2D and 3D variations of a high-Arctic glacier to recent climate change: Austre Lovénbreen, Svalbard (79°N)

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Abstract
The glaciers and ice caps are known to be particularly sensitive to changes in regional and global climate. The combination of information acquired using remote sensing techniques and in situ is necessary for the survey of glacier dynamics. Field records on the Austre Lovénbreen (79°N) are complemented, in order to follow the retreat of the glacier over the last 47 years, with 10 historic documents ranging from 1962 to 2009. The glacier constantly lost 0.032 km².a⁻¹ in surface between 1962 and 1995 and 2.3 Mm³.a⁻¹ in ice volume, versus 0.018 km².a⁻¹ in surface and 3.4 Mm³.a⁻¹ in ice volume, between 1995 and 2009 (i.e. 1% of its 2009 volume every year). Over the same time periods, the glacier loss in water equivalent rose from 195 mm.weq.a⁻¹ to 288 mm.weq.a⁻¹ with respect to the same watershed surface (10.45 km²). This amounts to a 33% increase even though the glacier area was reduced by 26% from its 1962 value. The total 121.9 Mm³ ice volume loss between 1962 and 2009 is observed with an accelerated ablation rate since 1995. Short climatic events significantly affect long term trends: the single 2010-2011 mass loss accounts for 1.5% of the total 2009 glacier volume.
1. Introduction

The glaciers and ice caps are known to be particularly sensitive to changes in regional and
global climate (Dyurgerov & Meier, 2005; Kohler et al., 2007). The ice masses adapt to
changes in climate conditions much more rapidly than large ice sheets do, because they have a
higher ratio between annual mass turnover and their total mass (IPCC, 2007). In the
glacierized areas, the most recent large extension period of ice caps and glaciers was the end
of the Little Ice Age (LIA, ~1850) in the northern hemisphere as well as in the southern
hemisphere. Since the end of the 19th century, the glaciers and ice caps have undergone
considerable changes. Most authors assess the dynamics of glaciers on the basis of the spatial
displacement of the glacial snout (photographical archives, aerial photographs, satellite
images and field measurements) or by calculating mass balances using stake network along a
central line of glaciers (WGMS, 2010).

The techniques of airborne and satellite remote sensing combined with other data (maps,
aerial photographs, DEM) imported into a GIS database constitute relevant and powerful tools
to spatialize glaciological data and to provide new data on the status of glaciers for the present
and recent past periods (Haakensen, 1986; Kohler et al., 2007; Moholdt et al., 2010; Rees et
al., 2007; Rippin et al., 2003). However, field measurements – including snow depth and
surface ice thickness evolution – remain a mandatory validation element complementary to
remote sensing techniques (Østrem & Brugman, 1991; Hock, 2005; Brandt & Kohler, 2006;
Xu et al., 2010;

Along the west coast of Spitsbergen, the Brøgger peninsula displays several valley glaciers
among which the Midtre Lovénbreen and the Brøggerbreen are well-studied since the 30s
(Hagen & Liestøl, 1990; Liestøl, 1993; WGMS, 2011). Long-term mass balance dataset are
related to climate series. No significant statistical trend is shown but summer mass balance
appears as the most variable term of the net mass balance.
Recently, investigations have been conducted on most of the valley glaciers of the Brøgger Peninsula (Rees *et al.*, 2007; Xu *et al.*, 2010). Most of the papers show a constant but not regular retreat of the glacier front line since the LIA. Some of them suggest an acceleration of thinning in the last decade (Rippin *et al.*, 2003). They all stress differences between remote sensing and in situ measurements (Murray *et al.*, 2007; Friedt *et al.* 2012).

While many studies have been conducted on the establishment of the mass balance of glaciers and on the quantification of glacier retreat in Svalbard, few studies are interested (1) in the relationship between the glacier dynamics and the climatic parameters, (2) the processes explaining the discrepancy between *in situ* measurements and remote sensing and (3) the analyses of the glacial dynamics on the basis of glacier volume variation instead of glacier surface change. The present paper analyses the spatio-temporal dynamics of a small polar glacier (Austre Lovénbreen, Brøgger peninsula, Svalbard, 79°N). To quantify the recent 2-D and 3-D glacier evolutions, a monitoring of the glacier ice was started in 2007 (climate data recording, 36 stake network). Beyond these field measurements, several documents are combined to assess the glacier dynamics over the last 50 years: (1) digitized contour map, (2) aerial photographs, (3) FORMOSAT-2 satellite images, (4) digital elevation models (DEM).

In addition, the Ny Alesund station (6 km west of the study area) provides climate data since 1969. The aim of this paper is to give a reliable estimation of the glacier reduction rates both in surface and volume and to compare the calculated rates with climatic data. Furthermore, data gathered through remote sensing techniques are compared with field measurements.

### 2. General settings

#### Geographical environment

Svalbard, an archipelago with 60% glacier cover, represents about 10% of the total Arctic small glaciers area (Liestøl, 1993; Kohler, 2007). Similarly to what is observed in the whole Arctic, it is very reactive to climate change: all the small glaciers are clearly retreating since
the end of the Little Ice Age (Hagen et al., 2003). Small valley glaciers of the Brøgger peninsula (79°N, 12°E) on the west coast of Spitsbergen, the main island of Svalbard, exhibit an important mass loss, which can be observed by aerial photographs and satellite images.

Similar observations have been made on the nearby glaciers by several authors (Hagen et al., 1993; Kohler et al., 1997; Liestøl, 1993; Lefauconnier et al., 1990; Lefauconnier et al., 1999). Among the Brøgger glaciers, the Midtre Lovénbreen and the Brøggerbreen have the longest continuous Arctic glacier mass balance time-series (Hagen et al., 2003; WGMS, 2011). In the same area, the Austre Lovénbreen, located on the north side of the peninsula, is a small land-based valley glacier, 4 km-long from South to North (Figure 1). The glacier area was 4.5 km² in 2009 and its elevation extends from 50 to 550 m.a.s.l. Its catchment area is 10.45 km² and is characterized by low-land coastal landscape surrounded by a series of rugged mountain peaks whose elevation reaches 876 m.a.s.l (Nobilefjellet). Nowadays, the glacier covers 43% of the total basin surface whereas it was occupying about 50% of the catchment in the 80s (Hagen et al., 1993). In a recent study, Kohler et al. (2007) demonstrated that the average thinning rate of the Midtre Lovenbreen (the glacier having one of the best data coverage in the study area) has increased steadily since 1936. They show that the thinning rates from 2003-2005 were more than 4 times the average of the first measurement period (1936-1962).
**Climatic conditions**

The climate is the main parameter controlling the dynamics of glaciers. The Brøgger peninsula is subject to the influence of the northern extremity of the warm North Atlantic current along the west coast of Spitsbergen (Liestøl, 1993). The present climate at Ny Alesund, along the northern shoreline of the Brøgger peninsula, is of polar oceanic climate type. Considering hydrological years (1st October of a given year to 30th September of the following year), the annual average air temperature is -5.77°C (1969-1998) for an average precipitation amount of 391 mm (1969-1998), (source DNMI at [http://eklima.met.no](http://eklima.met.no); Figure 2). Over the period 1969 to 2010, these parameters display values increasing with time: +0.51°C per decade in temperature and +14 mm per decade in precipitation. However, the
time-series may be separated into two distinct periods, indicating that a significant climate change has occurred from the late 90s.

1. during the first 29 years (1969-1998), the mean value was -5.77°C. There was no significant temporal gradient (-0.02°C per decade) in comparison with the last 12 years (1998-2010).

2. From 1998 until 2010, the air temperature significantly increased with time (annual gradient of +1.26°C per decade). This recent gradient is around 2.5 times the average calculated for the whole period (1969-2010). The mean air temperature during this 12-year period is always above the 1969-1998 -5.77°C average value (Figure 2). The mean air temperature value is -4.20°C for the 1998 to 2010 period.

Figure 2 – Air temperature and precipitation in Ny Alesund 1969-2010 (source DNMI at http://eklima.met.no).
A – Annual air temperature deviation to the mean 1969-1998 (-5.77°C). The temperature gradient is +0.5°C per decade with a significant change for the last 12-year period during which the annual air temperature is always above the 1969-1998 average value. There is no significant gradient for the first 29 years (dashed line) whereas the slope spectacularly increases since 1998 with a decade gradient of 1.26 °C.
B – Annual amount of precipitation: the increase of the global annual amount of precipitation since 1969, is only due to increase of the rain amount (+14 mm per decade) while the snow amount remains constant.
3. **Data and methods**

To assess the recent change (1948-2010) of the Austre Lovénbreen, this paper is based on a set of 3 different types of documents: (1) aerial stereography photographs and satellite images, (2) a historical map and Digital Elevation Models (DEM) and (3) a network of 36 ablation stakes distributed across the Austre Lovénbreen.

3.1 **Aerial photos and satellite imagery**

Several aerial stereography photographs provided by the Norsk Polarinstitutt (NPI) have been used to determine the front position at different dates: 1948, 1966, 1971, 1977, 1990 and 1995. Three FORMOSAT-2 pictures (2007, 2008 and 2009) complete the image dataset.

3.2 **Maps and DEM**

In order to monitor the retreat of the glacier over the last 47 years both in areas and in volumes, we compared different documents available for the Austre Lovénbreen: (1) a map established by German scientists between 1962 and 1965, (2) a DEM made in 1995 by the Norsk Polarinstittut and (3) a new DEM obtained with measurements by a dual-frequency GPS (Trimble Geo XH, Zephir antenna) giving the 2009 summer level.

According to a recent study made by Friedt *et al.* (2012), other documents available to assess the Austre Lovénbreen evolution exhibit insufficient resolution or accuracy to be comparable to this dataset (1990 NPI DEM with 20 m spatial resolution; SPIRIT DEM 2007 with an unacceptable vertical accuracy over the studied glacier as shown by the data quality map (Korona, 2009). Thus, they are not used in this paper. A 2005 Scott Polar Institute DEM from LIDAR measurements by Rees & Arnold (2007) provides the best resolution but only covers the moraine area of the Austre Loverbreen: it was used to delimitate the front position in 2005. Hence, the two periods considered in this work range from 1962 to 1995, and 1995 to
2009 respectively.

All documents were re-sampled in order to get the same 5 m x 5 m resolution. (Figure 3).

Figure 3 – Maps, DEM and documents used to determine the 2D and 3D changes of the Austre Lovén glacier.

• German Map of 1962-1965
The German scientists have made a 1/25 000 map from 1962 to 1965 in the framework of the "Deutschen Spitzbergen-Expeditionen 1962-1965 des Nationalkomitees für Geodäsie und Geophysik der DDR" (Pillewizer, 1967). This map was georeferenced and contour lines were
digitized. Based on this linear altitude information, interpolation was performed in order to obtain a continuous DEM of the glacier surface. Cartographical approximations on the original map and computation artefacts are at the source of cumulative errors. This dataset is therefore considered of medium quality even though it is already a fairly reliable and quite rare data source. This dataset will be referred to as the “1962-1965 map” since the Austre Lovénbreen snout (elevation lower than 300 m.a.s.l.) was mapped in 1962 and the higher part of the glacier was mapped in 1965 (elevations higher than 300 m.a.s.l).

- 1995 DEM
The DEM provided by the NPI was derived using analytical photogrammetry from six stereo-overlapping aerial photographs taken in August 1995 (Kohler et al., 2007; Rippin et al., 2003).

- 2009 DEM
The 2009 DEM has been made by snow scooter tracked dual-frequency GPS in April 2010 over glacier surface only. The resulting dataset was corrected with RINEX post-processing. Interpolated in-situ snow thickness measurements were used to remove the snow height contribution and thus provide the end of summer 2009 ice elevation (Friedt et al., 2012).

3.3 Measurements of glacier ablation and accumulation
Field measurements of ablation and accumulation are performed yearly since 2007 using a 36 stake network covering the whole glacier surface including the cirques. Measurements are made twice a year: at the end of winter (late April - early May) and at the end of the summer (late September - early October). The annual mass balances have been calculated for three years (2007-2008, 2008-2009 and 2009-2010). In addition, a past mass balance has been
assessed for the period 1965-1975 on the basis of the stake network installed by Geoffray (1968) and used by Brossard and Joly (1986).

4. Results and discussion

4.1 Fluctuations in length and in area

As the Brøgger peninsula has been intensively surveyed since the 30s, the retreat of glaciers of this area including Austre Lovénbreen can be estimated by taking into account ten documents since 1948: six orthorectified aerial photos (1948, 1966, 1971, 1977, 1990 and 1995), the 1962-1965 German map and three FORMOSAT-2 satellite images (2007, 2008, 2009 ; Figure 4). A hillshaded version of the DEM provided by the Scott Polar Research Institute (Rees & Arnold, 2007) was also used to determine the front position in 2005.

The front position as well as the glacier limit have been manually delineated and reported on figure 4b. Since the margin is covered with rock debris and some residual ice may remain in the moraine, the actual glacier front is not always easy to delineate neither on documents nor on the field. In the same way, the glacier lateral boundaries are also difficult to identify since some residual snow or shadow areas may hide the actual ice/rock interface at the foot of mountains. The global error margin on the glacier limit position is estimated to 10 meters. Thus, the distance difference between two boundaries exhibits a standard deviation of 20 m, which hardly allows for a yearly retreat assessment but provides usable results when using datasets separated by multiple years.

Since 1948, the glacier edge has clearly changed in the front area (Figure 4). Even if the glacier limits may also have changed in the upper part of the glacier, the available documents are not precise enough to determine accurately any significant difference upstream the glacier. This is due to (1) the high slope of relief upstream and/or (2) the snow cover at the foot of reliefs covering the slope-glacier edge. The measurement of the glacier surface reduction has
been therefore made using the same upper limit of 2009.

Figure 4 – Surface evolution of the Austre Lovén glacier: (A) different 2D document showing the glacier front positions (1948, 1962, 1966, 1971, 1977, 1990, 1990, 2005, 2007 and 2008) and reported on the FORMOSAT-2 image of 2009 (B). The eight transects for calculating the front retreat have been reported in Figure 3C. In figure 3D, the glacier surface has been plotted against time. A break in the slope is visible from 1990.

Since 1948, the most important change in the glacier surface and length is visible in the proglacial moraine where the glacier front displays a progressive retreat (Figure 4). As seen in figure 4c, the recession is not equally distributed over the front. A maximal retreat distance may be estimated along a central flowline. The calculations indicate a maximal recession of 1080 m between 1948 and 2009 (Figure 4c), i.e. an apparent retreat rate of -18 m.a\(^{-1}\). Eight
profiles have actually been considered to assess the average value variability of the glacial retreat in the moraine because of the irregularity of the glacier palaeo-front lines (Figure 4c). The results indicate that the retreat distance from 1948 until 2009 (e.g. 61 years) falls within a narrow range (range of -940 ± 20 m to -1110 ± 20 m, average value of -1030, standard deviation of 60 m), implying an average retreat rate of -15 to -18 m.a⁻¹ (average value of -17 m.a⁻¹, standard deviation of 1 m.a⁻¹). This calculated reduction rate range is consistent with that indicated for the central line of both the Austre Lovénbreen and the Midtre Lovénbreen, e.g. 15 m.a⁻¹ (Hansen, 1999). However, the retreat rate widely differs in time, from -10 ± 4 m.a⁻¹ (1990-1995) to -30 ± 20 m.a⁻¹ (2008-2009) and do not show any progressive increase over time in parallel with the increase of the air temperature or of the precipitation amount as shown in figure 2. Even though the observation of front positions over time is probably one of the most visible consequences of the glacial recession, this proxy shows only one aspect of the ice reduction of a glacier. Yearly measurements by GPS or by determination on the satellite images are not reliable because the yearly ablation rate lies within the error bar of the dual-frequency GPS altitude measurement or that of the delimitation line on the image. Xu et al. (2010) mention an average rate of 21.83 m/a between 2005 and 2006 (minimum of 2.76 maximum of 77.3 m.a⁻¹ along the glacier snout) and showed a similar disparity in the front retreat rates.

In order to better integrate the whole retreat occurring in the proglacial moraine, calculations of glacier area reduction has been made. The results obtained indicate that in 2009 the Austre Lovénbreen was representing 72% of its 1948 surface since its area was 6.26 km² in 1948 and 4.53 km² in 2009. In other words, in 2009, the glacier was covering only 43% of the total basin surface (10.45 km²) whereas it was occupying 60% of the catchment in the 1940s. The glacier area data are plotted against time in figure 4d in order to estimate the stability of the ice reduction process. The distribution of data points indicates a progressive decrease of the
glacier area with an average reduction rate estimated to -0.028 km$^2$.a$^{-1}$ over the period 1948-2009. However, the gradient is irregular throughout the period, with a decreasing gradient, appearing suddenly around the beginning of the 1990s: the gradient decreases from -0.034 km$^2$.a$^{-1}$ for 1948-1990 to -0.017 km$^2$.a$^{-1}$ for 1990-2009 (Figure 4d). The trend observed in the glacier surface reduction before and after 1990 may be surprising when considering the air temperature data series: the air temperature gradient increases after 1998 whereas the reduction rate of the glacier surface seems to slow down. This change may be partially explained by the surface reduction of the glacier snout exposed to the ambient air. Indeed, in 1948, the glacier was characterized by an area of 6.26 km$^2$ for an ice-front moraine linear interface 4.3 km long while in 2009, its surface was 4.53 km$^2$ for a linear front length of 1.9 km.

The fluctuations of both length or surface of glaciers are useful proxies to study the glacier retreat responding to climate change but may be hard to interpret. These indicators do combine several processes that are not only dependent on climate conditions. The glacier reduction is also related to parameters including the glacier velocity, the basal thermal state of the glacier, the roughness of the basement and the geological structures (slope, fractures).

Two important elements have to be mentioned to understand the recent evolution of the Austre Lovenbreen. First, as it was receding in surface, its altitudinal setting changed drastically. Taking into consideration the 250 m altitude contour lines, in 1948 39 % of the glacier area was below this altitude. In 1995, only 19 % of the glacier surface was below this altitude, while in 2009, 16 % was below this altitude. The area ratio of the glacier at low altitude is therefore clearly different now than what it used to be. This could explain part of the glacier front retreat slowing. Another explanatory factor may lie in the topographical settings of the glacier basin. In 1948, the glacier snout was widely spread out in the flat areas along the coastline of King's bay. The glacier tongue was not very thick and the front itself
was not steep as it was not constrained by the surrounding terrain. In the current configuration, the glacier snout is now clearly constrained on its eastern and western sides by steep slopes of the glacier basin valley. The glacier is thicker and its front turned steeper over time. These parameters might explain why the glacier front retreat slowed while in the meantime glacier melt volumes increased.

According to Vincent et al. (2000), it is also well known that due to the glacier flow, the front position shows a delay with respect to climate conditions. This is in agreement with the results presented in this paper. The ice melting enhanced by positive air temperatures over the glacier may be compensated for by glacier flow. The Austre Lovenbreen velocity is consistent with that of the neighbouring Midtre Lovenbreen (Rees & Arnold, 2007). It was measured by Xu et al. (2010) at 2.5 ± 0.5 m.a⁻¹ using differential GPS measurements: the surface flow rate is at least seven times lower than the glacier margin retreat rate (~17 m.a⁻¹). This implies that the observed front retreat due to ice melting would have been more important by 15% if no glacier flow was occurring.

4.2 Fluctuations in volume determined by DEM differences

The change in glacier volume of Austre Lovenbreen is estimated from the 1962-1965 digitized German map and two digital elevation models (1995 and 2009). Three maps with a 5 m spatial resolution have been produced and subtracted two by two in order to calculate the elevation difference between two years: 1962-1995, 1995-2009 and then 1962-2009 (Figure 5).
Figure 5 – Elevation variation of Austrelovén glacier for three periods: 1962-1995, 1995-2009 and 1969-2009. The red levels indicate ablation areas whereas the blue levels indicate accumulation areas.

For the whole 1962-2009 period, a total 121.9 Mm$^3$ volume of glacier ice loss has been calculated. An apparent average reduction rate of -2.6 Mm$^3$.a$^{-1}$ is thus inferred by dividing this volume by the duration of the period (47 years). However the volume change is not constant between the two periods even if the ablation rate always exceeds the accumulation rate.
resulting in the progressive glacier ice reduction during the last 47 years. The glacier reduction rate is about 50 % higher for 1995-2009 than for 1962-1995 according to the following results:

- 74.8 Mm$^3$ ice loss by melting between 1962 and 1995, e.g. an average reduction rate of -2.3 Mm$^3$.a$^{-1}$. The glacier volume in accumulation accounts for 6.5 Mm$^3$ whereas the volume in ablation is 81.3 Mm$^3$. This implies that only 8 % of the ablation volume are compensated for by accumulation;

- 47.1 Mm$^3$ glacier ice loss by melting between 1995 and 2009, e.g. an average reduction rate of 3.4 Mm$^3$.a$^{-1}$. The volume of accumulated ice is very small (0.02 Mm$^3$) and might be a simple calculation artefact. The volume of ablation is much stronger, at 47.1 Mm$^3$ (e.g. 3.3 Mm$^3$.a$^{-1}$). For this period, the ablation volume is not compensated for by accumulation.

As the values are positive in accumulation area and negative in ablation area, the average elevation difference may be positive (glacier growth) or negative (glacier reduction). For 1962-2009, the glacier is reducing as the calculated mean elevation is negative in all cases (-23.5 m, i.e. -0.50 m.a$^{-1}$). A 14.1 m average lowering of the glacier altitude has been obtained for 1962-1995 (e.g. -0.43 m.a$^{-1}$ with respect to the 1962 surface) and 10.1 m for 1995-2009 (e.g. -0.72 m.a$^{-1}$ with respect to the 1995 surface).

The ice thickness data obtained by Ground Penetrating RADAR (GPR) on the Austre Lovénbreen are useful to assess the variation of volume of the glacier (Saintenoy et al., 2011). The 2009 glacier volume was measured at 0.345 ±0.019 km$^3$ (end of summer). The original 1962 volume can therefore be evaluated to 0.466 ±0.019 km$^3$ and to 0.392 ±0.019 km$^3$ in 1995. Thus the 1962-2009 loss represents 26% of the 1962 glacier volume. In the first 33 years the glacier lost 16 % of its 1962 volume at an annual rate of 0.5%. In the last 14 years, the glacier lost 12% of its 1995 volume at an annual rate of 0.9%.
In terms of accumulation/ablation surface, for any period, the data show that the glacier area in ablation is much more extended than that in accumulation:

- For 1962-1995, taking into account the limits of the glacier in 1962 (5.8 km$^2$), 12% of the glacier surface was in accumulation (difference elevation $elev_{1995} - elev_{1962} \geq 0$ m) whereas 88% was in ablation (difference elevation $elev_{1995} - elev_{1962} > 0$ m). In the ablation area, the glacier lost up to 15.7 m of ice (ablation rate of -0.46 m.a$^{-1}$) whereas the glacier only gained 9.0 m of ice (accumulation rate of 0.27 m) in the accumulation area;

- For 1995-2009, taking into account the limits of the glacier in 1995 (4.8 km$^2$), only 0.1% of the surface glacier was in accumulation whereas 99% of the surface was in ablation. In terms of glacier elevation, the glacier lost a mean height of 13 m in the ablation area (i.e. 0.73 m.a$^{-1}$). The negligible gain in the ablation area has to be considered as an artefact.

In terms of water volumes, using a mean density of 0.9 (Moholdt et al., 2010), the Austre Lovénbreen lost a water equivalent of 67.3 Mm$^3$ during the first 33 years (1962-1995), and 42.4 Mm$^3$ for the last 14 years (1995-2009). This is consistent with the trend in the air temperature data mentioned above (fig 2). That means that, even if the glacier surface was reduced, the global water volume generated by ice melt has increased. We might have thought that by reducing the area of ice exposed to the air, the total volume of fresh water arriving to the sea would decrease, which did not occur. Overall, the glacier reduced its area S by 12 % (mean $S_{1962-1995}: 5.31$ km$^2$; mean $S_{1995-2009}: 4.64$ km$^2$) but increased its contribution to the flux of fresh water by one third. (2.04 Mm$^3$.a$^{-1}$ for 1962-1995; 3.02 Mm$^3$.a$^{-1}$ for 1995-2009). Since the total catchment area did not change (10.45 km$^2$) over time, the water per unit area (ratio of the volume of water divided by the catchment area) provided by the melting of the ice is 195 mm.a$^{-1}$ for the period 1962-1995 and 288 mm.a$^{-1}$ for 1995-2009.
4.3 Glacier mass balance

The mass balance of the Austre Lovenbreen is measured through a network of 36 stakes set up on the glacier in 2007. Data obtained were interpolated in order to provide a spatialized representation of the mass balance (Bernard et al., 2009; Figure 6). The results indicate that the glacier is well in recession with a decrease of the mean glacier elevation of 0.28 m (252 mm weq vs glacier area) for 2007-2008, and 0.37 m (333 mm weq vs glacier area) for 2008-2009 and 2009-2010 respectively. The total for the three observed years represents a loss of 1.02 m (918 mm weq vs glacier area) of ice for 2007-2010, i.e. an annual ice loss of 0.34 m.a⁻¹ (306 mm weq vs glacier area).

Figure 6 – Glacier annual mass-balance measured on the Austre Lovén glacier for the year 2007-2008, 2008-2009 and 2009-2010 using ablation stakes. A global mass-balance has also been calculated for 2007-2010.
Based on measurements on the stake network of Geoffray (1968), Brossard & Joly (1986) reported a mass balance of the Austre Lovénbreen glacier for 1965-1975. The ablation rate was 1.0 m.a⁻¹ (± 0.2 m) in the lowest part and 0.24 m.a⁻¹ (± 0.2 m) in the highest part of the glacier (Figure 7): that is in the same order of magnitude than the rates deducted by the DEM differences for the period 1962-1995. The 1965-1975 results are also consistent with those obtained annually with the data given by the current 36 stake network (Figure 7). The ratio between the 2007-2009 results and those of Geoffray (1968) show that recent mass balances measured are 30% higher than during the 1965-1975 period.

For 2005-2006, Xu et al. (2010) found a water mass balance of -440 mm vs glacier area for Austre Lovénbreen, which is in agreement with the data given by WGMS (2011) for Midtre Lovénbreen for the same period (-480 mm weq with respect to the glacier area).

The loss of ice obtained with the stakes is twice the one calculated by DEM difference (cf. Section 4.2; Figure 7). Rees et al. (2007) made the same observation for the Midtre Lovénbreen. Friedt et al., (2012) showed that the difference of DEM is accurate enough for long periods but is less efficient for short periods. The DEM extraction from sources obtained through different means (map for 1962-65, DEM for 1995, GPS for 2009) prevents mass
balance computations on short periods (shorter than a decade) when using the oldest datasets (Haakensen, 1986). As was shown by other authors (Kohler et al., 2007; Moholdt et al., 2010; Rees et al., 2007), these results hint that computing glacier volume differences from DEMs overestimates ice losses. The DEMs are based on an elevation datum common to all years, while stake measurements imply relative surface thicknesses (no fixed datum). Hence, stake measurements can not include melting within or at the bottom of the glacier, neither basal melting indicated by Anderson (2004) and MacGregor (2005) or collapse proposed by Griselin (1982) while the differences between DEMs integrate both processes.

For the Austre Lovénbreen it seems that the subtraction of DEMs yields higher ablation than what is measured with a stake network. It also suggests that for the 1995-2009 period, the accumulation area is negligible. This is not consistent with the available satellite images and in situ photos (Bernard et al., in press). Each year, areas covered by snow (easily identifiable by white surfaces due to the presence of snow) remain at the end of summer and definitively seem to prove the occurrence of accumulation areas (Figure 3 and Figure 4). Nevertheless stake measurements in 2008 showed that the ELA (equilibrium line altitude) does not necessarily correspond to the firn-ice transition zone even if it is the most common indicator used in remote sensing (Bernard, 2011).

4.4 Impact of extreme climatic events

During the 2010-2011 hydrological year, glaciers of the northern part of the Brogger peninsula have been significantly impacted by melting. A mass balance of -1.18 m i.e. -1062 mm weq vs glacier area has been obtained using the 36 stake network (Bernard, 2011). These values are more than 3 times the cumulative value of the three previous years (-1.02 m of ice i.e. -918 mm weq for 2007-2010). With such a huge negative mass balance in 2010-2011, the glacier was everywhere in ablation even in the higher parts of the cirques, despite
the presence of some localized avalanche cones. Overall in 2010-2011 the glacier lost 0.053 km$^3$ of ice which represents 1.5% of its volume.

The detailed analysis of the mass balances related to the climate conditions show that warm conditions in summer significantly increase glacier melt but liquid precipitation are much more efficient to increase the melting of snow and ice (Bernard, 2011). This is particularly visible when heavy rainfall occurs in autumn, which may induce the total disappearance of the remaining snow cover and expose the ice to fast melting. For instance, in September 2008, 78% of the summer rain felt over a short period of two weeks and led to major floods totalizing 44% of the summer river flows. This event was responsible for a 0.20 m average melt and contributed to 71% of the annual mass balance (Bernard, 2011). The repetition over time of particular years like 2007-2008 or 2010-2011 might be an explanation of the long-term trend identified by DEM subtraction. Even though areas can annually remain in accumulation, the benefits of accumulation can be totally countered by particular warm and/or rainy climatic events.

**Conclusion**

By combining remote sensing information, ten historic datasets dating from 1948 to 2009, and *in-situ* measurements, the contemporary evolutions of a small polar glacier in western Spitsbergen have been detailed. On the base of records from the Ny Alesund weather station, the air temperature exhibits a significant increase since 1998. Glacier evolution was considered from the classical snout position indicator, covered area and the volume loss related to the total ice volume as identified by Ground Penetrating RADAR raster scan maps. We conclude that there is no obvious link between the air temperature time-series and the glacier area or length evolution in time. However, the temperature change is more likely in agreement with the volume fluctuations. Although the glacier area significantly shrunk over
the last 47 years, the annual volume of water reaching the sea has raised in the latest 12 years, emphasizing the increased melting rate. The major difference between the mass balance estimated from ablation stake measurements (referenced with respect to the glacier surface) and Digital Elevation Model subtraction (referenced to an absolute coordinate system) is attributed to basal ice loss or short climatic events. Short events significantly contribute to the long term trend, whether through one short liquid precipitation event changing the yearly mass balance trend, or through a single year of important ablation defining the decade long mass balance trend. Such results emphasize the need for continuous monitoring with high temporal resolution as demonstrated using various in-situ measurement techniques.

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References


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Figure captions

Figure 1: Location map

Figure 2: Air temperature and precipitation in Ny Alesund 1969-2010 (source DNMI at http://eklima.met.no).

A – Annual air temperature deviation to the mean 1969-1998 (-5.77°C). The temperature gradient is +0.5°C per decade with a significant change for the last 12-year period during which the annual air temperature is always above the 1969-1998 average value. There is no significant gradient for the first 29 years (dashed line) whereas the slope spectacularly increases since 1998 with a decade gradient of 1.26 °C.

B – Annual amount of precipitation: the increase of the global annual amount of precipitation since 1969, is only due to increase of the rain amount (+14 mm per decade) while the snow amount remains constant.

Figure 3: Maps, DEM and documents used to determine the 2D and 3D changes of the Austre Lovén glacier.

Figure 4: Surface evolution of the Austre Lovénbreen: (A) different 2D document showing the glacier front positions (1948, 1962, 1966, 1971, 1977, 1990, 1990, 2005, 2007 and 2008) and reported on the FORMOSAT-2 image of 2009 (B). The eight transects for calculating the front retreat have been reported in Figure 4C. In figure 4D, the glacier surface has been plotted against time. A break in the slope is visible from 1990.

Figure 5: Elevation variation of Austre Lovénbreen for three periods: 1962-1995, 1995-2009 and 1969-2009. The red levels indicate ablation areas whereas the blue levels indicate accumulation areas.

Figure 6: Glacier annual mass-balance measured on the Austre Lovén glacier for the year 2007-2008, 2008-2009 and 2009-2010 using ablation stakes. A global mass-balance has been also calculated for 2007-2010.

Figure 7: Comparison of the ablation obtained at 7 points over the glacier for four periods: 1965-1975 (Geoffray’s stakes), and 2 differences of DEMs: 1962-1995, 1995-2009 and
The period 1962-1995 shows a similar evolution between the glacier surface and altitude loss while for 1995-2009 altitude loss is twice the ablation rate. This difference may indicate a basal melting or a subsidence of the glacier by subglacial cavities collapse (as observed on the eastern front of the Austre Lovén glacier in 1981 by Griselin, 1982).