POLISH POLAR RESEARCH
vol. 34, no. 4, pp. 327–352, 2013 doi: 10.2478/popore-2013-0024

Fluctuations of tidewater glaciers in Hornsund Fjord (Southern Svalbard) since the beginning of the 20th century

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Abstract: Significant retreat of glaciers terminating in Hornsund Fjord (Southern Spitsbergen, Svalbard) has been observed during the 20th century and in the first decade of the 21st century. The objective of this paper is to present, as complete as possible, a record of front positions changes of 14 tidewater glaciers during this period and to distinguish the main factors influencing their fluctuations. Results are based on a GIS analysis of archival maps, field measurements, and aerial and satellite images. Accuracy was based on an assessment of seasonal fluctuations of a glacier's ice cliff position with respect to its minimum length in winter (November–December) and its maximum advance position in June or July. Morphometric features and the environmental setting of each glacier are also presented. The total area of the glacier cover in Hornsund Fjord in the period of 1899–2010 diminished approximately 172 km^2, with an average areal retreat rate of 1.6 km^2a^{-1}. The recession rate increased from ~1 km^2a^{-1} in first decades of the 20th century up to ~3 km^2a^{-1} in years 2001–2010. The latest period was more thoroughly studied using optical satellite images acquired almost every year. The importance of glacier morphology and hypsometry, as well as fjord bathymetry and topography is analyzed. Large glacier systems with low slopes terminating in deeper waters are retreating faster than small steep glaciers terminating in shallower water. A relation between mean annual air temperature and aerial retreat rate of tidewater glaciers was found for long time scales. A sudden temperature increase, known as the early 20th century warming in Svalbard, and an increase in temperatures during recent decades are well reflected in deglaciation rate. Influence of sea water temperatures on calving and retreat of glaciers was considered and is significant in short-time intervals of the last decade. Surge events are non-climatic factors which complicate the record. They are reflected in front advance or fast retreat due to a massive calving depending on the relation between ice thickness and water depth. Despite the influence of many factors, the response of tidewater glaciers to climate change is evident. The average linear retreat rate of all the tidewater glaciers in Hornsund amounted to ~70 ma^{-1} in 2001–2010 and was higher than the average retreat of other Svalbard tidewater glaciers (~45 ma^{-1}). Thus, glaciers of this basin can be considered as more sensitive to climate than glaciers of other regions of the archipelago.

Key words: Arctic, Spitsbergen, Hornsund, tidewater glacier retreat, seasonal front fluctuation, climate change.

Pol. Polar Res. 34 (4): 327–352, 2013

Introduction

Climate warming has accelerated during recent decades causing changes in the extent, volume and dynamics of glaciers. This warming is more pronounced in the Arctic than in the mid-latitudes (*cf.* ACIA 2005; IPCC 2007), influencing the mass balance of Svalbard glaciers. The ice masses of Svalbard cover an area of ~36 600 km^2, (~60% of the land surface) and are among the largest glacierized areas in the Arctic (Dowdeswell and Hagen 2004). More than 60% of the total glacierized area of archipelago terminates at tidewater glaciers (Błaszczyk *et al*. 2009). There is extensive evidence that Svalbard glaciers are very sensitive to climatic change, presumably because of the influence of the North Atlantic warm ocean current system to the regional climate. The majority of Svalbard glaciers are known to have been in the retreat stage since the termination of the Little Ice Age (LIA) at the end of the 19th century (*e.g.* Hagen *et al*. 1993; Svendsen and Mangerud 1997; Rachlewicz *et al*. 2007; Nuth *et al*. 2007). In Sørkappland (Southern Spitsbergen) along, the areal extent of glaciers decreased ~18% between 1936 and 1991 (Ziaja 2001).

The main objective of the paper is to establish the leading factors and processes governing the fluctuations and retreat rate of glaciers terminating at tidewater in Spitsbergen fjords, with a specific focus on Hornsund Fjord (Southern Spitsbergen). Studies are based upon data extracted from archival topographic maps, aerial photographs, satellite images and field measurements. The front retreat of fourteen polythermal tidewater glaciers of different sizes and morphological is analyzed over the period 1899–2010 (Figs 1, 2). The mode of the dynamic response of these glaciers to climate warming is discussed. Annual front fluctuations of Hornsund glaciers were also studied using satellite images and terrestrial remote sensing methods. Mass transfer due to surge events complicates the climate signals derived from measurements of glacier extent and their geometry changes (Sund *et al*. 2011). For this reason, terminus fluctuations resulting from surging processes are also discussed in the study.

This study aims to update earlier work on Hornsund terminus position (*e.g.* Pillewizer 1939; Koryakin 1975a; Jania 1988; Jania *et al*. 2003). Results are used to answer two questions: are Hornsund glaciers representative of Spitsbergen glaciers, and can their behavior be used to future deglaciation of the Svalbard Archipelago? A satellite orthophotomap (Supplementary Online Material available at http://www.degruyter.com/view/j/popore.2013.34.issue-4/popore-2013-0024/appendix1.pdf) (1: 50 000) illustrating tidewater glacier terminus positions in 1899–2010 is enclosed with this paper.

Hornsund Fjord and its glaciers

Topography and geomorphology of the fjord surroundings. — Hornsund is the southernmost fjord of Spitsbergen located on the western coast of the island,

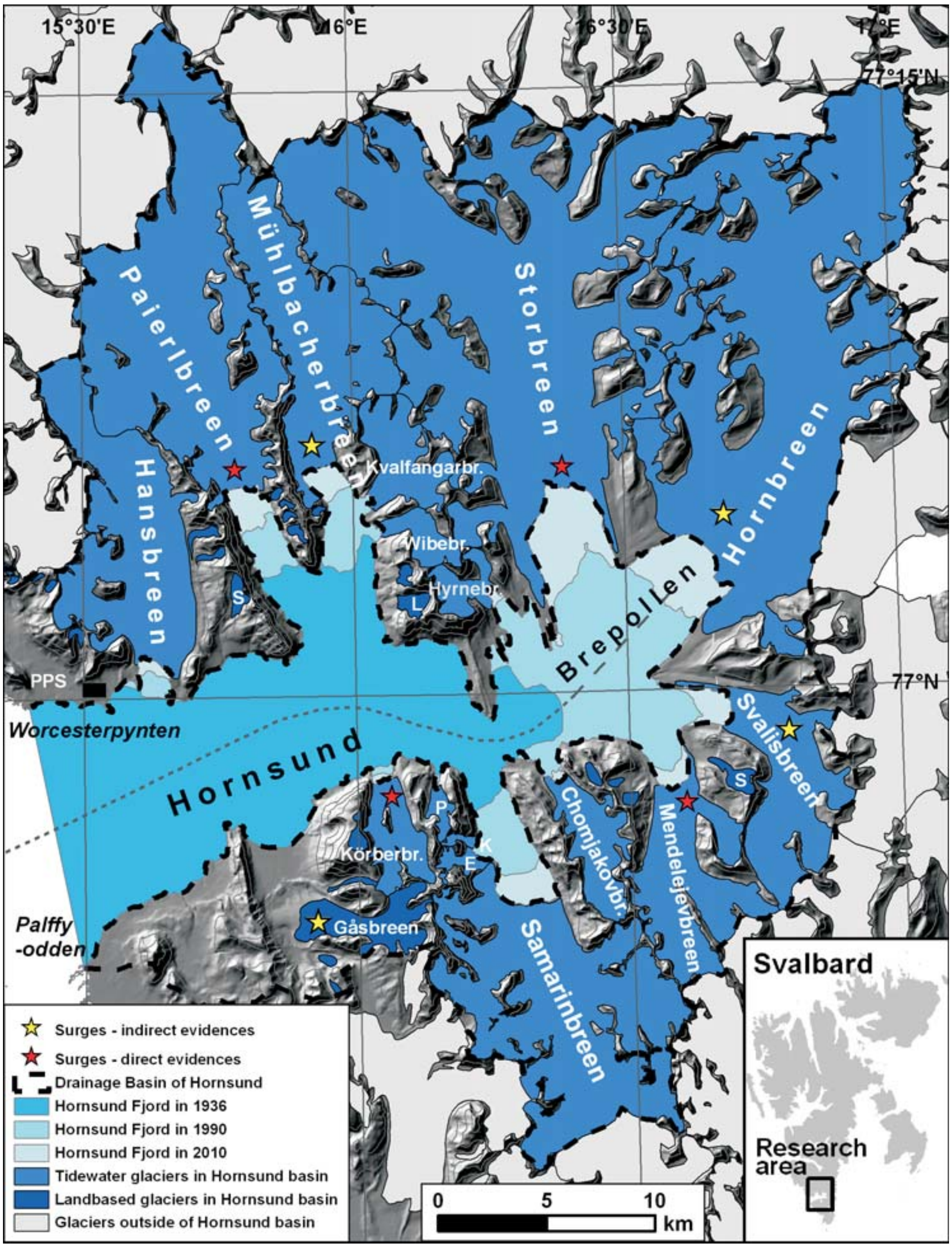

Fig. 1. Hornsund glacial basin and location map (PPS – Polish Polar Station). P – Petersbreen, E – Eggbreen, K – Kvasseggbreen, Si – Signybreen, L – Lorchbreen, S – Sofiebreen; dashed lines – sections along fjord axis where data on water temperature were collected.

and one of the smallest ones. Its mouth lies between the distinct capes of Worcesterpynten on the northern shore and Palffyodden in the south (Fig. 1). Due to retreat of tidewater glaciers its area increased from ca. 188 km^2 in 1936 to *ca* 264 km^2

in 1990 and was *ca* 303 km^2 in 2010 (measured from the arbitrary selected line between the mentioned points). Hornsund was about 24 km long in 1936 and its length is ~34 km nowadays. The entire drainage basin area of Hornsund amounts to ~1200 km^2, of which ~67% (802 km^2) is covered by glaciers (Fig. 1). Tidewater glaciers constitute 97% of the glacierized area (781 km^2). The length of tidewater glacier cliffs amounted to 34.7 km in 2010.

Narrow coastal plains with raised marine terraces surround the fjord shores and they are wider in the western part. In the central part of the fjord they are very narrow (200–400m) and disappear completely where glaciers or steep mountain slopes descend directly to the sea. Six mountain ridges or distinct massifs run orthogonally to the fjord axis on both shores. However, continuity of particular ridges is not directly visible across the fjord due to a complicated geological structure of the Hecla Hoek Precambrian and Cambrian formation with a number of folds, faults and overthursts (Birkenmajer 1978a, 1978b, 1990; Harland 1997). It is assumed that the fjord developed along a significant tectonic zone.

A strongly developed coastline is the reason for the existence of five secondary bays within Hornsund Fjord: Vestre and Austre Burgerbukta, Samarinvågen, Adriabukta and Brepollen Bay. Within Brepollen, several smaller, inner bays have developed in the forefields of tidewater glaciers. In the northern and eastern parts of Brepollen, glacier valleys are separated by peninsulas. Their relief is generally flat with a relatively big plain. In the southern part of Brepollen, the valleys of the glaciers are separated by longitudinal mountain massifs (Karczewski *et al*. 1984; Moskalik *et al*. 2013; series of Norsk Polarinstitutt topographic maps 1:100 000).

Fjord bathymetry. — Depths surveys in the western and central parts of Hornsund were conducted in 2009-2011 by the teams from University of Silesia and Institute of Oceanology (Polish Academy of Science) using a dual frequency (50 kHz/200 kHz) echo sounder SI-TEX CVS 211 mounted on the s/y *Eltanin* and echo sounders Lowrance LCX-17M and GARMIN GPSmap 526s mounted on inflatable boats. The deepest waters are found in the inner part of Hornsund (Moskalik *et al*. 2013, in press). The depths at the front of Hansbreen and in Austre Burgerbukta reach ~100 m, in Vestre Burgerbukta exceed 170 m and in Samarinvågen – 150 m. Bathymetric data in Brepollen basin were collected during the summer months of 2007 and 2008, using a Lowrance LMS-527cDF type echosounder, coupled with a GPS receiver (Moskalik *et al*. 2013). The region of Brepollen has areas of significant glacier impact (areas occupied at the moment by the Storebreen, Hornbreen, and the central part of the Brepollen), and areas without significant glacier impact (Treskelbukta, and the areas occupied at the moment by the Chomjakovbreen and Hyrnebreen). These correspond respectively to U-shaped and V-shaped valleys (Moskalik *et al*. in press). Maximum depths exceed 140 m in the central part of Brepollen, while the maximal depths near the fronts of glaciers are more typically in the range from 45 m to 92 m (Moskalik *et al*. 2013).

Climate conditions. — The climate conditions of the Hornsund area are typical for the western coast of Spitsbergen (Marsz and Styszyńska 2013). They are influenced mainly by meteorological conditions driven by atmospheric circulation (Niedźwiedź 2013) and the North Atlantic ocean current system (Walczowski and Piechura 2006; Walczowski 2009).

Meteorological observations at the Polish Polar Station (77°00’ N, 15°33’ E and 10 m a.s.l., see attached map for location) give insight into climatological characteristics of the area. The mean annual air temperature for the period of 1979–2006 is -4.4°C. In the recent years of 2009 and 2010 it was above the mean and reached -2.7°C and -3.5°C respectively (Grabiec *et al*. 2012).

Mean July sea surface temperatures in different parts of the fjord have varied from 1.5°C to almost 3.5°C in the last decade (Walczowski, Promińska, unpublished data) probably because of variations in the intensity of inflow of warm Atlantic water into the fjord, and sea ice conditions. Summers are usually ice free, except for brash glacier ice and small icebergs. The first fast ice starts to form at Brepollen in late autumn. Fast ice is only observed in innermost basins of Hornsund (Brepollen, Burgerbukta, Samarinvågen and, in certain years, in Adriabukta and Isbjørnhamna). The winter and spring ice cover in the central part of the fjord varies from year to year. The sea ice pack drifting with the Sørkapp Current from the Barents Sea enters the western and central parts of the fjord and may remain until July. However, this sea ice cover is prone to destruction by very strong east winds, resulting in most of the ice being removed from the fjord (Styszyńska and Kowalczyk 2007; Styszyńska and Rozwadowska 2008; Styszyńska 2009).

Annual precipitation in Hornsund in 1979–2009 was 434.4 mm, ranging between 230.2 mm (1987) to 635.9 mm (1996). The share of winter precipitation is ~60% of total. Rainfall constitutes 44% of the mean annual total, while the solid and mixed precipitation portions are 30% and 26% respectively (Łupikasza 2013). Most of the winds originate from the NE, E and SE directions (more than 80%). The prevailing easterly winds are strengthened by the E-W direction of the fjord. On average, 40 days with wind speed over 15 ms^{-1} occur annually. Strong winds affect the distribution of the snow cover thickness on the glaciers. It is significantly unequal, with higher values in the eastern part of the studied area. Thicker snow cover is along found at higher surface elevations. For instance, the mean snow cover thickness measured on Hansbreen by high frequency radar sounding in spring 2008 was 2.8 m, but varied from 0.5 m near the glacier front to 4.5 m in the accumulation area (Grabiec *et al*. 2011).

Morphometry of glaciers. — The major part of the Hornsund glacial drainage is covered by valley-type tidewater glaciers (Fig. 1). Six of them have shared their accumulation area with other glaciers (Hansbreen, Paierlbreen, Hornbreen, Svalisbreen, Mendelejevbreen and Samarinbreen). Glacier extent increases towards the east. Large tidewater glaciers had low slopes (~1.3–2.2°, Fig. 2). Smaller land based glaciers are usually of a cirque-, apron- or valley-type and are steeper.

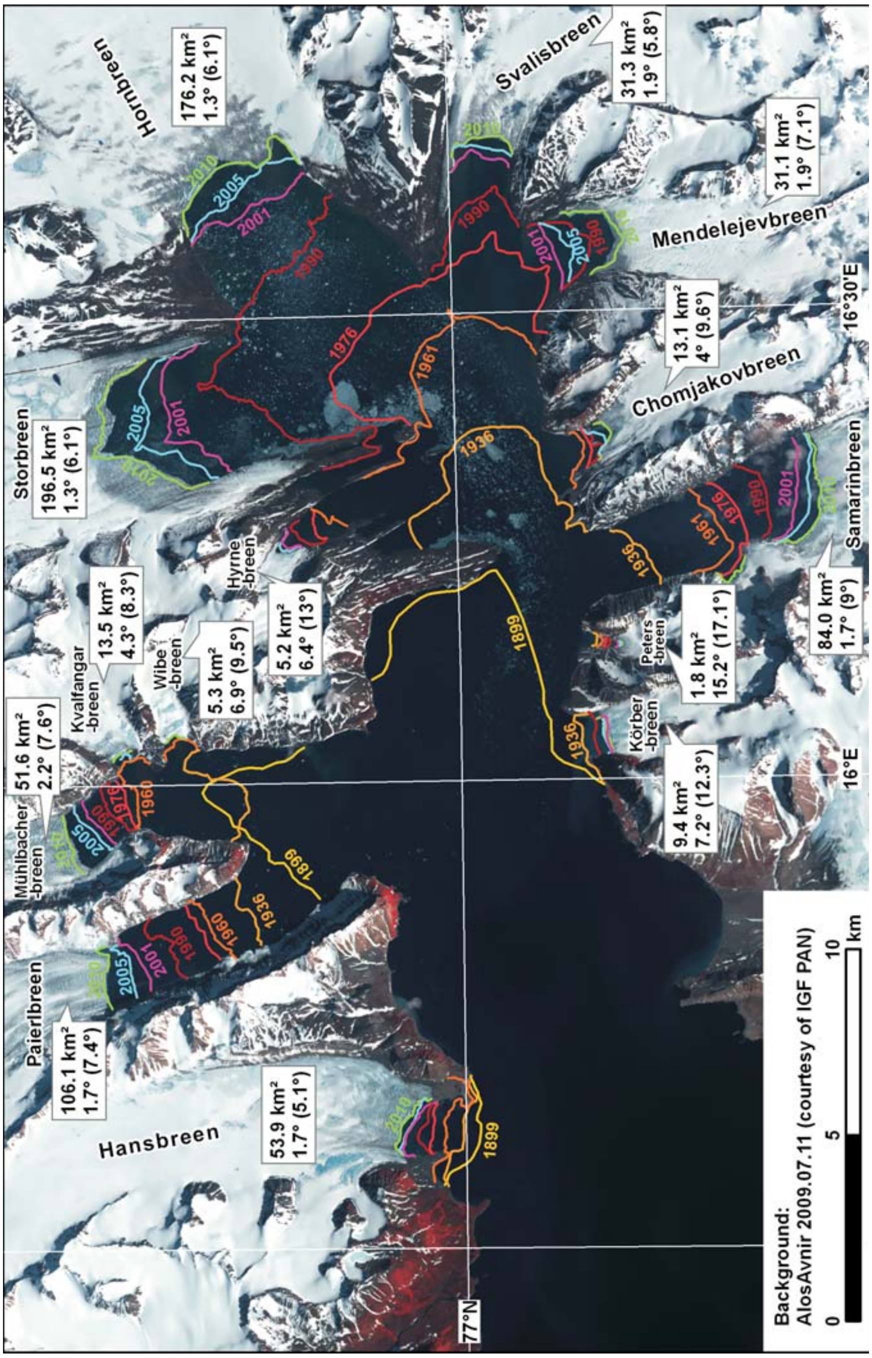

Fig. 2. Post-LIA retreat of tidewater glaciers in Hornsund Fiord and selected morphometric features: glacier area, glacier slope along the centerline and mean slope of the whole glacier surface (in brackets); slope calculated with use of DEM SPOT 2008. For more detailed front positions, the source and accuracy of the data see text and enclosed satellite orthophotomap.

Table 1

Glaciers of the Hornsund basin with selected morphometric features based upon measurements on the geocoded ASTER and Landsat images (2010) and DEM SPOT (2008).

ID	Name	Glacier length [m]	Cliff length [m]	Aspect	Type	Area [km^2]	Average height [m]
124 02	Gåsbreen	6600	–	W	landbased	10.2	407
124 04	Körberbreen	5300	1240	N	tidewater	9.4	317
124 05	Petersbreen	2400	390	N	tidewater	1.8	320
124 06	Eggbreen and Kvasseggbreen	2000	1150	E	tidewater	2.5	304
124 07	Samarinbreen	10600	3960	NW	tidewater	84.0	333
124 08	Chomjakovbreen	7000	1480	NW	tidewater	13.1	313
124 09	Mendelejevbreen	9200	3570	N	tidewater	31.1	222
124 sg8	Signybreen	2700		NW	landbased	1.6	293
124 10	Svalisbreen	10200	2280	NW	tidewater	31.3	232
124 11	Hornbreen	25500	5470	SW	tidewater	176.2	289
124 12	Storbreen	21700	6890	S	tidewater	196.5	287
124 13	Hyrnebreen	3050	1020	SE	tidewater	5.2	241
124 14	Lorchbreen	1600	–	W	landbased	1.2	231
124 15	Wibebreen	4300	650	NW	tidewater	5.3	311
124 16	Kvalfangarbreen	5200	630	SW	tidewater	13.5	277
124 17	Mühlbacherbreen	14050	1820	SE	tidewater	51.6	376
124 18	Paierlbreen	22000	2150	S	tidewater	106.1	370
124 19	Sofiebreen	2050	–	S	landbased	1.0	355
124 20	Hansbreen	15370	1990	S	tidewater	53.9	291

An updated glacier inventory of Southern Spitsbergen has been created. Glaciers were delineated manually from satellite images (geocoded ASTER – Advanced Spaceborne Thermal Emission Radiometer – and Landsat from 2010), field observations and a 2008 digital elevation model (DEM SPOT) from the IPY-SPIRIT Project (Korona *et al*. 2009). Hornsund glacier basin is included in this inventory. Morphological properties are listed in Table 1. The area of tidewater glaciers differs from the inventory by Błaszczyk *et al*. (2009) because the previous work did not include the lateral land based parts of the tidewater glaciers, and the basins were delineated by a semi-automatic method. Glacier lengths reflecting retreat since the previous inventory was compiled, and delineation of accumulation boundaries were improved using the SPOT DEM.

There are 26 small landbased glaciers and glaciarets in the area (Fig. 1). Consistent with the first inventory of Svalbard glaciers (Hagen *et al*. 1993) we treat each drainage basin separately, although we present data only for glaciers exceeding ~1 km^2 in area. Smaller ice masses were also measured (their total area amounts to 7 km^2) and given new identification numbers (124_sg1, 124_sg2, etc;

"sg" stands for small glacier) but are not listed individually in the Table 1. Eggbreen and Kvasseggbreen, confluent with Samarinbreen in the past, are considered here as separate ones, owing to a progressive recession of the latter, but their retreat rate is not analyzed (*cf.* enclosed satellite orthophotomap).

Surges of glaciers are common in Svalbard (Liestøl 1969; Dowdeswell *et al.* 1991; Hagen *et al.* 1993), although there are disagreements on fraction of surging glaciers within their total number. According to Hamilton and Dowdeswell (1996) 36% of Svalbard glaciers are surge-type, while Jiskoot *et al.* (1998) estimated their number on 13%, Błaszczyk *et al.* (2009) on 40–45%. Other authors suggest that up to 90% of the larger glaciers probably are surge-type ones. Surges result in a large ice flux from high to low elevation portions of a glacier, usually accompanied by a rapid advance of the glacier front and, in the case of tidewater glaciers, by increased iceberg production.

In the case of Hornsund, eight glaciers experienced surges during the study period (Table 2). The influence of those surges on glacier fluctuations is discussed later.

Table 2

Surges of glaciers in Hornsund Fjord.

ID	Glacier	Surge
124 02	Gåsbreen	at the end of LIE – indirect evidences, assumed from Geer (1923)
124 04	Körberbreen	1938 (Hagen *et al.* 1993), ~1960 (Jania 1988)
124 09	Mendelejevbreen	~1995–2002 (Sund e*t al.* 2011)
124 10	Svalisbreen	indirect evidences
124 11	Hornbreen	Pälli *et al.* 2003. possible 50s or 60s 20th century – indirect evidences
124 12	Storbreen	1958 K. Birkenmajer – personal com. possible ~1990 – indirect evidences
124 17	Mühlbacherbreen	1961, 1990 (Sund *et al.* 2009) – indirect evidences
124 18	Paierlbreen	~1993–99 (Jania *et al.* 2006)

Data and methods

In our study we analyzed glacier retreat rate by measuring the average ice-marginal retreat rate, *i.e.* rate of diminishing of the glacier area in km^2 per year, and width-averaged linear retreat rate (Shild and Hamilton 2013) *i.e.* area of the glacier terminus retreat per year divided by the average width of glacier at the cliff. According to Schild and Hamilton (2013) and Howat *et al.* (2008) this method allows to quantify calving-front changes that often occur asymmetrically across the width of the terminus and gives a more complete record of terminus change than mapping a linear position to evaluate the distance of advance or retreat along the center line.

Different sources of data were used to examine fluctuations of the tidewater glaciers during the twentieth and twenty-first centuries. The first map of the Hornsund coast showing glacier fronts is a marine chart drawn to a scale of 1:200 000, without meridians and parallels. It was prepared during the Austro-Hungarian North Pole Expedition 1872–1874, when a support ship "Isbjørn" explored Hornsund Fjord and the coasts of Southern Spitsbergen (Weyprecht 1875). The majority of the mapped coastal area received geographical names related to the sponsors of the expedition, the Austro-Hungarian emperor's family, the leaders and members of the expedition (Hoel 1991). Because of the missing meridians and parallels, we considered the accuracy of this chart too poor to be included in this study.

Ice front position of the tidewater glaciers in Hornsund was examined during the following periods: 1899–1936–1960/1961–1976–1990–2001–2005–2010 (Fig. 2). For the period 1899–1990, we used several archival maps of varying accuracy, which was sometimes difficult to assess. All the topographical maps were digitally scanned, geocoded using ground control points and reprojected (when needed) into UTM 33X system on the WGS 84 datum. For the period 1976–2010, we used optical and radar satellite images. The details on source and data accuracy are collected in the Table "The front position changes" on the enclosed satellite orthophotomap.

For glacier extents in 1899, we used a scanned map (Wassiliew 1925) from the Russian-Swedish expedition to Spitsbergen. During that expedition the meridian arch was surveyed and a triangulation network was established on the southern and eastern coasts of Spitsbergen. Despite the small scale (1:200 000) and low accuracy of cliffs positions on Vasiliev's map (~300 m), it is still valuable, due to lack of any other data from this time.

Glacier extents in 1936 were derived from topographic maps prepared and published by the Norsk Polarinstitutt (NP) in 1986–1994 at a scale of 1:100 000 based on oblique aerial photos taken in 1936–1938. The accuracy of these maps is very inhomogeneous and may vary from ten meters up to a few hundred of meters (H.F. Aas – 28 June 2011). Nevertheless, oblique photos from flights along the coastline are giving higher accuracy (~100 m) of ice cliff positions than for distant inland areas.

Front positions in 1961 for a few glaciers are plotted on the NP 1:100 000 map (C13 – Sørkapp, published in 1986). Due to revealed errors of front position of some glaciers for this period on the NP maps, in our study the cliffs lines in the western part of the Hornsund Fjord in the 1960s were plotted using aerial photographs form the S60 and S61 series kindly provided by the NP. Fronts were measured photogrammetrically with Erdas software. For the rest of the region, topographical maps were used (Barna 1987).

The cliff positions based on the NP aerial campaign in 1990 were plotted on both the re-edited series of NP maps (1:100 000) from 1986 and 1994, and on the maps issued in 2007 and 2008. Due to some discrepancies between both of editions, we checked fronts positions with the orthophotomap prepared for the Polish Polar Station area (Kolondra 2003 – unpublished data) on the basis of 1990's aerial photos kindly provided in digital form by the NP. Terminus positions were in accordance with the latest map edition (2007, 2008), therefore these maps were used to determine front positions of the tidewater glaciers in 1990 for the whole fjord.

Glacier extents in the period 1976–2010 were determined using satellite images: multispectral Landsat2 MMS (resolution 60 m), ALOS AVNIR (10 m, courtesy of Institute of Geophysics, Polish Academy of Sciences), ASTER (15 m), and panchromatic bands of Landsat-7 (15 m). Landsat images were freely acquired from the USGS EarthExplorer web page (http://earthexplorer.usgs.gov). Despite of the failure of Scan Line Corrector on ETM+ in May 2003, images were still usable for mapping glacier margins. For precise measurements of the dynamic changes of the glaciers, both orthorectified and non-orthorectified images needed geometrical correction in order to precisely map changes. We used the ALOS AVNIR image from 2009 (10 m resolution) as the reference image. In the first stage the ALOS AVNIR image was co-registered using the NP topographic maps 1:100 000 (2007, 2008), and then the other satellite images were co-registered to the ALOS AVNIR image. Generally, the same ground control points close to sea level were applied in the co-registration process.

We show additional front positions for 1918, 1949 and 1984 on the enclosed orthophotomap. These positions are only available for a few glaciers and come from maps of unknown accuracy, and we do not use them for computing twentieth century recession rates. Additional front positions from ASTER images, ALOS AVNIR and Landsat acquired in the last decade are also presented. ERS SAR winter images from 1992, 1995 and 1999 were digitized and useful in the case of surging glaciers (*cf.* Figs 6, 7).

One of the factors influencing the accuracy of the retreat estimates is seasonal fluctuations of tidewater glaciers. Seasonal oscillations on Spitsbergen were recognized at the end of 19th century by Gerhard de Geer (Hoppe 1959) and confirmed by a systematic terrestrial photogrammetric record of Kongsvegen in 1964/1965 (Voigt 1979) and others authors (Jania 1988; Mansell *et al*. 2012). Nowadays it is well known that tidewater glaciers retreat rapidly during summer due to intense calving and advance in winter/spring period due to cessation of calving. In Svalbard, seasonal oscillations of ~250 m have been observed on Kongsvegen (Voigt 1979) and ~50–190 m on Hansbreen.

In our study, the annual cycle of front fluctuations of tidewater glaciers in Hornsund was observed using 45 SAR images (Fig. 3). Our results confirm that seasonal oscillations of glaciers fronts along the centerline can be significantly larger than their average long-term retreat. Retreat begins in June or July, depending on the year. The maximum of calving and the fastest retreat take place in August–November. The maximum retreat position occurs in December and January, when calving ceases. During spring time (February–June) the glacier fronts advance with very sporadic calving. The amplitude of the seasonal oscillations in Hornsund measured on SAR images was on the order of 0–460 m, depending on the year and the glacier and reached a maximum of 600 m for post-surge stage of Paierlbreen (Fig. 3). The

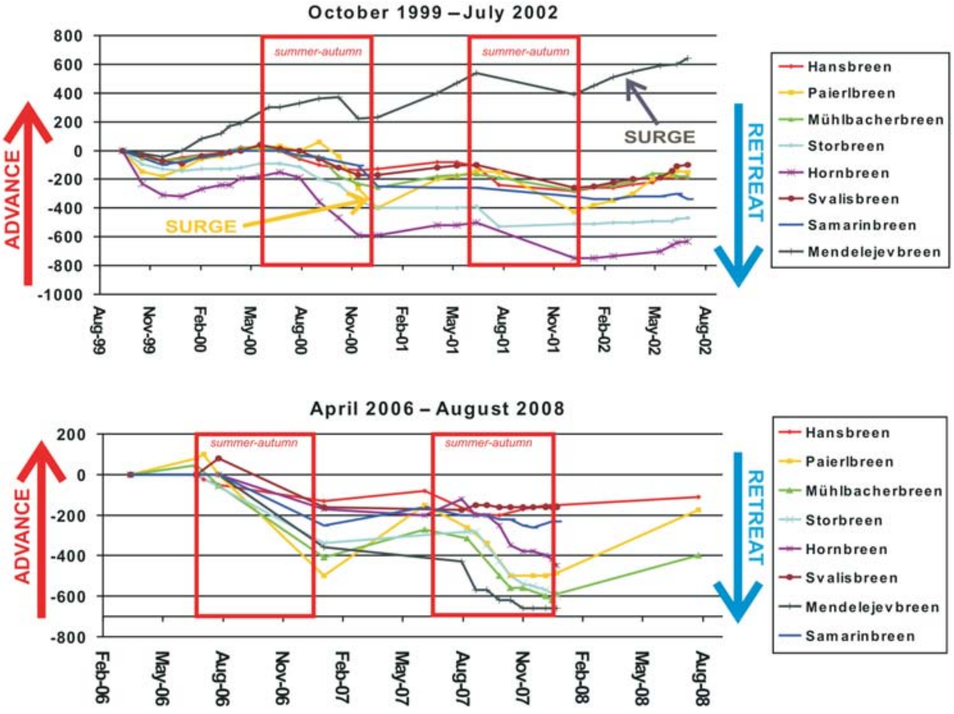

Fig. 3. Seasonal fluctuations of tidewater glaciers fronts in Hornsund basing upon ERS SAR (1999–2002) and Envisat ASAR (2006–2008) images.

average seasonal oscillations amounts to ~160 ma^{-1}. Results are in a good accordance with field observations of Hansbreen with the Garmin panoramical radar GMR 18HD and the Riegl FG21-LR laser distance meter in 2010–2012. The amplitude of Hansbreen fluctuation varied between 50–190 m from year to year.

In this paper we do not take seasonal oscillations into account because terminus positions used to calculate twentieth century long-term retreat rates come only from summer observations *e.g.* from period of transition from advance to retreat and from the first stage of recession. According to measurements basing upon satellite radar (SAR) images, the average retreat of all tidewater glaciers in Hornsund in two summer months amounts to ~45 m. Results from Hansbreen studies with laser distance ranger and horizontal panoramical radar show similar values. Thus, the error of front position delineation in twentieth century caused by seasonal oscillations is similar to reliability of older data sources and ~2–3 time larger than reliability of delineation coming from satellite images resolution (±15 m, *cf.* satellite orthophotomap). Also, one has to remember that the actual date in summer when the minimum front position is reached is variable from year to year. Therefore, glaciers positions at the turn of the 21st century should be considered carefully as the Landsat image used for determination of fronts position in 2001 was acquired in late-June, *e.g.* in period of maximal glaciers extent, as we know from the Hansbreen monitoring by the time lapse photos. The Hansbreen data might be treated as a proxy for other Hornsund tidewater glaciers, when compared to remote sensing data. Therefore, the estimate of retreat (*cf.* Table 4) seems to be underestimated for period 1990–2001 and overestimated for years 2001–2005, but the general trend of increase of retreat rate in last decades is still undisputed.

Results

Average ice-marginal retreat rate. — Long-term changes in tidewater glacier front position (1899–1936–1960/1961–1976–1990–2001–2005–2010) are presented in Figs 2, 4 and Tables 3, 4. Detailed terminus positions are plotted on the enclosed satellite orthophotomap. We examined the ice-marginal retreat rate for the whole Hornsund basin, without distinguishing between individual glaciers, because the borders between confluent basins are not well known. All the tidewater glaciers terminating in Hornsund Fjord have been retreating since 1899 except for a few surge episodes. Reduction in the general area of all tidewater glaciers between 1899 and 2010 is difficult to evaluate because of questionable data on their landbased parts termini. Therefore, the rate of the retreat was calculated in two stages (Table 3). Firstly, the coastline of Hornsund Fjord was delineated on the basis of a 2009 ALOS AVNIR image and then the extents of the glaciers over the sea area in consecutive time-spans were measured. At the second stage, recession rates of the landbased parts of the tidewater glaciers were evaluated between 1936 and other years for which we had uniform satellite data for the whole region. Estimated accuracy in Table 3 is the error resulted from the reliability of source data *e.g.* errors of glacier front delineation (*cf.* satellite orthophotomap – Table "Source of data").

Table 4 shows the average retreat rate of Hornsund glaciers since the last LIA.

Since the termination of the Little Ice Age, six large glaciers in our study underwent a surge event and large advance between 1899–2010 (Table 2), followed by the retreat. Area loss at the marine margins between 1899 and 2010 is ~142 km^2 with an average retreat rate of 1.3 km^{2}a^{-1} (Tables 3, 4). Area loss from the terrestrial portions of tidewater glaciers between 1936 and 2010 equals ~30 km^2 with the average rate of 0.3 km^{2}a^{-1}. The total area of glacier cover in Hornsund decreased by 172 km^2, at an average rate of 1.6 km^{2}a^{-1} ±0.2 km^{2}a^{-1}. The retreat rate increased from ~1 km^{2}a^{-1} in the first part of the 20th century up to ~3 km^{2}a^{-1} in the first decade of 21th century.

Discussion

Most of the decrease in tidewater glacier area in Hornsund Fjord is due to retreat of the marine margins (*cf.* Table 4). Results from Hornsund conform in gener-

Table 3

Total area (in km^2) of glacier retreat between 1899 and 2010 in the Hornsund Fjord basin and estimated accuracy for particular periods.

Periods	1899–1936	1936–1960/61	1960/61–1976	1976–1990	1990–2001	2001–2005	2005–2010	1899–2010
Area of glacier retreat at the marine margin	27.8	30.5	15.9	28.8	20.0	7.0	11.8	141.8
Area of glacier retreat over the land area	Lack of data	14.8		8.4		7.1		30.3
Estimated accuracy	±7.1	±4.4	±3.4	±2.7	±2.1	±0.8	±0.9	±10

Table 4

Ice-marginal retreat rate (in km^{2}a^{-1}) of tidewater glaciers terminating into Hornsund Fjord.

Periods	1899–1936	1936–1960/61	1960/61–1976	1976–1990	1990–2001	2001–2005	2005–2010	Average
Retreat rate at the marine margin	0.8	1.2	1.1	2.1	1.8	1.8	2.4	1.3
Retreat rate over the land area	Lack of data	0.4	0.4	0.3	0.3	0.8	0.8	0.3
Total retreat rate	0.8	1.6	1.5	2.4	2.1	2.6	3.2	1.6
Estimated accuracy	±0.2	±0.2	±0.2	±0.2	±0.2	±0.2	±0.2	±0.2

ally with those from other regions of Svalbard. Most of the glaciers in Svalbard experienced retreat and low-elevation thinning combined with front retreat (Moholdt *et al*. 2010). According to Ziaja (2001) the recession of almost all of the glaciers in Sørkappland (Southern Spitsbergen) since 1936 has been accompanied by a decrease in thickness up to 50 m, despite the increase of annual precipitation in the Svalbard region by 15–25% during the last 80 to 90 years (Førland and Hanssen-Bauer 2003). The equilibrium-line altitude in Sørkappland has risen by 100–200 m (Ziaja 2001). A similar geometric change to Southern Spitsbergen (decrease in area throughout the past century and negative surface mass balances) has been also observed recently in many other regions of the Arctic *e.g.* in Canada (Sharp *et al*. in press), Alaska (Arendt *et al*. 2008) and Greenland (Wouters *et al*. 2008).

Glacier recession *versus* climate conditions. — The retreat of Hornsund tidewater glaciers from their Little Ice Age position, similar to the retreat of other Svalbard glaciers, occurred sometime after 1920 as a result of a sudden temperature increase, known as the early 20th century warming present in all long-term Norwe-

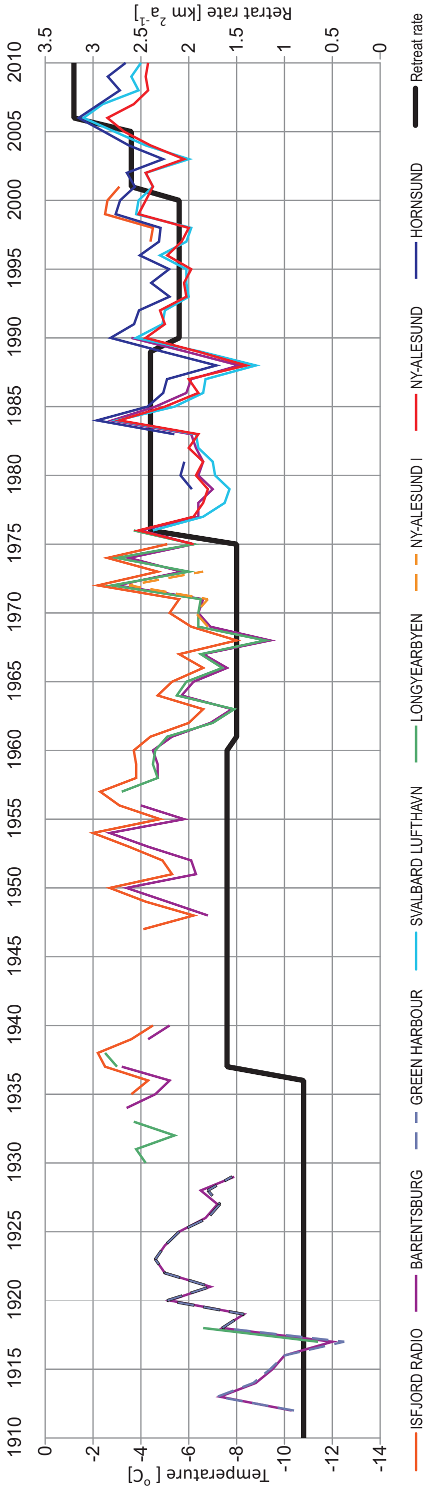

Fig. 4. The course of the mean annual air temperature in Spitsbergen meteorological stations (based on data from www.eklima.no) and the ice-marginal retreat rate of tidewater glaciers in Hornsund. Note the increase in the temperature and retreat rate during the last decade.

gian and Svalbard temperature series (Nordli and Kohler 2003). For example, the linear increase of air temperatures reconstructed for the Svalbard Airport station in Longyearbyen was +0.183°Ca^{-1} for the period 1912–1930. The period between 1931–1960 was cooler (trend of -0.066°Ca^{-1}) before warming again (+0.049°Ca^{-1}) between 1960 and 2000 (Hansen-Bauer *et al*. 2006). Similar trends were observed at other meteorological stations in Spitsbergen (Fig. 4). The record at Hornsund is shorter (started in 1978) but is consistent with the Longyearbyen record for the period of overlap (r = 0.98). Mean annual air temperatures at Hornsund showed a distinct linear increase (+0.097°Ca^{-1}) between 1979–2010 (Grabiec *et al*. 2012). Data for the most recent decade (2000–2010) show even higher trend +0.16° Ca^{-1}, although statistically unreliable due to the short time span of the data.

The recession rate of glaciers during the study period is related to the course of the mean annual temperature in Spitsbergen. An increase in the temperature is followed by an increase in the retreat rate (Fig. 4), and the decrease in the temperature in the 1960s and 90s is accompanied by a slower retreat rate. There is no relationship between temperatures and the retreat rate in the 1970s and 80s, but that might be an artifact of the time series not overlapping. A more detailed study on a correlation between air temperature and the retreat behavior requires an additional data on the front positions.

The records of terminus positions contain internannual variability, characterized by different amounts of retreat and even some periods of terminus advance (*cf.* 2005 and 2010 in enclosed satellite orthophotomap). The results reflect and coincide with the temperature of the sea in those years. Water-column average temperature close to the West Spitsbergen coast seems to influence air temperature, as suggested by Walczowski (2009), Walczowski and Piechura (2006, 2011). Data on water temperature in the fjord were collected by the Institute of Oceanology Polish Academy of Sciences from the r/v *Oceania* every summer, between 22–29 July in the period 2001–2012 (Walczowski, Promińska, unpublished data). Mean temperatures of surface water were collected along two section of fjord axis: Hornsund and Brepollen presented in Fig. 1. Near-surface water (0–32 m depth) temperatures in Hornsund in 2005, 2010 and 2011 were 0.42°C, 0.9°C and 0.8°C (respectively) cooler than the eleven-year average (2.6°C). In Brepollen, years 2005 and 2009–2011 were characterized by lower sea temperatures than in adjacent years. Cooler temperatures in 2005, 2010 and 2011 were also observed for the intermediate waters (32–100 m) in Hornsund. Lower sea temperatures could explain lower air temperatures and less intense calving and glaciers retreat in those years. The best studied glacier is Hansbreen, where front positions have been surveyed using a laser distance meter. According to many observations (Jania 1988; Vieli *et al*. 2002; O'Leary and Christoffersen 2013) and recent studies of Hansbreen (M. Ciepły – personal communication, 24 September 2013) development of notch at the waterline melted out by sea waves is triggering calving of the ice cliff face of grounded tidewater glaciers. Warmer sea water leads to more intense melting of ice at and below sea surface and thereafter more intense calving. Waves are stimulating turbulence at the sea-ice interface and facilitate heat transfer to the ice wall. Such mechanism was proved by observations of Hansbreen ice cliff behavior in summer 2011. Hornsund was blocked by sea ice pack migrated from the Barents in late July 2011 (M. Ciepły – personal communication, 24 September 2013). Sea ice lowered temperature in upper layers of sea and damped down height of waves. In consequence, contrary to the general trend, calving intensity was low and the seasonal retreat reached only 90 m. In consequence, Hansbreen front did not reach even minimal summer position from 2009.

In contrast, warm Atlantic water intake to the fjord in 2012 (Walczowski, Promińska, unpublished data) increased sea water temperature and summer calving of Hansbreen was intensive, causing the seasonal retreat by 190 m. Sea temperatures in Hornsund were 0.32°C higher than the long-term average. Also the number of PDD (positive degree days) in 2012 was the highest since 2002. Such observations confirm theoretical studies on influence of submarine ice cliff melting on calving by O'Leary and Christoffersen (2013), which suggests that undercutting of the ice front due to frontal melting can drive calving losses up to ten times the mean melt rate. Sea temperatures in Hornsund are well correlated ($r = 0.67$) with the PDD index calculated from measurements at the Polish Polar Station. We can conclude from the above that higher summer air temperature influences glacier melting and thus water supply to its bed. For this reason subglacier water pressure increases and affects basal sliding and in further consequence calving speed. Additionally, melting of ice cliff at the contact with warmer sea water stimulate calving and glacier retreat. Recent studies of tidewater glacier fronts variability in Greenland confirm connection of significant retreat of glaciers with warm oceanic conditions associated with increased transport of subtropical waters (Motyka *et al.* 2003; Seale *et al*. 2011), although Schild and Hamilton (2013) not find clear links between seasonal retreat and air and sea surface temperature conditions.

Retreat of Hornsund glacier in Svalbard-wide context. — There is general lack of data on the long-term retreat of the tidewater glaciers for the whole archipelago, except older works of Koryakin (1975b, 1985). Furthermore, comparing glacier retreat rates between different studies is complicated by the different intervals used, and whether authors reported if they were presenting width-averaged linear retreat rates or linear retreat rates measured along centerlines. Nevertheless, the range of linear retreat rate of the glaciers from the LIA position in Hornsund is in good accordance with the estimates by other authors (Ziaja 2001; Svendsen *et al*. 2002; Carlsen *et al*. 2003; Pälli *et al*. 2003; Rachlewicz *et al*. 2007; Dowdeswell *et al*. 2008; Grześ *et al*. 2009; Ziaja *et al.* 2011).

Above reports concern only a few individual glaciers or regions and do not show a general retreat of Svalbard tidewater glaciers. To enable comparing retreat of Hornsund glaciers with other part of Svalbard we measured width-averaged linear retreat rate for the whole archipelago in the first decade of 21th century, basing on the set of ASTER and Landsat images from 2000–2010. We have not taken into consideration the glaciers of Nordaustlandet and actively surging glaciers in this period. Fig. 5 presents the distribution of the retreat rate of the tidewater glaciers in Svalbard. The average width-averaged linear retreat rate of 128 Svalbard glaciers in time spans of 5–10 years ranges from 0 to 260 ma^{-1} with an average value of ~45 ma^{-1} ±15 ma^{-1}. 43 glaciers were characterized by distinguishing recession. For the rest of tidewater glaciers any noticeable front position changes were detected on optical satellite images. The average retreat rate of all the tidewater glaciers in Hornsund in 2001–2010 amounts to ~70 ma^{-1} ±15 ma^{-1} and is higher than the Svalbard-wide average. One can speculate on importance of increased amounts of heat transported to the fjord by the waters of West Spitsbergen Current in recent years (Walczowski and Piechura 2006, 2011). Hornsund is the southernmost fjord of Spitsbergen with wide mouth opened to the ocean. Furthermore, there is no bedrock *sill* or shoal in the entrance to the fjord reducing intakes of warmer Atlantic waters to it inner part. High recession rate of Hornsund tidewater glaciers is in agreement with results of Nuth *et al*. (2010) showing that Southern Spitsbergen is characterized by the most negative geodetic mass balance on the Svalbard Archipelago.

Surge events and water depth as a factor in glacier fluctuations. — Tidewater glaciers are sensitive to small perturbations causing an increase in calving,

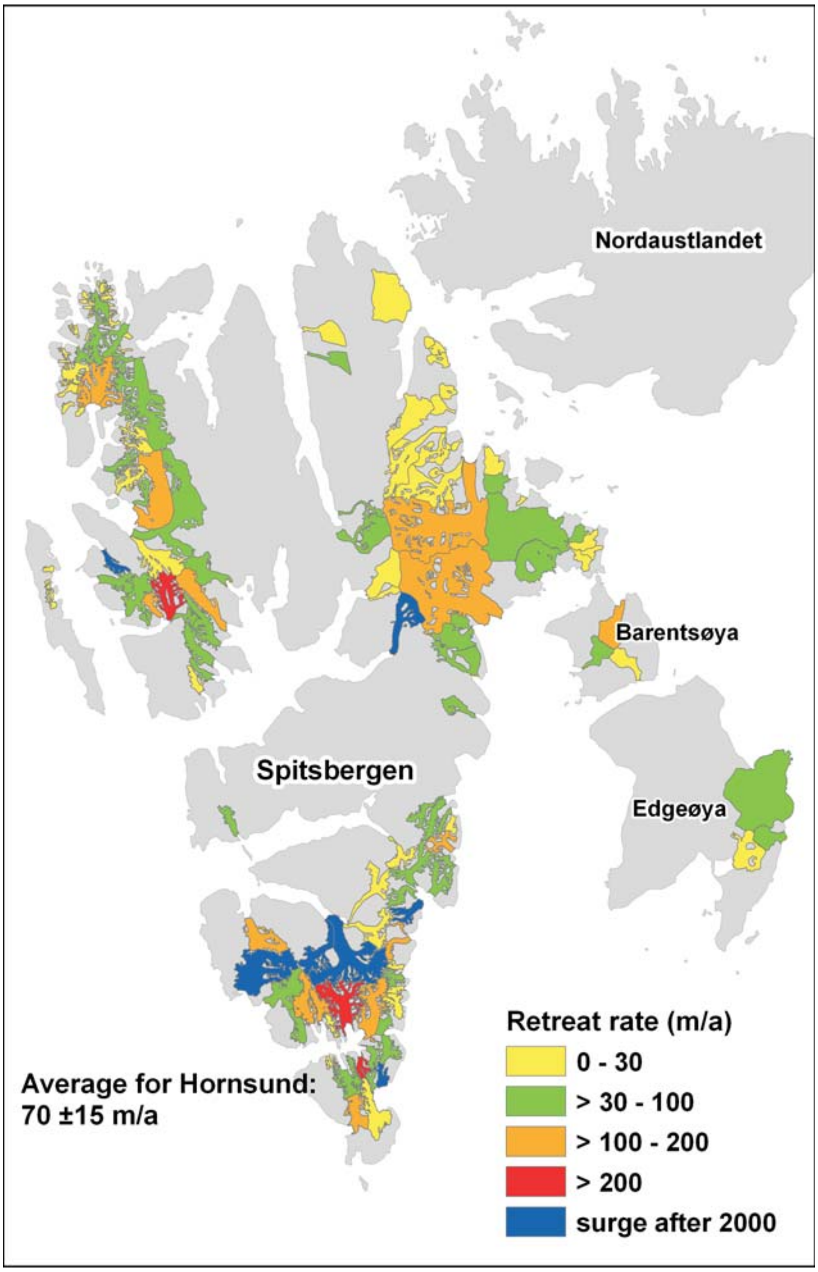

Fig. 5. Distribution of the retreat rate of tidewater glaciers over Svalbard Archipelago (without Nordaustlandet).

and they react to fluctuation in ice flow velocity, water depth and its temperature at the ice cliff (Meier and Post 1987; Jania 1988; Vieli *et al*. 2002, 2004; Rachlewicz *et al*. 2007). Surges complicate the extraction of climate signals directly from gla-

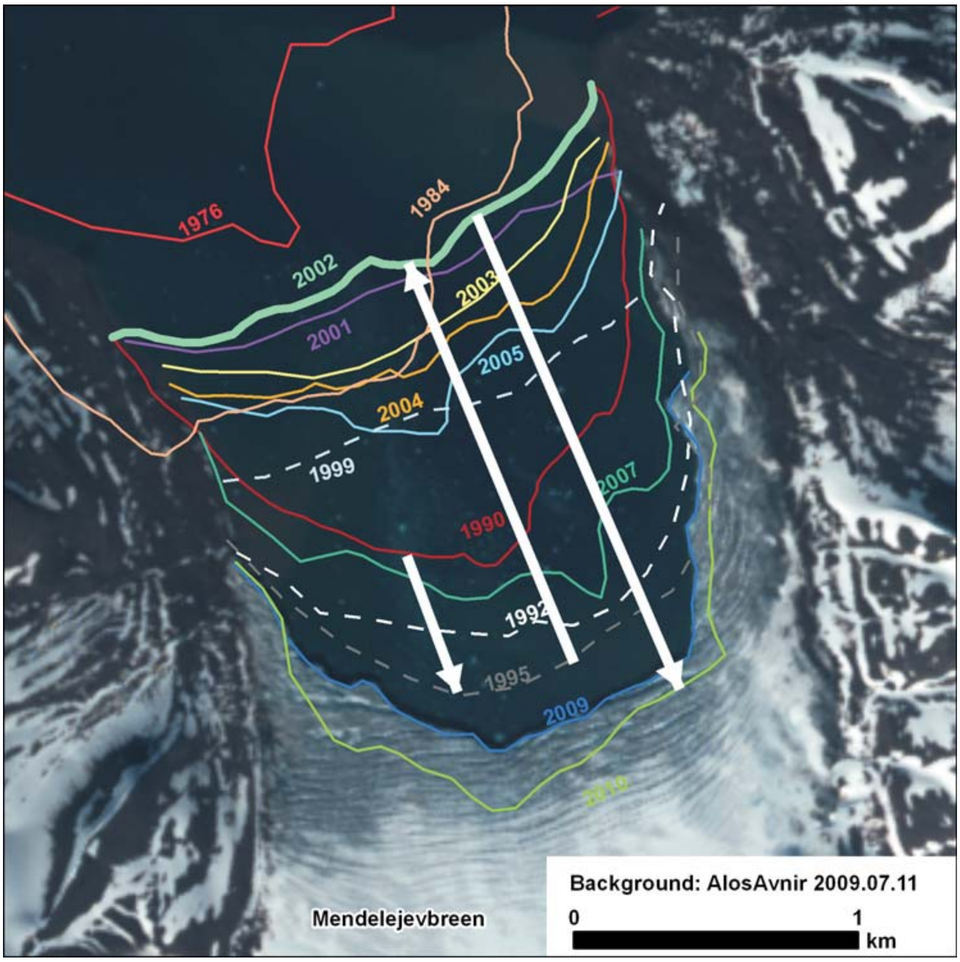

Fig. 6. Front positions of Mendelejevbreen; dashed lines – positions from ERS SAR winter images with an accuracy of ±25 m; arrows show the pre-surge retreat, surge advance and post-surge significant retreat.

cier terminus fluctuations, because they are due to internal changes in the dynamics of the glacier system rather than climatic impulse (Meier and Post 1969).

Seven out of fourteen tidewater glaciers in Hornsund underwent surges at some point in the study period (Table 2) based on a direct observation or indirect evidence. The recent behavior of Paierlbreen and Mendelejevbreen is largely explained by two contemporary surge events, together with fjord bathymetry. The surge of Mendelejevbreen and terminus advance occurred between ~1995 and 2002, although detailed information on the start and end of the surge is not available (Fig. 6). The glacier moved ~1.5 km forward in period 1995–2002 with the ice-marginal advance 0.33 km^2a^{-1} (linear advance on the centerline by 220 ma^{-1}). After the surge glacier front retreated 1.8 km in period 2002–2010. The ice-marginal retreat increased sig-

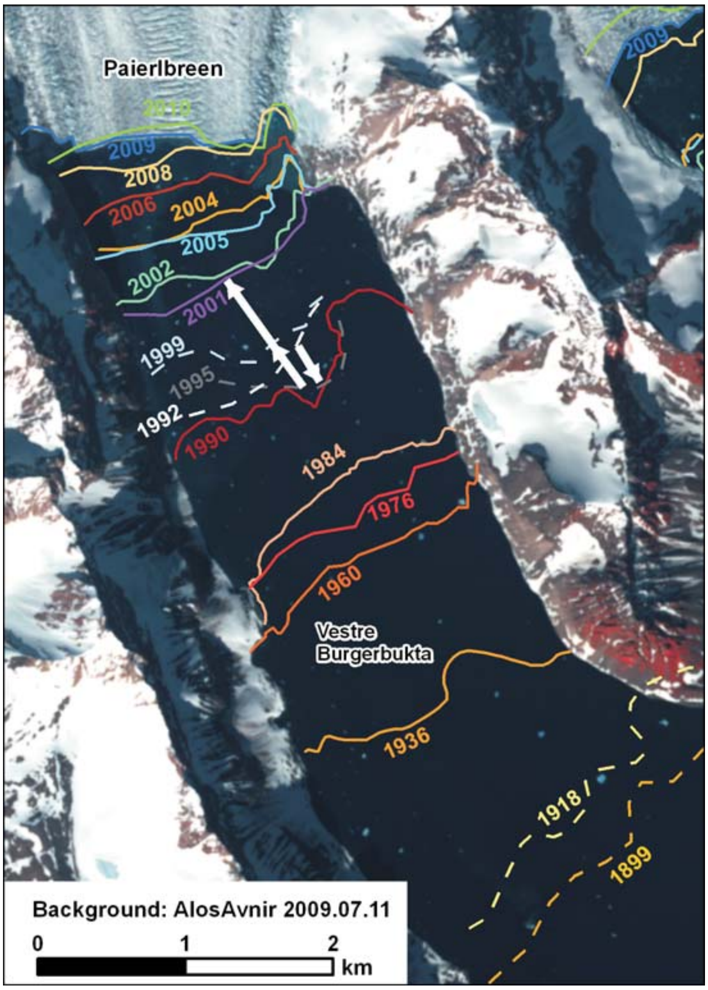

Fig. 7. Front positions of Paierlbreen; dashed lines for 1992, 1995 and 1999 – positions from ERS SAR winter images with an accuracy of ±25 m; arrows show the front during the surge.

nificantly up to 0.36 km^{2}a^{-1} (linear retreat ~250 ma^{-1}), mainly due to the intensive calving caused by the highly crevassed surface of the glacier and retreat from pinning point at the submarine moraine ridge (depth ~45 m) to deeper water (60–80 m). That relation of calving to sea depth is well known (Mercer 1961; Meier and Post 1987). The fastest retreat occurs when the glacier front terminates in relatively deep water (Brown *et al*. 1982; Jania 1988; Carlsen *et al*. 2003). Although the driving factor here is not the water depth itself but the terminus height above buoyancy (Van der Veen 1996; Vieli *et al*. 2002). In the flotation model, the part of the terminus where the ice thickness is below the critical thickness calves off because the ice can no longer resist the buoyancy force (Van der Veen 1996). Assuming average thickness of glaciers fronts in the archipelago on 100 m (Dowdeswell *et al*. 1984;

Dowdeswell 1989; Hagen *et al*. 2003; Błaszczyk *et al*. 2009) the sea depth when glaciers reach the flotation amounts to ~90 m.

The surge of Paierlbreen occurred between 1993 and 1999 based on observations by scientists working in the vicinity of the Polish Polar Station. ERS radar images (Fig. 7) showed that there was barely any advance of the terminus during the surge. Only a small part of the front advanced between 1992 and 1995. Glacier retreated continuously since 1995 up to 2010 with the ice-marginal retreat by 0.19 km^2a^{-1} (linear retreat on the centerline ~130 ma^{-1}). Recession following the surge was probably the result of very intensive calving due to the highly crevassed glacier surface and very deep water in the central part of Vestre Burgerbukta (up to ~170 m), significantly larger than value when glaciers reach flotation.

Surges and fjord bottom topography had a significant influence on the past and future deglaciation of the region. In general, the glaciers in the eastern part of Hornsund are characterized by much larger area wastage than in the western part. During the first early surge of Hornbreen system the glaciers advanced and large masses of ice moved to the ablation area. Front position was stabilized by Treskelen peninsula and shallow water nearby. In the same area the glacier valley is also significantly narrower between Hyrnefiellet and Påskefjella mountains than upstream. Those topographic conditions anchored the advanced tongue for longer time. Faster retreat started after significant thinning of glacier frontal zone due to superficial melting and in consequence retreat to deep water of Brepollen (over 140 m, Moskalik *et al*. 2013). According to Pälli *et al*. (2003) in the last 100 years the volume of Hornbreen and Hambergbreen glacier system decreased by 37–50% and the glaciers are unable to build up again their mass in the reservoir-area for a new surge due to low altitudes of accumulation zones. This is supported by our analysis of Envisat ASAR image from April 2004 which shows that firn lines in the eastern part of southern Spitsbergen are located very high in the cirques of the glaciers. That refers to a very small accumulation area and no chance for building up reservoir area for a succeeding surge in current climate conditions.

From above, two types of surge consequences could be distinguished: (a) faster flow of semi-grounded glacier to deep water (>90 m) is usually not reflected by front advance and intense ice mass transfer from the upper part of glacier is rapidly lost due to massive calving; (b) surge advance to shallower water (40–60 m deep) is pushing of bottom sediments building up a submarine shoal bedrock which usually appears to be new pinning point stabilizing terminus position. After considerable thinning of the tongue due to superficial melting and retreat from the pinning point to deeper water, fast calving could start facilitated by weaker structure of the glacier broken by dense net of superficial and bottom crevasses from the galloping stage surge. Bottom undulations of bare bedrock are playing similar role for stabilization of tidewater glacier fronts.

In general, all the examples show that the surge and a complicated geological structure determining fjord topography (the valleys height and water depth) have a significant influence on the overall mode of the fjord deglaciation. Therefore, one should remember about the importance of surge events for glaciers geometry (fast advance and retreat during ~two, three decades) when analyzing long-term glaciers fluctuations. According to Sund *et al.* (2009) majority of current Svalbard glaciers are of surge type so fast retreat after active phase of surge may be misinterpreted as a rapid response to climate change. We can suggest that only retreat rate of non surging tidewater glaciers or glaciers during quiescent phase reflects climate signal.

Conclusions

Fluctuations of tidewater glaciers in Hornsund over the last ~110 years were reconstructed based on archival maps, terrestrial surveys, and aerial and satellite remote sensing. Seasonal fluctuations of glacier fronts are superimposed on a pattern of multidecadal recession. The maximum seasonal extent of glaciers occurs in June or July while the minimum position usually occurs in early winter (November–December). These seasonal changes complicate the interpretation of long records of front positions.

We discuss the dominant factors governing observed fluctuations of tidewater glaciers in the Hornsund region. Climate fluctuations, glacier morphometry, bedrock topography and surge events were taken into consideration. Results of our studies are leading to following conclusions:

- Tidewater glaciers in Hornsund have lost ~142 km^2 along their marine margins and ~30 km^2 along their terrestrial margins between 1899–2010. A clear acceleration of retreat is noted, from ~1 km^2a^{-1} in the early twentieth century to ~3 km^2a^{-1} in the last decade. Large glaciers with low slopes, such as Hornbreen, are major contributors to the accelerating shrinkage of ice masses in the Hornsund region. The magnitude of retreat of land-terminating glaciers, or the lateral margins of tidewater glaciers is much smaller.
- Recession rate reflects complex of factors related to a climate signal via mass balance of glacier and its dynamics. Air temperature changes influencing faster melting and increase of bed lubrication by water, and thus faster flow and calving. Recent studies suggest importance of sea water temperature related to inflow of warmer Atlantic waters to the region and influencing both air temperatures and directly melting at the ice cliff – sea interface, what stimulate calving intensity. Additional observational data and studies of mechanisms is needed.
- Fjord bathymetry and topography play an important role in modulating terminus position change, as shown by observations confirming the classical relation between sea water depth and glacier retreat rate.
- Surge events with frontal advance interrupt the response of glaciers to climate forcing. Advance of ice cliff as result of surge can be observed for ground tidewater glaciers, while surge to deep water couldn’t be noted in the front position

due to massive calving in time of surge. In the first case fast calving and retreat could start facilitated by crevassed surface and bottom of glaciers, after front thinning and retreat from the pinning point to deeper water.

- Tidewater glaciers in Hornsund are retreating faster (~70 $\mathrm{ma^{-1}}$ on average) than glaciers elsewhere on Svalbard (~45 $\mathrm{ma^{-1}}$ on average). The regional maritime climate and exposure to relatively warm Atlantic waters, together with local topographic conditions, are likely explanations for this difference. We conclude that glaciers in this region are more sensitive to influences of climate-oceanic system change than glaciers in other parts of the archipelago.

Acknowledgements. — A significant part of remote sensing studies was supported from the Polish-Norwegian Research Found on the project *Arctic Climate and Environment of the Nordic Seas and the Svalbard – Greenland Area – AWAKE* (PNRF-22-AI-1/07) and Polar-CLIMATE Project – SvalGlac *Sensitivity of Svalbard glaciers to climate change*. Polish contribution to the Project was financed by the National Centre of Research and Development (grant No. NCBiR/PolarCLIMATE-2009/2-1/2010). The final stage of this work was supported by funding to the ice2sea project from the European Union 7th Framework Programme, grant number 226375, ice2sea contribution number 64. Satellite data founded ASTER © METI and NASA [2003–2010]. ERS SAR images provided by ESA (Project No C1P.9630). The SPOT-5 DEM data are courtesy of the French Space Agency © CNES 2008. We wish to thank Prof. Piotr Głowacki and Dr. Dariusz Puczko for their kind providing of meteorological data from the Polish Polar Station, Hornsund and SAR and ALOS AVNIR satellite images. The same thanks are to Norwegian Meteorological Institute for providing long time series of air temperature data from meteorological station in Svalbard, Prof. Waldemar Walczowski and Agnieszka Promińska for mean water temperature in Hornsund data, Michał Ciepły and Dariusz Ignatiuk for field data for Hansbreen. We thank reviewers Prof. Gordon Hamilton and Prof. Grzegorz Rachlewicz for very thoughtful suggestions improving significantly the paper.

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Received 11 June 2013
Accepted 7 October 2013