Acta Oceanol. Sin., 2021, Vol. 40, No. 1, P. 22–32
https://doi.org/10.1007/s13131-021-1718-1
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Quantitative analysis of Arctic ice flow acceleration with increasing temperature

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Received 14 August 2020; accepted 17 September 2020

Abstract

This study explores the ice flow acceleration (21.1%) of Pedersenbreen during 2016–2017 after the extremely warm winter throughout the whole Arctic in 2015/2016 using *in situ* data and quantitatively analyses the factors contributing to this acceleration. Several data sets, including 2008–2018 air temperature data from Ny-Ålesund, ten-year *in situ* GPS measurements and Elmer/Ice ice flow modelling under different ice temperature scenarios, suggest that the following factors contributed to the ice flow acceleration: the softened glacier ice caused by an increase in the air temperature (1.5°C) contributed 2.7%–30.5%, while basal lubrication contributed 69.5%–97.3%. The enhanced basal sliding was mostly due to the increased surface meltwater penetrating to the bedrock under the rising air temperature conditions; consequently, the glacier ice flow acceleration was caused mainly by an increase in subglacial water. For Pedersenbreen, there was an approximately one-year time lag between the change in air temperature and the change in glacier ice flow velocity.

Key words: ice flow velocity, Arctic temperature rising, Pedersenbreen, Elmer/Ice, meltwater

Citation: Wang Zemin, Yan Boya, Ai Songtao, Holmén Kim, An Jiachun, Ma Hongmei. 2021. Quantitative analysis of Arctic ice flow acceleration with increasing temperature. Acta Oceanologica Sinica, 40(1): 22–32, doi: 10.1007/s13131-021-1718-1

1 Introduction

Warming of the climate system is unequivocal (IPCC, 2013), especially in the Arctic. The Arctic region has warmed more than twice as fast as the global average (Cohen et al., 2014; Lei and Wei, 2020), which is a phenomenon known as Arctic amplification. As the climate warms, the summer melt season lengthens and intensifies in the Arctic (Serreze et al., 2009). Arctic warming is the strongest at the surface during most of the year and is primarily consistent with reductions in sea ice cover (Screen and Simmonds, 2010). With Arctic warming, there is also an increasing trend in Arctic precipitation over the 20th century, and hydroclimate changes are expected to continue and possibly accelerate in the coming century (Linderholm et al., 2018).

With the warming climate of the Arctic, glaciers around this region can be valuable indicators for past climate, being sensitive to summer temperatures and winter precipitation (Huss and Hock, 2015). Recently, there were strong warming events in winter 2015/2016 throughout the whole Arctic (Moore, 2016), which might derive from the splitting of the polar vortex (Overland and Wang, 2016) and the entry of a strong Atlantic windstorm bringing moist and warm air (Kim et al., 2017). Not coincidently, clear ice flow acceleration of many glaciers in the Arctic, including Greenland, western North America, Arctic Canada and the Russian Arctic, occurred after that warm winter, based on our study (Section 3.1). However, the over 200 m spatial and one-year temporal resolutions of the ice flow velocity products cannot satisfy our study of changes in ice flow velocity, and higher-resolution data are needed.

The area around Spitsbergen and the Fram Strait is one of the most climatically sensitive in the world (Rogers et al., 2005), and the *in situ* GPS measurement of Austre Lovénbreen and Pedersnebreen, on Ny-Ålesund, Svalbard, was started after the establishment of the Chinese Yellow River Station (CNYR) (Ren and Yan, 2005). The GPS tracking station beside the CNYR can ensure data precision of 2 cm or better (Ai et al., 2006), and the GPS surveying was performed twice a year after 2008, providing data with better temporal resolution than that of the velocity products.

At present, numerous studies have studied the evolution of Austre Lovénbreen and Pedersnebreen via the CNYR, revealing changes in glacier geometry and movement and variations in ice flow velocity. In 2006, the horizontal ice flow velocity of Austre Lovénbreen was 2.28 m/a, and the ice flow velocity of Pedersenbreen was 6.74 m/a (Xu et al., 2010). From 2006 to 2010, the mean horizontal ice flow velocity of Austre Lovénbreen was 2.4 m/a, and the mean horizontal ice flow velocity of Pedersenbreen was 6.8 m/a (Ai et al., 2012). However, in 2011, the Austre Lovénbreen and Pedersenbreen ice flow slowed down. Thus, the average ice flow velocity of Austre Lovénbreen from 2006 to 2011 was 2.14 m/a, and the average ice flow velocity of Pedersenbreen was 6.28 m/a (Li et al., 2015). Pedersenbreen has retreated considerably since 1936, with an estimated loss in ice volume of 0.054 km^3, or approximately 12%, during the period 1936–2009 (Ai et al., 2013, 2014). Moreover, in recent years, Pedersenbreen has distinctly sped up according to *in situ* measurements.

Foundation item: The National Key R&D Program of China under contract No. 2016YFC1402701; the National Natural Science Foundation of China under contract Nos 41941010, 41531069 and 41476162.
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The mechanism of glacier ice flow acceleration has been studied through various methods. Some studies have investigated supraglacial lake levels and the surface expression of submarine meltwater plumes (Everett et al., 2016; Slater et al., 2015). Some studies have focused on subglacial water-pressure changes (How et al., 2017) because high water pressure in subglacial systems can reduce basal friction and lead to sliding (Iken and Bindschadler, 1986). However, none of these studies have indicated the exact contribution of subglacial meltwater and the contribution of viscoplastic ice deformation in response to rising temperatures. Therefore, this study seeks to quantify the influence of factors inducing glacier ice flow acceleration.

2 Data and methods

2.1 *Data*

2.1.1 *Ice surface velocity product*

For the warm 2015/2016 winter, glaciers with high-quality data from around the 2015/2016 winter in as many ice surface velocity products as possible were chosen (Fig. 1).

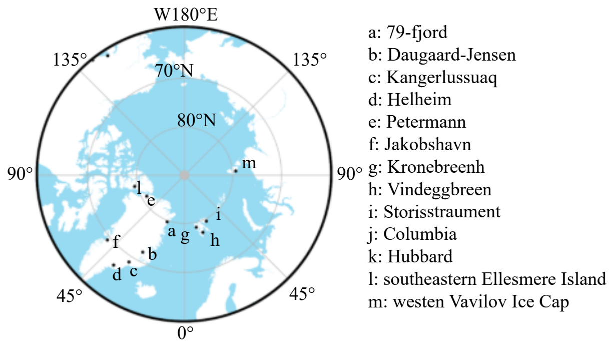

Fig. 1. Glaciers around the Arctic with available ice flow velocity data. These glaciers are the ones we chose to analyse the ice flow velocity, and the regions include Greenland, western North America, Arctic Canada and Russian Arctic.

These glaciers are distributed in the Arctic, including Greenland, western North America, Arctic Canada and the Russian Arctic. Ice surface velocities of glaciers on Greenland are available from CryoPortal (spatial resolution: 250 m), which is operated by ENVEO (http://cryoportal.enveo.at/). For western North America, Arctic Canada and the Russian Arctic, velocity data (spatial resolution: 240 m) have been generated using auto-RIFT (Gardner et al., 2018) and are provided by the NASA MEaSUREs ITS_LIVE project (Gardner et al., 2019).

2.1.2 *In situ GPS measurement data on Pedersenbreen*

Five fibreglass stakes were set up as monitoring points on Pedersenbreen in July 2005. The movement of these stakes, which were drilled 2 m (5–6 m after 2016 with aluminium stakes) into the glacier surface, has been monitored with high precision by using dual-frequency global positioning system (GPS) instruments. If a stake became inclined over time, a new stake was installed nearby and used as a substitute for the old stake. However, some new stakes could be set up only near previous positions because the stakes' exact previous positions could not be located after their removal by glacial ablation. Thus, not all GPS records of the stakes cover the entire 11-year period (Table 1).

Table 1. Percentage of missing records

	P1	P2	P3	P4	P5
Percentage/%	37	21	21	11	5

A GPS tracking station was set up beside the CNYR in July 2004 as an accurate reference station for measuring glacier motion. The exact coordinates of the CNYR were calculated via data from the GPS station and the nearest International GNSS Service (IGS) station (http://igscb.jpl.nasa.gov/). The coordinates of the CNYR in the World Geodetic System 1984 (78°55′21.36″N, 11°56′07.81″E; 46.12 m) and its elevation (10.96 m) can be used for converting elevation systems, and the precision of the coordinates is 2 cm or better (Ai et al., 2006).

The first GPS survey in our study was conducted in July 2008, and during the GPS survey from April 2009 to September 2018 twice a year, the September 2012 and May 2017 GPS surveys were not performed.

2.1.3 *Meteorological data*

Meteorological data were obtained from the Ny-Ålesund observation station, operated by the Norwegian Meteorological Institute (https://seklima.met.no/observations/). The Ny-Ålesund observation station (Svalbard) is located at 78°55′27.48″N, 11°55′52.32″E at an elevation of 8 m above sea level. It is the closest official weather station. The station was established in July 1974 and measures precipitation, temperature, snow depth and other parameters.

Meteorological data, including air temperature data from July 19, 2008, to September 6, 2018, are employed in this article. The temperature data were measured at 2 m above ground level every hour and divided into different days. However, some data points (1 265 h over 11 years) are missing for some days, and some whole days lack measurements.

2.2 *Methods*

2.2.1 *Horizontal ice flow velocity of Pedersenbreen*

The horizontal ice flow velocity of a stake is defined as the horizontal displacement (without vertical data) per year, as described by Eq. (1). The horizontal ice flow velocity represents the motion of the glacier ice surface adjacent to a stake in a year.

$$V_{\rm h}=\frac{365.25\sqrt{(x_{i+1}-x_i)^2+(y_{i+1}-y_i)^2}}{\Delta t}. \tag{1}$$

The coordinates of a stake at one observation time are (x_i, y_i), and those at the next observation time are (x_{i+1}, y_{i+1}). The time span between two observations can be calculated in days as Δt.

In this study, annual ice flow velocities were calculated with the data collected in September except for the year 2012 while the seasonal ice flow velocities were calculated with the data collected between every 2 adjacent observations in the time series except for the years of 2012 and 2017.

2.2.2 *Steady-state simulation of Pedersenbreen*

We used the Elmer/Ice ice flow model (Zwinger and Moore, 2009) to simulate the ice flow of Pedersenbreen.

Elmer/Ice, which is used to model ice sheets, glaciers and ice flow, is a full-Stokes, finite-element, ice sheet/ice flow model. In this study, a steady-state simulation was performed as the initial phase in conjunction with GPS data and glacier ice temperature data describing the initial conditions of Pedersenbreen, i.e., the surface digital elevation model (DEM), the bedrock DEM, ice flow velocity, ice temperature and initial parameters.

The initial parameters are shown in Table 2. The surface DEM and the bedrock DEM were derived using kriging to interpolate high-density GPS/GPR points acquired *in situ* in 2009 (Ai et al., 2014). The mean annual horizontal velocities from 2005 to 2015 were used in this study (P1: 1.07 m/a, P2: 6.54 m/a, P3: 8.20 m/a, P4: 8.39 m/a, and P5: 5.95 m/a) (Ai et al., 2019). The surface ice temperature of –3°C was chosen for ice flow modelling because this ice temperature was measured from Austre Lovénbreen, which neighbours Pedersenbreen (Sun et al., 2016).

The basal friction parameter β and the Glen enhancement factor E are two important parameters in the ice flow model (Wang et al., 2019), and the steady-state simulation was performed mainly to obtain the values of β and E. β and E were determined through comparison between the GPS-measured ice flow velocities and the simulated values from multiple steady-state simulations. The least squares technique was used to judge the best β and E, and the simulated horizontal ice flow velocities of every stake with different β and E values were compared with the measured values in Fig. 2. As the minimum residual sum of squares is 0.442, the best β is 0.02, and the best E is 0.938.

The simulated result with β = 0.02 and E = 0.938 is shown in Fig. 3. The maximum horizontal ice flow velocity is 8.44 m/a (Fig. 3a). In this case, the maximum error is 0.50 m/a at stake P5, and the simulated result at stake P3 is 0.43 m/a less than the measured value (Fig. 3b).

Table 2. The parameters of the ice flow model

Symbol	Constant	Value
ρ	ice density	910 kg/m^3
g	gravitational acceleration	9.81 kg/s^2
n	glen exponent	3

2.2.3 *Indexes for air temperature*

Several indexes are used in this article to explain the temperature variation during the 11 years based on the various factors associated with different mean temperatures during a year.

Ice ablation is related to air temperature by the positive degree-day factor (Braithwaite, 1995). Only under conditions in which the air temperature exceeds 0°C does the sensible heat flux contribute directly to melt (Cuffey and Paterson, 2010). The index positive degree-day (D) is defined for time period Δt measured in days by Eq. (2):

$$D(\Delta t)=\int_{\Delta t} T_{\rm C}H(T_{\rm C})\,{\rm d}t \quad \text{with} \quad H(T_{\rm C})=\begin{cases}1 & T_{\rm C}>0\\ 0 & T_{\rm C}<0\end{cases}, \tag{2}$$

where $T_{\rm C}$ signifies the temperature in Celsius of the air.

In contrast, the index negative degree-day (N) is defined by Eq. (3):

$$N(\Delta t)=\int_{\Delta t} T_{\rm C}H(T_{\rm C})\,{\rm d}t \quad \text{with} \quad H(T_{\rm C})=\begin{cases}0 & T_{\rm C}>0\\ 1 & T_{\rm C}<0\end{cases}. \tag{3}$$

Ice will melt when the air temperature is above 0°C; thus, the count of positive temperature days in each year makes it possible to determine how long a glacier remains in ablation over the course of a whole year. The index positive temperature days (F_1) is defined by Eq. (4):

$$F_1(\Delta t)=\int_{\Delta t} H(T_{\rm C})\,{\rm d}t \quad \text{with} \quad H(T_{\rm C})=\begin{cases}1 & T_{\rm C}>0\\ 0 & T_{\rm C}<0\end{cases}. \tag{4}$$

The index negative temperature days (F_2) is defined by Eq. (5):

$$F_2(\Delta t)=\int_{\Delta t} H(T_{\rm C})\,{\rm d}t \quad \text{with} \quad H(T_{\rm C})=\begin{cases}0 & T_{\rm C}>0\\ 1 & T_{\rm C}<0\end{cases}. \tag{5}$$

Finally, the indexes positive mean temperature (M_1) and negative mean temperature (M_2) can be calculated as in Eq. (6) and Eq. (7), respectively.

$$M_1(\Delta t)=\frac{D(\Delta t)}{F_1(\Delta t)}, \tag{6}$$

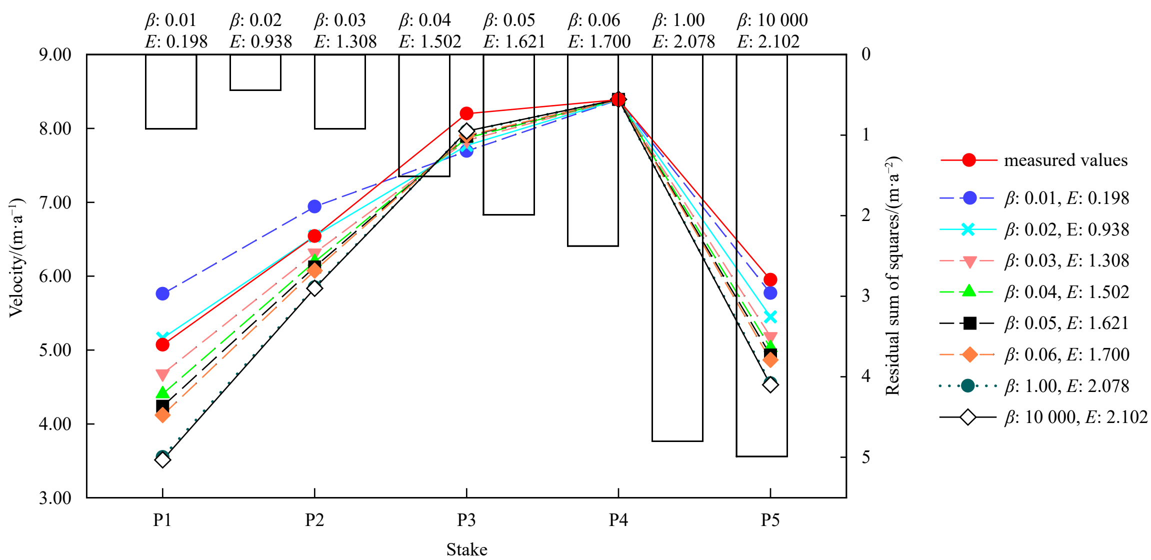

Fig. 2. Simulation results for the states of no sliding and full sliding at the glacier base and residual sum of squares between measured and simulated ice flow velocities for the states of no sliding and full sliding at the glacier base.

$$M_2(\Delta t) = \frac{N(\Delta t)}{F_2(\Delta t)}. \tag{7}$$

3 Results

3.1 *Clear acceleration after the 2015/2016 winter around the Arctic*

There was clear ice flow acceleration of glaciers in the Arctic after the 2015/2016 winter, according to the glaciers we chose in the ice velocity products. As shown in Fig. 4, in Greenland, the ice flow of most glaciers accelerated after 2016, and as shown in Fig. 5, most glacial ice flow in other Arctic areas had high velocities in 2017 and 2018.

3.2 *Climate conditions in the Ny-Ålesund area*

The winter of 2015/2016 was warm in the Ny-Ålesund area (Yamanouchi, 2019), which might correspond to the high mean temperature in 2016, and there are two obvious high mean temperatures, from 2008 to 2018, in 2012 and 2016, in Fig. 6a.

In 2012, the mean temperature was approximately –2.5°C, with negative degree-day and negative mean temperature values that were higher than those in the years before 2012. That year, the positive degree-day and positive mean temperature were slightly lower than those in 2011.

In 2016, the mean temperature, –1.1°C, was the maximum during the 11 years, and that year featured the highest number of positive temperature days and the lowest number of negative temperature days. Furthermore, the maximum positive degree-day and the negative degree-day among the 11 years both occurred in 2016.

3.3 *Ice flow velocity of Pedersenbreen*

The velocity changes of the 4 stakes other than stake P1 show comparable trends over the 11 years (Fig. 7). The velocities of stake P1 were mainly affected by melting and retreat of the glacier tongue, so stake P1 tended to tilt, and the continuity of velocity measurements in the time series could not be ensured. The

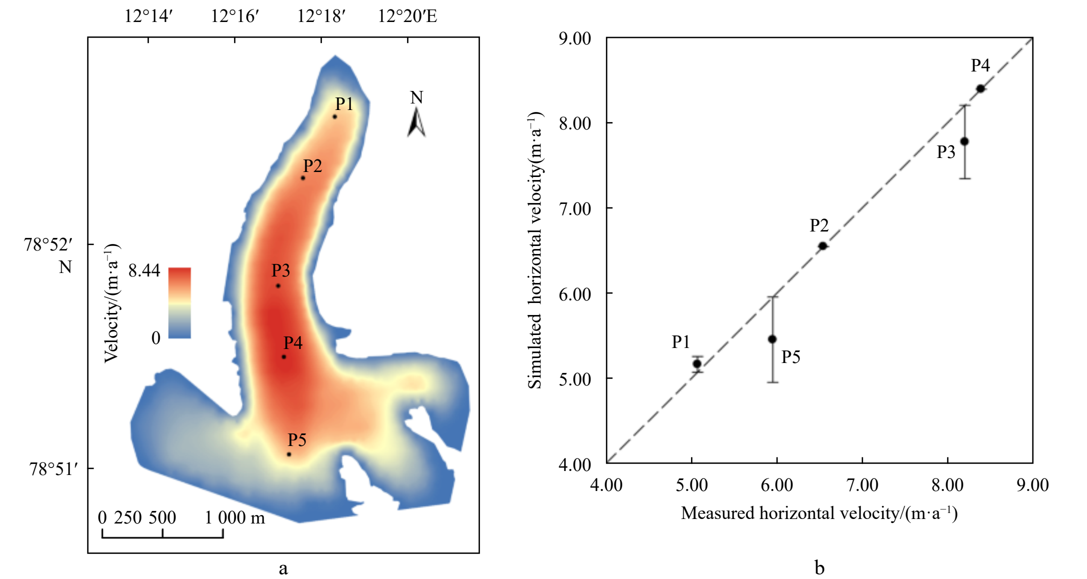

Fig. 3. The simulated result with $\beta = 0.02$ and $E = 0.938$. a. Simulated horizontal ice flow velocity results for Pedersenbreen, and b. error graph with the best estimates of the model parameters. The error bars are computed from the differences between simulation and *in situ* measurement velocities.

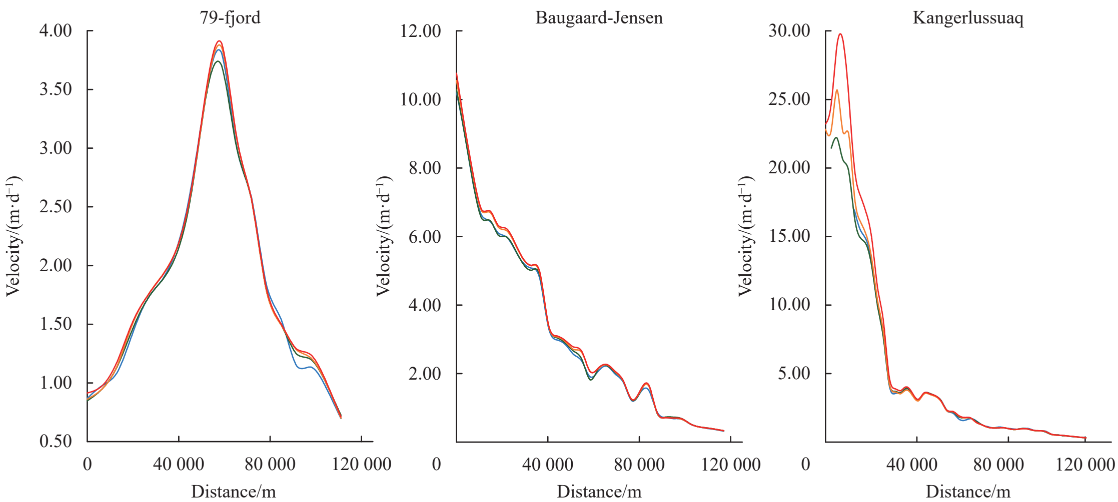

Fig. 4.

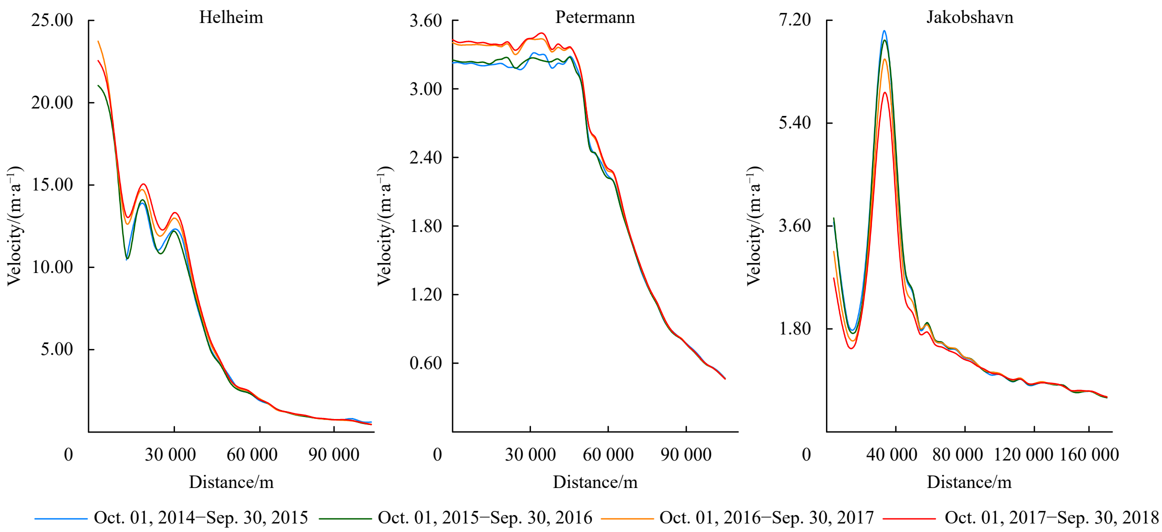

Fig. 4. Glacier ice flow velocities in Greenland. The distance starts from the glacier front. The legend explains the start and end times of the velocity series.

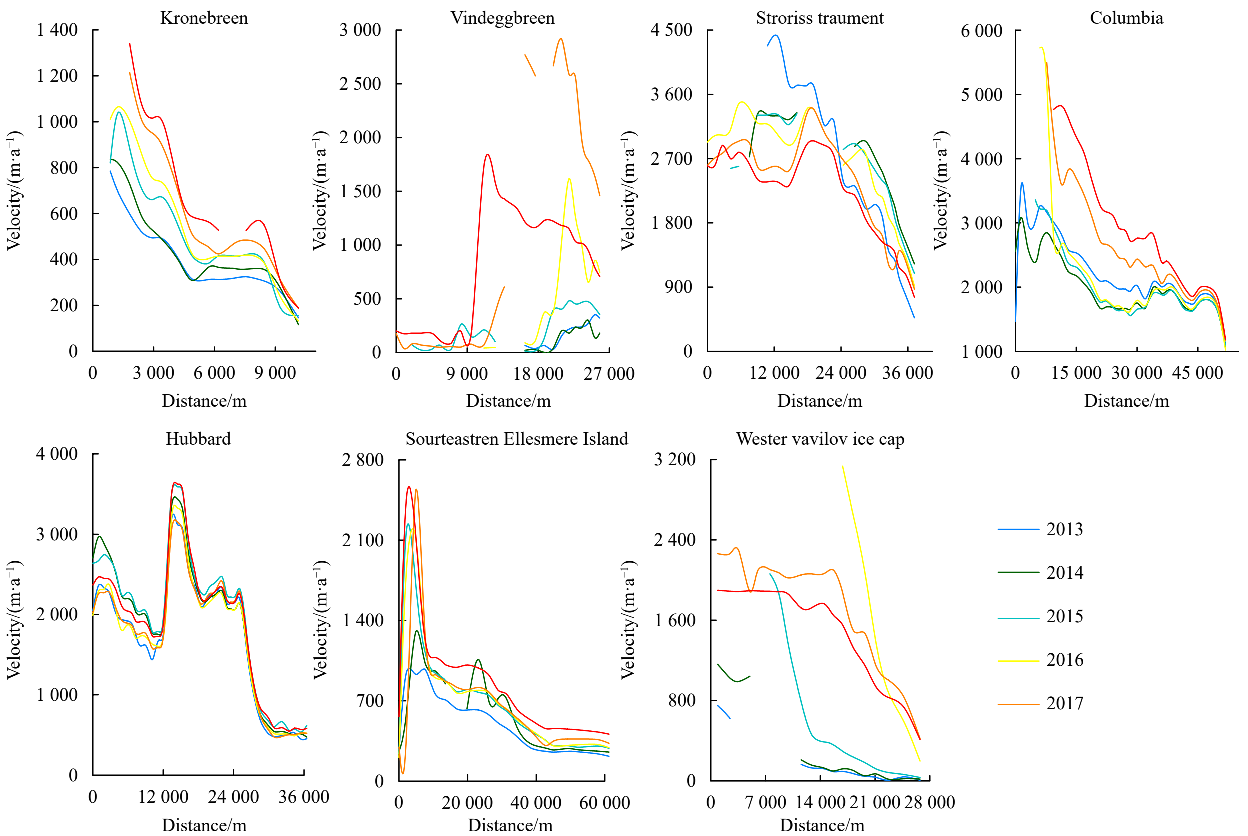

Fig. 5. Glacier ice flow velocities in the Arctic (except Greenland). The distance starts from the glacier front. The legend explains the annual velocity series.

velocities of stakes P2–P5 from September 2016 to September 2017 were markedly higher than those from September 2015 to September 2016, and for stake P5, the velocity increased by a maximum of 21.4%. This phenomenon appears to be similar to the increases between 2005–2015 velocities and 2016–2017 velocities, with the maximum percentage increase (37.3%) at stake P5 (Table 3).

Actually, no abrupt increase in the annual ice flow velocity incident occurred from 2005 to 2015 (Ai et al., 2019), similar to what appeared from September 2016 to September 2017, which means that the change in ice flow velocity from 2005 to 2015 was more stable than that from 2008 to 2018. Therefore, we chose the mean velocities of the 5 stakes from 2005 to 2015 to be elements of the initial steady-state simulation. On the one hand, the velocities during this period agree well with the DEMs in 2009 (we did not obtain data for every stake in 2009 for stake inclination). On the

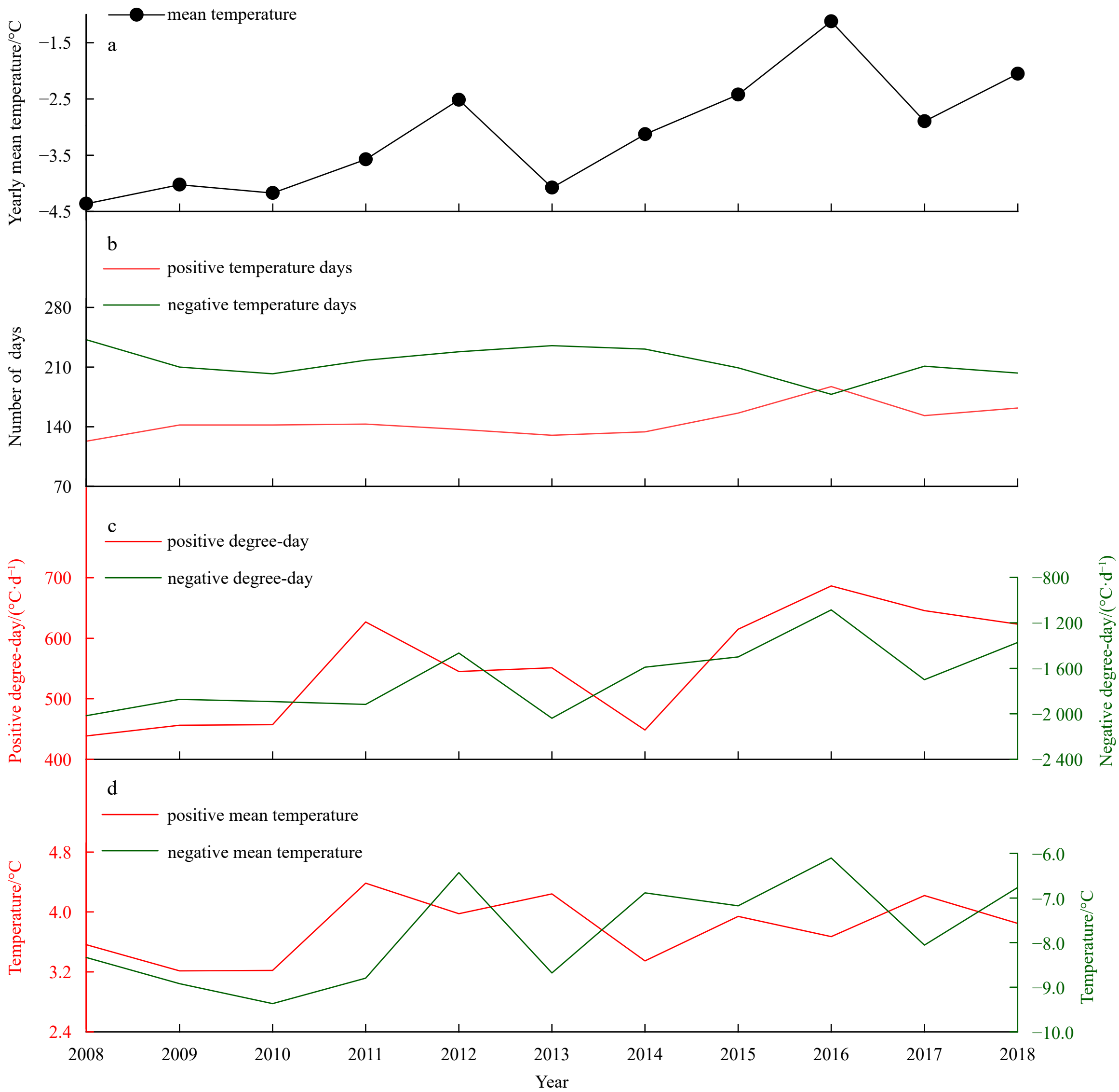

Fig. 6. Air temperature (https://seklima.met.no/observations/) conditions during the 11-year study period. a. Yearly mean temperature, b. positive temperature days and negative temperature days of every year, c. positive degree-day and negative degree-day of every year, and d. positive mean temperature measured in days and negative mean temperature measured in days of every year. The figures are used to reveal the temperature variation, and some indexes correlate closely with the mean temperature.

other hand, with stable velocities, a stable simulation can be constructed to facilitate further simulations.

The velocities varied clearly along different seasons (Fig. 8), with lower velocities in winter than in the adjacent summers. Stake P4 featured the fastest flow among the 5 stakes during the observation period; therefore, stake P4 was chosen to analyse the ice flow features. There were no observations in the 2012 summer and 2016/2017 winter; therefore, these two time periods are not included in Table 4. The largest change was approximately 50% and occurred between the September 2017–May 2018 and May 2018–September 2018 results.

Except for stake P1, the one-year velocities from September 2016 to September 2017 are as high as the summertime velocities from June to September 2016 (in Fig. 8). However, before 2016, the annual velocities were much lower than the summertime velocities. This change suggests that the velocities in the winter from 2016 to 2017 were much higher than those in previous winters or that the velocities in the summer of 2017 were much higher than those in previous summers.

3.4 *Ice flow changes under different scenarios*

Glacial ice temperature increases in response to changes in the local climatic environment soon or later. The glacier usually receives heat from increasingly warm air over long time periods, so the glacier ice temperature changes after the change in air temperature.

Suppose the ice temperature increases from –4.0°C to –0.5°C; then, we can obtain the maximum horizontal ice flow velocity with steps in 0.5°C increments in Elmer/Ice, while holding the values of β and E constant at 0.02 and 0.938, respectively (Fig. 9). The results represent the change in the glacier based on the conditions from 2005 to 2015.

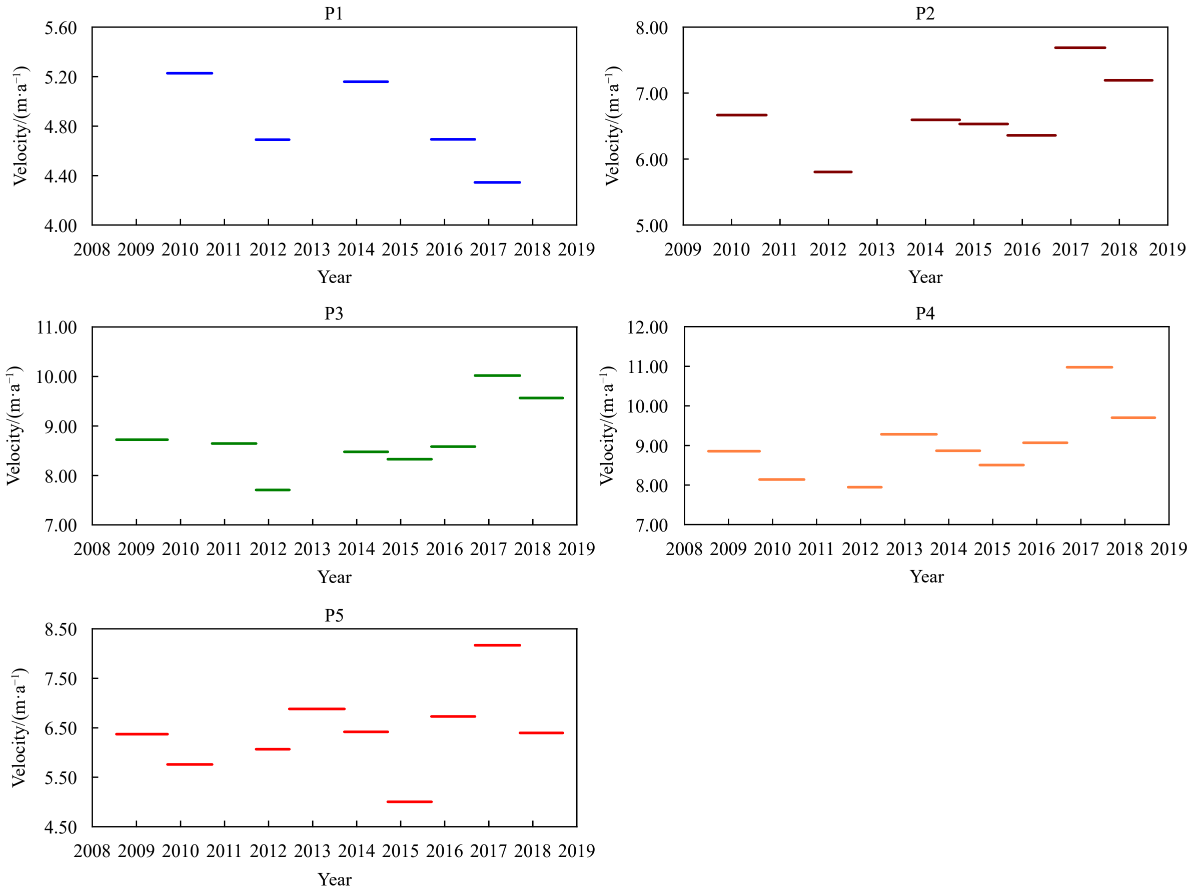

Fig. 7. Annual velocity of each stake. The start and end of a line represent the beginning and ending times of observations, so the length of the line represents the observation time span. The point on the *y*-axis corresponding to the line represents the annual velocity during the observation time span.

Table 3. Velocities and percentage increases

Stake	Velocity/(m·a^{-1})			Percentage increase$^{1)}$/%	Percentage increase$^{2)}$/%
	2005–2015	2015–2016	2016–2017		
P2	6.45	6.36	7.69	19.2	20.9
P3	8.20	8.58	10.02	22.2	16.8
P4	8.39	9.07	10.98	30.9	21.1
P5	5.95	6.73	8.17	37.3	21.4

Note: 1) Percentage increase between 2005–2015 velocities and 2016–2017 velocities; 2) Percentage increase between 2015–2016 velocities and 2016–2017 velocities.

4 Discussion

4.1 *Factors for ice flow acceleration in the simulation*

Topographic focusing, reduced ice viscosity and basal lubrication account for faster glacier ice flow (Cuffey and Paterson, 2010). Specific topographical features such as lowering bed elevations or narrowing valleys make ice flow faster. Because the topography was fixed in the simulation, we considered only the last two factors.

The viscosity of ice decreases by a factor of approximately seven as ice warms from –10°C to 0°C (Cuffey and Paterson, 2010). Therefore, with higher ice temperatures put into the simulation of the glacier, different ice flow velocity fields would appear. As the penetration of seasonal and long-period changes in surface temperature can be analysed by heat conduction theory, and the surface layer is approximately 10 m thick, putting different ice temperatures in the simulation was supposed to exaggerate the influence of rising air temperature on glacier ice flow.

Fluctuations in surface melting related to basal lubrication are known to affect the ice flow velocity of glaciers and ice sheets (Joughin et al., 2008; Shepherd et al., 2009; van de Wal et al., 2008; Palmer et al., 2011; Bartholomew et al., 2010; Das et al., 2008; Zwally et al., 2002). It has been widely hypothesized that a warmer climate may increase the volume of lubricating surface meltwater reaching the ice-bedrock interface, accelerating ice flow (Joughin et al., 2008). Interannual variations in ice acceleration are correlated with variations in the intensity of surface melting, with larger increases accompanying higher amounts of summer melting (Zwally et al., 2002).

Correlated with rising air temperature, this simulation quantified the influence of rising ice temperature on the glacier ice flow in an extreme assumption, and only in that case, can we conservatively estimate the impact of basal lubrication on the glacier ice flow.

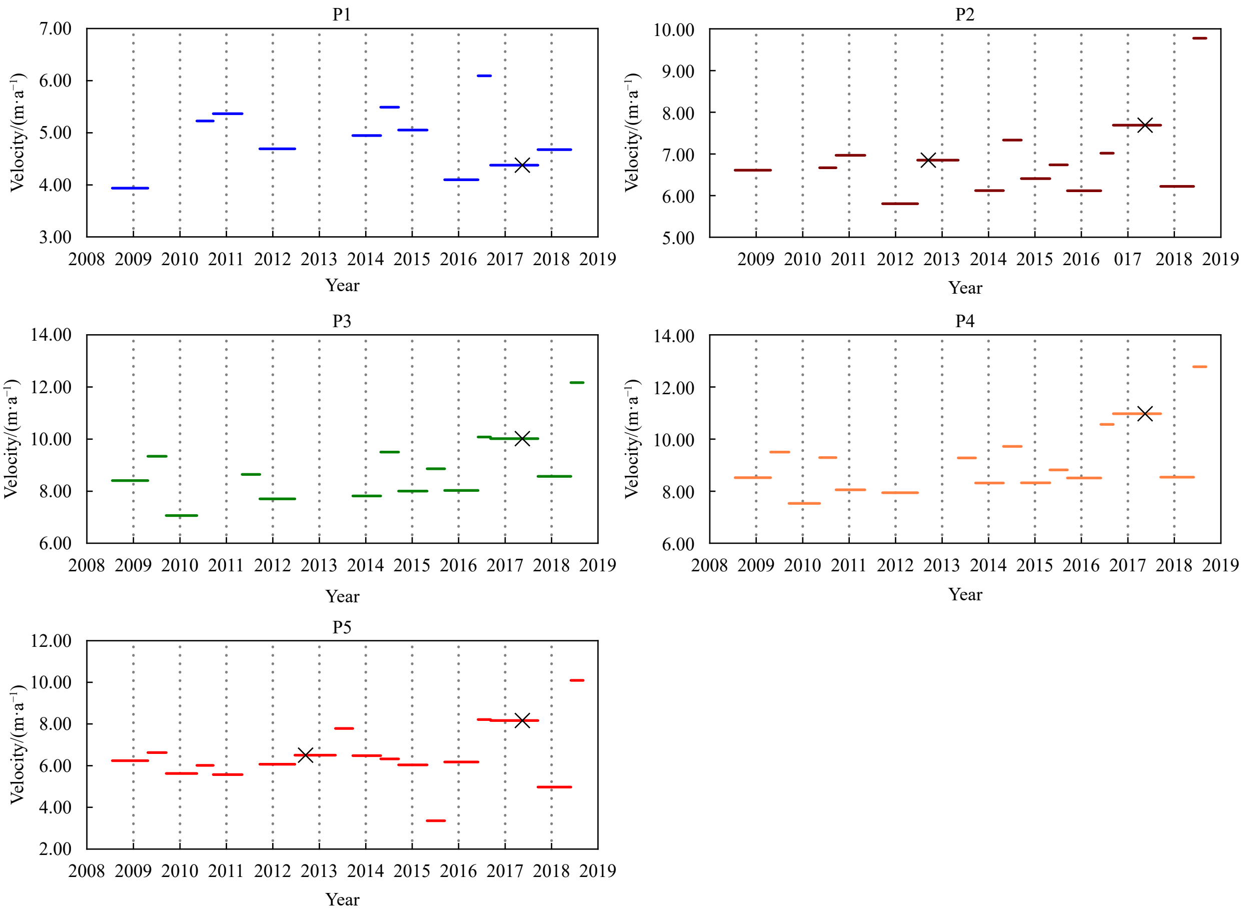

Fig. 8. Seasonal velocities of the stakes. Crosses indicate missing observations, so only annual velocities can be calculated during these time spans (June 2012 to May 2013, and September 2016 to September 2017).

Table 4. Velocity change of the stake P4 velocities between adjacent time spans

Time spans	Velocity/(m·a^{-1})	Velocity change/%
2008/07–2009/04	8.52	–
2009/04–2009/09	9.50	11.5
2009/09–2010/05	7.53	–20.7
2010/05–2010/09	9.29	23.3
2010/09–2011/05	8.06	–13.3
2011/09–2012/06	7.94	–
2013/05–2013/09	9.28	–
2013/09–2014/04	8.32	–10.4
2014/04–2014/09	9.72	16.9
2014/09–2015/04	8.32	–14.4
2015/04–2015/09	8.82	6.0
2015/09–2016/06	8.51	–3.5
2016/06–2016/09	10.57	24.2
2017/09–2018/05	8.54	–
2018/05–2018/09	12.78	49.6

Note: – means the seasonal velocity change in a time span could not be calculated due to lack of adjacent summer/winter velocity.

4.2 *Quantitative analysis of glacier ice flow acceleration*

According to Fig. 6a, the mean temperature in 2016 was approximately 1.5°C higher than that in 2015, causing the ice flow velocity of Pedersenbreen from September 2016 to September 2017 to be higher than that from September 2015 to September 2016 (Fig. 7). In this study, Elmer/Ice, as a glacier simulation tool, facilitates our quantitative analysis of glacier ice flow acceleration in the three scenarios.

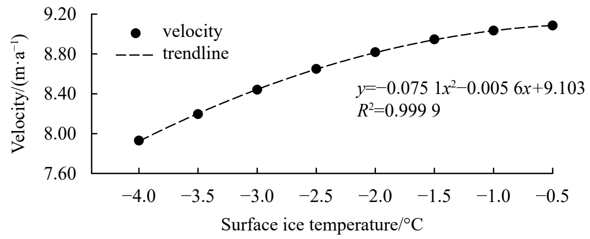

Fig. 9. Maximum horizontal ice flow velocities in different scenarios with different ice temperatures

When the ice surface temperature increases by 1.5°C, the maximum horizontal ice flow velocity of Pedersenbreen increases (Fig. 9), and the percentage velocity increase varies with different temperature interval (ΔT) (Table 5).

There are differences between the percentage increase in the simulation results and that of the measured values. In Table 5, the increase in surface ice temperature could accelerate the glacier ice flow by 0.6%–9.1%, but in Table 3, the velocity of stake P4 (the stake with the highest velocity) increased by a maximum of 21.1% during the 11-year study period. If the glacier ice flow behaved as expected based on the glacial conditions from 2005 to 2015, the velocity change in response to increasing temperatures should be similar to the simulated results; however, in reality, the measured and simulated values differ. Therefore, basal lubrication contributes to the increase in the glacier ice flow velocity.

Normalized to 21.1% (the percentage increase in stake P4 in Table 3), the glacier ice flow acceleration factors can be quantitatively analysed, as shown in Table 6. Under all three scenarios, softened ice due to increasing temperature accounts for 2.7%–43.0% of the glacier ice flow acceleration, while basal lubrication contributes 57.0%–97.3%. Considering that the ice temperature of the glacier Austre Lovénbreen was approximately −3.0°C at a depth of 14 m in 2009 (Sun et al., 2016) and that a 1.5°C increase in ice temperature is impossible over the same time period, the temperature-induced softened ice contributed 2.7%–30.5%, while basal lubrication contributed 69.5%–97.3%. Therefore, the air temperature increase did not directly impact the ice flow, although indirect processes, such as meltwater penetration, may have had stronger impacts.

4.3 *Melt-induced ice flow acceleration*

The penetration of surface meltwater to the base of an ice sheet represents a mechanism for the rapid response to ice flow to climate change (Das et al., 2008). Enhanced basal sliding can occur in response to the penetration of surface meltwater to the base of the glacier because of the lubrication between the ice and the bedrock. When surface meltwater reaches the bed in summer, high water pressure can develop, which reduces basal resistance and increases the ice flow velocity (Hewitt, 2013).

How long will it take for melt water to induce the acceleration of glacier ice flow? For Pedersenbreen, we tried to obtain the answer from data with limited temporal resolution.

The change in velocities was an annual period after the changes in temperature in Fig. 10. The velocities of stakes P2–P5 decreased from B to C, increased from C to E and then decreased from E to F. The mean temperature from A to B decreased, increased from B to D, and then decreased from D to E. The high temperatures in D induced high velocities in E, while the low temperatures in E induced low velocities in F. Therefore, under the one-year temporal resolution data, it can be assumed that there is a one-year time lag between temperature variations and glacier ice flow velocity variations.

Table 5. Velocity changes under different increasing temperature scenarios

Surface ice temperature/°C	Velocity change/%		
	Δ*T*=0.5°C	Δ*T*=1°C	Δ*T*=1.5°C
−4.0	3.3	6.4	9.1
−3.5	3.0	5.5	7.6
−3.0	2.5	4.5	6.0
−2.5	1.9	3.4	4.4
−2.0	1.5	2.5	3.0
−1.5	1.0	1.6	–
−1.0	0.6	–	–

Note: – means not available.

Table 6. Quantification of ice flow acceleration factors

Ice flow acceleration factor	Factor contribution rate/%		
	Δ*T*=0.5°C	Δ*T*=1°C	Δ*T*=1.5°C
Softened ice	2.7–15.9	7.4–30.5	14.4–43.0
Basal lubrication	84.1–97.3	69.5–92.6	57.0–85.6

4.3.1 *One-year temporal resolution*

For the continuity of velocity results of the 5 stakes and the lack of data in September 2012, we chose velocities of P2–P5 stakes from September 2013 to September 2018 and mean temperature with the same time in Fig. 10 (annual mean temperature from September 2012 to September 2013 is discussed later).

4.3.2 *Less than one-year temporal resolution*

Analysing the highest annual velocity from September 2016 to September 2017, the velocities of the P4 stake around this observation time period were compared with the mean temperature from May 2013 to September 2018 (Fig. 11).

The highest 2016/2017 annual velocity was not induced by temperature in the same observation time period. It has been discussed in Section 3.3 that the highest 2016/2017 annual velocity contains higher velocity in the winter from 2016 to 2017 or higher velocity in the summer of 2017. However, in Fig. 11, the two mean temperatures calculated between the September 2016 and September 2017 observations were not as high as the winter or summer mean temperature before. Focusing on the summer/winter velocities in Fig. 11, a higher/lower summer/winter velocity corresponds with the higher/lower mean summer/winter temperature the last year. Thus, the high annual velocity must be influenced by the high temperature from September 2015 to September 2016.

In the analyses of data with different temporal resolutions, a

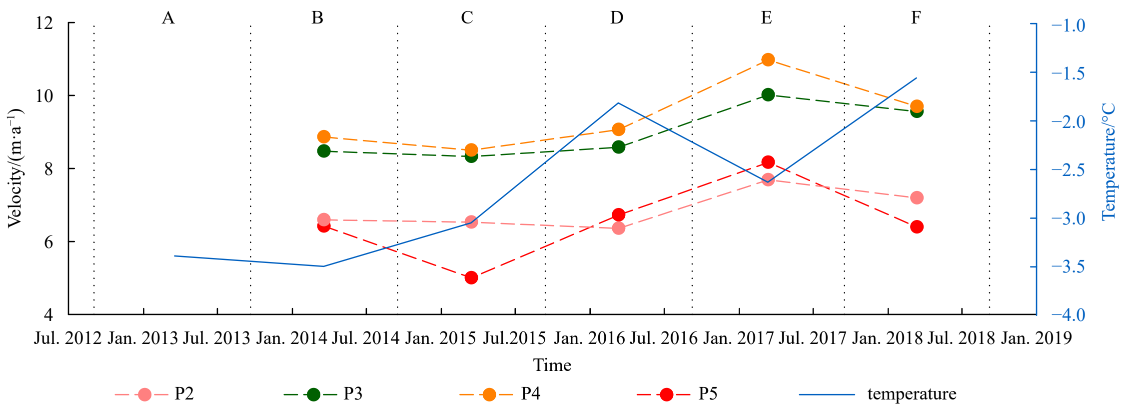

Fig. 10. Annual mean temperature and annual velocities. Dotted lines divide the time series into annual periods from A to F. The annual mean temperature is the mean temperature in each annual period, and the annual velocities are calculated from the annual observation data, with the point located at the centre of each observation time interval.

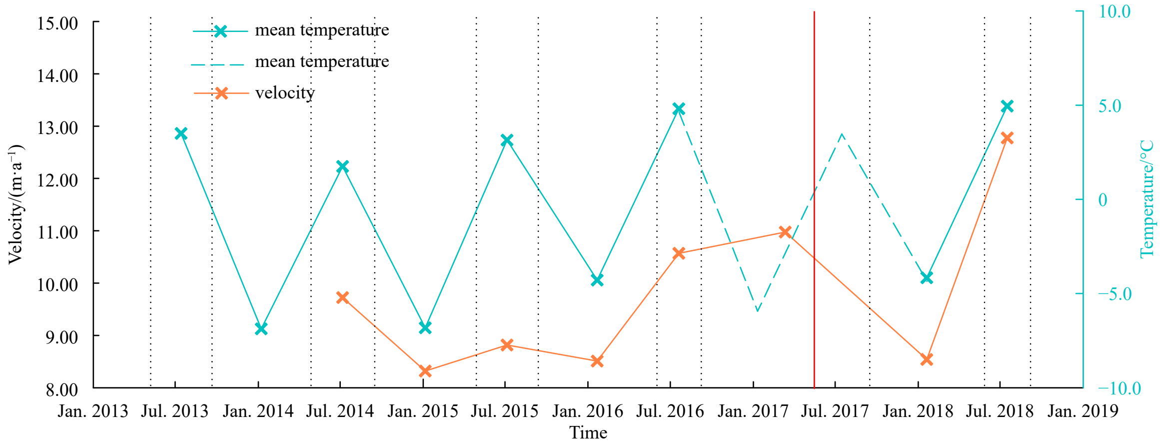

Fig. 11. Seasonal velocities of stake P4 and seasonal temperature. The dotted lines mark the observation times on the date axis; the light blue line connects mean temperatures in the observation periods; the orange line connects velocities in the observation periods. The red line marks a hypothetical observation time in May 2017 on the date axis. Considering the May 2017 observations, the dashed light blue line connects the mean temperatures.

less than one-year time lag between the change in air temperature and the change in glacier ice flow velocity is presumed. It takes time for meltwater to reach the glacier bed and run off the glacier, and the water sometimes may also refreeze because of a decrease in temperature. For Pedersenbreen, the glacier surface meltwater caused by the rising temperature permeated to the bedrock, intensifying basal sliding and allowing the glacier ice flow to accelerate in the following year (or less than one year). Conversely, when the air temperature decreased, the meltwater production decreased and permeated less to the base.

5 Conclusions

The combination of glacier modelling and *in situ* measurement is an effective way to quantitatively analyse the contribution of meltwater to glacier ice flow acceleration. Based on this method, we found that the 2016/2017 acceleration of Pedersenbreen ice flow was governed by the increase in subglacial water in response to rising temperatures. The softened glacier ice caused by an increase in air temperature (1.5°C) contributed 2.7%–30.5% of the acceleration while basal lubrication, dominantly enhanced by meltwater penetrating to the bedrock, contributed 69.5%–97.3%.

The change in glacier ice flow velocity occurs some time after the change in the local air temperature. The glacier surface meltwater caused by increasing temperatures may penetrate through moulins to the glacier base and enhance the lubrication between the ice and bedrock, leading to ice flow acceleration. However, when the temperature decreases, it takes some time for the englacial water to discharge, eventually reducing the basal sliding and slowing the ice flow. This process explains the time lag between changes in the local air temperature and changes in the ice flow velocity. For Pedersenbreen, there is a less than one-year time lag between a change in the air temperature and a change in the glacier ice flow velocity.

A change in the temperature influences glacier ice flow, and even a small glacier can play a role in climate change. In this study, the clear ice flow acceleration of Pedersenbreen from 2016 to 2017 is one of the simultaneous acceleration events following the extremely warm winter of 2015/2016 in the Arctic. Therefore, changes in a small glacier may be closely related to extreme climate events on a large scale and represent some potential environmental reactions afterwards.

Acknowledgements

The field data in this study were acquired by researchers from the Chinese Arctic Yellow River Station. We thank the Chinese Arctic and Antarctic Administration of the State Oceanic Administration, Ministry of Natural Resources for sponsoring the field expeditions around the Chinese Arctic Yellow River Station. We are grateful to the team members who supported our *in situ* observations.

References

Ai Songtao, E Dongchen, Yan Ming, et al. 2006. Arctic glacier movement monitoring with GPS method in 2005. Chinese Journal of Polar Research (in Chinese), 18(1): 1–8

Ai Songtao, Wang Zemin, E Dongchen, et al. 2012. Surface movement research of Arctic glaciers using GPS method. Geomatics and Information Science of Wuhan University (in Chinese), 37(11): 1337–1340

Ai Songtao, Wang Zemin, E Dongchen, et al. 2014. Topography, ice thickness and ice volume of the glacier Pedersenbreen in Svalbard, using GPR and GPS. Polar Research, 33: 18533, doi: 10.3402/polar.v33.18533

Ai Songtao, Wang Zemin, Tan Zhi, et al. 2013. Mass change study on Arctic glacier Pedersenbreen, during 1936–1990–2009. Chinese Science Bulletin, 58(25): 3148–3154, doi: 10.1007/s11434-013-5772-8

Ai Songtao, Yan Boya, Wang Zemin, et al. 2019. A decadal record of inter-annual surface ice flow from Pedersenbreen, Svalbard (2005–15). Polar Science, 22: 100485, doi: 10.1016/j.polar.2019.100485

Bartholomew I, Nienow P, Mair D, et al. 2010. Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier. Nature Geoscience, 3(6): 408–411, doi: 10.1038/ngeo863

Braithwaite R J. 1995. Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling. Journal of Glaciology, 41(137): 153–160, doi: 10.1017/S0022143000017846

Cohen J, Screen J A, Furtado J C, et al. 2014. Recent Arctic amplification and extreme mid-latitude weather. Nature Geoscience, 7(9): 627–637, doi: 10.1038/ngeo2234

Cuffey K M, Paterson W S B. 2010. The Physics of Glaciers. 4th ed. Burlington: Elsevier, 163–362

Das S B, Joughin I, Behn M D, et al. 2008. Fracture propagation to the base of the Greenland ice sheet during supraglacial lake drainage. Science, 320(5877): 778–781, doi: 10.1126/science.1153360

Everett A, Murray T, Selmes N, et al. 2016. Annual down-glacier drainage of lakes and water-filled crevasses at Helheim Glacier, southeast Greenland. Journal of Geophysical Research, 121(10): 1819–1833

Gardner A S, Fahnestock M A, Scambos T A. 2019. ITS_LIVE regional glacier and ice sheet surface velocities. Data archived at National Snow and Ice Data Center, doi: 10.5067/6 II 6VW8LLWJ7

Gardner A S, Moholdt G, Scambos T, et al. 2018. Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. The Cryosphere, 12(2): 521–547, doi: 10.5194/tc-12-521-2018

Hewitt I J. 2013. Seasonal changes in ice sheet motion due to melt water lubrication. Earth and Planetary Science Letters, 371–372: 16–25, doi: 10.1016/j.epsl.2013.04.022

How P, Benn D I, Hulton N R J, et al. 2017. Rapidly changing subglacial hydrological pathways at a tidewater glacier revealed through simultaneous observations of water pressure, supraglacial lakes, meltwater plumes and surface velocities. The Cryosphere, 11(6): 2691–2710, doi: 10.5194/tc-11-2691-2017

Huss M, Hock R. 2015. A new model for global glacier change and sea-level rise. Frontiers in Earth Science, 3: 54

Iken A, Bindschadler R A. 1986. Combined measurements of subglacial water pressure and surface velocity of findelengletscher, Switzerland: Conclusions about drainage system and sliding mechanism. Journal of Glaciology, 32(110): 101–119, doi: 10.1017/S0022143000006936

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press, 4

Joughin I, Das S B, King M A, et al. 2008. Seasonal speedup along the western flank of the Greenland Ice Sheet. Science, 320(5877): 781–783, doi: 10.1126/science.1153288

Kim B M, Hong J Y, Jun S Y, et al. 2017. Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm. Scientific Reports, 7: 40051, doi: 10.1038/srep40051

Lei Ruibo, Wei Zexun. 2020. Exploring the Arctic Ocean under Arctic amplification. Acta Oceanologica Sinica, 39(9): 1–4, doi: 10.1007/s13131-020-1642-9

Li Peng, Yan Ming, Ai Songtao, et al. 2015. Characteristics of surface movement on the Austre Lovénbreen and Pedersenbreen glaciers, Svalbard, the Arctic. Chinese Journal of Polar Research (in Chinese), 27(4): 402–411

Linderholm H W, Nicolle M, Francus P, et al. 2018. Arctic hydroclimate variability during the last 2000 years: Current understanding and research challenges. Climate of the Past, 14(4): 473–514, doi: 10.5194/cp-14-473-2018

Moore G W K. 2016. The December 2015 north pole warming event and the increasing occurrence of such events. Scientific Reports, 6: 39084, doi: 10.1038/srep39084

Overland J E, Wang Muyin. 2016. Recent extreme Arctic temperatures are due to a split polar vortex. Journal of Climate, 29(15): 5609–5616, doi: 10.1175/JCLI-D-16-0320.1

Palmer S, Shepherd A, Nienow P, et al. 2011. Seasonal speedup of the Greenland ice sheet linked to routing of surface water. Earth and Planetary Science Letters, 302(3–4): 423–428, doi: 10.1016/j.epsl.2010.12.037

Ren Jiawen, Yan Ming. 2005. Glaciological investigation during the first scientific expedition of Chinese Arctic Yellow River Station, 2004. Journal of Glaciology and Geocryology (in Chinese), 27(1): 124–127

Rogers J C, Yang Lei, Li Lin. 2005. The role of Fram Strait winter cyclones on sea ice flux and on Spitsbergen air temperatures. Geophysical Research Letters, 32(6): L06709

Screen J A, Simmonds I. 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. Nature, 464(7293): 1334–1337, doi: 10.1038/nature09051

Serreze M C, Barrett A P, Stroeve J C, et al. 2009. The emergence of surface-based Arctic amplification. The Cryosphere, 3(1): 11–19, doi: 10.5194/tc-3-11-2009

Shepherd A, Hubbard A, Nienow P, et al. 2009. Greenland ice sheet motion coupled with daily melting in late summer. Geophysical Research Letters, 36(1): L01501

Slater D A, Nienow P W, Cowton T R, et al. 2015. Effect of near-terminus subglacial hydrology on tidewater glacier submarine melt rates. Geophysical Research Letters, 42(8): 2861–2868, doi: 10.1002/2014GL062494

Sun Weijun, Yan Ming, Ai Songtao, et al. 2016. Ice temperature characteristics of the Austre lovénbreen glacier in NY-Ålesund, arctic region. Geomatics and Information Science of Wuhan University (in Chinese), 41(1): 79–85

van de Wal R S W, Boot W, van den Broeke M R, et al. 2008. Large and rapid melt-induced velocity changes in the ablation zone of the Greenland ice sheet. Science, 321(5885): 111–113, doi: 10.1126/science.1158540

Wang Zemin, Lin Guobiao, Ai Songtao. 2019. How long will an Arctic mountain glacier survive? A case study of Austre Lovénbreen, Svalbard. Polar Research, 38: 3519

Xu Mingxing, Yan Ming, Ren Jiawen, et al. 2010. The studies of surface mass balance and ice flow on glaciers Austre Lovénbreen and Pedersenbreen, Svalbard, Arctic. Chinese Journal of Polar Research (in Chinese), 22(1): 10–22, doi: 10.3724/SP.J.1084.2010.00010

Yamanouchi T. 2019. Arctic warming by cloud radiation enhanced by moist air intrusion observed at Ny-Ålesund, Svalbard. Polar Science, 21: 110–116, doi: 10.1016/j.polar.2018.10.009

Zwally H J, Abdalati W, Herring T, et al. 2002. Surface melt-induced acceleration of Greenland ice-sheet flow. Science, 297(5579): 218–222, doi: 10.1126/science.1072708

Zwinger T, Moore J C. 2009. Diagnostic and prognostic simulations with a full Stokes model accounting for superimposed ice of Midtre Lovénbreen, Svalbard. The Cryosphere, 3(2): 217–229, doi: 10.5194/tc-3-217-2009