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Studying changes of ice coasts in the European Arctic

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Abstract The present extent of European ice coasts, their spatial changes in the past 50 years and the velocities of ice flow in marginal parts of tidewater glaciers were determined and mapped at a regional scale using spaceborne image data, both optical and radar. The methods of satellite photogrammetry and radar interferometry provided efficient solutions to the integral estimation of ice-coast dynamics in the Franz Josef Land, Novaya Zemlya and Svalbard archipelagos. Studies revealed significant degradation of the ice coasts (−7.7% by length) compared to the situation represented in the available maps. The results obtained in the laboratory were verified during several field campaigns.

Introduction

Ice coasts, i.e. coasts formed by glaciers extending into the sea, are predominant in Antarctica, well developed in Greenland and relatively rare in the Old World. There are no glaciers entering the sea at present on the Eurasian continent and people wishing to see European ice coasts must travel to the high-latitudinal arctic archipelagos of Franz Josef Land, Svalbard or Novaya Zemlya, where tidewater glaciers form a distinct coastal category (Fig. 1). The present total length of the glaciered coastlines in the Eurasian Arctic can be approximately estimated at 4,100 km (Table 1), which accounts for about 4% of the Eurasian coastline.

Despite their geographic isolation and relatively low socio-economic significance, arctic ice coasts have recently been receiving closer scientific attention since their dynamic environment and interesting natural scenery is proving highly sensitive to climatic changes (Koryakin 1988; Hanson and Hooke 2000). Seaward ice cliffs rising 2–50 m and sometimes even 100 m above sea level stand at the forefront of glaciomarine interactions and represent a unique object for comprehensive environmental research at the "cutting edge" of several scientific disciplines such as oceanography, glaciology and coastal geomorphology. Paleogeographers consider the present glaciomarine settings along ice cliffs as being analogous to those in the Ice Age and find them useful for retrospective reconstructions (Korsun and Hald 1998).

Glacier ice is destroyed relatively fast, even in cold water, and ice shores are thus among the most varied elements of the arctic coastline. Global climatic warming, current glacier retreat and the eustatic rise of the sea level lead to rapid degradation of the Eurasian ice shores, which can be referred to as an endangered type of coastal morphology. Our recent cartometric estimations showed that the total length of Eurasian ice coasts was reduced by nearly 7% in the past 50 years (Table 1). Rapid glacial retreat reveals new, as yet uncharted islands, bays and capes formerly covered by glacier ice, which brings about additional interest for surveyors. The directed character of variations in the physical characteristics of ice coasts can serve as an important and reactive indicator of present environmental trends in the Arctic, which responds quickly to climatic changes and might help in forecasting the short-term consequences of those changes with a high degree of predictability.

Studying the dynamics of ice shores presents a special problem since their changes are controlled to a very great extent by glacier motion and calving of icebergs. For many tidewater glaciers the strain rate, the ice velocity and the ice flux attain their maximum at the glacier front thus intensifying the coastal evolution. The acceleration of ice flow towards the front of tidewater glaciers is typical for both warm and cold seasons and ice cliffs remain "active" throughout the year. The

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Fig. 1 Ice coast at the front of Vera Glacier, northern Novaya Zemlya

formation of icebergs and the intensive inflow of melt water affect the circulation and surface salinity of coastal waters with the consequential impacts on the thickness and extent of sea ice thus incurring and amplifying further hydrographic changes. In addition, some other geophysical agents act simultaneously along the ice shoreline and shape glacier faces, namely meteorological effects, waves, currents and tides as well as glacial deposition. Relationships between all these counteractive factors vary from place to place through time following natural cycles and occasional events. This makes the estimation of the relative intensity of glaciomarine interactions technically difficult.

The noticeable lack of reliable knowledge on environmental high-latitudinal processes and their impact on ice coasts requires complex studies comprising different types of ice coasts, extents and periods. The dynamic system, the remoteness from economically developed regions and the harsh environment impeding both aerial surveying and extensive fieldwork are the principal causes for applying methods of satellite remote sensing to studying changes of ice coasts in the Arctic.

The present paper discusses the use of space-borne image data obtained from automatic polar-orbiting satellites, both optical and radar, for the reliable analysis and mapping of ice-coast changes in the European Arctic. The method of satellite radar interferometry (INSAR) using synthetic-aperture radar (SAR) data from the ERS-1/2 satellites has been successfully applied to the unsupervised detection of coastal changes and to the evaluation of frontal glacier velocities and calving fluxes, while the high-resolution multi-spectral data obtained from LANDSAT-7 and ASTER were used for measuring ice-coast changes in linear, areal and volumetric terms by means of comparison with available topographic maps and hydrographic charts.

The study region comprises the Svalbard, Franz Josef Land and Novaya Zemlya archipelagos, Jan Mayen and Ushakova islands exemplifying different types of ice coasts. Factual knowledge about the regional and seasonal specifics of glacial dynamics and coastal changes in the study region is very limited and integral estimations at a regional level are few in number. One of the first attempts to investigate spatial variations of ice coasts in the Eurasian Arctic was undertaken in the 1960s by the Russian scientists L. Govorukha and P. Mikhalenko, who examined data from multi-temporal topographic surveys. V. Koryakin compared available topographic maps issued in the 1950s with LANDSAT imagery of the 1970s and published a short albeit comprehensive book about glacial flow and changes of ice coastlines in the whole Arctic (Koryakin 1988). Recent studies of coastal dynamics on Svalbard and northern Novaya Zemlya using high-resolution CORONA-KH4A optical images, ScanSAR scenes obtained from the Canadian RADARSAT satellite as well as ERS-1/2 SAR and INSAR data were reported in Lefauconnier et al. (1993), Weydahl (2001), Zeeberg and Forman (2001), and Sharov et al. (2003).

Fragmented and temporally rather limited previous observations do not, however, permit the total amount, general character and rates of ice-coast changes in the European Arctic to be assessed reliably. Data heterogeneity, variations in method and the different principles applied by different investigators to the interpretation and categorization of glaciated shores in space-borne images make the comparative analysis of the available knowledge of coastal dynamics in the study region difficult.

Classification of ice coasts

A detailed comprehensive classification of ice coasts does not exist, as yet. Some information on different types of glaciated coasts and approaches to their classification considering the coastal morphology, the configuration of the glacier bed and the rate of ice influx, thermal state and buoyancy, etc. can be found in Grosswald et al. (1973) and Wilhelm (1975). Three basic types of ice coasts can be distinguished, depending on the position of the glacier face with respect to sea level and sea bottom: ice cliff, ice wall and ice front. Longitudinal profiles of ice coasts typical of the European

Table 1 Length (km) of Euroasian ice coasts in the 1950s and 2000s

Period/region	Franz Josef Land and Victory Island	Svalbard and Kvitøya Island	Severnaya Zemlya	Novaya Zemlya	Ushakova, De Long, Jan Mayen islands
1950-s	2,661	1,050.7	500.8	208.4	85
2000-s	2,522 (−5.2%)	903 (−14.0%)	490 (−2.2%)	192 (−7.9%)	82 (−3.5%)

Arctic are shown in Fig. 2. Coasts composed of permafrost and ground (fossil) ice, such as tundra cliffs are not considered.

In contrast to ice cliffs, which form at the slowly 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 for which the frontal velocity of ice flow exceeds the velocity of marine abrasion. Ice walls and fronts produce icebergs (Fig. 2b, c) and undergo large spatial changes amounting to several hundred meters across the shore each year. Hence, evidence of coastal changes or stability can also be used to categorize ice coasts. In the present paper, a simplified approach to the classification of ice coasts based on the observed gain or loss of ice, i.e. advance or recession of the coastline, is offered. In accordance with this principle, all ice coasts are divided into four large groups:

– Stable ice coasts
– Retreating ice coasts
– Advancing and surging ice coasts
– Ice coasts with uncertain/unknown dynamics Such a classification system is morphologically neutral and does not require special thematic, e.g. bathymetric studies. It necessitates substantial knowledge of coastal evolution and marginal velocities of glacial flow, however, which can be gained from remote sensing studies comprising relatively short periods (from several days to several months) of observation.

Representation of ice coasts in space-borne optical and radar images

The large terrestrial coverage and homogeneity of image data obtained from polar orbiting satellites, the high repetition interval of space-borne surveys and the low data price per square kilometer makes remotely sensed data an ideal tool for monitoring and mapping the arctic coastline. In the warm season, ice borders on both dry land and water are more easily detectable in space-borne optical imagery due to the reduction of backscattering from wet snow and bare ice and the low contrast of marginal glacial areas in summer radar images. Coastlines free of glacier ice are reproduced with better contrast in radar imagery, if the surrounding water surface is smooth. A marked difference is visible, especially in the recognition of small islands, rocks and drying lands. Heavy seas drastically reduce the interpretability of microwave data of coastlines.

In the cold season, the fast sea ice attached to the ice shore and covered with snow poses considerable problems to the recognition of ice coastlines using optical data. Radar images usually depict glaciers and sea-ice floes with more gradations and structural detail than optical imagery. In winter, high-resolution images of polar regions can only be obtained with active SAR systems. Elements of coastal relief such as ice cliffs, large crevasses, moraines, escarpments, valleys, coastal planes and separate rocks are usually distinguishable in winter SAR images, thus supporting the reliable delineation of coastlines. Clouds and fog masking coastal details in optical images have no direct influence on the representation of ice coasts in radar images (Sharov 1997).

In space-borne optical images and amplitude radar scenes, the different types of ice coasts appear very similar, rendering their interpretation in single pictures difficult (Fig. 3a, b). In multi-temporal data sets, spatial changes of ice shores can be detected, measured and used in the simplified classification scheme offered by the author. The spatial resolution of modern LANDSAT–7 ETM + (30 m) and ASTER-Terra (15 m) space-borne optical sensors is comparable with that of SAR systems on board the European ERS-1/2 and Canadian RADARSAT satellites and is sufficient for detecting and measuring significant seasonal or annual changes in the configuration of ice coastlines ranging from several hundred meters to kilometers. Even if obtained with a time interval of approximately 1 year, such imagery is still insufficient for detecting spatial changes in the frontier parts of relatively slow-moving glaciers with a mean velocity of less than 100 m/year or 30 cm/day.

Interferometric analysis of space-borne coherent SAR scenes taken from two neighboring orbital points by the same or identical radar systems at a rather short time interval (one to several days) has recently proved to be a powerful tool for detecting and measuring quite small coastal changes and motions in the centimeter and even sub-centimeter range. The INSAR method is based on the generation of an interferogram, a specific "striped picture", by combining two coherent radar images, which contain amplitude and phase information of radio signals reflected from the Earth's surface (Fig. 3d). Each fringe in the resultant interferogram corresponds to a certain phase difference between radio signals, which in its turn depends on the relief of terrain and on physical changes of the surface, e.g. its displacement between the SAR data acquisitions (Sharov et al. 2003). The basic principles of INSAR can be found in other comprehensive publications (e.g. Bamler and Hartl 1998;

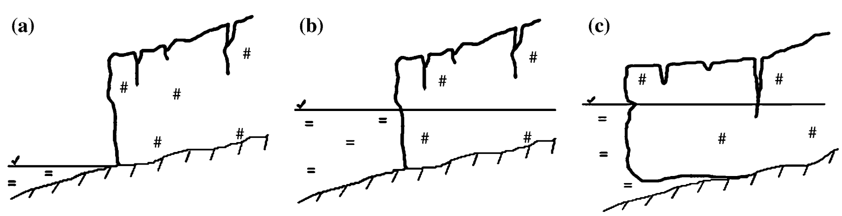


Fig. 2 Different types of ice coasts (not to scale): ice cliff (**a**), ice wall (**b**), ice front (floating glacier tongue, **c**)

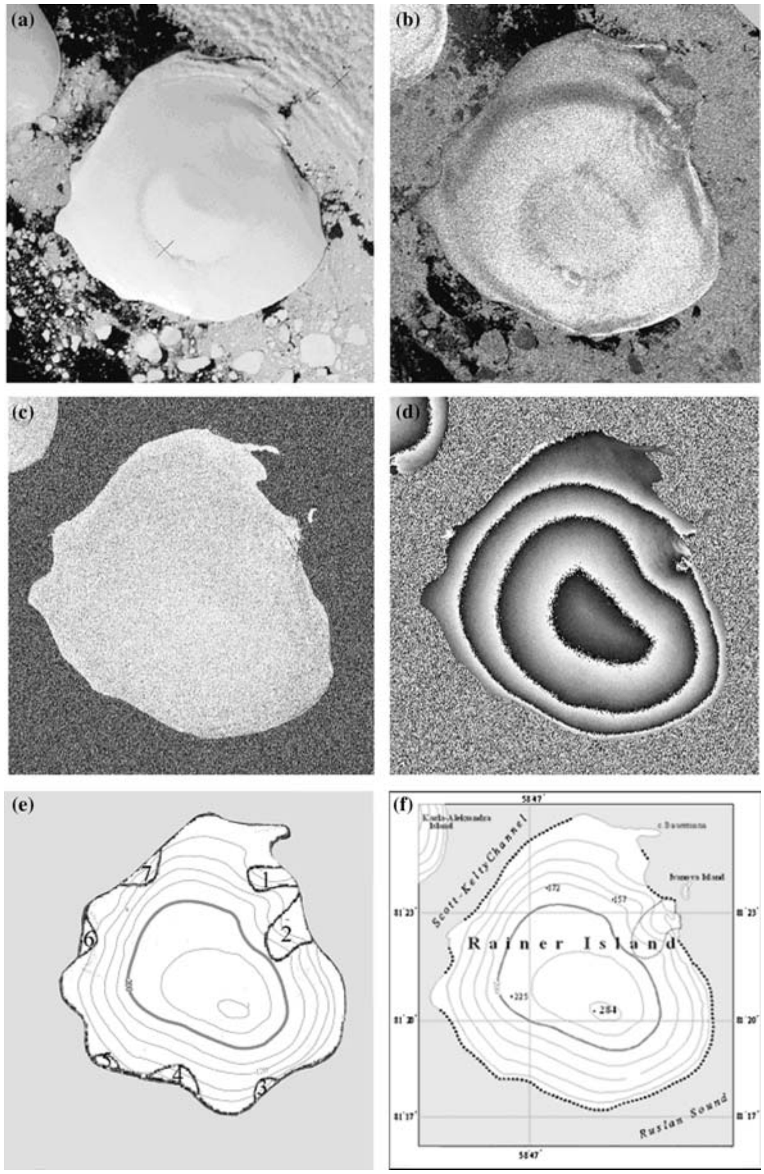


Fig. 3 Fragments from optical (**a**) and radar (**b–d**) images, and available maps (**e, f**) showing Rainer Island, Franz Josef Land

Hanssen 2001) and are thus excluded from consideration in the present paper.

For the sake of illustration, Fig. 3 shows Rainer Island situated in the Franz Josef Land archipelago, Russian High Arctic, which is entirely covered by the large Vostok-2 Ice Dome as represented in an optical KATE-200 image (a), an ERS-1-SAR amplitude image (b), ERS-1/2-INSAR coherence (c) and fringe (d) images, a Russian topographic map (1971, f) and a thematic Glacier Inventory map (1965, e). The automatic delineation of ice coasts in space-borne optical and amplitude radar images (Fig. 3a, b), both taken on 28 August 1993, is complicated due to the presence of clouds in the upper-right part of the optical scene and speckle noise and low contrast between the glacier and sea ice floes in the upper-left part of the SAR scene. In the INSAR coherence image of 08/09 October 1995, all objects that underwent essential physical changes during the time interval between the two SAR surveys, e.g. the sea surface, are shown by dark-grey values and the shorelines even of small islets, e.g. Ivanova Island (on the right), are easily distinguished.

An older thematic map from the Inventory of Glaciers in the Franz Josef Land archipelago (Vinogradov and Psaryova 1965) shows seven separate glacial tracts in the marginal part of the ice dome, which were incorrectly interpreted as outlet glaciers in single aerial photographs taken in the 1950s. The shape of interferometric fringes in the SAR interferogram of 08/09 October 1995 (Fig. 3d) shows that only one (Glacier No. 2 at mid-right) of those areas can be considered to be a mobile outlet glacier. Therefore, INSAR data can be successfully applied to measuring areas draining ice into each outlet glacier (ice sheds), to reliable modelling of the ice flux towards the sea and the calving flux, and to detecting and forecasting changes in the configuration of ice coasts at both local and regional scales.

In space-borne SAR interferograms, the sea ice attached to the ice shore and floating parts of glacier tongues are shown by particular "motion fringes" corresponding to swaying (tidal) motions of the ice surface and can thus be reliably detected. The ice-free and glaciated tracts of the coastline and the inland borders of outlet glaciers can be precisely delineated even if the terrain is snow covered. Frontal velocities of tidewater glaciers can be measured from single SAR interferograms by analyzing the displacement of the fast sea ice pushed away from the shore by moving glacier front. These unprecedented technical capabilities and the notable availability of space-borne interferometric data in arctic regions are greatly valued by experts studying the dynamics of tidewater glaciers and ice coasts (Sharov et al. 2002).

Most ice coasts in the High Arctic are precipitous. In satellite images, the position of the upper crest of the glacier slab is generally displaced inward or outward with respect to the nadir (sub-satellite track) depending on the type of image data and the location of the ice face. Image distortion of this kind is referred to as relief displacement. The displacement D of an image point along the scan line due to the relief Δh can be approximately calculated as

$$\begin{aligned} D &\cong +\frac{\Delta h}{\tan\theta} \quad \text{for SAR and INSAR scenes;} \\ D &\cong -\Delta h \cdot \tan\theta \quad \text{for optical scenes,} \end{aligned} \tag{1}$$

where θ is the viewing angle. Positive or negative values of D imply the direction of displacement towards or away from the sub-satellite track, respectively.

In satellite remote sensing, the typical value of the viewing angle θ is relatively small (several degrees) and the relief displacement in space-borne optical imagery is usually neglected. In space-borne SAR scenes, the relief displacement is commonly 10–20 times larger than in optical images and the corresponding distortion may reach several hundred meters. For example, in the ERS-1/2-SAR scene with a mean look angle $\theta = 23°$, the upper crest of an ice cliff with a height of 80 m above the sea level will be shifted towards the sub-satellite track by 200 m with respect to the true position. Such errors cannot be neglected and special geometric corrections requiring some reference data on the height of the ice shores must be made in order to provide accurate coastal determinations with radar imagery.

The use of space-borne stereoscopic photographs, such as those obtained by KATE-200, KFA-1000 and MK-4 film cameras from the Russian "Resource F1/F2" satellites, for measuring the height of ice cliffs and walls is expedient in this respect. The interpretation of coastal topography and the marginal zones of the glacier surface in space-borne photographs have been considered previously in Sharov (1997).

The precipitous character of ice coasts ensures a negligible range of variations in the horizontal position of the shoreline due to tidal effects. The height of tides in the European High Arctic can reach 1.0–1.5 m and even more under heavy winds, but systematic observations show that changes in annual and monthly mean sea level usually do not exceed 20–30 cm. Hence, the sea level recorded at the time of the satellite survey can be used as a datum plane for practical hydrographic work along European ice coasts. This fact enables the unhindered joint use of multi-source and multi-temporal image data for practical monitoring and mapping of ice-coast changes in different regions of the European Arctic.

Remote sensing studies of ice-coast dynamics in Franz Josef Land

Franz Josef Land (FJL) has the highest index of glaciation of all arctic lands: glaciers cover nearly 85% of its terrain. In FJL, there are 488 tidewater glaciers carrying ice to the sea, and the glaciated coastline extends for 2,520 km. The specific length of the ice coast, defined as the ratio between the perimeter and the area of islands, amounts to 0.19 km^{-1}, i.e. 1 km of ice coast corresponds to 5.3 km^2 of glacial area, thus indicating the high dissection rate of the coastline. The fronts of active outlet glaciers constitute 59% of the ice shore and contemporary topographic maps and hydrographic charts of FJL show more than half of the calving ice coasts by dashed lines, i.e. as uncertain coastlines.

According to present notions, the glaciers of the archipelago are in the regressive stage. According to B. Lefauconnier and H. Slupetzky, the total mass balance over FJL has remained negative during the past 70 years due to considerable calving, whereas ice-flow velocities are decreasing and the specific throughput of ice at glacier fronts is largely uncertain (Barr 1995). Only a few regional-scale investigations of changes in glacial extent have been carried out. One of them was performed by V. Koryakin, who compared topographic maps issued in 1953 with LANDSAT images obtained in 1978 over the western part of FJL. Glacial retreat at four large islands (Alexander and Prince George lands, Bruce and Northbrook islands) was determined as 56 km^2. Assuming similar environmental conditions in different parts of the archipelago, total glacial retreat in FJL for the period of 1953–1978 was given in (Koryakin 1988) as approximately 230 km^2 (−1.7%).

The semi-controlled mosaic of five space-borne multispectral photographs obtained by the KATE-200 film camera in August/September 1993 with an average ground resolution of 25 m covering the whole archipelago has been successfully and recently used for the detection and analysis of glacial changes in FJL (Sharov 1997). The delineation of ice shorelines and inland glacial borders in the mosaic was performed using different classification algorithms and showed significant changes in the location of ice coasts compared to the situation represented in available maps. The areal extent of glaciation in FJL (13,524.9 ± 200 km^2) as well as the total area of the archipelago (15,956.7 ± 300 km^2) was determined from seven independent measurements. The total reduction of glacial cover between 1953 and 1993 was estimated at 210 km^2 (−1.53%).

The largest extent of deglaciation was observed in the southeastern part of FJL at Wilczek Land, Hall, La Ronciere and McClintock islands. The maximum retreat of ice shores was 3.6 km at the margins of Sonklar Glacier (No.12) where it flows into Rough Bay on Hall Island. Significant changes of ice shorelines occurred at the fronts of apron glaciers situated in relatively protected embayments and which are thus constrained and supported by shores from three sides. Large frontier parts—more than 500 m across the shore—of apron glaciers on Prince George Land, Jackson, Karl Alexander, McClintock and Salisbury islands were broken off. Large tabular icebergs found in space-borne photographs close to these ice coasts indicate that this destruction happened nearly simultaneously in all places and probably not long ago. The present total area of 155 apron glaciers in FJL was reported to be only 65.6 km^2. Their average thickness is supposed to be about 20 m (Macheret et al. 1999).

A very interesting exception to the common glacial retreat in FJL was recognized in space-borne imagery: the largest outlet glaciers have advanced offshore by several hundreds of meters. The front of Eastern Glacier at Salisbury Island has flowed about 500 m into the Rhodes Channel; Perilous Ice Cap at the front of Renowned Glacier on Wilczek Land advanced 100 m; the front of Impetuous Glacier in Wilczek Land has moved 600 m from its position in the late 1950s. According to Prof. N. Krenke (N. Krenke, personal communication) these are the only evidence of glacier advancement in FJL. The phenomenon has yet to be explained, but together with other data on glacial dynamics, it supports a hypothesis about the presence of surging glaciers in the archipelago. Comprehensive knowledge of flow velocities and bedrock topography is necessary for a better understanding of the glacier dynamics and motion modes in the region.

There is only limited data on ice thickness and ice flow velocities at glacial fronts, and the rate of change in ice flow and thickness in FJL is practically unidentified. All reports on the changes in ice thickness and velocities in marginal parts of tidewater glaciers found by the author resulted from single measurements performed on Hooker Island. Repeated surveys in the marginal part of the Sedov Outlet Glacier have shown its thinning from 42 to 31 m during the period 1948–1958 and the average rate of thinning was estimated at 1 m a^{-1}. Tachometric surveys at the same glacier in 1947/1949 and 1957/1959 revealed a decrease in maximum velocities from 70 to 50 m a^{-1}. Studies performed at Hooker Island showed that on average, approximately 1×10^6 m^3 of ice was lost each year from 1 km of ice coast due to marine abrasion and calving. The extrapolation of this result to the whole archipelago gave approx. 2.3×10^9 tons of annual ice wastage at all glacier fronts in the late 1950s (Grosswald et al. 1973). Information on the heights of ice coasts given in available topographic maps and hydrographic charts of FJL is extremely scarce, obsolete and inaccurate. In the vicinity of calving ice shores, bathymetric marks are not available, bathymetric contours are broken within 1 km offshore and the possible water depths at ice walls and fronts are usually unknown.

Although the ice thickness in some locations in FJL is insufficient to hide broad features of underlying relief, the character of bedrock topography controlling ice movements in the archipelago was practically unknown until recently. Airborne radio-echo sounding of the ice caps on FJL in 1994 gave new insight into the structure of the land below and allowed some ice-flow features to be reliably interpreted. It has been revealed that several large ice caps in FJL, e.g. Vostok-1 and Vostok-4, have submerged beds below present sea level (Dowdeswell et al. 1994). It is supposed that, in the near future, such ice coasts will demonstrate the highest rates of change.

In 1999–2003, the author initiated and coordinated the AMETHYST FP5 INCO research project focused on satellite hydrographic monitoring of Russian ice coasts (Sharov 2002). The main emphasis was put on the use of ScanSAR imagery and INSAR data obtained from the Canadian RADARSAT and European ERS-1/2 satellites, respectively. A single geocoded ScanSAR image, which was obtained on 18 March 1997 and covers the whole archipelago with a ground resolution of 100 m, was used for analyzing and mapping the most recent spatial changes of ice coasts in FJL. Since the moderate-resolution ScanSAR image has not been duly rectified over precipitous ice coasts, the values of glacier changes were very approximate and total glacial retreat in FJL for the period of 1953–1997 was roughly estimated at 375 km^2 (−2.73%).

Fourteen ERS-1/2-INSAR image pairs obtained in 1994–1997 at intervals of 1 and 3 days were successfully used for studying local changes and dynamics of ice coasts in FJL. Fourteen interferometric models including standard products such as amplitude, coherence and fringe images, as well as value-added products such as topograms, fluxograms and velograms were processed using differential and transferential approaches to rheological modelling at glacial margins.

The joint analysis of multi-temporal SAR interferograms revealed that a large (up to 15 km^2) marginal part of the outlet glacier No.5 in Prince George Land undergoes both horizontal motion due to glacial flow and local vertical movements caused by tidal effects. This provides good verification for the assumption made in (Dowdeswell et al. 1994) and allows the conclusion to be drawn that this glacier is the largest floating ice shelf in FJL. Furthermore, it has been discovered that two smaller outlet glaciers, Nos. 18 and 89, also undergo tidal movements. Other outlet glaciers in Prince George Land did not show essential vertical motions in winter 1996–1997. There is also some evidence of a floating marginal part of outlet glaciers No.6 in Salisbury Island and No. 26 near Bystrova Cape in Jackson Island.

Large tabular icebergs with a length of up to several kilometers frequently observed at the fronts of large outlet glaciers may also attest to the presence of floating glacier tongues in FJL (Grosswald et al. 1973). Large icebergs are usually grounded on banks near the ice coast, but after some thinning, they drift away from the straits of the archipelago, mainly southwards and southwestwards. Observations show that the time between calving events in FJL usually varies from 1 to 2–3 years and the typical size of tabular icebergs might indicate the possible rate of ice flow at glacier fronts.

Horizontal ice flow velocities at the fronts of 28 tidewater glaciers in the cold seasons of 1994–1996 were precisely measured in the lab using INSAR data for the first time in the history of their exploration (Sharov et al. 2002). The measurements were based on the interferometric analysis of the motion of fast sea ice away from the shore as a result of glacier flow. The effect of the fast ice pushed away from the shore by the outlet glacier is manifested in the form of so-called ''outflows'', which can be observed in winter interferograms on the sea-ice surface at the fronts of all active tidewater glaciers oriented along the SAR-range direction (R, Fig. 4).

Figure 4, for example, shows the amplitude image (a) and two fringe images (interferograms) generated from ERS-1/2-SAR images taken at 1-day (b) and 3-day (c) intervals representing typical ''outflows'' at the front of Impetuous Outlet Glacier. In SAR interferograms without significant tidal effects, the frontal glacier velocity can be directly determined by counting the number k of secondary fringes within the outflow as

$$V_{\mathrm{hor}} \cong 0.5\lambda \cdot k \cdot (T \cdot \cos\beta \cdot \sin\theta)^{-1}, \qquad (2)$$

where $\lambda = 5.66$ cm is the wavelength of the SAR signal, β is the flow direction angle measured from the cross-track direction, θ is the viewing angle, and $T = 1$ day is the temporal baseline of the interferogram. The frontal velocities of several tidewater glaciers were measured several times using different interferograms and the results were very consistent (Table 2).

Comparative analysis of multi-temporal space-borne images with topographic maps has led to the discovery of several new islands, e.g. Renta (81°03′N, 58°26′E, approximately 9,000 m^2), Radar (80°36.5′N, 56°33′E, approximately 1,000 m^2) and Malyshok (80°50.2′N, 58°10′E, approximately 600 m^2), islands that were formerly covered by glacier ice and appeared as a result of glacial retreat (Sharov 2000). It was also discovered that Mother-of-Pearl (Perlamutrovy) Island with a total area of 1.5 km^2 and a maximum height of 22 m a.s.l., shown on all topographic maps as entirely covered by the ice cap, no longer exists (Fig. 5a). The same applies to the largest of the Lyuriki Islands, which is shown in the contemporary topographic map issued in 1990 (Fig. 5b).

Several satellite image maps showing the present position and areal changes of ice coasts in the archipelago were compiled, edited and published (Sharov 1997; Sharov et al. 2003). A small-size copy of the 1:1,000,000 satellite image map of FJL is given in Fig. 6. The results of image processing and mapping were verified during three field campaigns in August 1994, July 1995 and June 1999 (Sharov et al. 2000). Large deposits of ground (fossil) ice were discovered in coastlands at Alexandra Land, La-Ronciere and Hall islands.

Changes of ice coasts in northern Novaya Zemlya

The Novaya Zemlya archipelago (NZ) is situated approximately 500 km south of Franz Josef Land and tidewater glaciers exist only on its North Island, which is the largest island (48,100 km^2) in NZ and in the whole Eurasian Arctic. Nearly 50% of its surface is occupied by the Main Ice Sheet, which is reputed to be the largest mass of land ice (23,800 km^2) in Europe. Forty-one outlet glaciers drain ice from the Main Ice Sheet into the sea; 27 outlet glaciers reach the Barents Sea and 14 glaciers terminate in the Kara Sea (Varnakova and Koryakin 1978). In Koryakin (1988), the total length of ice coasts in NZ is given as 208.4 km, which represents only 5.2% of the total coastline. 125 km (60%) belong to the Barents Sea region, while the remaining 83.4 km complete the Kara Sea coastline. Typical heights of these precipitous ice coasts vary from 15 to 45 m. The highest ice walls exceed 60 m and were observed on the western coast at the fronts of the Rykachova and Anuchina tidewater glaciers. Very approximate estimations of total ice discharge through maritime glacier fronts on North Island range from 2.0 to 2.3 km^3 (Chizhov et al. 1968; Koryakin 1988).

The height of semi-diurnal tides ranges from 0.6 m at the northern coast to 0.8 and 1.0 m for the middle and southern parts of North Island, respectively (Atlas of the Arctic 1985). A relatively narrow strip of fast ice with a

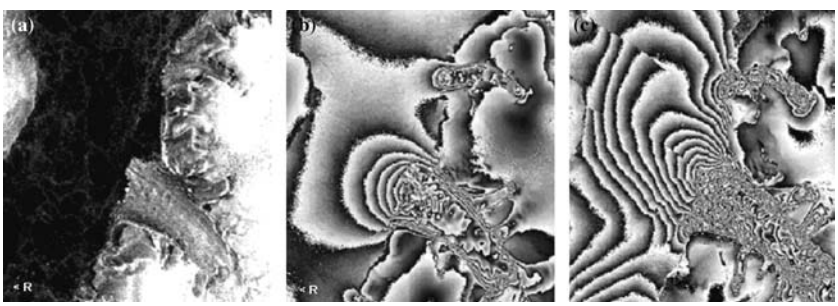


Fig. 4 Amplitude image and fringe images of Impetuous Glacier, Franz Josef Land: 17/18 December 1995 (**a, b**) and 23/25 February 1994 (**c**)

Table 2 Frontal velocities of tidewater glaciers in Franz Josef Land and northern Novaya Zemlya (cold seasons, 1994–1996)

Island, glacier name, No.	INSAR velocity (cm/day)	Date
Franz Josef Land		
Champ Island, Nos. 5, 6	32.6, 21.7	17/18 December 1995
Hall Island, Sonklar, Nos. 7, 17	30.2, 47.4, 18.9	17/18 December 1995
Payer Island, Nos. 2, 3, 4, 7	4.8, 1.4, 33.4, 12.9	17/18 December 1995
La Ronciere Island, Nos. 1, 2, 3, 4	11.6, 7.6, 44.0, 18.5	17/18 December 1995
Prince George Land, Nos. 5, 18, 23	29.8, 32.5, 46.9	31.12.1995/01.01 1996
Salisbury Island, Eastern, No. 13	18.1, 34.8	17/18 December 1995
Wiener Neustadt Island, Nos. 3, 5	5.1, 21.7	17/18 December 1995
Wilczek Land, Nos. 2, 9, 5, Impetuous, Milky, Karo n/s, Renown	9.4, 36.2, 10.4–16.6, 27.8–45.1, 15.5–27.8, 47.5/85.0, 27.9–31.4	23/25 February 1994—18/19 October 1995—17/18 December 1995
North Novaya Zemlya		
Inostrantseva, No. 13	25.4/24.4–27.8/25.9	05/06, 18/19, 21/22 March 1996
Pavlova, No. 15	20.5/21.7	18/19, 21/22 March 1996
Vera, No. 16	41.0–47.8/44.4	18/19, 21/22 March 1996
Central (Anna), No. 17	3.4	21/22 March 1996
Bunge, No. 18	37.5	18/19 March 1996
Petersen, No. 19	13.9	18/19 March 1996
Roze, No. 38	7.9–11.8	21/22 March 1996
Sredniy, No.39	3.2–5.0/9.3	05/06, 21/22 March 1996
Rozhdestvenskogo, No. 40	22.4	05/06 March 1996
Vershinskogo, No. 41	20.1	05/06 March 1996
Moschniy, No. 44	18.4	05/06 March 1996
Kropotkina, No. 47	18.8	05/06 March 1996
Shokal'skogo, No. 86	31.2–31.8	05/06 March 1996
Chaeva, No. 87	16.2	05/06 March 1996
Rykachova, No. 88	34.8	05/06 March 1996
Velkena, No. 90	23.4/34.8	05/06, 21/22 March 1996
Mack, No. 91	17.1–36.6	05/06 March 1996
Voeikova, No. 92	27.5/35.2	05/06, 21/22 March 1996
Brounova, No. 93	20.4/20.1/28.4	05/06, 18/19, 21/22 March 1996
Anuchina, No. 94	7.4/10.0/7.1	05/06, 18/19, 21/22 March 1996
Vize, No. 95	15.9/14.3	05/06, 18/19 March 1996

typical width of 5–15 km forms along the northern part of the coastline in winter.

Previous studies of ice coasts in NZ were local rather than regional in character and relevant data on the coastal changes in the region are still very scarce (Zeeberg and Forman 2001). Practically nothing is known about coastal changes along the eastern shore of the island. There is very little factual knowledge about the rate of glacier ice flow in NZ. Substantial tachometric surveys were repeatedly performed (in 1933, 1957–1958 and 1969) only at Shokal'skogo Tidewater Glacier (280 km^2), which lies within a distance of 0.5 km from the Russkaya Gavan' Polar Station (76°11′N, 62°36′E) on the western coast of North Island (Fig. 7a). Instrumental records documenting the rate of glacial ice flow in other coastal areas of NZ, e.g. on the Kara Sea coast, were not available prior to the present study.

The general character of ice motion on Shokal'skogo Glacier is reputed to be typical of other outlet glaciers in North Island. The maximum velocity at the front of Shokal'skogo Glacier is supposed to be about 150 m^{-1}, or up to 70 cm/day, on summer days. The velocity of glacial flow increases notably in warm periods with the most intensive melting and precipitation from July to September, the summer motion rate being about 2.2 times greater than that in the coldest month (Koryakin 1988). All present mass-balance estimates for Novaya Zemlya glaciers are derived from surveys on the Shokal'skogo Glacier.

No extensive radio-echo sounding surveys have been performed in the archipelago and no reliable data on the character of bedrock topography and the present-day thickness of glacier masses in NZ exist. According to the indirect geomorphologic estimations performed by M. Ermolaev in 1933, the approximate mean thickness of the Main Ice Sheet is about 300–400 m, but in some places it might even reach 700 m (Koryakin 1988). The lack of reliable knowledge on glacial rheology renders an understanding of ice-coast evolution in the region difficult.

Original remote sensing studies have recently been carried out in order to detect, to analyze and to map current ice-coast changes in north Novaya Zemlya on a regional scale (Sharov et al. 2003). The study region comprised 21 large tidewater glaciers situated eastwards of the meridian passing through the Russkaya Gavan' station (Table 2). The experimental data set included:

- Six repeat-pass ERS-1/2 INSAR tandem pairs taken in October 1995 and March 1996 at 1-day intervals under steady and cold weather conditions
- A semi-controlled mosaic of two geocoded ScanSAR RADARSAT images obtained in March 1998 covering the whole study area

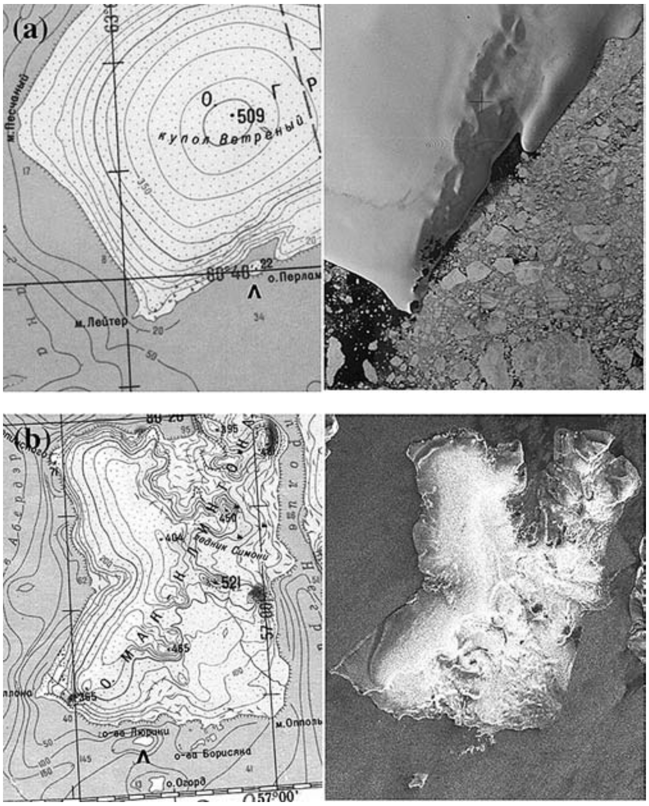


Fig. 5 Nonexistent islands in FJL: Mother-of-Pearl Island (**a**, Λ) and the largest of the Lyuriki islands (**b**, Λ)

– Six quick-looks of the ASTER space-borne images obtained over northern Novaya Zemlya on 13 April and 1 July 2001.

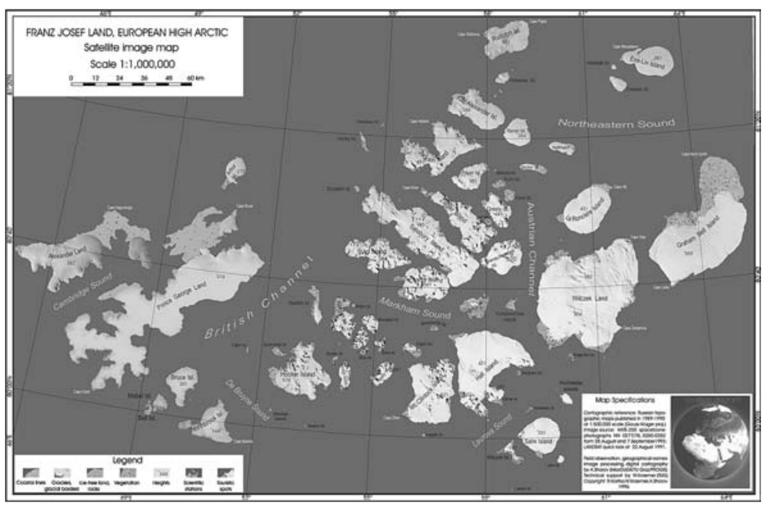
Russian topographic maps at 1:200,000 scale issued in 1970/1971 on the basis of aerial and geodetic surveys of 1952 laid the groundwork for change detection.

Careful comparative analysis of the space-borne image data with available topographic maps revealed a significant retreat of glacial termini and essential changes in the configuration of ice coasts in the study region. The maximum losses of glacier ice between 1952 and 2001 were recorded at the calving face of Vera Glacier (30 km^2) on the western coast and at the front part of Roze Glacier (28 km^2) on the eastern coast of North Island. The 20–25 m high face of Vera Glacier receded approximately 5 km during the period of 1952–1996. As a result, a new bay about 4.5–5 km wide, called Lucid (Svetlaya) Bay, has been formed (Fig. 1).

Due to the significant retreat of Rykachova Glacier, a large marginal part of its northern lobe became grounded on the land surface of Hare Cape and a long stretch (nearly 3 km) of the former calving glacier face shown in present topographic maps can no longer be regarded as an ice coast. The formerly confluent glaciers Mack and Velkena retreated nearly 2 km so that the glacier fronts became separated from each other by a large nunatak with a maximum height of 636 m a.s.l., which turned out to be a new cape called Fidelity (Verny) Cape. Its preliminary coordinates can be given as 76°17'N and 64°12'E. In the period 1952–2001, the total length of the nine northernmost tidewater fronts on the western coast of North Island was reduced from 31.5 to 29.4 km (−6.6%). Changes in the total length of all ice coasts on North Island are estimated at approximately 16 km (−7.9%) for the past 50 years.

At the same time, there are some exceptions to the general shrinkage of ice coasts in the region. Between 1952 and 1996, there was a relatively small retreat of only about 0.3 km in the northern and southern parts of the calving face at Shokal'skogo Glacier. The outline of some glacial fronts became irregular, e.g. at Pavlova and Sredniy glaciers, and the length of some ice coasts increased correspondingly by several hundred meters due to the inhomogeneous retreat of the coastline. In SAR scenes of 1996, the front of Brounova Glacier (Fig. 7c) appears to have advanced 2.4 km from its position in 1952. The length of its ice wall increased from 1.4 to 2.3 km. In 1998, the glacier retreated by 0.6 km compared to its position in March 1996.

Fig. 6 Small-size copy of the satellite image map of FJL, 1:1,000,000 (by Sharov 1996)



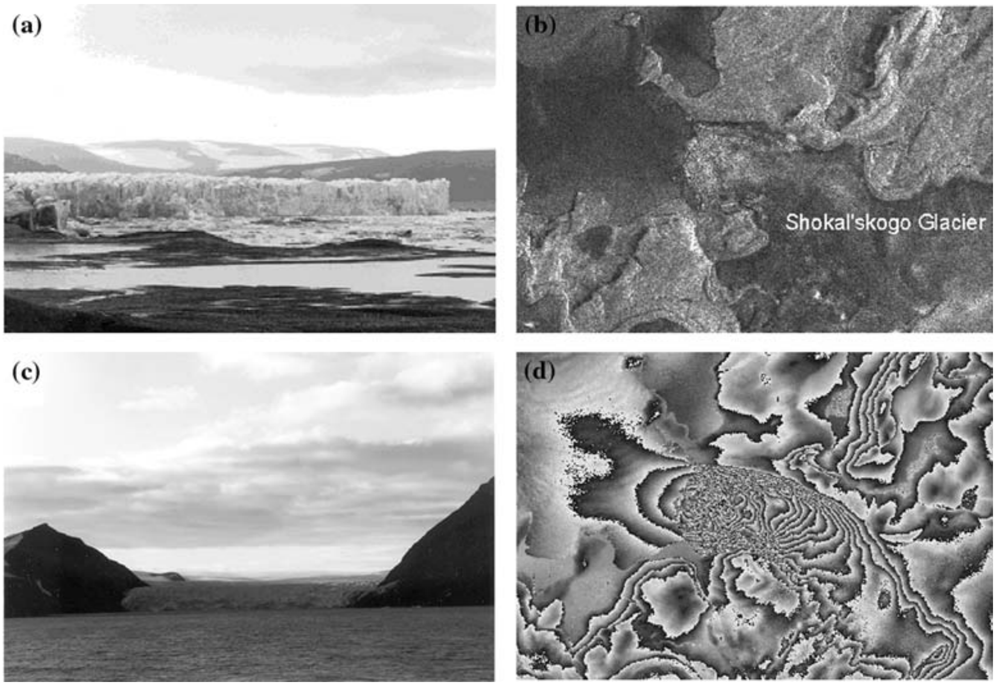


Fig. 7 Photographs of Shokal'skogo (**a**) and Brounova (**c**) glacier fronts; ERS-1/2-INSAR amplitude image (**b**) and fringe image (**d**) of Shokal'skogo Glacier

Together with other data on glacial dynamics this fact supports a hypothesis on the surging character of this glacier and is somewhat curious because it was stated that the extent of this glacier ''has not varied appreciably since 1952'' (Zeeberg and Forman 2001).

The frontal velocities of 21 tidewater glaciers, including those on the eastern coast of North Island, were precisely measured from the repeat pass interferometric SAR data obtained in March 1996 using the transferential approach (from Latin transferre: trans—-across, change + ferre—to carry) based on the interferometric measurement of the fast-ice translation forced by the glacier flow (Sharov et al. 2003). In the tide-coordinated INSAR data without significant tidal effects, the local speed of the fast-ice translation was supposed to be equal to the frontal velocity of tidewater glaciers and was determined in accordance with Eq. 2.

Transverse variations of the frontal velocity along the glacier face were evaluated by analyzing the shape of outflows (see Fig. 7d). In SAR interferograms, the magnitude of tidal effects can be evaluated by analyzing the fast-sea-ice motion along the glacier-free coast. The interferometric picture in Fig. 7b, d indicates, for example, the absence of essential tidal effects in Profound Bay, which is situated 0.5 km north of the glacier front. Typical results of velocity measurements in [cm/day] are specified in Table 2. The maximum winter INSAR velocity of Shokal'skogo Glacier (31.5 cm/day) corresponds well to the maximum annual velocity of 150 m a^{-1} determined by other investigators. It is worth noting that as early as 70 years ago, M. Ermolaev from the Arctic and Antarctic Research Institute in St. Petersburg used terrestrial measurements of fast-ice motions to evaluate the frontal velocity of Shokal'skogo Glacier.

In September 2001, the author had the opportunity to participate in a hydrographic expedition to the Novaya Zemlya archipelago on board the ship ''Hydrologist'' and to perform field surveys of ice coasts. The ship's navigational radar was applied to recording the present positions of ice coasts with subsequent planimetric measurements of areal changes at the fronts of test glaciers using a grid transparency. Field surveys were focused on measuring the heights of ice walls above the sea level and surveying frontal velocities in marginal parts of six test apron glaciers.

Frontal glacier velocities were measured using the conventional geodetic technique of forward intersection and a non-traditional ''touch-and-go'' technique. The polar idea of the ''touch-and-go'' technique is to install the laser line in a tangential position at a predefined distance from the glacier front and to frequently measure the distance to any steady point on the opposite coast in order to record the instant when the glacier will cross the laser line and the measured distance will change abruptly (Sharov et al. 2003). This technique made use of the LDI-3 laser rangefinder with a range up to 10 km (without corner reflector) mounted on the Leica T1602 theodolite with an angular accuracy of ± 0.5 mgon. Some results of these observations are given in Table 3. All glacier change values and the present length of the ice coasts determined in this study were documented in the form of several satellite image maps. One of them is represented in Fig. 8.

The results obtained indicate that almost all test glacier fronts have become higher. This can be explained by current glacial retreat and the rapid disintegration of lower frontal parts of tidewater glaciers. Hence, the general lowering of the glacial surface in northern Novaya Zemlya mentioned in Koryakin (1988) could not be

Table 3 Some results from field surveys of ice coasts and glacier fronts in northern Novaya Zemlya

Glacier name, No.	Change in area: 1952/2001 (km^2)	Ice wall height: 1952/2001 (m a.s.l.)	Frontal velocity (cm/day)	
			Forward intersection	Touch-and-go
Shokal'skogo, No. 86	−1.2	42/48	–	90 ± 15
Rykachova, No. 88	−11.7	20/59	68 ± 14	83 ± 20
Mack, No. 91	−7.3	34/34	61 ± 13	73 ± 15
Vera, No. 16	−30.1	21/24	Swaying, 1–2 cm/min	
Sredniy, No. 39	−8.0	25/28	Swaying, < 0.5 cm/min	
Rozhdestvenskogo, No. 40	−7.2	21/29	49 ± 12	–

verified. The summer glacial velocities surveyed in the field are significantly higher than the winter INSAR velocities given in Table 2, which corresponds to observations of other investigators. The spatial correlation between summer and winter velocities was quite high. The velocity values obtained were applied to the approximate quantitative analysis of ice discharge through glacier fronts of six test glaciers (Sharov et al. 2003). It has been deduced that the current glacial activity along the western coast of NZ is much higher than that along the eastern shore.

Field observations of numerous calving effects have shown that in the study region, the daily peak of glacial activity with the corresponding maximum loss of ice from calving faces is attained at midday and is probably related to tides and melting processes. Vertical swaying motions with a maximum rate of 2 cm min^{-1} were recorded at the fronts of Vera (Fig. 1) and Sredniy glaciers. This fact verifies the existence of, at least partially or transiently, floating ice tongues in Novaya Zemlya.

Ice coasts of Svalbard

Major spatial information about ice coasts in Svalbard is available in the form of Norwegian topographic maps and hydrographic charts, which were photogrammetrically compiled from air photos by the Norwegian Polar Institute (NPI). The large standard map series, which includes 60 sheets covering the whole area of the archipelago at 1:100,000 scale, was published in 1947. Four map sheets at 1:500,000 scale published by NPI in 1964 and updated in 1979–1988 provide smaller-scale coverage of ice-coast position in the 1970s. General maps of Spitsbergen at 1:1,000,000 and 1:2,000,000 were last published in 1983. These cartographic sources are undoubtedly important for any environmental study of the region, but their use for precise up-to-date hydrographic determinations is restricted because of essential coastal changes having occurred in the archipelago in the past 50 years. There is, however, little information available on the present state of ice coasts, especially in the northern part of the archipelago, and the character and rate of their changes at a regional level are not fully understood. This is probably due to the fact that nearly 90% of all glaciers in the region are of the surging type and periodically demonstrate a dramatic increase in the velocity, usually accompanied by an essential, albeit transient, advance of the glacier front (Sörbel et al. 2001). Fifty-one glacial surges were registered in Svalbard in the twentieth century. The total increase of the glaciated area due to those surges was estimated to be nearly 1,000 km^2 (Koryakin 1988). The topographic map 1:500,000 of Svalbard (Blad 3) issued in 1982 by the NPI shows that Aawatsmarkbreen, Conwaybreen, Dahlbreen, Idabreen, Kongsvegen, Nordenskjoldbreen

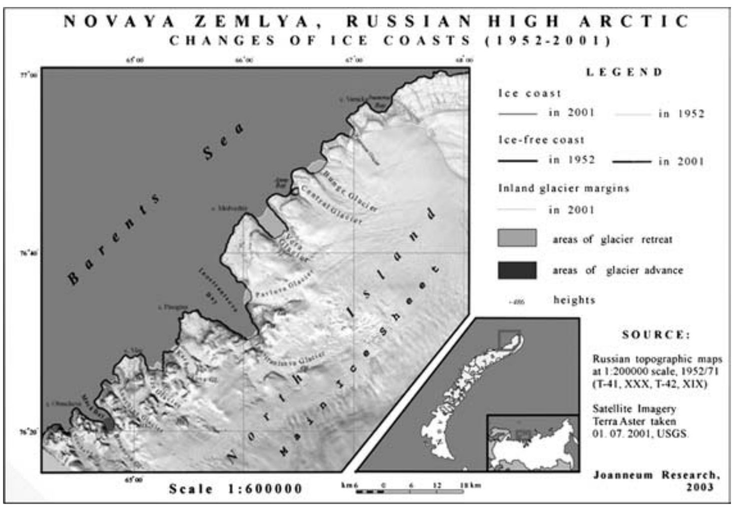


Fig. 8 Small-size copy of the satellite image map showing changes of ice coasts on northwestern Novaya Zemlya

and Raudfjordbreen advanced ca.1.5 km from their positions in 1976. A considerable advance of the ice coasts was observed at the fronts of Markhambreen (2.2 km), Monacobreen (3 km), Osbornebreen (4 km), Hochstätterbreen (7 km), Hayesbreen (8.5 km), and Stonebreen (9 km) glaciers. The largest ice coast advance (25 km) with a subsequent retreat was recorded at Bråsvellbreen in the southeastern part of Nordaustlandet (Schütt 1969; Troitskiy et al. 1975).

New results demonstrating considerable changes in the present position and configuration of ice coasts have been obtained by the author through the analysis of LANDSAT-7 ETM+ space-borne RGB-scenes taken over Svalbard in June 2001 and July 2002. A semi-controlled image mosaic of nine quick-looks from those scenes with a ground resolution of 240 m provided a good basis for a provisional satellite image map of Svalbard ice coasts (Fig. 9). The precise interpretation, delineation and measurement of the length of ice coasts in the provisional map represented in UTM coordinates was performed using the Corel Draw 7.0 and ERDAS Imagine 8.5 software packages. The main results of the cartometric studies illustrating changes of ice coasts in the archipelago in the course of the past 30 years are given in Table 4.

The largest retreat of ice coasts during the past 30 years was detected in the southernmost part of Spitsbergen, where the fronts of Stoorbreen and Hornbreen tidewater glaciers receded 4.1 and 4.8 km, respectively, and the width of the icy isthmus connecting Sörkapp Land with the main island narrowed from 14.4 to 9.4 km. The total length of the ice coastline in Svalbard was determined by averaging between five estimations. The accuracy of the final estimation is evaluated as ±1.5%, which is not worse than that of manual planimetric measurements in the standard small-scale map.

In the LANDSAT quick-look of Storøya Island, the presence of fast coast ice cannot be excluded and the present length of the ice coasts at this island should be considered as approximate and, possibly, somewhat overestimated. In spite of all efforts, areas with significant glacier advancement could not be detected in other parts of Svalbard. A preliminary analysis of the most recent ASTER image obtained on 5 August 2003 revealed a further rapid retreat of ice coasts in Svalbard.

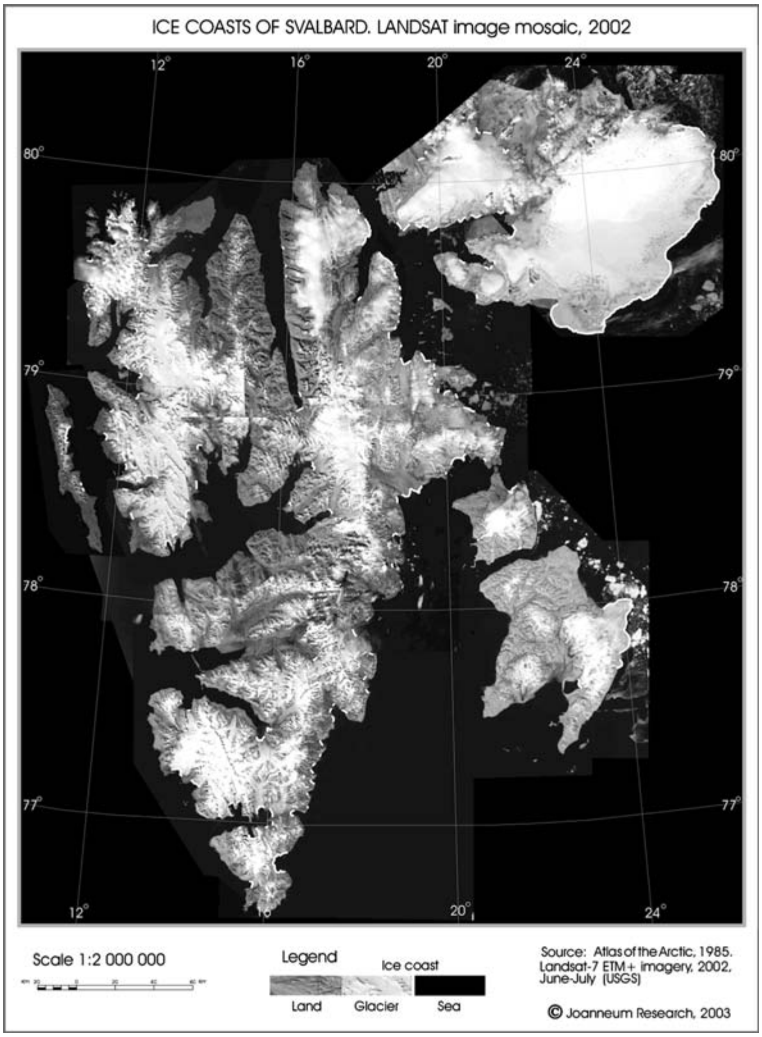


Fig. 9 Provisional satellite image map of ice coasts in Svalbard

Table 4 The length of ice coasts in Svalbard (1970s and 2000s)

Island/Ice coast length (km)	1970s	2000s	Change, [km (%)]
Spitsbergen	496.5	415.7	−80.8 (−16.2%)
Nordaustlandet	318.6	279.5	−39.1 (−12.3%)
Edgeøya	83.6	60.2	−23.4 (−27.9%)
Barentsøya	19.6	11.1	−8.5 (−43.3%)
Prins Karls Forland	16.1	14.9	−1.2 (−7.4%)
Storøya	11.8	12.0	+ 0.2 (+ 1.6 %)
Total	946.2 ± 0.2	794.2 ± 10	−152 (−16.0%)

The length of the ice coasts at the fronts of the large Negribreen (20.5 km), Vasilievbreen (16.7 km) and Stonebreen (48.0 km) tidewater glaciers has significantly changed from the state represented in available topographic maps. The emergence of several new, as yet uncharted islands and capes was detected in multi-temporal space-borne images. For example, Mount Arrheniusfjellet, with a height of 882 m a.s.l., became Cape Arrhenius. Isispynten Ice Cape situated on the eastern coast of Nordaustlandet at 79°42.5′N and 26°28′E turned out to be a separate island with an area of approximately 7 km^2. Another new island was "discovered" in the shallow (13 m) Isbukta close to the ice coast of Vasil'eva Glacier in south Spitsbergen at 76°49.5′N and 17°05.0′E. The real existence of these islands and capes must still be verified by field observations, however.

Ice coasts of other islands

Tidewater glaciers can be found not only on the FJL, NZ and Svalbard archipelagos but also on several separate European islands, namely Jan Mayen, Kvitøya and Victory islands. According to my estimations using LANDSAT-7 imagery of September 2002, the length of the ice coasts at Jan Mayen Island has decreased from 3.5 to 3.1 km (−11.5%) during the past 50 years. The LANDSAT-7 image obtained on 23 May 2002 revealed that the ice coasts of Victoria Island with a total length of about 12 km have not significantly changed during the second half of the twentieth century. In all ASTER and LANDSAT space-borne images taken in 2002 and 2003, the outlines of Kvitøya Island appeared somewhat broader than those on available topographic maps, and the total length of ice coasts seems to have increased from 104.5 to 108.2 km (+3.4%).

Ushakova Island is situated in the Kara Sea approximately 240 km east of the FJL archipelago and thus belongs to the Asian part of the Arctic. Nevertheless, I obtained two quick-look ASTER images taken on 21 May 2001 with a ground resolution of 140 m, which revealed that the total length of the 2–30 m high ice coasts on this island has decreased by 3.5%. All my attempts to obtain appropriate space-borne image data of De Long Islands in the East-Siberian Sea with a total ice coast length of approximately 2 km failed. Studies of ice coasts in Severnaya Zemlya are beyond the scope of the present paper and those interested in a detailed description of coastal ice dynamics in this archipelago are referred to other publications (Sharov et al. 2002).

Discussion and conclusions

An integral assessment of the extent and spatial changes of glaciated coastlines in the European Arctic during the past 50 years has been performed by comparing available topographic maps with up-to-date geocoded space-borne image data, both optical and radar, featuring high ground resolution and broad terrestrial coverage. Ice-coast changes have been expressed both in linear and areal terms and represented in the most versatile and easily interpreted form of satellite image maps. This is the first time that spatial changes in coastlines have been recorded, measured and mapped for all European ice coasts within a single study.

The extent of changes revealed at the fronts of tidewater glaciers clearly shows the strong tendency of relatively rapid degradation of ice coasts in all parts of the study region. The maximum retreat amounting to 4–6 km across the shore was recorded in Svalbard and northern Novaya Zemlya at glaciated coastlines situated south of latitude 77°N. In relative terms, the strongest reduction in coastline length was observed in Svalbard (−14.0%), north Novaya Zemlya (−7.9%) and at Jan Mayen Island (−11.5%). The total length of European ice coasts decreased from 3,924 to 3,620 km (−7.7%).

Numerous hydrographic findings, e.g. one large island that has disappeared, and several geographic discoveries including five new islands, three new capes, two new bays, one new channel, etc. resulted from this study. After verifying the real existence of all these objects by field observations, they should be registered in special hydrographic and navigational publications.

Short-term frontal velocities of 50 tidewater glaciers oriented across the sub-satellite track were precisely measured in the lab from ERS-1/2-SAR winter interferometric "snap-shots". Summer ice flow velocities were measured during field surveys at the test sites and compared with those derived from INSAR data. In addition to the methodological verification, such comparisons might provide some evidence on the motion character and basal conditions at glacier margins.

The existence of at least partially or transiently floating glacier fronts in Franz Josef Land and Novaya Zemlya has been verified, thus supporting the hypothesis that glacier margins become buoyant due to bottom melting and the thinning of ice tongues. The essential and relatively rapid advance of Impetuous and Eastern glaciers detected in FJL and Brounova Glacier in NZ has led to a hypothesis on the surging character of these glaciers. Fast disintegration of thinner frontal parts of most tidewater glaciers resulted in an increase in the height of some ice coasts. Apart from the somewhat tedious stereophotogrammetric method, which is not always feasible in the arctic environment, no robust space-borne technology for rapid and precise surveying of ice wall heights at the regional scale exists at present, and it is believed that the launch of a GLAS laser altimeter on board the ICESat satellite in 2003 and a SIRAL interferometric altimeter on board the CryoSat satellite in 2004 will give a new impetus to studying ice-coast morphology from space.

Geometric and rheological quantities, such as the configuration and height of the glacier front, ice velocity, strain rate and calving flux, determined in different seasons for ice coasts with different characteristics in terms of morphology, dynamics and extent are essential for reliable modelling of ice-coast evolution, a better understanding of their response to climatic changes and adequate forecasting of possible alterations in glaciated coastlines. Indeed, an ice coast will advance if the frontal velocity exceeds the limit established by the intensity of marine abrasion, calving and melting, and it will recede if the ice wastage at the front exceeds the input. The intensity of frontal ablation is one of the principal unknowns in environmental forcing related to climatic changes and may thus be estimated through the joint analysis of coastal morphology and dynamics.

Especially for projections on short time scales, ice velocity variations represent more susceptible and representative indicators of climatic changes than the front position of a tidewater glacier, even if the front positions are averaged over many different glaciers. Due the lack of reliable tachometric records at a regional scale, I could not compare all velocities determined in this study with the velocities measured earlier by other investigators. Nevertheless, the results obtained are believed to be useful for subsequent surveys and for retrospective coastal hydrographic monitoring in the study region.

The present length of ice coasts, the total "land area" of glaciated islands, ice-coast changes in linear, areal and volumetric terms, frontal velocities of glaciers and some other rheological characteristics determined in this study will be documented in the form of a new inventory of the Eurasian ice coasts covering the high-latitudinal archipelagos of Svalbard, Novaya Zemlya, Severnaya Zemlya, Franz Josef Land, as well as Jan Mayen, De Long, Ushakova, Victory and Kvitoya islands. The inventory will contain several full-value image maps showing the present state and dynamics of ice coasts at the local and regional scale and will thus provide a sound foundation for further multidisciplinary studies of these remote, wild and beautiful objects.

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