is assumed to be ±0.2 km³.

The maximum rate of elevation changes ranging from -2 to +1.5 m/a was observed at Komsomolets and Schmidt islands in the northern part of the archipelago. The mean change in glacier thickness in SZ is -7.8 m averaged over 21,442 ICESat points 46. The annual rate of ice loss is 4.8 km³/a, which indicates a strongly negative net balance of SZ glaciation and is very close to the most pessimistic estimate given in (Govorukha 1970). The rate of ice loss due to calving seems to be, at least, 2 times higher than the maximum value given by other investigators.

3.1.2 Ushakova Island

Significant height changes of -15 to +50 m were also registered at the ice cap covering Ushakova Island (Fig. 14). Ablation processes were more strongly manifested on the southern slopes of the ice cap, while snow accumulation was generally higher on its northern slopes. The top height of this glacier rose from 294 m in 1952 to 320 m in 2005 and the glacier volume increased from 35 km³ to nearly 38 km³, while the glacier area decreased slightly by 2.5 km². The average ice thickness increased from 107 to 118 m. The total length of the ice coast, which is 2 to 30 m high, decreased by 3.1 %.

These glacier changes can be explained by the essential accumulation of snow and generally low velocities of ice flow. The Catalogue of Glaciers in the USSR, v. 16 lists only one outlet glacier with an area of 14.3 km² in the northern part of Ushakova Ice Cap (O. Vinogradov 1980). The shape of interferometric fringes in the SAR interferogram of 24/25 November 1995 (Fig. 14) shows that even this part of the glacier is not moving faster than a few centimetres per day. Hence, we can conclude that the glacier change signal at Ushakova Island with an average rate of +0.21 m/a is not “distorted” by ice flow and thus directly represents the combined effect of variations in air temperature, pressure and precipitation on the glacier. Long-term (1973-1991) hydrometeorological records including precipitation data from the polar

46 This value would appear to be overestimated by approximately 12 % (See Chapter 3.1.3).
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Station located on the island (47 m asl) are available in the TuTiempo online archive of historical weather²⁷.

3.1.3 Franz Josef Land

Careful cartometric analysis of glacier change maps revealed that, by the 2000s, glaciers in the Franz Josef Land (FJL) archipelago have lost 280 km² in area, or -2% in relative expression. The most significant retreat of glacial termini occurred at fronts of tidewater outlet glaciers because of marine abrasion and calving. The maximum withdrawal of ice shores was detected on the largest islands occupied by large ice caps with fast-flowing outlets, such as Wilczek Land (-34 km²), Prince George Land (-28 km²), Hall (-26 km²), Hooker (-22 km²) and Mc.Clintock (-20 km²) islands. All these islands are situated in the southern part of the archipelago. The retreat of tidewater glaciers in the central, eastern and northern parts of the archipelago is somewhat smaller in scope. The relative amount of deglaciation on Salisbury (-16 km²), Graham Bell (-12 km²) and Rudolph (-4 km²) islands ranges between 1.8 and 1.3 %. The present extent of glaciation on FJL amounts to 13,455±100 km².

Differential interferometric analysis of ERS-1/2-SAR data showed that many outlet glaciers in the region have decelerated. For example, the frontal velocity of Sedov Outlet Glacier at Hooker Island decreased from 70 m/a to 40 m/a in the past half-century (encircled in Fig.16, a). Besides, Fig. 16, a) also demonstrates the stagnancy of Ice Cap No.3 at Költitz Island and the southward ice drainage from the Jackson Ice Cap through Kirov and Obruchev outlet glaciers. The area of maximum snow accumulation in the southern part of Költitz Island is shaded in light grey.

![Image of ice-flow pattern]  
Figure 16. Ice-flow pattern at Hooker and surrounding islands: 2-pass DINSAR model (mid-October 1995, a); map of surface velocities on Sedov Glacier (Grosswald et al. 1973, b)

The measurements showed a lowering of the glacier surface of approx. -15.7 m averaged over 46,683 ICESat points. This value is overestimated, however, by approximately 25% due to the relatively sparse coverage of glacier tops by the ICESat GLAS tracks and corresponding


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underestimation of the accumulation signal. The highest rates, between 80 and 90 meters, were measured in the upper parts of Renowned, Karo and Eastern outlet glaciers on Wilczek Land and Salisbury Island, at the top of Brousslov Ice Cap on Prince George Land, in the upper part of Jackson Ice Cap and in the lower part of Sedov Glacier at Hooker Island. The reduction in glacier volume in FJL was estimated at 214 km³, which means that the impact of surface lowering on glacier shrinkage is, at least, 6 times greater than the contribution from marginal disintegration of tidewater glaciers (max. 28 km³). This impact is much stronger than that observed in other meso-regions, which is in agreement with the suggestions by (Koryakin 1988). The comparison with previous estimates made by other investigators showed that the total glacier mass balance for FJL remained negative over the past 70 years and land-ice loss has accelerated by approximately 20 % during the past decades.

Still, the semi-centennial glacier change signal is not uniform and, despite general glacial retreat in FJL, we detected at least 5 large ice caps which increased their volumes in the reference period. Essential positive elevation changes ranging from 25 to 50 m were found in the accumulation areas of large and medium-size insular ice caps in FJL. The strongest accumulation signal was registered in the northern part of Windy Ice Cap at Graham Bell Island (+70 m), in the southern part of Ice Cap No. 3 at Költitz Island (+60 m) and at the tops of Unnamed Ice Cap at Hooker Island (+45 m), Vostock-2 Ice Cap at Rainer Island (+40 m), Tyndall Ice Cap on Wilczek Land (+ 35 m) and Chernyshev Ice Cap (+25 m) at Salm Island. This observation is consistent with the results of repeated field measurements of maximum annual snow accumulation at the tops of Tyndall (0.46 m w.e.), Windy (0.5 m w.e.) and Chernyshev (0.55 m w.e.) ice caps (c.f. Jania & Hagen 1996). Similarly to Severnaya Zemlya most thickening glaciers are slow moving and terminate on the land or in shallow waters.

3.1.4 Kvitoya and Victoria islands

Two digital elevation models of Kvitoya and Victoria islands were generated with different pixel sizes of 50 and 5 meters from Norwegian and Russian topographic maps showing the glacier state in the 1980s and 1950s respectively. First ERS-1/2 interferometric models were built and geocoded in order to determine the glacier dynamics on these islands for the first time in the history of their exploration (Fig. 17). The UTM projection, Zone 37N, and the reference ellipsoid WGS 84 were used for cartographic representations. Hydrometeorological data recorded at the polar meteorological station on Victoria Island (Cape Knipovich) were also at our disposal.

The investigations revealed seven outlet glaciers at Kvitoya, but none on Victoria Island. It was therefore concluded that the Victoria Ice Cap is climatically dead. Frontal velocities of outlet glaciers at Kvitoya varied between 8 and 28 cm/day. Careful comparison of INSAR and ICESat altimetry data with available elevation models revealed both negative and positive elevation changes on Kvitoyjokulen and essential surface lowering at Victoria Island. The ice cap area at Victoria Island decreased from 10.6 km² in the 1950s to 7.8 km² in the 1990s. The elevation of its highest point lowered from 105 to approx. 90 m. The area of Kvitoyjokulen decreased from 705 to 686 km². The amplitude of the elevation change signal on this ice cap was ± 35 m. The maximum accumulation signal was recorded northwards of spot height 410 m. The ice divide of Kvitoyjokulen shifted 1.5 km to the north (Fig. 17, c). The volume

48 It should be noted that an updated (preliminary J3) topographic map of Kvitoya exists showing two peaks with heights of 433 and 405 m aligned east-west on the ice cap. Unfortunately we could not obtain the original of this map.

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reduction at Kvitoyjokulen and Victoria Ice Cap was 4.1 km³ and 0.2 km³; the average thickness decreased by 6 and 9 meters respectively.

3.1.5 Novaya Zemlya and Svalbard archipelagos

Detailed glacier change mapping in the Novaya Zemlya and Svalbard archipelagos was beyond the scope of the SMARAGD project. Here we provide a concise summary of glacier change observations previously performed by our group in these meso-regions in order to complete and to generalize the assessment of glacier dynamics in the Barents-Kara region and to estimate glacier mass balance on a regional scale.

The Novaya Zemlya archipelago (NZ) is situated approx. 500 km south of Franz Josef Land. Its glacioclimatic conditions are characterized by a higher amount of precipitation and a much lower calving rate due to its short ice coast (208 km). Ice flow velocities in the frontal parts of its 41 outlet glaciers are somewhat lower than those in Franz Josef Land and Severnaya Zemlya. The Northern Glacial Complex (NGC) on North Island in the NZ archipelago covers 22,800 km² (1952) and is thus reputed to be the largest mass of land ice in Eurasia. Spatial asymmetry in the shape of the NGC and in the ice flow pattern and calving characteristics with much faster ice flow (up to 200 m/a) towards the Barents Sea than in the opposite direction was deduced in (Sharov & Nikolskiy 2007).

Quantitative estimations of glacier changes in northern Novaya Zemlya showed that in the period between 1952 and 2003 the NGC lost approx. 300 km² in area and 200 km³ in volume, i.e. nearly 6 km³/a and 4 km³/a in average. The maximum retreat of ice shores (6 km)

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49 Total annual precipitation at the ice divide of Shokalskogo Outlet Glacier (760 m asl) is 800 mm (Chizhov et al. 1968).
50 Due to disintegration of glacier margins.
was recorded at Vera Outlet Glacier, one of the fastest (48 cm/day) glaciers in northern NZ. In the reference period this glacier lost 30 km² or 45% of its total area, which is extraordinary. The existence of, at least, partially floating ice tongues in Novaya Zemlya was verified in (Sharov et al. 2003).

The highest points measured on the NGC were 817 m on the Northern Ice Cap and 982 m on the Main Ice Shield, which differ significantly from the corresponding heights given in old topographic maps. The strongest lowering of the glacier surface was detected in the upper parts of Vera (-180 m) and Chemyshcheva (-210 m) outlet glaciers. The average thinning of glaciation in northern NZ still amounts to -8.4 m, which is somewhat less than in other extensively glaciated areas of the Barents-Kara region. In the topographically homogeneous upper part of the NGC, we detected several glacial areas with evidently positive elevation changes up to +110 m alternating with areas of negative changes up to -50 m (Fig. 18, a). The most distinct positive elevation changes (>150 m) were detected at the top of the Northern Ice Cap (NIC) and we suppose that the net mass balance of NIC has remained positive over the past 50 years. This is surprising since this large (2,260 km²) ice cap is drained by several large and fast tidewater outlets, such as Inostrantseva, Pavlova, Vera, Bunge and Petersen glaciers. Typical hypsometric profiles of Petersen Glacier derived from the topographic map (1950s, green) and ICESat altimetry data (2003, blue) are given in Fig. 18, b. There is a hypothesis that Petersen is a surging glacier.

![Hypsometric profiles from topographic maps (green) and ICESat elevation (blue) and roughness (cyan, d) transects across NIC (a), Hornbreen and Samarinbreen (c, d) and along Petersen Outlet Glacier (b)](image)

The largest extent of deglaciation in the reference period was observed in the Svalbard archipelago, which is situated in the westernmost part of the Barents-Kara region and is confronted with rapid changes in heat and moisture fluxes driven by the North Atlantic Drift and atmospheric circulation. Due to the general retreat of tidewater glacier termini and essential changes in the configuration of ice coasts, the total length of the ice coastline in Svalbard including Kvitoya decreased from 1,051 km to 894 ± 14 km (Sharov 2005) and further to 859 km (Blaczczuk et al. 2009).
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Based on previous results published in (Sharov & Etzold 2004, Nuth et al. 2008, Moholdt et al. 2010) the conclusion can be made that Svalbard and Kvitoya lost 444 km³ in ice volume at a rate of -11.2 km³/a in the period from the 1960s to 2000s. This value is still much lower than the estimate of -30 km³/a mentioned in (Blaczczuk et al. 2009), which would appear to be overestimated. The average thickness of Svalbard glaciation has decreased by 7 m. The highest accumulation rate exceeding 0.5 m/a was recorded in the accumulation area of Austfonna (Moholdt et al. 2010). The strongest lowering of the glacier surface, ranging from -130 m to -200 m, was detected at Hamborgbreen, Hornbreen and Samarinbreen in Hornsund, South Spitsbergen (Fig. 18, Sharov & Osokin 2006). The glacier termini in this area have retreated 12 km over the past 100 years, which is the largest and most consistent withdrawal of ice shores in the Barents-Kara region. A hypothesis has been proposed about the presence of an ice bridge in Hornsund (Troitskiy et al. 1975, Sharov & Wack 2007).

There are many fast-flowing outlets and surging glaciers in Svalbard. Consistently high glacier flow velocities, ranging from 140 m/a to 300 m/a and more, were recorded in the north-eastern and north-western parts of Svalbard respectively. The total areal reduction in glaciation remains uncertain and the mean loss rate was roughly estimated at 26 km²/a or approximately 1040 km² (2.8%) for the past 40 years. In (Blaczczuk et al. 2009) the surface loss rate for tidewater glaciers in Svalbard excluding Kvitoya was given as 22.8 km²/a. No floating glacier fronts were found in Svalbard (Dowdeswell 1989).

3.2 Regional assessment of glacier changes

In the second half of the 20th century, the total area of glaciers occupying separate islands and archipelagos of the Barents and Kara seas exceeded 92,600 km². The overall glacier volume reached 22,400 km³ and the average ice thickness was 242 m (Table 1). Our remote sensing studies using ERS-1/2 radar interferometric mosaics, ICESat altimetry data and reference elevation models revealed that, in the 2000s, the areal extent and volume of Barents–Kara glaciation amounted to 90,900±200 km² and 21,420±20 km³, respectively (Table 5). The annual loss of land ice was approx. 11 km³/a in Svalbard, 4.2 km³/a in Franz Josef Land, 4.0 km³/a in Novaya Zemlya and 4.8 km³/a in Severnaya Zemlya over the reference periods specified in Table 6. The average ice thickness of remaining glaciation decreased to 236 m.

Tables 5 and 6 represent the main geometric parameters of the Barents-Kara glaciation for the first decade of the 21st century and their changes compared with the reference state specified in Table 1. Those wishing to obtain average annual rates of glacier changes should divide the cumulative values given in Table 6 by the length of the reference period specified in the last line of this table.

The largest negative elevation changes were typically detected in the seaward basins of fast-flowing outlet glaciers, both at their fronts and tops. Ablation processes were more marked on southern slopes of ice caps, while the accumulation of snow was generally higher on northern slopes with the result that main ice divides “shifted” to the north. This finding indicates that at glacier tops the relation between accumulation and ablation was influenced by direct insolation rather than by the greenhouse effect. Besides, we revealed that more than 70% of all “stressed” areas at glacier margins and in glacier interiors manifested in our phase-gradient / strain-rate image products of the 1990s underwent essential elevation changes later on, as

51 Minimum estimate based on the results published in (Sharov & Osokin 200&, Dowdeswell et al. 2008)
Measurement and interpretation of glacier changes

shown in our maps from the 2000s. A high strain rate value indicates the possible occurrence of crevasses on the glacier surface and can reliably indicate future surface changes.

Table 5. Geometric parameters of the Barents-Kara glaciation in 2000s

<table>
<thead>
<tr>
<th>Meso-Region Parameter</th>
<th>Svalbard &amp; Kvitoya</th>
<th>Franz Josef Land &amp; Victoria</th>
<th>Novaya Zemlya</th>
<th>Ushakova Island</th>
<th>Severnaya Zemlya</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier area, km²</td>
<td>35,535</td>
<td>13,463</td>
<td>23,345</td>
<td>324</td>
<td>18,237</td>
<td>90,907</td>
</tr>
<tr>
<td>Glaciation index, %</td>
<td>57</td>
<td>84</td>
<td>29</td>
<td>100</td>
<td>50</td>
<td>46</td>
</tr>
<tr>
<td>Glacier volume, km³</td>
<td>7,123</td>
<td>2,258</td>
<td>6,630</td>
<td>38</td>
<td>5,370</td>
<td>21,423</td>
</tr>
<tr>
<td>Average thickness, m</td>
<td>200</td>
<td>168</td>
<td>284</td>
<td>118</td>
<td>294</td>
<td>236</td>
</tr>
<tr>
<td>Length of ice coasts, km</td>
<td>894</td>
<td>2,522</td>
<td>192</td>
<td>78</td>
<td>490</td>
<td>4,176</td>
</tr>
</tbody>
</table>

Table 6. Changes in geometric parameters of the Barents-Kara glaciation

<table>
<thead>
<tr>
<th>Meso-Region Parameter</th>
<th>Svalbard &amp; Kvitoya</th>
<th>Franz Josef Land &amp; Victoria</th>
<th>Novaya Zemlya</th>
<th>Ushakova Island</th>
<th>Severnaya Zemlya</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier area, km²</td>
<td>-1,056*</td>
<td>-283</td>
<td>-300*</td>
<td>-2.5</td>
<td>-88</td>
<td>-1,726</td>
</tr>
<tr>
<td>Glaciation index, %</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Glacier volume, km³</td>
<td>-444</td>
<td>-214</td>
<td>-200</td>
<td>+3</td>
<td>-131</td>
<td>-982</td>
</tr>
<tr>
<td>Average thickness, m</td>
<td>-7</td>
<td>-12</td>
<td>-5</td>
<td>+11</td>
<td>-6</td>
<td>-6</td>
</tr>
<tr>
<td>Length of ice coasts, km</td>
<td>-157</td>
<td>-144</td>
<td>-16</td>
<td>-2</td>
<td>-11</td>
<td>-330</td>
</tr>
<tr>
<td>Reference period, years</td>
<td>40</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>27</td>
<td>-</td>
</tr>
</tbody>
</table>

*) approximate, non-controlled value

The largest positive elevation changes (about 100 m) were found in the accumulation areas of the largest ice caps, such as Northern Ice Cap in Novaya Zemlya, Austfonna in Svalbard, Tyndall and Windy ice domes in Franz Josef Land, Schmidt and Vavilov ice caps in Severnaya Zemlya and Kvitoyjokulen at Kvitoya. The sides of these glaciers steepened. Significant positive height changes of 25 to 50 m were also registered at several other insular ice caps smaller than 400 km² with top heights of about 300 m.

The resultant values of glacier changes correlate well with previous estimations made by other explorers (Chizhov et al. 1968, Grosswald et al. 1973, Govorukha et al. 1987, Koryakin 1988, Hagen et al. 1993, Jania & Hagen 1996, Zeeberg & Forman 2001) and show that, in the past decades, the rate of land-ice loss in Novaya Zemlya, Franz Josef Land and Severnaya Zemlya accelerated by 10%, 20% and 25% respectively, while it has not changed significantly in Svalbard. The results obtained clearly demonstrate that the Barents-Kara glaciation is in the regressive stage and indicate severe climate change in longitudinal direction during the past years. Apart from real environmental changes these differences might also reflect the different history of explorations in each meso-region, methodical variations and, of course, measurement errors.
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The uniform quality of SMARAGD glacier change products based on homogeneous satellite data, the high level of automation of well-tested processing and measuring techniques, and, of course, our long experience helped us in keeping the error budget at a low level and ensured the comparability of glacier change measurements made in different meso-regions. Our practical work confirmed that it was much more convenient and, therefore, expedient to perform accurate planimetric measurements of glacier changes from precise cartographic products / maps than from raw data. The main results of regional analysis were represented in the form of observational maps showing glacier area and volume changes in the insular Eurasian Arctic at 1:5,000,000 scale (Fig. 19, small-size copy). Another map showing annual rates of glacier changes in the Barents-Kara region at 1:5,000,000 scale was generated for further geophysical inferences (Fig. 22). Both maps can be accessed on the project website52.

3.3 Geophysical factors of glacier changes

Most tidewater glaciers in the Barents-Kara region demonstrate a complex nonlinear reaction to climate change and it is believed that they may advance or retreat independently of climate variations. Still, the main glacioclimatic relation remains firm and comprehensible to everybody: glaciers melt and decline in response to global warming. That the influence of warming can be offset by the increased amount of solid precipitation accumulating on the

52 http://joanneum.dib.at/smaragd (cd results).
glacier surface, however, is less well known. There are very few reports about positive glacier changes, which seem to be “anomalous” (Bamber et al. 2004) and negligible in view of the retreat of numerous albeit relatively small alpine glaciers. Hence, the recently detected growth of several large and medium-size maritime ice caps in the Eurasian Arctic raised essential scientific and public interest in this “anomalous” effect (Raper et al. 2005, Sharov & Nikolskiy 2007). This is why, in the SMARAGD research project, the main emphasis was put on determining and explaining the dynamic reaction of large Eurasian ice caps and TWGs, especially those which grow in response to current climate change.

Studying the dynamics of active TWGs presents a special problem since their changes are controlled to a very great extent by ice flow and calving of icebergs, and depend essentially on water depth at the terminus (Sharov 2005). Fast-flowing glaciers extending into deep waters usually lose their mass faster than those terminating in shallows or on land. Most ice caps feeding fast tidewater outlets demonstrate essential surface lowering in their accumulation parts. Stressed, crevassed and polluted areas at glacier margins and in glacier interiors undergo faster, typically negative, changes than homogeneous parts with high albedo. Eurasian tidewater glaciers and insular ice caps terminating in shallow coastal waters of the Barents, Kara and Laptev seas exhibit somewhat different reactions to environmental forcing in that they shrink relatively slowly in response to rapid climate change (Aber & Klein 2003). Positive changes in glacier volume were detected exclusively in slow-moving parts of ice caps. In the SMARAGD project, the interpretation of positive elevation changes on maritime glaciers of the Barents-Kara region was based on a thorough analysis of the main environmental factors, both exogenic and endogenic, influencing the local intensity of solid precipitation and snow accumulation on study glaciers (see Fig. 4).

1) The greater part of glacier accumulation is attributed to precipitation of snow under cyclonic weather conditions, with hoarfrost accounting for only 8 - 10% of total accumulation (Grosswald et al. 1973). During the 20th century, all manifestations of positive glacier mass balance in the study region can be associated with a positive phase of the North Atlantic Oscillation (NAO), elevated sea surface temperature, and a concomitant increase in winter precipitation (c.f. Zeeberg & Forman 2001). Indeed, the analysis of hydrometeorological data recorded at 7 polar stations in the study region (Victoria, Nagoorskoe, Rudolph, Krenkel, Zhelania, Russian Harbour and Ushakova) demonstrates some increase in solid precipitation at sea level; we suppose that the same trend also applies to glacier tops. Average values of winter temperature and solid precipitation for 4 meteorological stations in the study region are given in Table 7. Still, intensified atmospheric circulation alone cannot explain the spatial heterogeneity of the glacier change signal at sub-regional scale.

Table 7. Temperature and solid precipitation at Barents-Kara polar stations in 1950s/1990s

<table>
<thead>
<tr>
<th>Parameter / Station</th>
<th>Nagoorskoe</th>
<th>Krenkel</th>
<th>Rudolph</th>
<th>Victoria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature winter, °C</td>
<td>-23.1 / -23.6</td>
<td>-23.8 / -24.7</td>
<td>-23.0 / -23.1</td>
<td>-23.3 / -20.9</td>
</tr>
<tr>
<td>Solid precipitation, mm</td>
<td>195 / 205</td>
<td>180 / 219</td>
<td>170 / 167</td>
<td>249 / -</td>
</tr>
</tbody>
</table>

2) The explanation of positive glacier elevation changes should account for the sea ice cover variability in the region (Sharov et al. 2009). The Arctic climate model offered in (Gildor & Tziperman 2000) simulates the hysteretic effect between sea and land ice under the assumption that sea ice controls, via its albedo and insulating effects, the atmospheric moisture fluxes and precipitation that enable land ice growth. For most of the year the coastal
Measurement and interpretation of glacier changes

waters, straits and glacier bays of high-latitudinal archipelagos are covered with drifting and immobile fast ice, but even in winter, large polynyas can be found at some locations along the shore (Martin 2001, Johannessen et al. 2001). Some of these polynyas are caused by shoals and strong currents, while others are formed by strong offshore winds. Most growing ice caps are located in close vicinity to permanent coastal polynyas appearing each year at the same place.

Several such polynyas can be observed in the northern part of FJL close to Rainer Island occupied by Vostock-2 Ice Cap (133 km²), which has increased its volume by nearly 2 km³ in the course of the past 50 years. Figure 20 represents several fragments from the historical map compiled by J. Payer in April 1874, an ERS-1/2 INSAR fringe image (December 1995) and a LANDSAT-7 image (June 2002) showing areas of open water in the fast sea ice around Rainer Island. Several elongated fringes in the upper part of the ERS-1/2 SAR interferogram are related to vertical movements of the sea ice due to tidal or ocean-swell propagation. In spring, strong tidal currents and storms break the fast sea ice in certain places and form temporary polynyas, which act as foci for further disintegration of the sea ice cover and favour the advection of humid and warm air to nearby ice caps. In still water, ice melting decelerates. Snow cover on sea ice plays an important role in the sea ice regime because it insulates the sea ice from upward heat loss during winter and reduces sea ice growth (Massom et al. 2001). Sea ice is thinner where snow cover is thicker, and thinner ice is more susceptible to break-ups.

3) Wind transport of snow (blizzards) causes a redistribution of accumulation over glaciers. The wind force necessary to start snowdrift can be estimated at 6-8 m/s. There is more accumulation on leeward sides of ice caps than on windward slopes. Snow is blown away from glacier tops towards its lower parts and the vertical gradient of accumulation is usually much lower than the vertical gradient of solid precipitation. Still, the intensity of snow accumulation increases with glacier height and, in FJL, the vertical gradient of snow accumulation is given as 18-20 mm per 100 m (Grosswald et al. 1973). It is worth noting that the accumulation period in the study region lasts for about 9 to 10 months and the snow distribution pattern is fairly stable, while the magnitude of winter accumulation can vary by 100% from year to year (Hagen et al. 2008).

![Figure 20. Historical map (a), ERS-1/2-SAR interferogram (b) and LANDSAT-7 scene (c) showing coastal polynyas in the fast sea ice around Rainer Island, north FJL](image)

4) Glacier topography (altitude) is another important factor in mass balance estimations. The mass balance rate over ice caps for any given year increases linearly with elevation (Kuhn

53 The vertical gradient of solid precipitation is 2.5 times larger, i.e. 40-50 mm per 100 m.)
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1984, Hanson 1987, Grosswald et al. 1973). 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 (Raper & Braithwaite 2006). Relevant numerical estimates of glacier mass balance versus glacier elevation are provided in Chapter 4.3.

5) At sub-regional scale the horizontal distribution of glacier changes correlated astonishingly well with the field of geopotential\textsuperscript{54} represented in existing maps of gravity anomalies in the Arctic. 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 (Sharov & Jackson 2007). At first glance, such hypothesis seems to be a little too one-sided or far-fetched, and we try to provide more substantial evidence to justify it in the next chapter.

3.4 Glacioclimatic settings in heterogeneous field of gravity

The supposition about endogenic gravity-driven or geotropic\textsuperscript{55} forcing on glacioclimatic settings and glacier dynamics in the study region is based on the results of comparison and joint interpretation of our glacier change maps and existing maps of free-air gravity anomalies in the Arctic (Sharov & Nikolskiy 2007). The interpretation of spatial cryogravic dependences was carried out using Russian gravimetric maps of the Barents-Kara Shelf (Zhuravlev 1988), the global map of free-air gravity anomalies from satellite altimetry (KMS 2002) kindly provided by one of its authors, Dr. Andersen O.B., and the ArcGP\textsuperscript{56} public-domain grid of the Arctic gravity field north of 64°N based on ground and airborne surveys (2008, Fig. 21). Fig. 21 represents a fragment from the ArcGP gravity field map visualized using the Dapple 2.1 software from Geosoft Inc.\textsuperscript{57}, which shows positive and negative gravity anomalies in the Barents-Kara region in shades of red and blue respectively.

For the sake of joint analysis the ArcGP map was conflated with our observational map of glacier changes in the Barents-Kara region at 1:5,000,000 scale. In order to obtain comparative estimates we calculated average values of elevation changes in [m/a] and ‘dyed’ each glacier in different shades of ochre and grey depending on the sign and magnitude of the average change value. Gravity anomaly values are represented in different shades of cyan. 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. 22.

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).

\textsuperscript{54} Geopotential is the potential of the Earth’s gravity field.
\textsuperscript{55} By analogy with the biological phenomenon of geotropism.
\textsuperscript{56} ArcGP - Arctic Gravity Project (http://earth-info.nima.mil/GandG/wgs84/agg/index.html)
\textsuperscript{57} http://dapple.geosoft.com
Figure 21. Map of free-air gravity anomalies in the Barents-Kara region (ArcGP grid, 2008)

Figure 22. Map of cryogravic dependences in the Barents-Kara region (small-size copy)
A negative correlation was obtained for small-size ice caps and several large fast-flowing outlet glaciers, such as Vera Outlet Glacier in northern Novaya Zemlya. The combined cryogravic map was subsequently compared with several cartographic products showing the sea ice concentration, snow accumulation on the sea ice and the location of steady polynyas in the study region published in (Atlas of the Arctic 1985, Martin 2001, Rigor & Wallace 2004). We again found an essential positive correlation 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. For the sake of illustration, Fig. 23 represents two Russian maps showing the spatial distribution of fast ice and flaw polynyas in the Eurasian Arctic Basin (Sovetskaya Arktika 1970) and the average maximum thickness [cm] of snow cover in the Russian Arctic (Atlas of the Arctic, 1985). The thinnest snow cover and the most consolidated one-year sea ice are observed in areas of "low gravity" or mass deficit, e.g. in the north-eastern part of the Kara Sea, known by sailors as "ice sack".

Figure 23. Small-scale maps showing the distribution of fast ice (a) and flaw polynyas (b) in the Eurasian Arctic Basin (top) and the average maximum thickness of snow cover in the Russian Arctic (bottom)
Interesting spatial interrelations can be found between the location of free-air gravity anomalies shown in Fig. 21 and summertime sea ice distribution in the Barents–Kara region shown in Fig. 24.

Figure 24. Summertime sea ice distribution in the Barents-Kara region 1983, 1988 and 2003 (from AARI 2006)

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. 25, adopted from Fowler, 1990). 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. In the equipotential sense the effect is not that small, since a gravity anomaly of +100 mGal is equivalent to the presence of a hill with a height of 300 to 900 m depending on rock density. In other words, the anomaly of 100 mGal or $1/9800$ of the acceleration due to gravity is small with respect to the globe, but strong enough to be felt at the local level.

Figure 25. Concept of converging precipitation in the area of positive gravity anomaly

58 Sea ice grows downwards, towards the center of the Earth and is thus, by biological analogy, positively geotropic. In contrast, snow accumulation is negatively geotropic, i.e., it grows upwards, or away from the Earth’s surface.

59 $1 \text{ mGal} = 1000 \text{ mcGal} = 10^{-5} \text{ m/s}^2$
Hence, one can conclude that lateral variations of snow accumulation, sea ice concentration and glacier changes are interrelated and influenced by the same endogenic factors. Following the ideas explaining possible causes of anomalous growth of Austfonna in Svalbard (Raper et al. 2005), 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. The large magnitude of the gravity anomalies and the spatial 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 a result of geometric errors in glacier mapping, and we believe that the gravity-driven impact on glacier topography and dynamics is quite probable.

The greater part of glacier accumulation in the study region, however, is due to precipitation of snow under cyclonic weather conditions and it is obvious that local meteorological, topographic, oceanographic, and ice flow effects mask the gravity-induced component of land- and sea ice variations. At best, such component can be determined at regional scale on topographically smooth, open and steady surfaces, like those of large ice caps, fast sea ice and ice-free planes. The period of study must be sufficiently long in order to compensate for or to diminish the influence of stochastic hydrometeorological, aeolian and hydrological factors. The reference period of 50 years chosen for our study is a trade-off between the desired time scale and the opportunities of modern EO systems. The oldest available topographic maps and hydrographic charts containing major historical information about glaciers in the Eurasian Arctic were mostly created through materials of the first extensive aerial and geodetic surveys carried out in the 1950s to 1960s. This means that glacier changes in the Eurasian Arctic could be accurately detected and measured only for the past 50 to 60 years.

Although a 100-year observation period might provide more reliable data, the 50-year study initiated in the SMARAGD framework and completed in the follow-on project “Ice-snow cover evolution and associated gravitational effects” (ICEAGE) brought essential results that were close to our expectations. The most interesting findings can be summarized as follows (Sharov et al. 2009):

- most glaciers occupy areas with heterogeneous geopotential in the close vicinity of positive gravity anomalies, while the closest and thickest sea ice can be found in areas of negative gravity anomalies;
- the majority of high-latitudinal albeit glacier-free islands with relatively large areas and significant top heights are situated in areas of low gravity;
- the largest positive glacier elevation changes (> 1 m/a) take place in the accumulation areas of the largest slow-moving ice caps and are usually adjacent to locations of strong positive gravity anomalies offshore;

60 Longer periods of glacier change can be studied where earlier airborne survey data are available, e.g. in the areas surveyed from the airship “Graf Zeppelin” in 1931.
61 http://www.inas.tugraz.at/iceage
the main loss of land ice occurs in the seaward basins of fast-flowing outlet glaciers, both at their fronts and tops; typically these glaciers flow towards strong positive gravity anomalies;

- the spatial distribution of steady polynyas and extreme annual values (max/min) of snow thickness on the fast ice and in low-land tundra correlate well with the field of geopotential represented in available gravity anomaly maps;

- under present environmental conditions in the Eurasian High Arctic, medium-term (from half-centennial to decadal) changes in glacier volumes and masses are interrelated with the extent and duration of sea ice cover nearby, so that slow-moving tracts of maritime ice caps grow when the sea ice cover in adjacent waters is small, and they thin when the sea ice cover consolidates.

As a result of these findings a new working hypothesis about gravity-driven fluctuations in the medium and long-term regime of snow and ice resources in the High Arctic was devised and argued. It has been tentatively suggested that strong gravity gradients increase the probability of snowfalls and intensify tidal currents, which destroy the fast sea ice and increase the evaporation with subsequent deposition of snow and rime on the glacier and sea ice surface, thus involving positive feedback effects, e.g. decelerated growth of the sea ice. This supposition was critically compared with the relevant knowledge obtained by some other investigators.

A simple graphic scheme explaining the glacioclimatic conditions in an area of strong positive anomaly marked with © is shown in Fig. 26. Vertical arrows represent descending and ascending movements of ice crystals and frazil ice involved in the snowfall and sea ice growth processes, while the advection of humid air originating from coastal polynyas is shown with a curved arrow. A brief analytical explanation of the cryogravic interplay is provided in the next chapter.

Figure 26. Glacioclimatic settings in an area of positive gravity anomaly
There is some analogy between our cryo-geophysical hypothesis and the empirical-theoretical practices developed by "astrometeorologists", who correlate meteorological phenomena with planetary configurations and explain periodic variations in terrestrial weather with the attraction of Moon and Sun. Even old astrometeorological calendars and observations had an element of truth in them and the practice of applying astronomical data to forecasting unseasonable weather, especially medium and long-range, continues to be admissible in modern times (Wikipedia 2009). The ancient astrometeorological theories about weather dependence on the constellation of celestial bodies were substantiated by Johannes Kepler, ?? Schröter and ?? Stark in the 17th and 18th centuries. Hydro-meteorological studies referring to a lunar influence (phase progression) on variations in precipitation, e.g. those by Luke Howard and Kaspar Sterr, were published in the 19th century (Lüdecke 2005). In the 20th century, the interest in astrometeorology continued and several studies were performed relating gravitational tidal forces to atmospheric processes (c.f. Brier 1965, Visvanathan 1966).

Simple mathematical formulations of gravity impact on local weather can be found in the paper published by A. Luiz from the University of Pisa in 1969. He demonstrated the dependence between the onset of rainfall and 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 (Luiz 1969). The idea was formally criticized by W. Jacoby, who pointed out the insufficient magnitude of gravitational tides in the atmosphere (Jacoby 1969). Jacoby used the following citation to emphasize his main contra-argument: "As the tidal variations of atmospheric pressure are too small to affect the weather noticeably the study of the atmospheric tides is only of interest for meteorology in its theoretical aspects" (Kertz 1957). Later on, Luiz responded to the criticism, but his idea did not become popular for a long time.

In this context we wish to note that a semi-diurnal pressure variation is quite noticeable in the low latitudes. It can reach 2 hPa either side of the mean. This atmospheric tide is associated with lunar and solar gravitation, solar heating and resonance, and considered as an internal gravity wave with a 12-hour frequency. Regular observations showed that the lowest and the highest pressure occurred during wintertime (Pasichnyk, 2002). The greatest atmospheric tide is observed in the 40° latitudes. Still, there seem to be no noticeable temporal variations of the Earth’s gravity field. Corresponding deviations of the gravitational acceleration in the range of mcGals can be measured by modern superconducting gravimeters only at local scale (Meurers 2000). The advance of CHAMP, GRACE and GOCE satellite gravimetry missions allowed temporal gravity changes to be determined and converted to the changes in surface mass on a regional and global basis. New studies focusing on barometric tendencies and characteristic precipitation patterns in time variable gravity fields were recently presented in (Makosko & Panin 2002, Morishita & Heki 2008, Seo et al. 2009).

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" (Morishita & Heki 2008). We can rephrase this statement as "Gravity anomalies leave signatures in precipitation fields..." Such paraphrase may make practical sense because the magnitude of lateral gravity variations is nearly four orders larger than that of temporal deviations. Moreover, it is natural to suggest that over a long period of time the steady influence of permanent gravity anomalies will result

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The maximum amplitude of glacioisostatic effects reaches approx. 3 mGal (Pail 2009).
Measurement and interpretation of glacier changes

in a more appreciable environmental effect than that of alternating tidal variations. It is surprising that most recent publications traditionally deal with temporal and / or vertical variations of gravity, whose typical amplitude does not exceed 0.3 mGal, and do not consider the impacts of lateral changes of gravity attaining several hundred mGals over relatively short distances. This is why we devised an idea of studying the long-term effect of lateral gravity variations on the evolution of large high-latitude glaciers and ice caps with homogeneous topography and essential heights in the Barents-Kara Sector representing the largest cluster of big tidewater glaciers and strong gravity anomalies in the Old World (Sharov et al., 2009).

3.5 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\textsuperscript{63} and use the well-known equation relating the change in hydrostatic pressure \( P \) to the change in height or depth

\[ P \equiv \rho \cdot g \cdot z. \]  

(3)

In equation (3) \( \rho \) is the medium density and \( g \) is the acceleration due to gravity and \( z \) is the height of the air or water column given as

\[ z = z_0 \pm h. \]  

(4)

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 land (glacier) topography.

In most applications \( g \) is considered as constant and the hydrostatic equation is usually written in differential form as

\[ \frac{dP}{dz} = \pm \rho \cdot g. \]  

(5)

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 (5) can be transformed into

\[ \frac{dP}{dg} = \rho \cdot z. \]  

(6)

The density of air and water is a function of temperature as well as of moisture content and salinity respectively. Air density decreases with increasing water vapour content. Salt water has a higher density than fresh water. An increase in temperature causes the air and water

\textsuperscript{63} as simplifying approximation
density to decrease. Hence, 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 (3) 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

$$\frac{dP_v}{dx} = \rho_v \left( \frac{z}{x} \cdot \frac{dg}{dx} - \frac{g}{x} \cdot \frac{dh}{dx} \right).$$

(7)

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 (7) 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 solid precipitation as a function of gravity gradient:

$$\frac{dW_{\text{salt}}}{dx} = \frac{a_d \cdot \rho_v}{2 \pi \cdot m_v \cdot k_B \cdot T} \left( \frac{z}{x} \cdot \frac{dg}{dx} - \frac{g}{x} \cdot \frac{dh}{dx} \right).$$

(8)

In equation (8) $a_d = 0.01 \, T_{\text{air}} + 1.0$ 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).

All other glacier-related processes, such as solid precipitation, snow accumulation, compaction and redistribution by wind, ice deformation, recrystallization and flow, exaration effects and moraine building, meltwater runoff and sediment transport, icequakes, calving and glacioisostatic processes are also controlled by the force of gravity. Gravitation plays the major role in glacier mechanics in that it determines the driving stress and resistive strain of land-ice masses during their motion. For static equilibrium the shear stress at glacier depth $z_g$ is determined by the weight of the ice column and in the case of an inclined glacier bed sloping at an angle $\alpha$, is defined as

$$\sigma_x = \rho_i \cdot g \cdot z_g \cdot \sin \alpha,$$

(9)

where $\rho_i = 917 \, \text{kg m}^{-3}$ is the glacier ice density, $z_g$ is the glacier thickness and $g$ is gravitational acceleration.

In the case of a horizontal bed and sloping glacier surface the next equation yields

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64 If saturation vapours pressure over ice does not vary in horizontal direction.
Measurement and interpretation of glacier changes

\[ \sigma_s = \rho_s \cdot g \cdot z_s \cdot \sin \alpha \]

Both equations are commonly written as

\[ \sigma_s = \rho_s \cdot g \cdot z_s \cdot \alpha \]

because glacier surface slopes are usually small and \( \sin \alpha \approx \tan \alpha \approx \alpha \).

The depth-averaged value of driving stress causing ice flow in large ice caps is defined by the next basic formula (Van der Veen 1996)

\[ \overline{\sigma_s} \approx 0.5 \cdot \rho_s \cdot g \cdot z_s . \]

The resistance to glacier flow or basal drag can be determined from the next equation (Hooke, 1998)

\[ \tau_b \equiv -S_f \cdot \rho_s \cdot g \cdot z_s \cdot \sin \alpha , \]

where \( S_f \) is known as the shape factor.

The interaction between the driving stress and resistive strain determines the horizontal velocity of a glacier, which represents one of the basic glaciological parameters controlling glacier topography and dynamics, ice loss and mass balance. Equations (9) through (13) describing glacier mechanics can also be presented in differential form involving gravity gradients and spatial variations of glacier thickness. Such a formulation can be useful since the ice thickness distribution can be inferred, although sometimes with a considerable and poorly specified error term, from known surface topography and mass flux (mass balance) using principles of flow mechanics. However, this is beyond the scope of the present publication 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 comprehensive publications (e.g. Dyunin 1983, Rapp 1998).
4. GLACIER MASS BALANCE ESTIMATES

by Wolfgang Schöner, Bernhard Hynek and Aleksey I. Sharov

4.1 Compilation and inspection of climate data set

The atmospheric pressure, intensity of solid precipitation and the amount of snow, hoarfrost and rime accumulated on the glacier surface during winter strongly influence glacier mass balance, i.e. the annual difference between accumulation and ablation (melting, calving and sublimation). Other climatic factors, such as air temperature and humidity, wind speed and direction, sunshine duration, cloudiness and sea ice concentration also play an important role in glacier regime and budget. Somewhat obsolete descriptions of the main glacioclimatic characteristics in each meso-region of the Barents-Kara sector can be found in (Chizhov et al. 1968, Grosswald et al. 1973, Koryakin 1988 and others). The detailed overall description of the climate in the Barents-Kara region given in (Alexandrov et al. 1990) is based on the dataset that ends in 1992. In the SMARAGD project we acquired the following datasets describing both the historical and present climate of the Barents-Kara region:

- monthly and daily meteorological data from polar stations Cape Zhelania, Krenkel, Nagoorskoe, Rudolf, Russkaya Gavan’, Ushakova, Victoria via the Arctic Climatology Project and the TuTiempo database\(^6\) for the period of 1948 – 2008;
- sub-daily and daily data on precipitation, temperature and other meteorological elements from the National Climatic Data Centre with updates until 2005 provided by P. Groisman (NCDC, 2005a);
- daily grid data of temperature and precipitation from NCEP/NCAR climate reanalysis 1948-2009 with spatial resolution of 2.5° downloaded from the NOAA web site.

These data were used for the general characterisation of climatic trends in the study region and as input for glacier mass balance modelling. The most representative meteorological dataset was collected for the Franz Josef Land region including 4 polar stations shown in Fig. 27. Three of them are operational WMO stations.

![Figure 27. Climate stations and fieldwork sites in Franz Josef Land (left); annual course of air temperature at climate stations in the FJL region (right)](http://www.tutiempo.net/en/Climate/Russia/RU.html)
The annual course of air temperature in the northern part of the study region is also shown in Figure 27. Victoria Island situated in the western part demonstrates typical features of maritime climate with warmer temperatures in winter and colder summers than in Franz Josef Land, while a more continental climate with colder temperatures during winter is observed at Ushakova and Vize islands in the eastern part of the study region. In FJL, the temperature gradient is directed from the south-west (warm) to the north-east (cold) and is smaller during summer (~2°C) than in winter (~5°C) (Kotlyakov 1997).

The annual amount of precipitation decreases generally from south to north and from west to east, as precipitation events are determined by cyclonic activity and the maximum moisture content of air decreases with temperature. Air masses get drier as they move over ice caps and solid precipitation decreases by a factor of 1.5 from the south-east to the north-west (Groswald et al. 1973, Jania & Hagen 1997). Relative humidity increases with altitude resulting in more extensive cloudiness and fogs, stronger precipitation and hoarfrost at higher elevations. The available estimates of annual accumulation rates on glaciers and ice caps varying from 0.2 to 0.8 mwe and even 1.0 mwe66 (Chizhov 1976, Groswald et al. 1978, Vinogradov 1980, Alexandrov et al. 2000) correlate well with the annual precipitation values measured at polar stations. In Franz Josef Land the maximum accumulation amount is observed in the south-east of the archipelago (e.g. Kotlyakov 1997). The average duration of snow cover at Nagorsko and Rudolf stations is 293 and 306 days respectively. Fig. 28 represents the long-term average of monthly precipitation and snow depth at the meteorological station on Rudolph Island (52 m asl). The maximum snow depth is observed in May.

Figure 28. Long-term average of monthly precipitation (left) and snow depth at the Rudolf Station (52 m asl., from Alexandrov et al., 2000)

The air temperatures show a warming trend for the study region, which is clearly seen from the beginning of the 2000s. Precipitation was decreasing until the 1990s and started to increase in the 2000s. The plausibility of NCEP/NCAR reanalysis data was checked against the meteorological data measured at the Krenkel Station on Hayes Island in the central part of FJL. We found that the air temperatures from NCEP were in good agreement with the station measurements. Fig. 29 shows mean annual and monthly values of temperature and precipitation at the Krenkel Station. Black bars represent the differences between the NCEP reanalysis and Krenkel Station data over 31 years of concurrent records. Air temperatures from NCEP show good agreement with station measurements over a long period, but since

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66 In northern Novaya Zemliya and Byrranga Mountains
1998 the reanalysis data do not reproduce cold periods during winter and spring, and show a much larger warming trend than the station data. The reason for this deviation is not quite clear. Probably, it is related to reanalysis data inaccuracies.

The NCEP precipitation values were systematically lower than the station measurements. Only in the last part of the reference period does the reanalysis show much higher precipitation amounts and an overestimation of air temperature. It is obvious that the reanalysis data has systematic variable bias and does not correctly reproduce the seasonal variability of the station climate. The precipitation reanalysis data shows somewhat better agreement with the station records when precipitation is expressed in the number of days with precipitation amounts over 0.1 mm (Fig. 30). In Fig. 30, black dots represent the differences between the two datasets. Precipitation events of more than 10 mm/day are usually underestimated by reanalysis.
Glacier mass balance estimates

Scatter plots of station data versus reanalysis data for daily, monthly and annual mean values as well as sums of temperature and precipitation are shown in Fig 31. A remarkably high correlation can be seen between the temperature datasets while there is no correlation between precipitation records.

Figure 31. Scatter plots of station temperature (red) and precipitation (blue) versus reanalysis data for daily (left), monthly (middle) and annual (right) means resp. sums

Differences between measurements and reanalysis vary with the season, as shown for the two datasets of temperature and precipitation in Fig. 32. The differences for the individual years are shown at the right (1976, 1977, 1984 and 1999 were excluded because of data gaps). The 31-year average value is highlighted in green. The reanalysis overestimates temperature in spring and early summer, and underestimates temperature during winter. The same applies to precipitation. Time series of monthly precipitation data from Krenkel Station and reanalysis (in grey) are plotted in Figure 33, a), which shows a clear underestimation of precipitation from reanalysis during winter, with a mean deviation of about 20 mm/month in February, i.e. approximately 10% of the annual precipitation amount at the station.

Figure 33, b) shows time series of temperature during different months of the year for all three operational climate stations on the archipelago and corresponding reanalysis data. Careful comparison of these time series reveals further inaccuracies in the reanalysis data. The overestimation of air temperature was confirmed by analyzing corresponding data from the grid points covering other parts of the archipelago (shown in grey) and from the temperatures recorded at Nagoorskoe and Rudolf stations. For example, temperature estimations in May are too high by 1.6° K over a long period of time. Maximum daily deviations between reanalysis and station data reach 10-15° K for some shorter sub-periods. However, summer temperatures are well reproduced by the reanalysis, which is more important for glacier mass balance modelling, as mass balance is more sensitive to temperatures in summer than in winter.
In the SMARAGD project we needed long-term continuous data series of air temperature and precipitation for the calculation of surface mass balance of the study glaciers and ice caps. The station measurements are quite precise, but due to different reasons they do not cover the entire reference period of the past 50 years. There are major data gaps for 1976 (I-XII), 1977 (I, XI), 1984 (VI), 1999 (XII), and from 2001(VII) to 2004(XI), when the station was out of service following a fire in 2001. Moreover, weather stations are sparsely distributed over the study region, especially around the large study glaciers. This is why the station data have limited value for the efficient analysis of climate variations that are responsible for glacier changes in the study region. Hence, the reanalysis data represented the single source of continuous uninterrupted records of air temperature and precipitation for the entire study region.

For mass balance modelling, daily temperature and precipitation values from the NCEP/NCAR reanalysis were adjusted using seasonal correction factors, which were determined from data discrepancies for the 31-year period of 1966-1997. The overestimation of air temperatures for the end of the 1990s occurred mainly during the winter, when almost no melting takes place, and therefore was not corrected.

The comparison between precipitation and temperature measurements and the reanalysis data from the National Centres for Environmental Prediction and Atmospheric Research (NCEP/NCAR) revealed essential discrepancies. However, it showed that the deviations can be reduced by adjustments and residual errors can be tolerated, thus confirming the general applicability of reanalysis data to glacier mass balance modelling.
Figure 33. Precipitation (a) and temperature (b) time series for selected months / seasons from station measurements and NCEP/NCAR gridpoints covering the entire archipelago.
4.2 Regional data on glacier mass balance

Climate change and related deviations of air temperature and snowfall cause fluctuations in glacier mass balance, which control a glacier's long-term behaviour and are crucial to glacier existence. Compared to alpine regions, only few mass balance studies have been carried out at regional scale in the Barents-Kara sector.

Some factual knowledge about glacier mass balance and its changes on separate archipelagos can be found in (Grosswald et al. 1973, Troitskiy et al. 1975, Vinogradov 1980, Hagen & Liestøl 1990, Zeeberg & Forman 2001). More or less complete overviews of glacier mass balance indices for different parts of the Barents-Kara region can be found in (Chizhov 1976, Govorukha 1984, Koryakin 1988, Jania & Hagen 1996). Several maps representing mass balance characteristics of separate glaciers are included in the World Atlas of Snow and Ice Resources (Kotlyakov, 1997). In the Barents-Kara region, the behaviour of glaciers in Svalbard is studied and reported at best (Koryakin 1988, Hagen et al. 2003).

Mean values of mass balance characteristics derived from literature data for each meso-region in the Barents-Kara sector are given in Table 8. They indicate that most glaciers and ice caps in the study region have negative net mass balance and their expected contribution to sea-level rise is rather small. The observed retreat of glacier termini, data from several ice cores and the results of repeated geodetic surveys on several ice caps confirmed the shrinkage of Barents-Kara glaciation. Krenke (1982) found that mass balance variations of ice caps in the region depend strongly on the variability of surface ablation. Another important source of mass balance variability is calving, as year to year changes in calving rates can be considerable. The strong long-term accumulation signal detected recently on several large ice caps with the aid of satellite altimetry cannot tip the scale, but compels us to revise previous one-sided interpretations of glacier budget in the study region (Raper et al. 2005, Sharov & Nikolskiy 2007).

Table 8. Glacier mass balance characteristics (mwe or g/cm²) for the Barents-Kara region

<table>
<thead>
<tr>
<th>Meso-region</th>
<th>Period</th>
<th>Accumul.</th>
<th>Melting</th>
<th>Calving</th>
<th>Balance</th>
<th>Contr. to sea-level rise, mm/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Svalbard</td>
<td>1950 - 1988</td>
<td>0.56</td>
<td>- 0.57</td>
<td>- 0.13</td>
<td>- 0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>Novaya Zemlya</td>
<td>1930 - 1960</td>
<td>0.35</td>
<td>- 0.32</td>
<td>- 0.08</td>
<td>- 0.25</td>
<td>0.009</td>
</tr>
<tr>
<td>Franz Josef Land</td>
<td>1930 - 1959</td>
<td>0.28</td>
<td>- 0.32</td>
<td>- 0.17</td>
<td>- 0.21</td>
<td>0.001</td>
</tr>
<tr>
<td>Ushakova Island</td>
<td>1955 - 1969</td>
<td>0.22</td>
<td>- 0.30</td>
<td>- 0.03</td>
<td>- 0.11</td>
<td>0.000</td>
</tr>
<tr>
<td>Severnaya Zemlya</td>
<td>1920 - 1972</td>
<td>0.25</td>
<td>- 0.35</td>
<td>- 0.03</td>
<td>- 0.13</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Direct mass balance measurements were performed only on a small number of Barents-Kara glaciers and then extrapolated to larger areas and longer periods of time. Mass balance time series of most large glaciers and ice caps represent indirect reconstructions from meteorological records obtained at the nearest polar stations. The integral values of mass
Glacier mass balance estimates

balance specified in Table 8 are provided for comparison only and thus should be treated as very approximate. The equal values of ice loss due to calving at Ushakova Island and on Severnaya Zemlya seem to be inaccurate.

Substantial direct glaciological measurements were performed on the following glaciers:

- Austre Broggerbreen, Midre Lovenbreen, Kongsvegen, Hansbreen etc. on Svalbard,
- Sedov Glacier, Churlyonis, Jury, Jackson and Windy ice caps in Franz Josef Land,
- Shokal’skogo Glacier in Novaya Zemlya,
- Vavilov Ice Cap in Severnaya Zemlya.

Some isolated measurements of accumulation and ablation have been carried out on other glaciers (e.g. Sinkevich 1995). It is worth noting, however, that there is still very little factual knowledge about spatiotemporal specifics of glacial budget in most other parts of the study region.

4.3 Glacier mass balance modelling and analysis

The SMARAGD project was designed to estimate the cumulative effect of climate change on glaciers and ice caps in the Barents-Kara region during the period of the 1950s to 2000s by modelling and analysing glacier mass balance characteristics. The main purpose of this study was

- to compare the mass loss of ice caps and outlet glaciers in the study region determined from remote sensing data with the potential mass loss due to climate change in the period of 1950s - 2000s;
- to compute possible scenarios of glacier mass balance for several study glaciers with high accumulation rates and to estimate maximum climatic contribution of these accumulation features;
- to estimate the relative intensity of glacioclimatic processes at the interface between the glacier and its environment, namely the atmosphere, bedrock, and - for tidewater glaciers - the ocean, and to define the main non-climatic, e.g. endogenic factors influencing glacier evolution in the study region.

This study was also focussed on the glaciers of Franz Josef Land, which is situated in the centre of the Barents-Kara region. The model we used for calculating the surface mass balance from the daily data of air temperature \( T_i \) and precipitation \( p_i \) is based on the elevation dependent temperature-index approach (e.g. Hock 1999, 2003, Oerlemans 2007). In this approach the surface mass balance \( b \) is calculated as the difference between glacier accumulation \( c \) and ablation \( a \)

\[
b = c - a .
\]  

(14)

The amount of glacier accumulation is determined as a sum of daily precipitation in [mm] for the number of days with air temperatures below the threshold determining the onset of solid precipitation \( T_c \)

\[
c \equiv \sum_{i=1}^{n} p_i , \text{where } n \text{ is the number of days with } T_i < T_c .
\]  

(15)
In our case the temperature threshold $T_c$ between liquid and solid precipitation was assumed to be 0°C.

Glacier ablation is calculated as a sum of positive air temperatures multiplied by a degree-day factor

$$a = f \cdot \sum_{i=1}^{m} T_i, \text{ where } m \text{ is the number of days with } T_i > 0^\circ C$$  \hfill (16)

and $f$ is a degree-day factor (DDF) for snow or ice [mm °C⁻¹ d⁻¹]. The degree day factor for snow surfaces depends on the snow density $\rho_s$ and can be determined for open areas as

$$f_s \equiv 19.6 \cdot \frac{\rho_s}{\rho_w} - 2.4$$  \hfill (17)

The degree-day factor for ice surfaces is assumed to be twice of that for snow (Braithwaite et al. 2003). The snow density at different glacier elevations was measured during our field campaigns in 2006 and 2008 and extrapolated over study glaciers using literature and cartographic information.

Previous estimations by other investigators have shown that the degree-day factor varies strongly with the concentration of dust on the glacier surface and the character of radiation (Groswald et al. 1973, Huintjes et al. 2010). Practical calculations using equation (17) and the relation between the degree-day factor for snow and ice gave the following values:

- degree-day factor for snow $f_s \equiv 5.5$ mm/°Cd,
- degree-day factor for firn $f_f \equiv 7.5$ mm/°Cd,
- degree-day factor for ice $f_i \equiv 10$ mm/°Cd.

The degree-day values ranging from 5 mm/°Cd to 10 mm/°Cd for the accumulation and ablation zone respectively are somewhat lower than those specified in the literature (e.g. Grosswald et al. 1973). This should compensate for the fact that our model does not account for the deposition of superimposed ice and assumes that all meltwater runs off the glacier, thus neglecting the refreezing of meltwater on the glacier surface.

The model was developed and tested using the MATLAB software. The altitudinal distribution of glacier area in Franz Josef Land was derived from the hypsographic scheme given in (Vinogradov and Psareva, 1965). The specific mass balance was calculated for each glacier elevation zone with a height interval of 40 m assuming a vertical lapse rate of temperature of -0.6°/100 m and an increase in precipitation with elevation of 50 mm/100 m as given in (Groswald et al.1973). The algebraic sum of partial balance values represented the total mass balance for the past 55 years. The modelling concept is illustrated in Fig. 34, adopted from (Sharov & Jackson 2007). The location of glacier boundaries and separate zones was determined from topographic maps showing the glacier state in 1953.

In order to estimate the relative role of each variable involved in the quantitative analysis of the glacier budget we varied the values of the basic parameters and performed the calculations using different input data files. First estimates of glacier accumulation and ablation were performed using daily data of air temperature and precipitation from the NCEP/NCAR reanalysis. Further model runs were carried out using the reanalysis data series adjusted to
Glacier mass balance estimates

the station measurements at Krenkel Polar Station. The following 7 different mass balance scenarios resulted from this study:

a) mass balance for the elevation range of 0-600 m with varying DDF and different precipitation amounts in the north-western and south-eastern parts of FJL;

b) mass balance at sea level with unvarying DDF for snow;

c) mass balance at sea level with the DDF changing from snow to firm in the zones where the winter snow cover is melting;

d) mass balance at sea level with the DDF changing from snow to ice in the zones where the winter snow cover has melted away;

e) mass balance at an elevation of 250 m with the DDF changing from snow to ice in the zones where the winter snow cover has melted away;

f) mass balance at an elevation of 250 m with unvarying DDF for snow;

g) mass balance at an elevation of 250 m with unvarying DDF for snow and the precipitation amount increased by a factor of 1.5.

Figure 34. Semi-distributed concept of the mass balance model based on temperature index

The results illustrating mass balance scenarios a), b) and c), d) and e), f) and g) are shown in Figs. 35 through 38. Fig. 35 represents the alitudinal distribution of glacier area (1953) and vertical profiles of short-term [mm/y] and long-term average [km³/y] accumulation, ablation, and surface mass balance (top) as well as time series of accumulation, ablation and mass balance for the period September 1948 – September 2008. Figs. 36, 37 and 38 represent the results achieved with the adjusted reanalysis data.

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Figure 35. Accumulation, ablation and surface mass balance of the entire Franz Josef Land archipelago in 1948-2008 modelled with uncorrected NCEP/NCAR reanalysis data.

The bottom graph in Fig. 35 shows a significant decrease in cumulative mass balance during the past decade, which is due to both real environmental changes and singularities in the NCEP/NCAR data. Still, the modelled reduction of 5 m in average ice thickness is 2 to 2.5 times less than the average surface lowering determined from remote sensing data (Table 6). This discrepancy can be explained by the fact that our mass balance model fails to take into account calving, wind drift of snow and orographic effects, which are difficult to model at the regional scale. Hence, our modelling results provide somewhat overestimated values of mass balance for all glaciers in the study region. They do, however, provide a good description of the long-term evolution of slow-moving ice caps with a nearly ideal homogeneous surface.

Figures 36 through 38 indicate a strong gradient of glacioclimatic conditions in vertical direction. One can observe a two- to three-fold increase in precipitation from the glacier termini around 10 meters above sea level to the accumulation areas of large ice caps at elevations ranging from 250 to 500 m. Annual mass balance estimates vary from -0.2 mwe/y at sea level to +0.18 mwe/y and more at an elevation of 250 m.

Moreover, our model does not account for the effect of temperature inversion with a positive lapse rate ranging from +0.3°/100m to +0.6°/100m systematically observed over glaciers at heights between 200 and 700 m under steady weather conditions in winter and mentioned in (Grosswald et al. 1973).
Figure 36. Mass balance at sea level with constant DDF for snow (top) and DDF changing from snow to firn once all winter snow has melted (bottom).
Figure 37. Mass balance scenarios at sea level (top) and at an elevation of 250 m (bottom) with DDF changing from snow to ice once all winter snow has melted.
Glacier mass balance estimates

Figure 38. Mass balance scenarios for 250m altitude with constant DDF for snow (top) and precipitation increased by a factor of 1.5 (bottom)
Glacier mass balance estimates

The mass balance time series for the period of 1949 - 1959 modelled with uncorrected reanalysis data showed somewhat better agreement with the mass balance measurements published in (Grosswald et al. 1973) than the modelling results obtained with the adjusted reanalysis data (Fig. 39). This effect was explained by better agreement between the NCEP/NCAR and station data in former years, as mentioned in the previous section.

Figure 39. Time series 1949-1959 of accumulation, ablation and surface mass balance modelled with uncorrected (top) and adjusted (bottom) reanalysis data in comparison with the station measurements (blue) published in (Grosswald et al. 1973)

4.4 Some remarks on modelling results

Annual values of accumulation, ablation and surface mass balance for Franz Josef Land glaciers and ice caps were estimated for the period of 1948 - 2008 using the simplest temperature-index model and NCEP/NCAR climate reanalysis data. The mass balance model was calibrated and validated using station and literature data. Subsequently, we compared the model outputs with the accumulation data from field measurements on two ice caps carried out in 2008 and found good agreement between these datasets. The lack of factual ablation and mass balance data for the past decades, however, did not allow the modelling results to be thoroughly checked and adjusted to actual glacioclimatic conditions.

Nevertheless, the results were sufficient to draw the following conclusions:

1) Model outputs indicate that, at regional scale, annual ablation is subjected to essential variations while winter accumulation remained stable throughout the past 60 years.

2) In the climate model, the strongest mass balance gradient is observed in the vertical direction, and the glacier budget increases rapidly with elevation. 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 (see Section 3.3).

3) The average lowering of FJL glaciation - 12 meters in the past 50 years, derived from remote sensing data (Table 6) - is still in the range of plausible impacts of climate change in the Barents-Kara region.
4) The strongest accumulation signal (up to +70 m) derived from remote sensing data exceeds the expectations based on modelling results and indicates that the spatial character of mass balance variations might be seriously influenced by non-climatic or insufficiently known climatic effects. Our simple numerical experiments coupled with remote sensing observations provide, at least symbolically, a new insight into the long-term glacioclimatic conditions on large slow-moving ice caps.

5) Cumulative values of surface mass balance on Franz Josef Land between 1948 and 2008 are strongly dependent on the quality of input data. The model is highly sensitive to internal parameters. The model outputs strongly depend on the value of the degree-day factor, which can vary from 5.0 to 6.4 mm °C$^{-1}$ day$^{-1}$ for clean and dusted snow and from 7.4 to 13.8 mm °C$^{-1}$ day$^{-1}$ and more for ice depending on the surface albedo (Schytt 1964, Singh et al. 2000). Spatial variations of the DDF affect the accuracy of snow- and ice-melt modelling.

6) We have intentionally neglected large effects, especially ice flow, calving, wind drift, superimposed ice and rime deposition and temperature inversions. This neglect, however, diminishes the value and applicability of the modelling results to further glacioclimatic analysis in the Barents-Kara region.

Additional glacioclimatic inferences were derived from the results of our glaciological and geodetic surveys in Franz Josef Land in 2008. Further modelling activities in the study region will focus on the diversification of model parameters and the improvement of input data quality.

5. FIELD SURVEYS AND VALIDATION OF GLACIER PRODUCTS

by Wolfgang Schöner, Aleksey I. Sharov, Christine Kroisleitner and Daniel Binder

5.1 Plans face reality

In July-August 2008, the authors were given the opportunity to participate in the international multidisciplinary expedition to Franz Josef Land on board the ship "Polaris" and to perform field surveys on several ice caps in the southern part of the archipelago. It has to be noted that the expedition was initially planned for summer 2007 but had to be cancelled because Russian authorities did not provide special administrative permission for glacier surveys in the FJL region. With the launch of the 4th IPY the restrictions on scientific access to the archipelago were relaxed and our research group including Wolfgang Schöner and Christine Kroisleitner, both from ZAMG and Aleksey Sharov and Roland Wack from JR was able to join the next expedition to FJL without excessive formalities.

This time the expedition was organized by Poseidon Arctic Voyages and was successfully carried out under the general leadership of Andreas Umbreit from the Terra Polaris agency. An expedition map showing the ship’s route (in green) and main sites of field surveys in FJL is given in Fig. 40. The expedition left from Longyearbyen harbour in Svalbard and reached FJL (Prince George Land) on August 1st. On this day we had observed the total solar eclipse and enjoyed the entire event despite sceptical forecasts which had predicted a 20% probability of

68 http://www.northpolevoyages.com
69 http://www.terrapolaris.com
clear skies for FJL. Further glaciological surveys and observations were also carried out under more or less steady and calm weather conditions (Fig. 41). The relevant meteorological and oceanographic parameters were registered at 3-hour intervals by the ship’s meteorological station.

Our plans to perform field surveys on FJL’s ice caps and glaciers with the strongest accumulation signal including Kvitoyjokulen at Kvitoya, Ice Cap No.3 at Koeftitz Island, Vostock-2 Ice Cap at Rainer Island, Simony Glacier at Mc.Clintock Island and Windy Ice Cap at Graham Bell Island, however, had to be altered. Kvitoya, Rainer and Graham Bell islands could not be accessed because of heavy sea ice conditions and all surveys had to be performed at Költitz and Mc.Clintock islands on August 2nd and 3rd respectively. The study glaciers on these islands terminate in shallow waters (marked in light cyan in Fig. 40) and we had to use Zodiac rubber boats for landings. Each landing was relatively short and did not last longer than 9 hours. All field surveys were thoroughly timed and coordinated with the ship crew. An overview of field surveys follows.

Figure 40. Expedition map showing the ship’s route and main sites of field work in Franz Josef Land in summer 2008 (small-size copy)
Field surveys and validation of glacier products

5.2 Glaciological surveys in summer 2008

During the field surveys in Franz Josef Land our interest focused on three main topics:
1) measuring present heights of the glacier surface, verifying the existence of positive changes in glacier elevations and determining their spatial distribution;
2) estimating the magnitude of snow accumulation and measuring snow density at different elevations;
3) validating glacier change maps, calibrating mass balance models and explaining the causes of glacier changes.
Field surveys and validation of glacier products

5.2.1 GPS measurements of glacier heights

The present height of the glacier surface was surveyed by 3-D kinematic differential GPS profiling using two Novatel DL4 GPS C/A code receivers. One GPS receiver was set up on the ice-free shore close to sea level and used as a reference station, while the second was moved by walking along the measurement profile. The glacier elevations obtained were referred to the WGS84 geodetic datum established by continuous GPS records at the reference station. The maximum distance from the measured points to the reference station did not exceed 5 km, and the rms elevation difference checked at cross- and close-up points was ± 0.1 m. The locations of reference stations could be well observed in the field and identified in available topographic maps and spaceborne imagery. Some of the GPS measurements in the highest part of the test site at Mc.Clintock Island were lost due to technical problems. There remain written records of present elevations in that part of the glacier, yet without planimetric coordinates.

Accuracy control was performed by comparing the GPS heights with the heights given in topographic maps through several check points situated in flat ice-free areas, such as beaches and plateaus. The root mean square difference between geodetic (GPS) and cartographic heights was ± 0.7 m. 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. Our tests proved the high elevation accuracy of glacier elevation (change) models, and typical height errors were estimated as being 10 to 20 times smaller than those in standard INSAR products.

5.2.2 Accumulation measurements by ground-penetrating radar

The thickness of the annual accumulation layer on the glacier surface was surveyed using a GSSI SIR-3000 ground-penetrating radar (GPR) with a 400 MHz antenna. While the underlying principles of GPS measurements are well known to the general public, most people are not so familiar with the fundamentals of radio-echo sounding. This is why we provide some background information here explaining the essentials of GPR.

Ground-penetrating radar, also called georadar or ice radar, is an active profiling sensor that uses short, intense pulses of electromagnetic radiation in the microwave band to image the glacier subsurface and to measure the ice and/or snow thickness. GPR contains transmitting and receiving antennas, as in our case, or only one antenna alternately performing both functions. The transmitting antenna radiates high-frequency (30 to 1500 MHz) pulses of polarized radio waves into the snowpack. The receiving antenna detects radio signals reflected from the interface of two relatively thick layers in the subsurface separating two media with different electrical conductivity. Both the transmitter and receiver are generally in contact with the ground for the strongest signal strength (Fig. 42).

The depth of snowpack and/or ice layer is determined by measuring the propagation time of the radar pulse in the medium. A clock is started with pulse emission and stopped at the moment of pulse return. The slant range \( R \) to a detected subsurface can then be calculated as

\[
R = \frac{c \cdot t}{2}
\]

where \( c \) is the velocity of light in the medium, called propagation velocity, and \( t \) is the elapsed time.
The propagation velocity depends on the electrical permittivity of the medium and is determined by the next formula

\[ c_r = \frac{c_0}{\sqrt{\varepsilon_r}} \]  \hspace{1cm} (18)

where \( c_0 \) is the velocity of light in vacuum, and \( \varepsilon_r \) is the relative permittivity or dielectric constant of the medium.

The relative permittivity of the medium influences the penetration depth of GPR. The penetration depth decreases with increasing permittivity because the electromagnetic energy is more quickly dissipated into heat, causing a loss in signal strength at depth (Wikipedia 2010). The attenuation factor \( \alpha \) can be derived from the next equation

\[ \alpha = 0.5 \cdot \sigma \cdot \sqrt{\frac{\mu}{\varepsilon}} \]  \hspace{1cm} (19)

where \( \varepsilon = \varepsilon_0 \cdot \varepsilon_r \) is the absolute permittivity of the material, \( \varepsilon_0 \) is the electric constant or vacuum permittivity, \( \mu \) is the magnetic permeability [N/A²] and \( \sigma \) is the specific conductivity.
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The attenuation of the GPR signal is mainly driven by the specific conductivity $\sigma$, because of its high variability compared to the other parameters. The penetration depth of GPR is limited by the electrical conductivity of the material, the transmitted centre frequency and the radiated power. Higher frequencies do not penetrate as far as lower frequencies, but give better resolution. Liquid water represents a natural barrier for electromagnetic waves, a consequence of its electric properties, while the electrical properties of frozen water favour the propagation of electromagnetic waves. The penetration depth in ice can reach several hundred meters. Good penetration is also achieved in dry snow, sand, sandy soils etc., while in water-saturated snow, moist soils and materials with high electrical conductivity, penetration is sometimes only a few centimetres.

Apart from the medium depth, the radar pathway is also determined by the baseline length or separation between transmitter and receiver $\Delta x$, which varies between 0 (in the case of single-antenna GPR) and several meters. The "common offset" geometry with the distance between transmitting and receiving antenna kept constant is most common since it directly yields a wave-field image of the subsurface. However, the common-offset technology does not provide direct information about the GPR propagation velocity. In the case of snowpack and ice thickness measurements, the medium is rather homogeneous and the GPR propagation velocity is approximately known.

We used a very compact and user-friendly GPR with a baseline $\Delta x = 20$ cm. The left picture in Fig. 43 shows a scale-up of the antenna block (red box). The GPR was mounted on a small sled and pulled by an operator (Fig. 43). The location of the GPR profiles and specific measurement points, e.g. snow pits, was determined through concurrent GPS measurements. The total length of the GPR profiles exceeded 10 km. Two cartographic sketches showing the location of the GPR-GPS profiles at Köttitz and Mc.Clintock islands are given in Fig. 44. For the sake of comparison, Fig. 44 depicts small fragments from the glacier change map showing a strong accumulation signal at both islands in shades of blue. The location of the upper part of the GPR profile at Mc.Clintock Island could not be shown on the map because of GPS data loss.

Figure 43. GPR survey in Franz Josef Land

The air temperature in FJL was relatively high during the first week of August 2008 so that several of our colleagues were even able to take a dip in the sea. Snow melting processes...
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were in progress, yet most observed glaciers were entirely covered with snow. GPR performance under relatively warm weather conditions with air temperatures of -5°C to +3°C and a relative humidity of 80 to 90% was checked to be generally satisfactory, but not perfect.

Some problems were related to missing reflections from the subsurface in the areas of melting snow. The high water content in the 2008 accumulation horizon brought about additional difficulties in the stratigraphic analysis of earlier accumulation layers in the snowpack. Besides, we had to manage without our bulky drill for shallow ice coring, which had been lost on the way to Longyearbyen. This made the calibration and validation of GPR surveys nearly impossible. All that could be done within the tight time schedule was to dig several shallow snow pits and take direct measurements of snow depth in the pits. Based on the experience from other GPR surveys, e.g. in the Alps and in Greenland, we were nevertheless able to scale the GPR profiles using a priori knowledge.

5.2.3 Snow density measurements

In addition to the snow depth measured by GPR, the snow density is crucial for estimating the snow water equivalent (SWE) and calibrating mass balance models. Snow density measurements in the snow pits at both islands were performed using a standard densitometer. We dug one snow pit on Ice Cap No.3 (Költitz Island) and two snow pits on Simony Glacier (Mc.Clintock Island). Their location is marked in Fig. 44 by red and pink dots. The density values obtained at different glacier elevations were used for the interpretation of GPR profiles and glacier change maps. The average value of snow density for subsequent calculations was 420 kg/m³.

5.3 Analysis of results

While the results achieved during the field campaign may appear modest, they are nevertheless of considerable interest. The existence of positive glacier elevation changes was confirmed in all three areas marked in shades of blue in the glacier change map. The existence of strong accumulation on the western slope of Ice Cap No.3 at Költitz Island was proved. We had to walk waist-deep in snow with snow depths reaching 0.7 and even 1.1 meter in that part of the glacier. The area can be clearly seen in our GPR profiles (encircled in Fig. 45, File 4). For the sake of illustration, Figs. 45 and 46 represent several radargrams obtained from GPR profiling at Költitz and Mc.Clintock islands respectively. The GPR file numbers correspond to those given in Figure 44.

Figure 44. Location of GPR-GPS profiles and snow pits at Költitz (left) and Mc.Clintock (right) islands
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Figure 45. GPR profiles from Ice Cap No.3, Költitz Island

Figure 46. GPR profiles from Simony Glacier, Mc.Clintock Island
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All profiles clearly show the 2008 accumulation horizon as a black broken line in the upper part of the radargrams. An essential accumulation layer was also detected on Simony Glacier (Profiles 34 and 37). It is worth noting that we could not reach the area of maximum accumulation on this glacier because of open crevasses and decided to return back to the ship after detecting that some of our batteries were low. We went back along the same route and proved the high repeatability of GPR profiling; the latter can be verified by comparing profiles 31 and 36, 32 and 35 in Fig. 46.

The accumulation horizon derived from GPR profiles correlates well with the magnitude of snow accumulation directly observed in all snow pits and with the accumulation pattern represented in the glacier change map. Extensive regions of water-saturated snow were found up to altitudes of 200 m asl. At lower elevations the water content of snow reached 30%. The detection of multi-year firm layers was practically impossible due to the high water content in the snowpack. The average amount of accumulation varies between 30 and 60 cm of (old, wet) snow, or 125 - 250 mm in water equivalent, at an average snow density of 420 kg/m³. The FJL glacier mass balance model was adjusted and newly tested using the results of the field surveys in summer 2008. In the SMARAGD final report we concluded that the model outputs were in good agreement with the accumulation data measured in the field.

The information content, completeness and high spatial accuracy of the satellite map of glacier changes in Franz Josef Land were verified during the field work and follow-on activities. The reliability, actuality, legibility and versatility of the map were highly valued by all expedition participants including both expedition and cruise leaders, Andreas Umbreit from Terra Polaris and Andrey Chernyshev from Poseidon Arctic Voyages. Both thematic and contour versions of the map proved to be invaluable for planning and carrying out field campaigns in Franz Josef Land. The map was delivered to many scientists, teachers, administrators and politicians. New requests for a printed version of our map have recently arrived from Germany, Norway, Russia and the UK. With the kind permission of the proprietors Andreas Umbreit placed the map on the official TerraPolaris partner website http://www.franz-joseph-land.info.

It should not be forgotten that the results of the GPR-GPS surveys in FJL represent a mere snapshot of the glacioclimatic conditions in the study region. The snapshot was made under less favourable weather conditions and within tight constraints of time and cost. Some bureaucratic burdens, technical failures and a certain lack of experience in polar surveys did not allow the entire plan of surveys to be realized. Nevertheless, we are satisfied with the results because they confirm, at least partially, the correctness of our working hypotheses and encourage us to continue our research work.

The field work also left us with positive impressions of the beautiful scenery and wildlife at these “frontiers of life” that served as a good basis for the adventurous accounts of our experiences, which we shared with our younger colleagues from Austrian schools at joint workshops in Vienna and Graz. The interest and positive feedback we received from teachers and scholars regarding the SMARAGD project were a great reward for our efforts. The next chapter describes in detail this kind of communicative collaboration frequently referred to as research-education cooperation.

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70 Relatively high energy consumption by GPR represents a serious problem for extensive field surveys in the Arctic.
6. RESEARCH-EDUCATION COOPERATION

by Markus Langer

6.1 Introduction

The SMARAGD Research-Education Cooperation (REC) initiative was devoted to the critical examination of how the media present the topics of climate change and polar research. The interdisciplinary initiative was coordinated by “FORUM Umweltbildung” and realized by experts in media-pedagogy from the Vienna Media Centre, researchers from the Central Institute for Meteorology and Geodynamics “ZAMG” and teachers and pupils from two Viennese secondary schools – “BG 8” and “GRG 21”, in cooperation with the Institute of Geography, Didactics Department at the Vienna University. Researchers, media experts, teachers and pupils worked together and shared their views and experiences at different workshops. These workshops included climate change tuition, media analysis, the realisation of short films and reports on climate change and the presentation and discussion of project results. The project was accompanied by concomitant research. The results draw a picture of the pupils’ use of the media, their perception of climate change and related research fields as well as the obstacles and opportunities in the REC framework.

6.2 Objectives and conditions of SMARAGD REC

Pupils serving as media researchers

Amidst the daily deluge of media reports about climate change, a formidable degree of media competence is needed to navigate through the resulting information jungle. The SMARAGD REC initiative was thus designed to examine potential means for improving the media competence of Austrian youths on the subject of climate change. A key goal was to enable the participating children and young people to learn how to deal with the overabundant supply of information, including its complex and sometimes contradictory nature.

The project exposed the secondary school pupils to real-world issues and questions, and let them contribute as active researchers. This, in turn, permitted the youths to arrive at a personal understanding of the relevance of climate change research. In addition, the participants learned how to utilize the related media and its contents in order to support their individual goals and needs (Fig. 47). The project even gave the students an opportunity to become media makers in their own right. A special video project week was carried out and students had to deal with important questions, such as

- How is climate change presented in the news?
- What do polar researchers say about climate change?

Some pupils were called on to support diverse positions within the debate, whilst others interviewed experts as part of their own reporting on polar research and climate change. Their ideas flowed into several short films, which were later shown to, and discussed with participating polar researchers. The participation of pupils in the SMARAGD polar research

71 Similar REC transactions were established between Joanneum Research and a secondary school in Graz (http://dib.joanneum.at/bhak_klima/ - note by A.Sharov)
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project meets the wish to find ways of connecting science and the public concerning the awareness of climate change.

Figure 47. Media analysis: pupils from the BG 8 preparing their written analysis (left) and reading their texts (right)

Research needs to go public

Filing scientific results away in a dusty drawer does not further the human cause, nor is it beneficial when experts isolate themselves inside the ivory towers of academia. Instead, climate change researchers need to get closer to the public, and this requires an ability to clearly communicate the results in terms a layperson can understand. Achieving this requires improved communication competence, which in turn will ensure that information better serves the public interest.

Equally important is the need for researchers to communicate in simpler terms with decision makers. And, lastly, researchers should keep in mind that they are not infallible, as underscored by the number of inaccurate research results and the many different climate change scenarios posited. Meeting persons who are generally not directly involved in the research field, but who are influenced by its results is a valuable experience for researchers, not least for the opportunity this provides to reflect on their self-image as professionals.

Researchers learning from students

The researchers who participated in SMARAGD REC had an opportunity to examine in practical terms how the media reports on “their” topic contribute to finding answers on how to bring school pupils, as well as the general public, closer to the issues of polar research. In addition, the researchers learned how to better prepare for communicating the complex interrelationships which exist between polar and climate research to the general public – and in particular to young people.

Goals of REC

REC concerns itself with sharing scientific content and engaging diverse individuals in scientific processes which are not traditionally considered a part of the scientific field. REC’s target group includes pupils, college students or adults from the general public. The framework of the SMARAGD REC project was targeted towards teenage pupils, with the latter participants coming from two secondary schools in Vienna and one in Graz.
The main goals of REC are

• to create a dialogue between people belonging to the fields of education and science;
• to reallocate traditional roles. Pupils and educators take the roles of researchers, while the scientists learn from the pupils.

The intention is not for one group to blindly assume the perspectives of the other. Instead, a key goal of REC is that both sides learn from each other for the benefit of all involved. In this fashion, new means and approaches may be found for helping students and educators – and, ultimately, the general public – make better sense and use of climate research findings and, possibly, of scientific methods. Another key goal of REC is to break the structural barriers which separate the educational and research systems. Not only should this facilitate a more qualified choice of studies, but also a faster transfer of scientific findings to the educational system and the broader public. The picture at the right is chosen to illustrate one of the key principles of REC: scientists and pupils meet at eye level.

6.3 Challenges and opportunities within the SMARAGD REC project

REC projects do not have a long tradition in Austria. It has become clear within a short period of time, however, that these projects hold a range of merits, as well as important challenges for all stakeholders – in particular since the Austrian Ministry of Science and Research began to specifically fund REC projects.

Critical thinking and problem solving

The goals of the SMARAGD REC initiative challenged conventionally entrenched views on climate change. Pupils had the opportunity to engage themselves with the issues, and to deeply examine the impact of climate change on their lives from a critical and more informed perspective. This helped them improve their capacity for analytical thinking and problem solving, and also their ability to make well-informed choices in everyday life. Teachers, on the other hand, were challenged by the need to cultivate a safe, non-judgmental classroom environment, and to avoid simply imposing their own values and beliefs on students.

Multi-perspective approach

The interdisciplinary nature of the REC project required teachers to research and to gather information from a variety of sources. In turn, this allowed the students’ knowledge base to be appropriately scaffolded as a means of facilitating effective, individualized engagement in discussions, debates and decision-making processes. Such an approach does also create difficulties, since most teachers specialize in one particular field. In addition, a lack of time and resources can impact the extent to which teachers and students are able to examine issues from multiple perspectives. Nevertheless, a multi-disciplinary approach clearly enables students to gain a more rounded perspective.
6.4 Realisation of the REC project

Transdisciplinary research process

Within the framework of the transdisciplinary research-education cooperation initiative, the responsible project partner – FORUM Umweltbildung – contracted the Vienna Media Centre to provide an expertise in media-pedagogy, and also gained the cooperation of the Didactics Department of the University of Vienna's Institute of Geography, whose representatives served in an advisory function. Two secondary schools were involved in the project: the BG 8 Piaristen Gymnasium in Vienna’s 8th district and the GRG 21 “Bertha von Suttner” - Schulschiff in Vienna’s 21st district. Several bi- and multilateral meetings were held by the working group in order to tune the procedures prior to commencing work with the pupils. In February 2008, Christian Vielhaber from the University of Vienna hosted a joint meeting where REC procedures were discussed and the following key points were approached:

- structuring the didactical project using an action-based approach providing room for individual creativity, personality and reflectivity as well as democratic consciousness
- finding ways to overcome organisational inhibitions (lack of time, change of teachers, etc.). Christine Kroisleitner explained why a focus on polar research is so essential and also pointed out the goals of the International Polar Year.

Concomitant Research

A quantitative questionnaire survey was developed and carried out prior to the actual project work in the schools. It served to query the extent to which the pupils of the participating Viennese secondary schools were aware of climate change and polar research issues, as well as their expectations for research-education cooperation. The initial survey was carried out in February 2008. In each school, the participating SMARAGD project class and respective parallel class took part in the survey. At the end of the project, a comparative survey was carried out to determine the change in awareness among participants and pupils’ experiences within the project. In addition, four university students working in pairs supervised the GRG 21 project class during the video workshop, with their task being to evaluate the cooperation process and pupils’ participation.

Phases of the implementation process

The implementation process of the project was divided into different phases of climate change tuition / inputs from research, media collection, analysis, production and presentation (Fig. 48).

Module I: Climate change tuition; inputs from research

In order to acquire specialized knowledge about climate change and polar research as a basis for both media analysis and the production of short films, interdisciplinary tuition (instruction) was carried out in both project classes. Teachers were provided with special materials to cover the topics, and a researcher from the ZAMG carried out a workshop with pupils from the participating schools.

Module II: Focusing on media competence

The objective of Module II was to find ways and approaches for intelligibly communicating the complex findings of polar and climate research to the public – and, in particular, to pupils and other young people. The existing ways and means were examined for increasing the media competence and media literacy of youths as these relate to the topics of climate change and polar research.
Phase 1a: Collection of media material

To help deal with the overflow of complex and, at times, contradictory information, pupils were asked to collect articles on climate change and polar research from newspapers, journals, web-sites, etc., and to showcase their press clippings on a pin board in the class room. In this fashion, the topic was constantly present and discussions were facilitated.

Phase 1b: Media analysis

The objective of the media-analysis phase was to deal discerningly with the topics of climate change and polar research, and to study how these are communicated by the media. Supported by an expert from the Vienna Media Centre, the pupils investigated such questions as:

- How do the various media outlets report on global warming, climate change and changes of ice caps?
- Which aspects of climate change are predominantly communicated?
- How do the students themselves deal with the predominantly negative headlines?
- Is polar research mentioned at all in the newspapers?

Beppo Stuhl from the Vienna Media Centre oversaw the media workshop held for the BG 8 and GRG 21 students. The trainer pointed out the key fundamentals of the Austrian media landscape and the power wielded by publishers. For their part, the pupils were keenly interested in finding out how one goes about becoming a journalist. The teenagers also learned how complex the path can be that a journalist’s report must take before it reaches the reader. In addition, one-way communication and transmission errors were simulated through the use of an information chain (Fig. 49).

Furthermore, the students analysed texts. Through text analysis, they learned that the same original text from a news agency can result in reports of varying length from media outlets. Thus, the youths performed a qualitative and quantitative analysis of three news report texts dealing with polar research and climate change, with each article varying in the degree of
The film analysis session called for students to carefully examine scenes from "The Day After Tomorrow". For this task, they had to consider what content and message the film attempts to convey. In addition, a mock press conference gave the teenagers the chance to ask a fictitious polar scientist (Beppo Stuhl) about polar research. The pupils received a list with bullet points summarizing the key statements of the "expert" and were then tasked as follows:

- to determine which newspaper each questioner represented;
- to formulate questions for the press conference;
- to write a news-style headline and lead based on the expert’s answers.

In the press conference scenario, the scientist supported the thesis of abrupt climate change. He claimed to have found evidence that icebergs which had formerly made their way into our latitudes and melted had thus changed the salt content of the ocean, which in turn caused the Gulf Stream (global conveyor belt) to gradually weaken. Based on the students’ questions and ensuing texts, it was obvious that they were able to relate intelligently to the respective media.

After the press conference, the young people were asked to summarize the information in the form of a report. By learning the proper structure for news writing (first the headline and lead, then the details) as well as the six key questions (how, when, where, why, what and who), the students were able to complete their own lead for a newspaper article.

Phase 2: Video Project Week and Workshop

How is climate change presented in the news? What do polar explorers have to say about climate change? To answer these and other questions, the participating pupils were called upon to support different positions within the climate change debate. The workshop included interviews with experts in polar research and climate change, and it gave the young people a chance to write their own reports. Their ideas also flowed into several short films, which were presented to, and then discussed with, the participating polar researchers. The following aspects have been particularly considered within the workshop process:

1) The ability of all project participants to make both individual and mutual decisions. During the introductory brainstorming sessions, each participant selected a descriptive word, or words, related to their field of interest, which they then used to contribute to the overall topic. By clustering the key ideas collected during the brainstorming, the pupils were able to mutually
filter out three specific topical areas and forms of implementation. This resulted in the formation of three groups, each of which was then able to intensify its examination of the issues. It was agreed at an early stage that a vague idea alone could not serve as the basis for a concrete video project, and thus the supervisors were asked to help gently steer the pupils in the right direction. With a little food for thought, the pupils were quickly able to make progress on their own.

2). The ability of each participant to contribute his/her strengths. Be it technical acumen, eloquence as a speaker or the ability to effectively lead discussions, each pupil was able to contribute his/her unique skills.

3). Given the intensive level of social contact, it was expected that disagreement or friction could ensue. An ability to see conflicts as an opportunity, and not simply as a threat, was thus called for. The supervising students had to take action once during the film-editing phase. However, they succeeded in convincing the group that every individual has strengths and weaknesses, and that the three “troublemaking” pupils had in fact also contributed constructively to the project.

4). Interdisciplinary. The pupils investigated survey methods and developed their own questionnaires, thus establishing relevance to their political education, as well as to the subjects of German and Informatics. The pupils also created an interview handbook which served as a guide for conducting interviews.

5). Embedded in reality. A key goal was to make the pupils aware of the potential impact of climate change on their daily lives, as well as the options available to them for counteracting said impact.

6). Taking action instead of being acted upon. All pupils in the participating class were called upon to take an active part. In some instances, this meant enticing pupils to leave their passive, everyday school existence behind.

7). Projects are intended to extend the typical boundaries of schools and to open them to their broader surroundings. The pupils presented their completed projects to experts, teachers and parents alike. They gained motivation from the fact that their work was recognized by “outsiders” and that it was also taken seriously by the experts.

8). Pupils should assume competences and responsibility. The pupils decided entirely on their own which images to use as film insert. They organized themselves within the various groups; and they independently conducted all interviews. In addition, one pupil per group was responsible for the technical equipment.

9). Teachers need to recede to the background and hand over leadership functions to the pupils step-by-step. In the words of a student-tutor: “Initially, we left it entirely open how the project should proceed. However, after the pupils had introduced their initial ideas, we did need to interject a bit of guidance to help steer them towards a visible structure and course of proceedings for the project week.”

Video project week at the Piaristen Gymnasium

Upper-level pupils (Class 7) of the Piaristen Gymnasium took part in the video project from June 16-20, 2008. The young people produced short films on climate change and polar research, for which they were called upon to support different positions in order to report about the topics from various perspectives. The first day of the project week started with an introduction which placed the video project in context with the SMARAGD Research-Education Cooperation project. In parallel, the practical portion was initiated. Working in smaller groups, the students became acquainted with cameras and learned about the various camera
angles/perspectives, such as wide-angle, close-up, birds-eye view, etc. Once back in the large group, the participants received a brief overview on how to produce a video film. A brainstorming session was held to discuss the different genres and formats: fictional film, documentary, feature film, etc. The group answered such questions as: What genres do we like to watch and why? In what genre/format have we already encountered the topics of polar research and climate change? This was followed by a brief comparison of documentary- and fictional-style cinematic works. The first day closed with another brainstorming session to determine what type of video on polar research and climate change the pupils wished to produce, upon which the pupils were divided into the corresponding groups.

On the second day the pupils finalized their ideas, worked out a short script and storyboard, and began shooting their films. Shooting continued on day three, whilst day four was reserved for editing and day five for putting on the finishing touches (Fig. 50).

**Video project week at the Schulschiff**

The video project week at the GRG 21 Schulschiff took place from September 15-18, 2008. On Monday, September 15, all persons involved – pupils and teachers, supervisors from the Vienna Media Centre, tutors from the University of Vienna’s Institute of Geography, and representatives of the FORUM Umweltbildung – met at the school for a mutual introduction. The pupils were divided into two groups for receiving camera instruction. One supervisor and two university-student tutors were assigned to each group. After the technical instruction, the pupils began a brainstorming session.

Initially, the participants were a bit reserved; nevertheless, within only half an hour some very good ideas had already been collected and written on the blackboard. The pupils’ ideas were subsequently clustered, which helped lead to the decision to produce three different types of films. The participants thus decided to form three working groups instead of four, which ultimately resulted in three groups of six pupils each. On Tuesday and Wednesday, September 16-17, the groups independently shot their respective documentary or fictional film. On Thursday and Friday, September 18-19, the students edited their films in the premises of the Vienna Media Centre. To conclude the week, each group presented its short film to the other two groups.

![Figure 50. Video Project Week: pupils from the Piaristen Gymnasium shooting their videos (left); preparation and revision of the videos (right)](image)

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Research-Education Cooperation

Phase 3: Presentation of results and discussion with scientists

On October 9, 2008, all participants in the SMARAGD Research-Education Cooperation project gathered in the University of Vienna’s Institute of Geography for the final presentation of results. After a formal greeting by the host (Christian Vielhaber, Institute of Geography), Wolfgang Schöner and Christine Kroisleitner (both from ZAMG) spoke about interesting link-ups which exist between the research community and schools, as well as the resulting opportunities for mutual learning. Then Hannes Heller (Vienna Media Centre) briefly introduced the short films which the pupils had made, as well as the young filmmakers themselves. After a few words by the pupils the following student films were shown to the audience:

1) Climate (Change)? (Technique: interviews on how teachers ought to be).
2) The Earth is Burning … and Humans Are Driving Onward (Technique: interview and newspaper clippings; professional interviews).
3) Coming Ever Closer … Climate Change (Technique: documentary).
4) Vienna News Flash (Technique: re-enactment of a news program followed by a commercial; global themes).
5) Some Like it Cold (Technique: sequence of several short films).

A discussion followed the showing of the last film. Aleksey Sharov (Institute of Digital Image Processing at Joanneum Research) was pleasantly surprised by the originality and diversity of the pupils’ films, not to mention the quality of research which went into them. The fact that the students did not require a prefabricated world view in order to present their ideas, but instead showed themselves capable of producing independent knowledge, impressed all project participants.

6.5 Results of Pupil Survey Questionnaires

In addition to the workshop products, an important result of the project is the learning process regarding the pupils’ perception of climate change and polar research. At the beginning and at the end of the project, the pupils from two project classes at the Viennese secondary schools – BG 8 “Piaristen Gymnasium” (11th grade) and GRG 21 “Bertha von Suttner – Schulschiff” (10th grade) – were asked a number of questions related to climate change and media use in the form of a combined quantitative questionnaire. The questionnaire served to query the pupils’ awareness and to evaluate the realization of the project. Furthermore it gave the students an opportunity to anonymously input their appraisals of climate change, and to indicate their expectations and how they experienced the project including their personal opinions and perceptions, as well as their fears, wishes and improvement suggestions. The main tendencies of pupils’ opinions on some key questions estimated through a comparison between the initial and final survey are summarized in the following.

What sources do pupils use to draw information about climate change and, in their opinion, how high is the information content of each source?

At the start of the project, the Internet, television and radio were all deemed to be media with a very high information content – first and foremost the Internet, chosen by over 50%. In the final survey, however, the Internet was so classified by less than 20% of the youths. Also radio and television lost ground regarding their information content. Conversely, journals ranked low in the initial survey, but the pupils regarded them as the media with the most informative climate change content in the final survey, followed by television and the Internet. To obtain well-
grounded information about climate change, young people learned that scientific journals are the most adequate media to rely on. Opinions of lectures varied; on average, however, the pupils judged lectures as providing a moderate level of information content (Fig. 51, a).

**How intensively is the topic of climate change dealt with in various subjects taught at school?**

The pupils were asked to judge how intensively they dealt with the topic of climate change in specific school subjects. The survey results clearly show that most pupils felt they dealt with the topic of climate change either not at all, much too little or too little in virtually all subjects, with the exception of Geography and Economics. Though many pupils deemed their exposure to climate change in Geography and Economics as intensive, some students felt that even these two subjects dealt with the topic too little or much too little. Ultimately, the results imply that the questioned youths would find it appropriate to deal more intensively with climate change in other subjects. In the final survey the treatment of the topic of climate change remains insufficient in the subjects Physics, Chemistry and German, regarding the perception of the pupils, while the topic gained weight in the class of Biology (Fig. 51, b).

![Figure 51. Results of survey on media with very high information content (a) and on climate change in school subjects (b)](image)

**With which key groups of persons, and how frequently, did pupils converse about climate change?**

The youths were asked to indicate with which groups of persons they had conversed about climate change during the previous two weeks and how often this was the case within the timeframe. Of the three key groups of persons, the pupils most frequently conversed about climate change with their teachers – both at the start of the project and upon its completion. This result shows that teachers are the most important reference group for the youths compared to family and peers to talk with about climate change. Also significant is that in the final survey, no pupil answered that he/she had never spoken about the topic with teachers during the previous two weeks. In other words, climate change was discussed with at least one teacher once or more during this timeframe. It is notable that in comparison to the conversations in school the youngsters rarely talk about climate change within their peer-group and within their family. In the students' estimation, the frequency of conversations remained similar in the final survey (Fig. 52, a).
Research-Education Cooperation

Attitudes regarding the financing of research projects

The students were asked about the level of financing they would allocate over the coming years to research projects on diverse research topics of climate change, assuming they had the opportunity to make this decision. Specifically, the following research topics were offered:

- global climate change, sea level rise and implications for European coastal areas,
- climate change effects on global agriculture and nutrition,
- impact of global warming on human health,
- connection between climate change and natural catastrophes in Austria,
- implications of climate change for ski tourism in Austria,
- climate change impact on biodiversity,
- investigating changes in polar ice caps.

The pupils indicated awareness for various negative implications of climate change, frequently perceiving climate change as a threat to natural habitats and to the extinction of diverse animal and plant species. A strong awareness for natural catastrophes, as well as the melting of glaciers and ice caps, was also noted among the youths. Both surveys demonstrated that pupils tend to emphasize projects that focus on global phenomena, rather than national problems (Fig. 52, b). The impact of climate change on natural occurrences in Austria was dealt with low to moderate financing. Some students felt that Austria is not affected at all, or only to a small degree, by climate change.

Which activities of the SMARAGD Research-Education Cooperation project were able to raise the most interest among the youths in the topics of climate change and polar research?

The pupils' responses indicate that discussing every-day topics, such as living in a more environmentally conscious way or the proper separation of household waste was of particular interest to them, as was the experience of encountering the participating researchers and learning about their research fields. The project classes had a hands-on opportunity to learn about film media and found this an especially inspiring way of dealing with the topic of climate change and its consequences. The students indicated that the ability to independently seek out information and to form and contribute individual opinions were other factors motivating them to take a keener interest in the topic of climate change. Pupils particularly appreciated the personal contact and cooperation with the researchers and the possibility to get a deep insight into their research fields, as well as their active involvement as media researchers within the project.

Figure 52. Results of survey on conversations about climate change (a) and on financing research projects (b)
What wishes did pupils express with regard to future topics and projects?

The pupils have mentioned the following as desirable topics for future REC projects:

- aid to developing countries, especially to children,
- the future of the Marchfeld basin,
- global economic crisis,
- extinction of animal species, animal testing,
- changes to expect in our daily lives as a result of climate change and human rights.

Suggestions and wishes for improvement of further RECs

Overall, the students expressed a high degree of satisfaction with the project and how it was carried out. They suggested additional support from researchers, whilst some pupils desired more information about filmmaking. In general, the pupils requested more time to be dedicated to such projects in the classroom. Concerning the realisation of the project the pupils were generally very satisfied and they request the possibility to participate in future research-education cooperation.

RÉSUMÉ

by Aleksey I. Sharov

The SMARAGD research project was completed in 2009. The research objectives and targets formulated at the outset of the project have been achieved. Now it is time to celebrate all that has been achieved over 2 years of research with a relatively low budget of approx. 150,000 €. Publication of this booklet marks fulfilment of our final and remaining duty as specified in our research plan for the 4th IPY (2007-2009).

The overall goal of the research project was to use satellite EO, ground-truth and cartographic data to generate and validate a new series of satellite data products, glacier change maps and mass balance estimates describing the present state and fluctuations of land ice resources in the main glacier areas of the Barents-Kara region and explaining how glaciers respond to climatic variations and endogenic forcing. This goal is deemed to have been reached. A new dual-sensor technique for joint geometric processing of satellite interferometry and altimetry data obtained via active imaging and profiling sensors was designed, tested and applied to determine present glacier dimensions and map glacier elevation, volume and mass balance changes over morphologically and dynamically varying masses of land ice with total areas ranging from tens to thousands of square kilometres.

In the past, geodetic mass balance measurements were carried out using airborne photography and laser scanning, but such measurements did not become fully operational, mainly due to economic constraints. The synergetic combination of differential interferometry and altimetry addressed in this booklet proved to be an economically efficient and highly informative remote sensing method for modelling glacier topography and geodetic measurements of mass balance on both large and medium-size ice caps. We systematically applied this technique to overall glacier change mapping in all archipelagos of the study region and obtained consistent spatially distributed information on glacier variations for the period ranging from the 1950s to the present day. A sufficiently large statistical sample of glacier fluctuations at regional scale was thus obtained for the first time in the history of remote sensing studies in that region.
In the 1950s, the total glacier area of separate islands and archipelagos of the Barents and Kara seas exceeded 92,600 km². The overall glacier volume was 22,400 km³ and the average ice thickness was 242 m. Our remote sensing studies and mass balance estimates using spaceborne ERS radar interferometric mosaics, ICESat altimetry transects, Russian topographic maps and ground-truth data revealed that, by the 2000s, the areal extent and volume of Barents–Kara glaciation have decreased by 1,700 ± 200 km² and 980 ± 20 km³ respectively. The present total area of remaining glaciation amounts to 90,900 km² and the overall volume does not exceed 21,450 km³. The average ice thickness fell to 236 m. The annual loss of land ice due to severe climate change in longitudinal direction was determined at approx. 8.8 km³/a in Svalbard, 4.3 km³/a in Franz Josef Land, 4.0 km³/a in Novaya Zemlya, and more than 4.5 km³/a in Severnaya Zemlya over the past 50 years.

The results obtained clearly demonstrate that glaciers and ice caps in the Barents-Kara region are currently in the regressive stage. The resultant values of glacier changes correlate well with previous estimations made by other investigators 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 has not changed significantly in Svalbard. The largest negative elevation changes were typically detected in the seaward basins of fast-flowing outlet glaciers, both at their fronts and tops. Ablation processes were more marked 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. This finding indicates that at glacier tops the relation between accumulation and ablation has been influenced rather by direct insolation than by the greenhouse effect.

It is of course not surprising to find that glaciers retreat in times of global warming. However, it was surprising to detect that some glaciers are growing under current climatic conditions. Essential positive elevation changes ranging from 35 to 70 m were found on several insular ice caps in Svalbard, Franz Josef Land and Severnaya Zemlya. Clear positive changes of +15 to +50 m were also registered on several insular ice caps with elevations higher than 300 m at Kvitoya, Schmidt and Ushakova islands. Most of the thickening ice caps are slow moving and terminate on land or in shallow waters. The sides of these glaciers have steepened and we presume that their net mass balance has remained positive during the past 50 years. In many places, growing insular ice caps are found adjacent to permanent coastal polynyas.

The largest positive elevation changes of +75 to +110 m alternating with areas of negative changes up to -50 m were registered in the upper part of the Northern Glacial Complex on Novaya Zemlya. The strongest accumulation signal exceeding 150 m was detected at the top of the Northern Ice Cap in northern Novaya Zemlya. This is surprising since this large ice cap is drained by several large and fast tidewater outlets, such as Inostrantseva, Pavlova, Vera, Bunge and Petersen glaciers. The measurements revealed that some outlet glaciers in the study region have decelerated. Positive elevation changes detected in lower parts of several outlet glaciers in Franz Josef Land, Novaya Zemlya and Severnaya Zemlya may be related to ice flow and surge events. A distinct accumulation signal was observed on several valley glaciers in the Byrranga Mountains on the Eurasian Continent, the easternmost part of the study region (Fig 1, a).

In total, essential surface rising was detected on 15 large and medium-size glaciers and ice caps and we concluded that these elevation changes are caused by real environmental processes and not by measurement errors. Our remote sensing observations were consistent with the results of our GPR surveys and repeated field measurements of snow accumulation previously performed at the tops of ice caps by other scientists. The vertical accuracy of glacier change models was proved to be ± 0.4 m/a rms based on field surveys on several
Résumé & Acknowledgements

small and large ice caps. It is worth noting that the accumulation signal in the topographically homogeneous upper parts of large and medium-size ice caps could not be detected by other (e.g. stereoscopic imaging) EO sensors because of their insufficient sensitivity to vertical changes in low-contrast objects. This is why the geodetic method of mass balance measurements based on the precise determination of glacier volume changes by differencing stereophotogrammetric maps or elevation models of the glacier surface topography from different years was infrequently used in satellite-based models. Probably this is the reason for the paucity of scientific reports on growing glaciers and the lack of a thorough explanation for such behaviour of land ice masses.

At sub-regional scale the horizontal distribution of glacier changes was not uniform and correlated astonishingly well with the geopotential field shown on existing gravity anomaly maps of the Arctic. 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. Hence we presume that significant lateral geopotential variations may influence the local intensity of solid precipitation, snow accumulation and glacier regime in the High Arctic. A high positive ($\geq +0.91$) spatial correlation between local extremities in glacier change signal, sea ice concentration and gravity anomalies was determined, mapped, hypothetically explained and analytically formulated using the basic concepts of hydrostatic stress, converging precipitation and external potential.

A basic set of simple differential equations describing glacioclimatic conditions in the heterogeneous field of gravity was compiled and critically compared with relevant knowledge obtained by other investigators. As a result, a new working hypothesis on gravity driven fluctuations in the long-term regime of ice and snow resources was devised and presented. Initial numerical simulations, statistical analyses of meteorological and tidal data series, error balance estimates and specific glaciological surveys in 2001, 2006 and 2008 demonstrated major spatiotemporal singularities, methodological advantages and better feasibility of the proposed hypothesis compared to similar empirical-theoretical concepts developed by astro-meteorologists.

A new series of satellite image maps representing glacier changes and cryogravic dependencies in the Barents-Kara region at scales ranging from 1:50,000 to 1.5,000,000 were composed, printed and verified as part of our field research and in joint discussions with other scientists. If you are interested in further details of our research or wish to obtain digital copies of our maps, please visit the project website at http://db.joanneum.at/smaragd (cd results) or the main website at http://db.joanneum.at/integral.

The key results of the SMARAGD project were presented at several conferences, published in 9 scientific papers and disseminated to teachers and pupils at Austrian schools (Fig. 53). A more detailed interpretation of glacier changes must yet be performed to gain a thorough understanding of all driving forces contributing to the current land and sea ice regime in the Arctic in general and in the Barents-Kara region in particular. The research work will be continued. New remote sensing data to be obtained from GOCE and CryoSat-2 satellites may make an essential contribution to the verification of several conjectural hypotheses, the improvement of possible interpretation errors and to a better prediction of fluctuations in snow and ice resources in the Arctic. We look forward to receiving both favourable and critical responses to the ideas presented in this booklet from people working on theoretical problems of glacier behaviour in a changing climate. Finally, I would like to conclude with a thought-provoking quotation, which would be equally well-placed at the beginning of the booklet: “Although glacier variations have been observed for more than four centuries, no quantitative theory linking glacier variations to climatic changes emerged…” (Schytt 1966).
ACKNOWLEDGEMENTS

The study was carried out under Contract No. GZ 37.541/1-II/4/2007 financed by the Austrian Ministry for Science and Research (BMWF). ERS-1/2 SAR data were provided by ESA through C1P.2611 SIGMA, AOP.3582 INTERSTEREO, AOP.4085 POLARIS and AOP.4272 GAIN projects. ICESat altimetry data were made available by NSIDC. The field research carried out in Franz Josef Land in August 2008 would not have been possible without the financial support received from the Austrian Academy of Sciences. As well as the authors, several other people played a decisive role in compiling and completing this booklet.

We are deeply indebted to Dr. Christian Smoliner, Dr. Celine Loibl and Doris Zabsky (all BMWF), Prof. Mathias Schardt, Dr. Roswitha Katter and Elmar Veitmeier (all Joanneum Research), Profs. Reinhard Böhm and Ingeborg Auer (both ZAMG) for their guidance and support, generously given to us in their capacities as programme leaders, scientific officers, project advisers and administrators. Our sincere gratitude also goes to Dmitry Nikolskiy (MIIGAiK), Roland Wack and Paco Lechner (Joanneum Research), Beata Weninger (Karl-Franzens University in Graz), and Barbara Höller (FORUM Umweltbildung) who were not mentioned as authors of this volume, but who contributed much to data processing, glacier mapping, field surveys and research-education cooperation within the framework of the SMARAGD project.

Prof. Tamara Vereshchaka from the Moscow State University of Geodesy and Cartography assisted us greatly in providing Russian topographic and thematic maps. Drs. Hannes Raggam and Karl-Heinz Gutjahr from Joanneum Research are warmly thanked for all the valuable technical consultations given on SAR and altimetry data processing with the RSG software. We were especially impressed by and grateful for the hospitality and assistance rendered by the entire crew of the “Polaris” vessel and its expedition leader Andreas Umbreit before, during and after the field survey in 2008. The final, but most heartfelt thanks go to all members of our institutions, friends and relatives for their detailed comments, critical remarks, insight, congeniality and encouragement that have all been of such great value to us.
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