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# Surface mass balance and ice flow of the glaciers Austre Lovénbreen and Pedersenbreen, Svalbard, Arctic

Xu Mingxing(徐明星)[1,2], Yan Ming(闫明)[1*], Ren Jiawen(任贾文)[3], Ai Songtao(艾松涛)[4], Kang Jiancheng(康建成)[2] and E Dongchen(鄂栋臣)[4]

*1 SOA Key Laboratory for Polar Science, Polar Research Institute of China, Shanghai 200136, China;*

*2 Urban-ecology and Environmental Restore Central of Shanghai Normal University, Shanghai 200234, China;*

*3 Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China;*

*4 Chinese Antarctic Center of Surveying and Mapping, School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, China*

[*] *E-mail: mingyan@pric.gov.cn*

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**Abstract** The glaciers Austre Lovénbreen and Pedersenbreen are located at Ny-Ålesund, Svalbard. The surface mass balance and ice flow velocity of both glaciers have been determined from the first year of observations (2005/2006), while the front edge of Austre Lovénbreen was also surveyed. The results are as follows: (1) The net mass balances of Austre Lovénbreen and Pedersenbreen are −0.44 and −0.20 m w.e., the annual ablation is −0.99 and −0.94 m w.e., and the corresponding equilibrium line altitudes are 478.10 and 494.87 m, respectively. (2) Austre Lovénbreen and Pedersenbreen are characterized as ice flow models of surge-type glaciers in Svalbard. The horizontal vectors of the ice flow velocities are parallel or converge to the central lines of both glaciers, with lower velocities in the lower ablation areas and higher velocities in the middle and upper reaches of the glaciers. The vertical vectors of ice flow velocities show that there is a mass loss in the ablation areas, which reduces with increasing altitude, while there is a mass gain near the equilibrium line of Austre Lovénbreen. (3) The front edge of Austre Lovénbreen receded at an average rate of 21.83 m · $a^{-1}$, with remarkable variability-a maximum rate of 77.30 m · $a^{-1}$ and a minimum rate of 2.76 m · $a^{-1}$.

**Key words** Svalbard, Glacier, Mass balance, Ice flow.

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## 1 Introduction

The Arctic Ocean is in the center of the Arctic region, where there are many islands, the largest being Greenland. Svalbard (74°-81°N, 10°-35°E), adjacent to

Greenland, is an important component of the Arctic. It has a total area of 62 000 $km^2$, and is about 60% covered by glaciers or ice cap. Svalbard is an archipelago at the northernmost extent of the Norwegian Current (a branch of the North Atlantic Current), and the glaciers in Svalbard are very sensitive to the oscillation of the North Atlantic Current and relevant climate change. Therefore, Svalbard is an internationally important area for the monitoring and study of glaciers. Svalbard is dominated by small sub-polar or polythermal glaciers (<10 $km^2$)[1], which respond to climate change rapidly, and play an important role in sea-level change on decadal to centennial scales[2]. Consequently, the initial signals of global climate change can be obtained by monitoring the glaciers in Svalbard. This paper presents the latest variations in glaciers in Svalbard determined from observations of mass balance and ice flow velocity for Austre Lovénbreen and Pedersenbreen (Fig. 1) in 2005/2006.

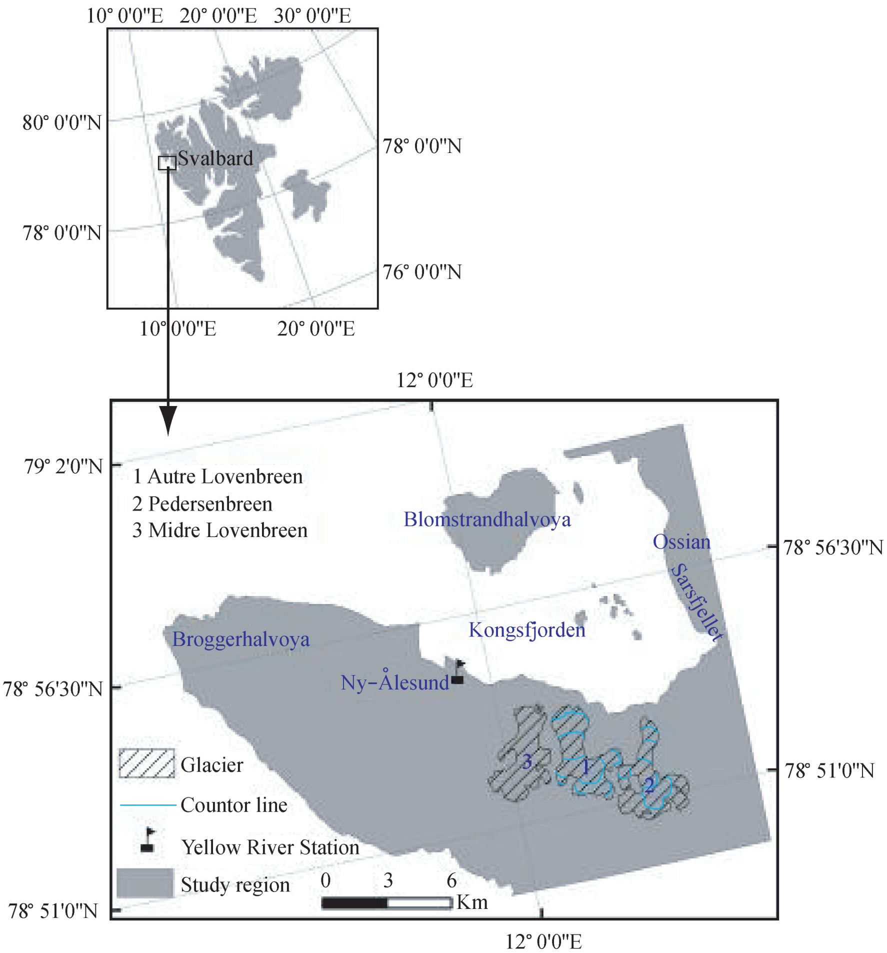


Fig. 1 Map showing the locations of Austre Lovénbreen and Pedersenbreen.

Foreign (mainly Norwegian) scientists have carried out much work on the glaciers in Svalbard; for instance, Austre Brøggerbreen and Midre Lovénbreen have been monitored and studied for more than 40 years. The results of the mass balances of these two glaciers show that during the observation period, the annual net balance has been generally negative, and inter-annual variation in winter accumulation has been comparatively stable, while summer ablation has had larger inter-annual oscillations; however, there has been no indication of increased melting[3-7]. Many glaciers in Svalbard are of surging type[1]. The ice flows of a few glaciers in Svalbard, especially the surging-type glaciers Kongsvegen and Kronebreen, have been observed and studied in terms of the temporal and spatial distributions of ice flow velocity[8-9], the mechanism of surge and the calving rate and process[10-11].

Only sporadic studies, mainly on glaciochemistry, were conducted in Svalbard by Chinese glaciologists before the Chinese Arctic Yellow River Station was built in 2004. Kang et al (1998)[12] collected snow-pit samples from glaciers near Longyearbyen, Svalbard and analyzed variations in their concentrations of main anions and cations. The establishment of the Chinese Arctic Yellow River Station provides a stable support platform for systematic glaciological research in Svalbard. During the first scientific expedition to the Chinese Arctic Yellow River Station in 2004, Chinese scientists carried out multidisciplinary field work around Ny-Ålesund, Svalbard, and the glaciers Austre Lovénbreen and Pedersenbreen (Fig. 1), near the head of the Kongsfjorden fjord, were selected for long-term monitoring[13-15].

## 2 General situation of the monitored glaciers

Austre Lovénbreen (12.09°E, 78.527°N) and Pedersenbreen (12.175°E, 78.515°N) are located at Ny-Ålesund, Svalbard (Fig. 1). The two glaciers are adjacent and classified as polythermal valley glaciers[1]. They are respectively 6.2 km and 10 km in a direct line from the Chinese Arctic Yellow River Station[15]. The altitudes of two neighboring mountain peaks are respectively 880 m and 1017 m[16]. Table 1 presents a series of parameters for Austre Lovénbreen and Pedersenbreen; the two glaciers have areas of 6.2 $km^2$ and 5.6 $km^2$ and maximum altitudes of 600 m and 650 m, respectively. The surfaces of the two glaciers are quite flat, and they have small amounts of moraine and few crevasses. Geomorphologically, Pedersenbreen is narrower and longer than Austre Lovénbreen.

Table. 1 Parameters of the glaciers Austre Lovénbreen and Pedersenbreen[Data from reference 1]

| Glacier | Length (km) | Max altitude (m) | Min altitude (m) | Aspect | | Volume. ($km^3$) | Area ($km^2$) | Location | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | AC | AB | | | Long (E) | Lat (N) |
| Austre Lovénbreen | 4.8 | 600 | 40 | NW | N | 0.53 | 6.2 | 12.09° | 78.527° |
| Pedersenbreen | 5.4 | 650 | 90 | N | N | 0.46 | 5.6 | 12.175° | 78.515° |

Note: Aspect refers to the direction of the slope of the accumulation area (AC) and ablation area (AB) given for the two glaciers.

## 3 Observation data

### *3.1 Field work and method*

From July 25, 2005, an observation network was established with the deployment of 20 stakes from sections A to E on Austre Lovénbreen and five stakes along the main stream line on Pedersenbreen for measurement of the surface mass balance and ice flow velocity (Fig. 2). The geographical coordinates of all stakes and 14 observation points on the front edge of Austre Lovénbreen, and vertical distances between the tops of the stakes and the glacial surfaces were measured for the first time[15]. From July 24, 2006, the above-mentioned items were remeasured during the third expedition to the Chinese Arctic Yellow River Station.

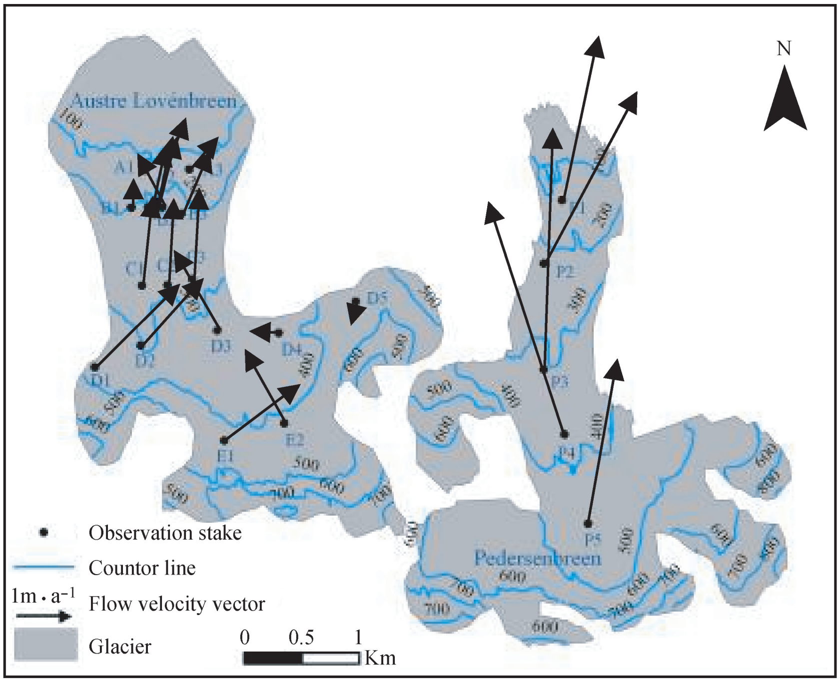


Fig. 2 Locations and surface flow velocities of stakes on Austre Lovénbreen and Pedersenbreen.

The glacier mass balance was directly measured, which involved setting stakes on the glacial surfaces, and regularly measuring the levels of the surfaces relative to the tops of the stakes[17]. In the case of an inclined stake, the angle between the stake and the horizontal plane was measured first, and subsequently, the vertical distance between the top of the stake and the glacial surface was calculated. With the annual net mass balance obtained for each stake, the mass balance of an entire glacier was calculated by weighting the areas of different altitude intervals.

With the global positioning system (GPS) satellite tracking station at the Yellow River Station as the reference station, the post processing differential GPS (D-GPS) method was employed to calculate the coordinates of all 25 stakes on the two glaciers and 14 observation points on the front edge of Austre Lovénbreen. Each stake was measured for more than 1 hour, and some stakes were repeatedly measured. The results from data processing indicate that the measurement precision was better than 1 cm in the horizontal direction and 2 cm in the vertical direction[14-15]. Each observation point on the front edge of Austre Lovénbreen was measured for about 20 minutes, and centimeter-level measurement precision was achieved, which completely meets the requirements of glaciological studies.

### *3.2 Data*

Due to the lack of winter accumulation and summer ablation observations, we only obtain the net mass balances for the two glaciers in 2005/2006. When the glacier mass balance was transformed from an ice equivalent into a water equivalent, a density of 0.9 $g \cdot cm^{-3}$ for glacial ice was taken from previous observations and studies at Svalbard[18-19].

Both glaciers are less than 10 km from the GPS satellite tracking station of the Yellow River Station, and thus, a short-distance differential calculation can be applied[15]. Because of the small-area observation, an independent coordinate system is selected, with the GPS satellite tracking station as the origin of the coordinates, the direction due east as the X axis, the direction due north as the Y axis, and the Z axis vertical to the XY plane. The relative variations in the positions of the stakes can be calculated by contrasting the changes in the X and Y distances between the stakes on the two glaciers and the origin of coordinates in different years. All stakes in section A on Austre Lovénbreen and the stake at P1 on Pedersenbreen fell over and the A1 borehole could not be found. Consequently, there is no mass balance data for section A on Austre Lovénbreen and the point P1 on Pedersenbreen, and no flow velocity data for the point A1. Table 2 presents the flow velocities of the two glaciers, where Vx and Vy are the ice flow velocity vectors in the X and Y directions respectively, and Vxy, Vz and Vz′ are the horizontal vector, vertical vector and actual vertical component of the ice flow velocity respectively.

## 4 Analysis of mass balance

### *4.1 Net mass balance*

The net mass balances of the two glaciers are calculated from the area-weighted mass balances of different altitude intervals (divided according to 50 m contour intervals):

$$B_n = \Sigma B_j S_j ,$$

where $B_j$ and $S_j$ are respectively the mass balance at different altitude intervals and the percentage of the projected area between contour lines. The mass balance in one altitude interval is the average mass balance for all stakes in the interval.

Figure 3 shows that there is a good relationship between the net mass balance and the altitude of the observation point for both glaciers. Both Austre Lovénbreen and Pedersenbreen had a negative net mass balance in 2005/2006, which is consistent with the observation results from the glaciers with long time series of mass balance records in Svalbard[3, 20-21]. The net mass balances of Austre Lovénbreen and Pedersenbreen are −0.44 m w.e. and −0.20 m w.e. respectively, and of the same order of magnitude as the mass balances of neighboring Austre Brøggerbreen and Midre Lovénbreen, which were −0.73 m w.e. and −0.48 m w.e. in 2005/2006[22]. Thus, no difference in the response of the glacier mass balance to climate change in this region is observed. The corresponding equilibrium line altitudes of Austre Lovénbreen and Pedersenbreen are 478.10 m and 494.87 m respectively.

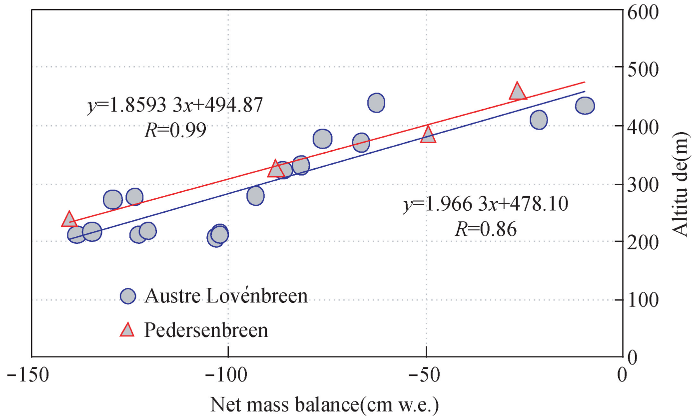


Fig. 3 Net mass balance of observation points on Austre Lovénbreen and Pedersenbreen.

## *4.2 Total ablation*

The degree-day model is applied in simulating the total ablation of Austre Lovénbreen and Pedersenbreen in 2005/2006; this approach has been widely used in the Northern Europe, the Alps, the Greenland ice sheet and the Qinghai-Tibet plateau[23-28]. The degree-day model is based on linear regression between ice ablation and air temperature (particularly, the positive degree) [23, 29], and it is expressed as

$$M = \mathrm{DDF} \cdot \mathrm{PDD}, \tag{1}$$

$$\mathrm{PDD} = \sum_{t_1}^{t_2} aT \begin{Bmatrix} a=1, T>0 \\ a=0, T\leqslant 0 \end{Bmatrix}, \tag{2}$$

where $M$ is the total ablation (m w.e.), DDF is the degree-day factor (m · $d^{-1}$ · $°C^{-1}$), PDD is the positive degree days obtained through integration of T between October 1 (t1) and September 30 (t2), and T is the daily average temperature(°C).

To calculate the total ablation of Austre Lovénbreen and Pedersenbreen in 2005/2006, PDD is collected from a weather station (at an altitude of 8 m; Norwegian Meteorological Institute) at Ny-Ålesund, Svalbard. Ohmura *et al*. (1992)[30] suggested that the climate of a glacier can best be represented by the climate at the equilibrium line altitude. Therefore, daily average temperatures at the mean equilibrium line altitude of each glacier are extrapolated from temperatures at Ny-Ålesund, Svalbard, assuming a lapse rate of 0.635 °C per 100 m[31]. PDD at the mean equilibrium line altitude represents PDD for each glacier. The mean annual DDF at the mean equilibrium line altitude of Midre Lovénbreen is adopted for Austre Lovénbreen and Pedersenbreen, since Midre Lovénbreen is adjacent to both glaciers (Fig. 1) and has high correlation between PDD and total ablation (Fig. 4). The total ablation of Austre Lovénbreen and Pedersenbreen is 0.99 m w.e. and 0.94 m w.e. respectively.

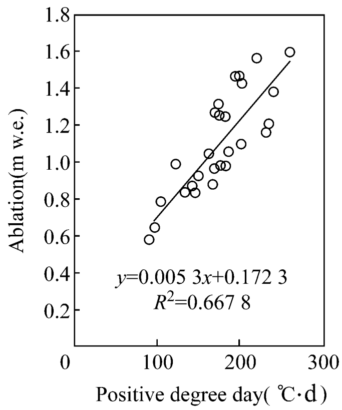


Fig. 4 Regression analysis between total ablation and positive degree days for Midre Lovénbreen [data from references 32-33 and the Norwegian Meteorological Institute].

## 4.3 *Effect of the area/altitude distribution on the net mass balance*

Following the gradual fall in air temperature and the thickening of snow, the ablation rate decreases with increasing altitude of the glacier surface. The negative mass balance gradually reduces from the end of a glacier to its firn basin, and therefore, the area/altitude distribution has an important effect on the glacier net mass balance[3, 34]. Figure 5 shows the area/altitude distribution and net mass balance for Austre Lovénbreen and Pedersenbreen. It is seen that the main body of Austre Lové-

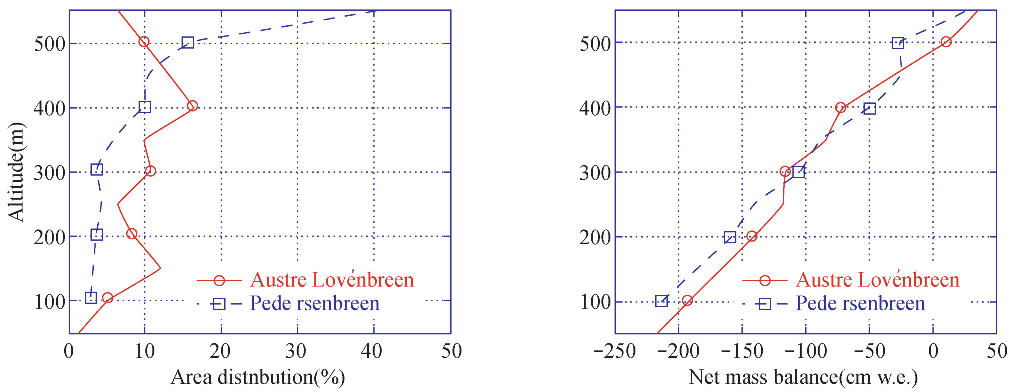


Fig. 5 Net mass balance and area distribution versus altitude for Austre Lovénbreen and Pedersenbreen.

nbreen is at lower altitudes, with only 16.4% of its total area being above an altitude of 500 m; however, 57% of the total area of Pedersenbreen is above an altitude of 500 m. Glacier morphology reflects the difference in the area/altitude distribution between the two glaciers: Pedersenbreen has a wider firn basin and narrower tongue than Austre Lovénbreen. If surface areas of Austre Lovénbreen and Pedersenbreen are equally divided, the corresponding MED (altitude of the contour line that divides the glacier surface in half) is 320 m and 450 m respectively[1]. As a result, both glaciers have an obvious discrepancy in the net mass balance in 2005/2006, although they are adjacent and have the same climatic and environmental background.

## 5 Analysis of ice flow

### *5.1 Horizontal vector of ice flow velocity*

The ice flow rate of glaciers in Svalbard is generally low owing to the low ice temperature. The horizontal vectors (Vxy) of the surface ice flow velocities are parallel or converge to the central stream lines of Austre Lovénbreen and Pedersenbreen in 2005/2006. Ice flow at points D1, D2, D4, D5 and E1 in sections D and E of Austre Lovénbreen converges to the central stream lines. Ice flow at other observation points on the two glaciers is parallel to the central stream lines, except that the flow at point B2E departs from the central stream line and heads northwest (Fig. 2).

Table 2 shows that the mean, maximum and minimum of horizontal vectors of the surface ice flow velocities in 2005/2006 are respectively 2.28, 3.91 and 0.81 m • $a^{-1}$ for Austre Lovénbreen—lower than the previously recorded maximum surface velocity of 7.0 m • $a^{-1}$[35]—and 6.74, 8.13 and 5.49 m • $a^{-1}$ on Pedersenbreen. Austre Lovénbreen has larger variation than Pedersenbreen in the ice flow velocity, although the ice flow is relatively slow. The results of geodesic, morphologic and statistical studies indicate that Pedersenbreen is probably a surge-type glacier[35-36]. Our observation does not contradict the previous conclusion.

Table. 2 Surface ice flow velocity (m • $a^{-1}$) at observation points on Austre Lovénbreen and Pedersenbreen

| Observation points | Vx | Vy | Vxy | Vz | Vz′ | Observation points | Vx | Vy | Vxy | Vz | Vz′ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Austre Lovénbreen | | | | D1 | 2.775 | 2.749 | 3.906 | −0.747 | 0.018 |
| A2 | 0.576 | 1.554 | 1.657 | −1.156 | | D2 | 2.078 | 2.249 | 3.042 | −0.549 | 0.315 |
| A3 | 0.908 | 1.075 | 1.414 | −1.475 | | D3 | −1.513 | 2.628 | 3.032 | −0.393 | 0.426 |
| B1 | 0.019 | 0.989 | 0.989 | −0.745 | 0.641 | D4 | 1.013 | 0.018 | 1.013 | −0.771 | −0.105 |
| B2 | 0.535 | 2.362 | 2.421 | −1.06 | 0.173 | D5 | −0.765 | −0.278 | 0.814 | −0.448 | 0.182 |
| B2S | 0.404 | 1.346 | 2.551 | −0.759 | 0.447 | E1 | 2.426 | 1.829 | 3.038 | 0.025 | 0.124 |
| B2N | 0.467 | 1.095 | 1.405 | −0.752 | 0.283 | E2 | −1.334 | 2.425 | 2.768 | 0.043 | 0.259 |
| B2W | 0.631 | 2.472 | 2.134 | −1.09 | −0.064 | | | | Pedersenbreen | | |
| B2E | −0.098 | 1.946 | 1.992 | −0.576 | 0.45 | P1 | 1.076 | 5.46 | 5.565 | −1.921 | |
| B3 | 0.902 | 2.042 | 2.232 | −1.107 | 0.243 | P2 | 3.098 | 5.761 | 6.502 | −1.5 | −0.096 |
| C1 | 0.316 | 2.939 | 2.956 | −0.656 | 0.28 | P3 | 0.335 | 7.987 | 7.994 | −0.843 | 0.039 |
| C2 | 0.176 | 3.417 | 2.944 | −0.95 | 0.292 | P4 | 1.563 | 7.976 | 8.128 | −0.599 | −0.104 |
| C3 | 0.171 | 3.014 | 3.019 | −0.702 | 0.594 | P5 | 1.02 | 5.394 | 5.49 | −0.421 | −0.151 |

With the GPS satellite tracking station of the Yellow River Station as the origin of coordinates, the average horizontal velocities of surface ice flow in each section of Austre Lovénbreen and the horizontal velocities of surface ice flow at each point of Pedersenbreen are plotted as an L curve in Figure 6. The figure shows that the maximum values correspond to section C and point P4 respectively. From the front edges of Austre Lovénbreen and Pedersenbreen to section C and point P4, Vxy increases gradually along L; i. e., $\partial Vxy/\partial L > 0$. In contrast, $\partial Vxy/\partial L < 0$ upstream of section C and point P4. $\partial Vxy/\partial L \approx 0$ in section C and at point P4. Thus, there are two types of zones with different ice flow characteristics: stretched zones ($\partial Vxy/\partial L > 0$) and compressed zones ($\partial Vxy/\partial L < 0$). The horizontal velocities of the surface ice flow for Austre Lovénbreen show that the glacier has a stretched-compressed-stretched distribution, and $\partial Vxy/\partial L$ is 0.15, 0.12 and 0.06 m/a · $(100\ \text{m})^{-1}$ for the respective zones. Pedersenbreen has a stretched-compressed distribution, and $\partial Vxy/\partial L$ is 0.13 and 0.33 m/a · $(100\ \text{m})^{-1}$ for the respective zones.

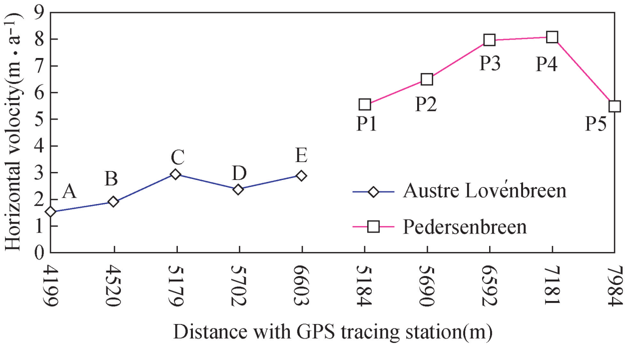


Fig. 6 Longitudinal profile of the surface ice flow velocity for Austre Lovénbreen and Pedersenbreen.

The actual characteristics of the above-mentioned horizontal vectors of the surface ice flow of Austre Lovénbreen are detailed here. The horizontal ice flow velocities increase from section A to C on Austre Lovénbreen. Section D is a local compression zone and has a low horizontal ice flow velocity. Section E is closer to the equilibrium line altitude than other sections, and therefore has a relatively high ice flow rate. The characteristic of the horizontal ice flow velocity from point P1 to P4 on Pedersenbreen is similar to that from section A to C on Austre Lovénbreen, and the point P5 corresponds to section D. Ice flow is relatively slow in the lower reaches of both glaciers, but fast in the middle and upper reaches, which is in accordance with the characteristic pattern of surge-type glaciers in Svalbard[1]. In this pattern, snow and ice in the accumulation area of a surge-type glacier cannot entirely move into the ablation area in a particular time. This results in a gradual steepening of the slope in the upper reaches of the glacier, and increases the possibility of glacier surge.

### 5.2 *Vertical vector of the ice flow velocity*

It has been shown that the altitude of the upper reaches increases and the altitude of the lower reaches decreases during the long quiescent phase of a surge-type glacier[36-37]. Table 2 shows that both Austre Lovénbreen and Pedersenbreen possessed the above-mentioned characteristics of the vertical ice flow velocity (Vz) in 2005/2006. The mass loss weakens with a rise in altitude in the ablation area, and there is even an altitude increase in section E of Austre Lovénbreen.

The vertical ice flow velocity originates from the combined effects of the glacier mass balance (Bn) and actual vertical displacement ($Vz'$); i. e., $Vz = Bn + Vz'$. Table 2 shows that $Vz'$ mainly presents an upward motion for Austre Lovénbreen, with all observation stakes being in the ablation area. $Vz'$ for Pedersenbreen shows that the points P4 and P5 have downward motion, P3 has upward motion and P2 contrarily has slightly downward motion. In general, $Vz'$ for both glaciers is in accordance with the ice flow pattern that the motion is downward in the accumulation zone and upward in the ablation zone[38].

### *5.3 Variations of the front edge of Austre Lovénbreen*

Figure 7 shows the variations of the front edge of Austre Lovénbreen in 2005/2006. The amount of glacial recession is obtained by as follows. Two curves are drawn through 14 observation points to indicate the position of the front edge of Austre Lovénbreen in 2005 and 2006. Under the premise that the longitudes of observation points are unchanged, vertical distances are measured between the 14 observation points on the curve for 2005 and those on the curve for 2006. To distribute 14 observation points uniformly, the points S04 and S06 were removed for 2006, and two new points were added between S08 and S01. The amounts of glacial retreat are calculated ignoring S06, and the curve for 2006 has to be slightly extended to obtain the glacial recession for the observation points S05 and S14 in 2005.

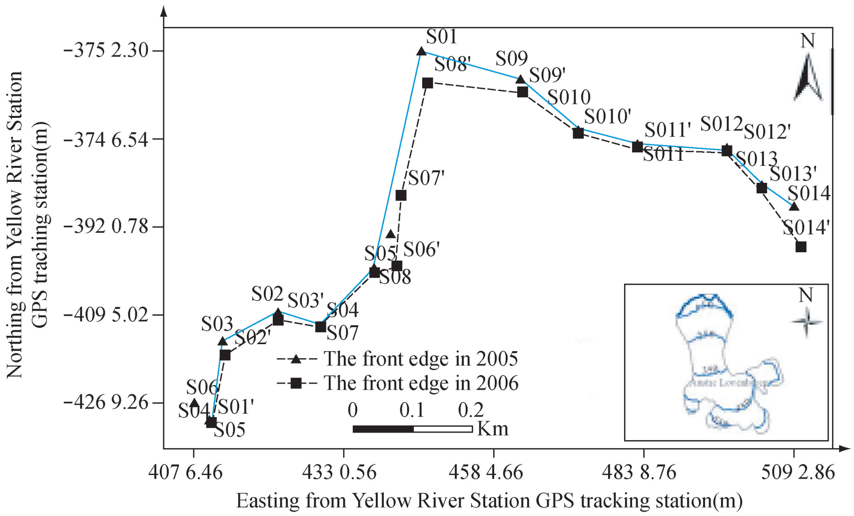


Fig. 7 Map showing the front edge of Austre Lovénbreen.

The front edge of Austre Lovénbreen receded at an average rate of 21.83 m • $a^{-1}$ (maximum of 77.30 m • $a^{-1}$ and minimum of 2.76 m • $a^{-1}$) in 2005/2006. The glacial recession varied remarkably at different observation points for two reasons. (1) There is a difference in the received solar radiation. The ablation area of Austre Lovénbreen lies to the north. The western part of its front edge receives more solar radiation than the eastern part (mainly in the half year of summer[39]), which leads to larger recession in the western part than that in the eastern part. (2) There is an effect of englacial melt-water channels. There is large development of englacial melt-water channels in the eastern part of the front edge of Austre Lovénbreen, and much melt water discharges from the end of glacier and results in intense retreat of the point S14. The intense recession at the front edge of Austre Lovénbreen in 2005/2006 is in accordance with the retreat at the end during the quiescent period for surge-type glaciers in Svalbard[1, 40-41].

## 6 Conclusion

Preliminary studies are carried out on the surface mass balance and ice flow of Austre Lovénbreen and Pedersenbreen in Svalbard. The results are as follows.

(1) The net mass balances of Austre Lovénbreen and Pedersenbreen in 2005/2006 are −0.44 m w.e. and −0.20 m w.e., respectively. The annual ablation is −0.99 m w.e. and −0.94 m w.e., respectively, and the corresponding equilibrium line altitudes are 478.10 m and 494.87 m, respectively.

(2) Austre Lovénbreen and Pedersenbreen are characterized as ice flow model of surge-type glaciers in Svalbard. The horizontal vectors of ice flow velocities are parallel or converge to the central lines of both glaciers, with lower velocities in the lower ablation zone and higher velocities in the middle and upper reaches of the glaciers. The mean, maximum and minimum ice flow velocities are respectively 2.28, 3.91 and 0.81 m • $a^{-1}$ for Austre Lovénbreen and 6.74, 8.13 and 5.49 m • $a^{-1}$ for Pedersenbreen. The vertical vectors of the ice flow velocity show that there is mass loss in the ablation area, which weakens with increasing altitude on Austre Lovénbreen. The actual vertical displacement is in accordance with the ice flow pattern in which motion is downward in the accumulation area and upward in the ablation area.

(3) The front edge of Austre Lovénbreen receded at an average rate of 21.83 m • $a^{-1}$, with remarkable variability—a maximum of 77.30 m • $a^{-1}$ and a minimum of 2.76 m • $a^{-1}$ in 2005/2006.

All stakes currently installed on Austre Lovénbreen and Pedersenbreen for the monitoring of the mass balance and ice flow are below the equilibrium line altitude, and only one year of observation data are available for this study. It is planned to set stakes in the accumulation area of Austre Lovénbreen, and the relationship between the surface mass balance and ice flow of Austre Lovénbreen and Pedersenbreen, Svalbard and climate change will be further studied on a long time scale.

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