ADVANCING EARTH AND SPACE SCIENCE

JGR Earth Surface

RESEARCH ARTICLE
10.1029/2022JF006911

The Response of Tidewater Glacier Termini Positions in Hornsund (Svalbard) to Climate Forcing, 1992–2020

Małgorzata Błaszczyk[1], Mateusz Moskalik[2], Mariusz Grabiec[1], Jacek Jania[1], Waldemar Walczowski[3], Tomasz Wawrzyniak[2], Agnieszka Strzelewicz[3], Eirik Malnes[4], Tom Rune Lauknes[4,5], and W. Tad Pfeffer[6]

[1]Faculty of Natural Sciences, University of Silesia in Katowice, Katowice, Poland, [2]Institute of Geophysics, Polish Academy of Sciences, Warszawa, Poland, [3]Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland, [4]NORCE Norwegian Research Centre AS, Tromsø, Norway, [5]Department of Geosciences, The Arctic University of Norway, Tromsø, Norway, [6]Department of Civil, Environmental, and Architectural Engineering, Institute of Arctic and Alpine Research, University of Colorado at Boulder, Boulder, CO, USA

Key Points:

- Record of tidewater glacier fluctuations in Hornsund (Svalbard) in 1992–2020
- At the regional scale, retreat pattern shows correlation with positive degree day index and sea surface temperature
- The retreat period starts in June following a rise in air and sea temperatures and terminates between October and December

Correspondence to:
M. Błaszczyk,
malgorzata.blaszczyk@us.edu.pl

Citation:
Błaszczyk, M., Moskalik, M., Grabiec, M., Jania, J., Walczowski, W., Wawrzyniak, T., et al. (2023). The response of tidewater glacier termini positions in Hornsund (Svalbard) to climate forcing, 1992–2020. *Journal of Geophysical Research: Earth Surface*, *128*, e2022JF006911. https://doi.org/10.1029/2022JF006911

Received 5 SEP 2022
Accepted 15 MAY 2023

Author Contributions:
Conceptualization: Mateusz Moskalik, Mariusz Grabiec
Formal analysis: Mateusz Moskalik, Tomasz Wawrzyniak
Funding acquisition: Mariusz Grabiec, Jacek Jania
Investigation: Mateusz Moskalik, Mariusz Grabiec
Methodology: Jacek Jania
Resources: Waldemar Walczowski, Tomasz Wawrzyniak, Agnieszka Strzelewicz, Eirik Malnes, Tom Rune Lauknes
Writing – original draft: Mateusz Moskalik, Mariusz Grabiec, Jacek Jania, W. Tad Pfeffer
Writing – review & editing: Waldemar Walczowski, Tomasz Wawrzyniak, Agnieszka Strzelewicz, Eirik Malnes, Tom Rune Lauknes

Abstract Many Arctic marine-terminating glaciers have undergone rapid retreats in recent decades. Seasonal and year-to-year variations in terminus position act on all tidewater glaciers, but the key controls on those changes vary from region to region. Here, we examined seasonal and decadal changes in termini positions of seven tidewater glaciers in the inner part of Hornsund, the southernmost fjord of Spitsbergen (Svalbard Archipelago), based on a variety of data from 1992 to 2020. Combining satellite imagery, basic meteorological data (air temperature, positive degree day index (PDD), liquid precipitation), sea surface temperature (SST), mean temperature in the glacier forefield bays, fast sea ice cover, and bathymetry near the glacier front, we examined the influence of potential controlling parameters on interannual and seasonal variability of the glacier termini. We found regional synchrony between terminus advance/retreat and climate variables. At a regional scale, annual fluctuation changes are related to PDD and SST, while summer fluctuations are linked to PDD, although individual glaciers are shown to have differing sensitivities to potential climate drivers. We also found that the retreat period in Hornsund generally lasts from June to October-December. Onset of the retreat is related to sea and air temperature, and in some cases follows the disappearance of the ice cover. These results indicate that the expected increase in meltwater runoff in Svalbard, the input of relatively warm Atlantic water to the fjord, and the increasing trend of longer summer and warmer winter periods will have implications for glacier velocity and frontal ablation.

Plain Language Summary In recent decades, marine-terminating glaciers in the Arctic have undergone rapid retreats. In addition to long-term changes in front position, those glaciers also experience seasonal advance and retreat. However, the key controls on those changes vary from region to region. Here, we used satellite images to investigate decadal and seasonal fluctuations of seven tidewater glaciers in Hornsund, the southernmost fjord of the Svalbard Archipelago. We compared glacier fluctuations with meteorological and oceanographic data to examine potential controls on variability of the glacier termini. Our results show a general synchronous pattern of glacier fluctuations with local climate variables. Front position changes are related to temperature-based index and sea surface temperature when analyzed regionally, although individual glaciers have differing sensitivities to potential climate drivers. We also found that the retreat period lasts from June to October-December in Hornsund. Glaciers start to retreat when sea and air temperatures are significantly high, and in some cases follow the disappearance of the ice cover. Our results indicate that the expected increase in air temperature, the amount of meltwater, input of warm water to the fjord, and longer summer and warmer winter periods will affect glacier velocity, calving, and terminus position of the glaciers in the future.

1. Introduction

The Arctic region has undergone significant warming over the last century, especially in recent decades (IPCC, 2019, 2021). The increase in air temperature is followed by glacier retreat in different Arctic regions (Carr et al., 2017; Cook et al., 2019; Enderlin et al., 2018; Fahrner et al., 2021; McNabb & Hock, 2014; Wood et al., 2018). Recent large-scale warming is also observed in Svalbard (Dahlke et al., 2020; Gjelten et al., 2016; Nordli & Kohler, 2003; Wawrzyniak & Osuch, 2020) and is accompanied by glacier retreat (Błaszczyk et al., 2013, 2019; Małecki, 2016; Nuth et al., 2007, 2013; Ziaja, 2001; Ziaja & Ostafin, 2015).

10.1029/2022JF006911

One of the most important and highly sought modeling inputs is a robust and validated relationship between observable environmental variables and changes in tidewater terminus position (De Andrés et al., 2018; Otero et al., 2017; Pfeffer, 2007; Rignot, Xu, et al., 2016; Vieli et al., 2002; Wood et al., 2021). Several hypotheses have been proposed to determine key controls on the terminus position of tidewater glaciers (TWG). One is the water-depth/glacier-thickness ratio (Brown et al., 1982; Jania, 1988; Meier & Post, 1987; Vieli et al., 2002, 2004), terminus height above buoyancy, and seabed slope (Van der Veen, 1996; Vieli et al., 2002). These parameters link the retreat or advance of the terminus to changes in calving rates driven by local basal topography near the glacier front. Recently, there has been increased interest in investigating the role of ocean heat on the stability of the marine-terminating glaciers in the Arctic. Several authors have attributed rapid changes observed at tidewater glacier termini in Alaska and Greenland to increasing surface melt, with meltwater runoff draining through glaciers and entering fjords at depth to form buoyant plumes which enhance submarine melting at glacier termini and calving (Bartholomaus et al., 2013; Cowton et al., 2018; Motyka et al., 2003, 2013; Rignot et al., 2010, 2015; Ritchie et al., 2008; Wood et al., 2021) or sea ice concentration at the glacier termini (Amundson et al., 2010; Carr et al., 2013, 2017; Christoffersen et al., 2012; Moon et al., 2015). Cook et al. (2019) attributed the retreat of marine-terminating glaciers in the Canadian Arctic Archipelago to surface melt, indicating that increased atmospheric temperature has been the primary driver of the acceleration in this region. Recent studies by Cowton et al. (2018) and Fahrner et al. (2021) have proved both oceanic and atmospheric warming as a key control of the retreat of TWG in Greenland. Similar results were found by Błaszczyk et al. (2021) for Hansbreen in Svalbard. The authors identified positive degree-day index and sea thermal conditions as the main factors closely related to the fluctuations of the glacier terminus.

The rate of change in a glacier's front position is governed by the difference between the area-averaged ice flux and the frontal ablation, and in most cases, frontal ablation and ice flux are almost exactly balanced (Truffer & Motyka, 2016). Both components vary seasonally and tidewater glaciers in Svalbard, as in other regions, undergo seasonal advance and retreat in addition to multiyear changes (Fried et al., 2018; Jania, 1988; Moon et al., 2015; Schild & Hamilton, 2013). Apart from changes in terminus position driven by mass balance, some glaciers can be susceptible to fast dynamic instabilities such as surges. Glacier surges are defined as quasi-periodic advances or increases in flow speeds unrelated to external triggers (Meier & Post, 1969). Surges transfer a large volume of ice from the upswelled upper part to the thinned lower reach of glaciers (Cogley et al., 2011), causing significant changes in the glacier elevation and terminus position. Svalbard is one of the best-known regions where surges occur (Sevestre & Benn, 2015). The surge cycles at Svalbard tend to be relatively long (50–500 years), with active phases of 3–10 years (Dowdeswell et al., 1991). Frontal advance related to the short active phase of the surge has already been studied in Svalbard (e.g., Dowdeswell & Benham, 2003; Flink et al., 2015; Sund et al., 2014; Szafraniec, 2020). Yet, to date, only two observational studies have focused in detail on the ice-ocean interface of glaciers and normal (non-surge) dynamics on a multiyear scale. Studies by Luckman et al. (2015) capture only a short period of evolution of three glaciers, while the decadal trends in terminus position have been examined for Hansbreen glacier in Hornsund fjord (Błaszczyk et al., 2021). So far, there is no comprehensive study covering the long-term response of glacier fronts from the Svalbard regional perspective.

This study examines factors that control seasonal oscillation and interannual changes in termini positions of seven tidewater glaciers terminating in tributary fjords of Hornsund during the period 1992–2020, excluding Hansbreen, with the exception of the previously studied Hansbreen by Błaszczyk et al. (2021). We compared time series of satellite-derived terminus positions with observations of environmental forcings, including air temperature, positive degree day index (PDD), sea surface temperature (SST), mean temperature in the glaciers forefield bays, liquid precipitation and bathymetry. Three glaciers were surging during the investigated period. This paper does not discuss their surge behavior but only effects, that is, changes in terminus position during and after the surge.

Further, continuous Copernicus Sentinel-1 data enabled a detailed study of terminus fluctuations, glacier velocity and the presence of fast ice cover with exceptionally high temporal resolution for 2016–2020. During that period, proglacial seawater temperature measurements were also conducted. Using these observations, we computed frontal ablation and analyzed the ratio between components of frontal ablation (solid ice flux and changes in terminus position). Results are discussed alongside meteorological and oceanographic conditions to improve our understanding of the primary environmental drivers of terminus position change in the Svalbard region.

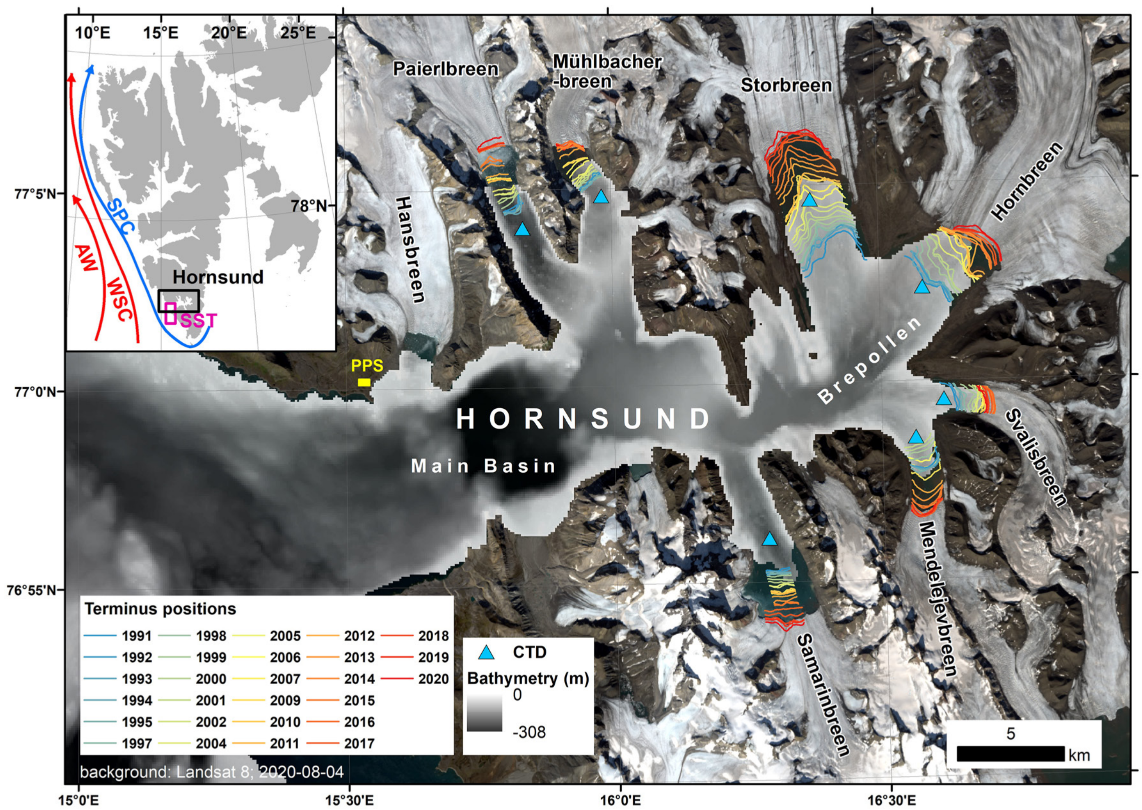

Figure 1. The location of the studied glaciers and fjord bathymetry in the Hornsund region. Terminus positions indicate annual minimum glacier extents. The pink rectangle on the Svalbard overview map presents the site of NOAA 1/4° Daily Optimum Interpolation Sea Surface Temperature (SST); the blue triangles indicate the position of Conductivity, Temperature and Depth (CTD) measurements; PPS denotes the location of the Polish Polar Station and weather station. AW, WSC, and SPC stand for Atlantic Water, West Spitsbergen Current and Spitsbergen Polar Current.

2. Study Area

Hornsund is the southernmost fjord of Spitsbergen (Figure 1). We constructed a time series of terminus position fluctuations for the seven major glaciers emptying into the fjord. Our study covers glaciers with an area between 31.1 and 196.5 km^2 (Table 1). Smaller glaciers were excluded from the analysis owing to a lack of adequate resolution in satellite imagery. Margin-to-margin widths of the studied TWG fronts vary from 1.82 to 6.89 km, although the actively calving portions of the fronts are shorter. Glacier slopes along the centerline vary between 1.3 and 2.2°. Three of the studied glaciers terminate in the main basin of the fjord and four in Brepollen, the bay in the eastern part of Hornsund. Based on direct and indirect evidence, six of these glaciers surged in the 20th century: Mühlbacherbreen, Storbreen, Hornbreen, Paierlbreen, Svalisbreen, and Mendelejevbreen (Błaszczyk et al., 2013; Szafraniec, 2020), with the latter three surging during the period of investigation.

Maximum water depths in the fjord exceed 240 m in the central part of the main basin and 140 m in the central part of Brepollen (Moskalik et al., 2013). The difference in hydrographic conditions between the main basin and Brepollen is strongly dependent on the geometry of the fjord. Brepollen is connected with the outer fjord by only a very narrow entrance (around 2 km wide, Figure 1) and a shallow sill to the west from it (ca. 50 m depth), which significantly restricts the exchange of water between the two basins (Jakacki et al., 2017; Promińska et al., 2018).

Table 1
Glaciers of the Hornsund Basin With Selected Morphometric Features, After Błaszczyk et al. (2013)

Glacier	Abbreviated names	Area (km^2)	Front width (km)	Slope (°)	Average water depth (m)
Paierlbreen	Pa	106.1	2.15	1.7	151
Mühlbacherbreen	Mu	51.6	1.82	2.2	90
Storbreen	St	196.5	6.89	1.3	45
Hornbreen	Ho	176.2	5.47	1.3	52
Svalisbreen	Sv	31.3	2.28	1.9	42
Mendelejevbreen	Me	31.1	3.57	1.9	52
Samarinbreen	Sa	84.0	3.96	1.7	86

Note. Glacier area and front width were measured on the georeferenced ASTER and Landsat images (2010), glacier slope was retrieved along the centerline from DEM SPOT (2008). Average water depth is retrieved for the area limited by the 1992 glacier extent and maximum range of bathymetric data.

10.1029/2022JF006911

Air temperatures in Hornsund and across Svalbard have been increasing over recent decades (Dahlke et al., 2020). The linear trend in average annual temperature for Hornsund for the period 1979–2018 is 1.0314°C/decade (Wawrzyniak & Osuch, 2020). The changes in air temperature are associated with prolongation of the period with positive temperature, an increase in liquid precipitation and the reduction of snow cover (Osuch et al., 2022).

The observed changes in large-scale atmospheric circulation patterns mean that warm Atlantic Water (AW) from the West Spitsbergen Current (WSC) flows more often onto the Western Spitsbergen Shelf (WSS) and into the fjords, even in winter (Cottier et al., 2007; Nilsen et al., 2008, 2016). This has prevented sea ice from forming, resulting in large areas of ice-free waters west and north of Svalbard (Cottier et al., 2007; Tverberg et al., 2014) and in the fjords (Muckenhuber et al., 2016). However, Hornsund differs from most Western Spitsbergen shelf sites by being more influenced by colder Arctic Water from the Barents Sea carried by the Spitsbergen Polar Current (SPC; Figure 1). The water of SPC during most of the year has a temperature close to or below zero (Marsz & Styszyńska, 2013). This water mixes slowly with warmer Atlantic Water (3.5–4.5°C; Piechura & Walczowski, 2009), forming strong density gradients along the south-western shelf of Spitsbergen (Saloranta & Svendsen, 2001) and resulting in decreased warm water inflow into Hornsund, in comparison to the northern fjords. In addition, the Hornsund fjord and adjacent shelf receive multiyear pack ice transported from the Barents Sea around Sørkapp (Marsz & Styszyńska, 2013). This influences Hornsund fjord hydrology, sediment flux and fjord biota (Lydersen et al., 2014). Nevertheless, studies of interannual variability of water mass distribution in Hornsund by Prominska et al. (2018) show a positive linear trend in water temperature and salinity in the period 2001 to 2015. Studies by Strzelewicz et al. (2022) found an increase in the Atlantic Water volume fraction on the shelf from 1999 to 2020, which was especially noticeable in the last decade. Changes in water properties of the upper water layers in Hornsund are attributed to these circulation changes.

3. Data and Methods

3.1. Front Positions of Glaciers

We used a variety of multispectral and Synthetic Aperture Radar (SAR) sources (Landsat 5, Landsat 7, Landsat 8, Terra ASTER, Alos AVNIR, SPOT 5, ERS-1, ERS-2, ENVISAT, ALOS PALSAR, TerraSAR-X, TanDEM-X, RADARSAT-2, Sentinel-1, and Sentinel-2) to determine changes in termini position. Manual digitizing of calving front outlines for each glacier between winters 1991/1992 and 2019/2020 produced more than 1,500 terminus outlines (an average of 190 front positions per glacier). Due to shadowing and parallax distortion in side-looking radar satellite data in mountainous regions, portions of the terminus near the glacier margins could not always be identified and digitized. Termini fluctuations were calculated using the commonly adopted box method, which accounts for asymmetric terminus changes (e.g., Bunce et al., 2021; Moon & Joughin, 2008). The accuracy of determining glacier fluctuations from different satellite missions was estimated by Błaszczyk et al. (2021) as ±45 m. Seasonal advance and retreat of TWG termini (winter and summer fluctuations, respectively) were calculated as the difference between the maximum and the minimum positions within the year, while the annual fluctuations were determined as the difference between the minimum terminus position in two consecutive years (i.e., excluding seasonal variations). The general behavior of glacier fronts during the year and in the summer and winter seasons is presented as cumulative fluctuation anomalies (annual, summer, winter). These indices were calculated by summing up separately: (a) all fluctuations of the Hornsund glaciers exceeding the average change in the glacier extent in 1992–2020 and (b) all fluctuations below the average.

3.2. Meteorological Data

Daily mean air temperatures and the sum of precipitation data were acquired from the Polish Polar Station Hornsund (Figure 1), located at the entrance to the Hornsund Fjord (Wawrzyniak & Osuch, 2020; https://monitoring-hornsund.igf.edu.pl/). Similar to previous work (Błaszczyk et al., 2021), we calculated the PDD (Braithwaite, 1985) as a proxy for glacier melting rate and thus subglacial water discharge, having in mind the physical basis of this index (Ohmura, 2001). In such a context, a potential relationship between air temperature and terminus fluctuations was investigated. The PDD anomaly denotes a deviation from the 1992–2020 PDD average. The monthly and annual sum of liquid precipitation was estimated based on the positive air temperature criterion for total precipitation measured at Hornsund.

3.3. Sea Water Temperature and Sea Ice

We used daily Sea Surface Temperature (SST) at the closest possible locations to the fjord entrance as a proxy for the water temperature in the fjord in the period 1992 to 2020. The NOAA 1/4° Daily Optimum Interpolation Sea Surface Temperature (OISST v2.1; https://www.ncei.noaa.gov/products/optimum-interpolation-sst) is a long term Climate Data Record that incorporates observations from different platforms (satellites, ships, buoys and Argo floats). A high SST at the entrance to the Hornsund fjord usually indicates an AW inflow over the shelf and into the fjord. The warm AW layer is thick enough to increase the temperature of the subsurface waters in the fjord. Previous results of Arntsen et al. (2019) and Błaszczyk et al. (2021) confirm the reflection of the SST data from the mouth area in the thermal water conditions in Hornsund. The SST anomaly denotes a deviation from the 1992–2020 SST average.

Additionally, fast ice cover and average water temperature in the water column were determined for 2016–2020. Ice cover was interpreted separately for each pro-glacier bay based on Sentinel-1 and other multispectral satellite data. The average water temperature in the water column was calculated from the CTD measurements in periods May/June to September/October from 2016 to 2021. CTD measurements were collected using a Valeport miniCTD and SAIV A/S SD208 probe at each glacier bay (Figure 1).

3.4. Bathymetry

Bathymetry data (Figure 1) were collected by the Norwegian Hydrographic Service before 2008 (The Norwegian Mapping Authority, Kartverk). Because of the glacier retreat, the data do not cover the proximate area at the front of the glaciers. Therefore, we used the average water depth from the area limited by the 1992 glacier extent and the range of bathymetric data.

3.5. Glacier Velocity

We estimated the glacier's velocity for 2016–2020 from the global time series and temporal mosaics of glacier surface velocities derived from Sentinel-1 data (Friedl et al., 2021). We used monthly averaged velocity mosaics at 200 m spatial resolution to measure average ice flux directly along the glacier front. Outliers have been removed from the velocity data. Annual velocity was estimated from the monthly time series.

3.6. Statistical Analyses

To determine the influence of climate drivers on individual and regional TWG behavior, we used Pearson correlation coefficients and Engle–Granger cointegration test, similar to studies of glacier retreat in Greenland (e.g., Cowton et al., 2018; Fahrner et al., 2021). The Engle–Granger cointegration test assesses the statistical relationship between two (or more) nonstationary time series that both have strong temporal trends (Engle & Granger, 1987). Where linear regression indicates a significant correlation ($p_{correlation} < 0.05$) but cointegration is not established (at $p_{cointegration} < 0.05$), there is an increased risk that this correlation may be spurious (Cowton et al., 2018). If two variables show cointegration, it further strengthens the significance of the Pearson correlation coefficient, whereas no cointegration suggests spurious regression and the correlation coefficient should be regarded with caution (Fahrner et al., 2021).

4. Results

4.1. Variations of Glacier Fronts

On the decadal timescales, TWG in Hornsund experienced periods of retreat with sporadic episodes of advance (Figure 2a). However, advance and retreat here refer to quasi-stable seasonal terminus adjustment and not to the long-term (order of a century) cycle of large-scale irreversible fast retreat followed by slow readvance (Meier & Post, 1987). One notable anomaly is the period 2017–2020, when five out of seven glaciers slowed down their multiyear terminus retreat, resulting in an advance in one or more years (Figure 2a). From 1992 to 2018, individual glaciers retreated between 50 and 190 ma^{-1} (100 ma^{-1} on average). The glaciers with the highest annual retreat rate over the study period are Storbreen (190 ma^{-1}), Paierlbreen (118 ma^{-1}) and Hornbreen (108 ma^{-1}). The retreat usually activates in June or July, while the minimum annual front extent occurs in early winter, that is, December and even January, with few cases of switch between retreat and advance in October or November.

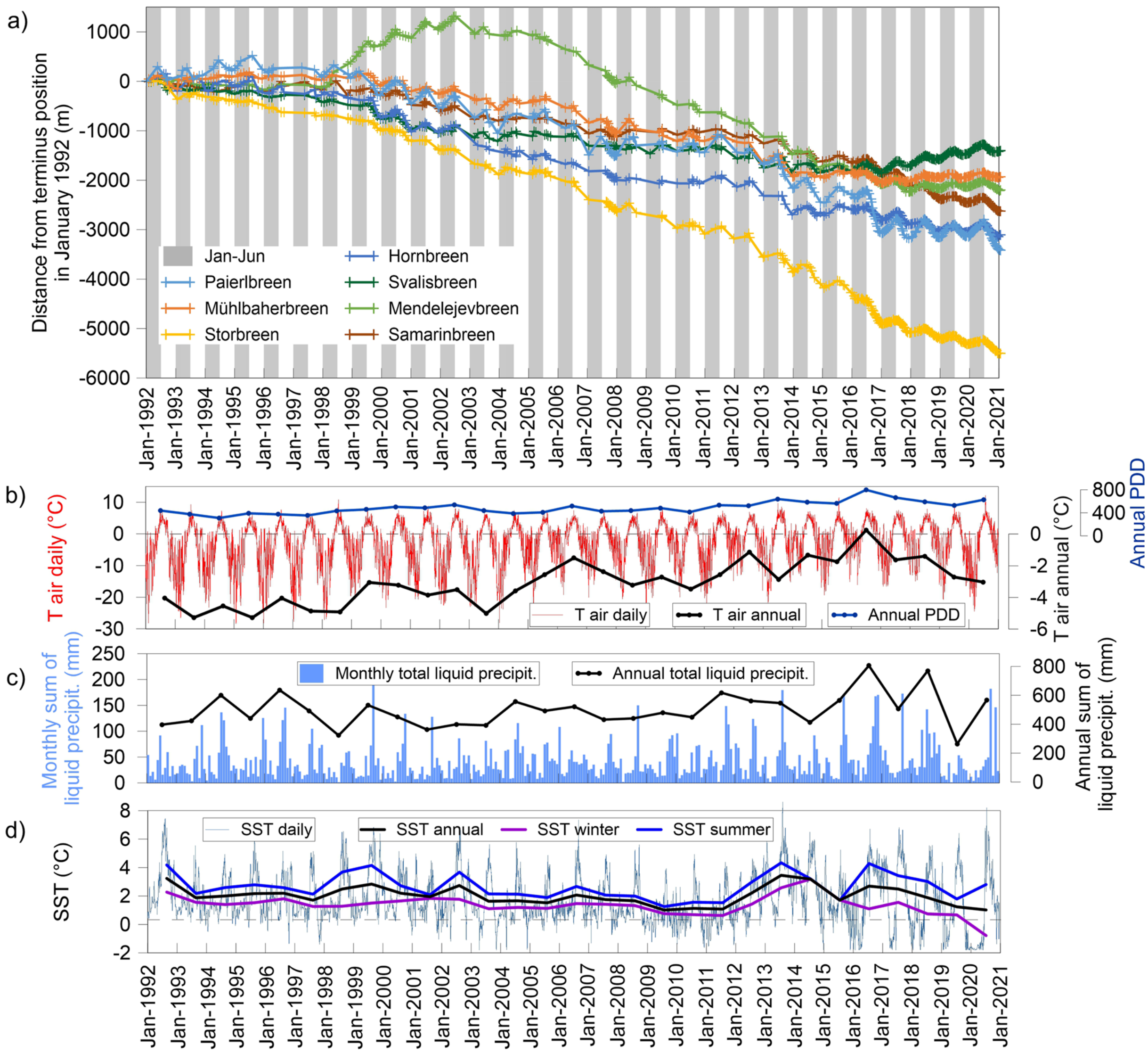

Figure 2. Relative fluctuations of glacier termini (a) show the cumulative front changes from the winter 1991/1992 reference position; crosses indicate individually measured front position; shadowed fields indicate periods of seasonal advance (January–June). Air temperatures: (b) T air daily, T air annual and(c) liquid precipitation were recorded at the PPS weather station, note different scales for both *y*-axes. The positive degree-day index (PDD) at panel (b) is calculated from positive daily average temperatures at the PPS. Sea Surface Temperature (SST) at panel (d) is retrieved from National Oceanic and Atmospheric Administration 1/4° Daily Optimum Interpolation Sea Surface Temperature.

The glacier fronts advance during late winter and in spring (usually between January and June). The magnitude of the seasonal advance and retreat varied considerably during the studied period. The glacier with the highest average retreat rate during summer is Paierlbreen (372 ma^{-1}), followed by Storbreen (241 ma^{-1}) and Hornbreen (232 ma^{-1}). Three glaciers, Mendelejevbreen, Paierlbreen (Błaszczyk et al., 2013), and Svalisbreen (Szafraniec, 2020), underwent a surge during the studied period, resulting in a few years episodes of the front advance. The terminus of Mendelejevbreen advanced 1.5 km from winter 1997/1998 to summer 2002 (Figures 2a and 3f). Paierlbreen advanced 380 m in 1992–1995 (Figures 2a and 3a), and Svalisbreen about 400 m in 2016–2020 (Figures 2a and 3e).

4.2. Relationships Between Terminus Position and Atmosphere-Ocean Factors

A qualitative analysis of the time series shows the close relationship of glacier annual and seasonal retreat with atmosphere-ocean factors (AOF): PDD and SST in some years. The most significant annual and seasonal retreat

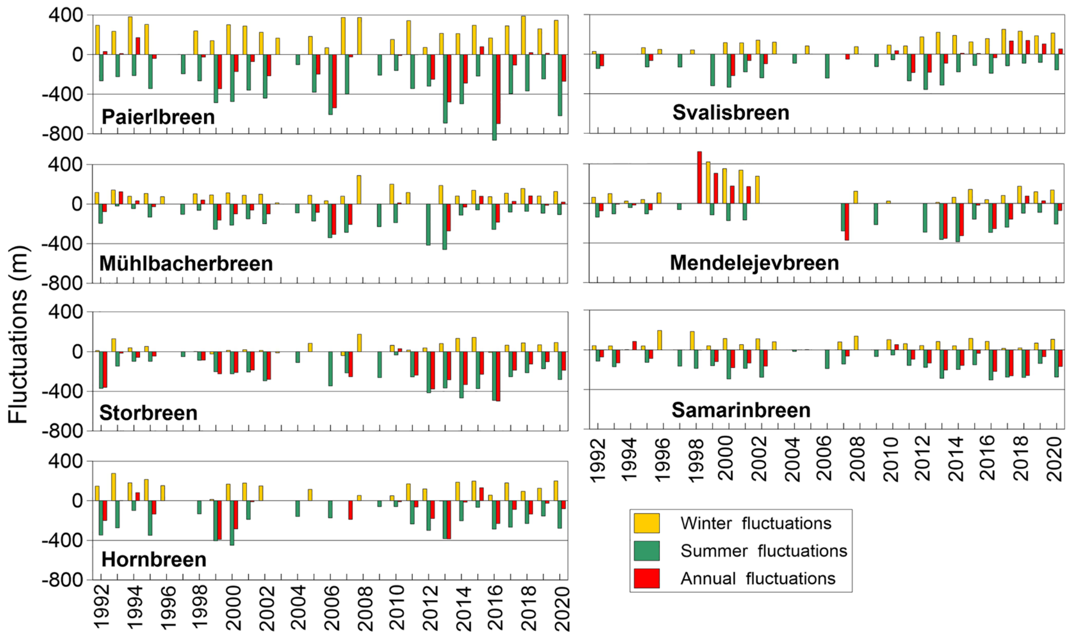

Figure 3. Annual, summer, and winter fluctuations of glacier termini.

for most glaciers (Figure 3) was noted in 2013 and 2016, together with the highest records of PDD (Figure 2b), SST annual, and SST summer (Figure 2d). In contrast, some glaciers retreated less intensively during summers when AOF was exceptionally low (e.g., 1993, 1994, 2004, 2010, 2015, 2019), resulting in periods of terminus advance. This is more visible when cumulative anomalies of glacier fluctuations from the multiyear average (1992–2020) are compared with anomalies of PDD and SST (Figure 4). Generally, positive or negative cumulative anomalies of annual fluctuations (Figure 4a) and seasonal fluctuations (Figure 4b) coincide with positive or negative anomalies of PDD and SST. We noticed, however, exceptions to this pattern (e.g., 1998, 2007, or 2018). Also, we have not found a link between winter advance and AOF (Figure 4c).

To explain potential forcings driving termini position, we calculated the correlation coefficients between termini fluctuations and climatic and oceanographic factors for the period 1992–2020 (Table 2). In the case of the surging glaciers, we also present correlations excluding years of terminus advance. Significant negative correlations ($p_{\text{correlation}} < 0.05$) between annual or seasonal terminus change and one of the climate forcings (PDD, SST annual, and SST summer) occurs across all glaciers besides Mühlbacherbreen. However, Engle–Granger cointegration tests showed that only the results for four glaciers can be considered not to be spurious ($p_{\text{cointegration}} < 0.05$). Annual and summer fluctuations, analyzed without surge period, are cointegrated with PDD annual and at least one of the SST parameters only for Paierlbreen and Samarinbreen (with r between −0.42 and −0.74 depending on the glacier and forcing). Annual and summer fluctuations for Storbreen are correlated and cointegrated only with PDD annual ($r = -0.64$ and −0.74, respectively). In the case of Hornbreen, correlation occurs only between summer fluctuations and SST ($r = -0.55$ and −0.64 for SST annual and summer, respectively). However, investigation for spurious regression between the sum of all termini fluctuations and individual forcings revealed that on a regional scale, annual fluctuations are correlated with PDD annual ($r = -0.64$) and SST annual ($r = -0.55$), while summer fluctuations are correlated only with PDD ($r = -0.77$). Also, we have not found a correlation between terminus changes and liquid precipitation measured at the Polish Polar Station Hornsund.

A detailed study of monthly terminus fluctuations, glacier velocity and the presence of fast ice cover from 2016 to 2020 is presented in Figure 5. The retreat rate of glaciers termini during the summer ranges from around 1 to 4 m/day, except Paierlbreen, which retreated at a rate up to 9 m/day in 2016 (Figure 5a). The pattern of velocities differs between seasons and years (Figure 5b). Ice flux to the front during the summer peak varies among glaciers from 0.5 to 3 m/day for the most rapid Paierlbreen. The average 5-year velocity of glacier termini ranges from 0.36 m/day for the slowest flowing Storbreen to 1.5 m/day for the fastest Paierlbreen. Further, we estimated the correlation of monthly retreat and velocity with AOF (Table 2) for the summer months (July–December). A significant and cointegrated relationship is revealed between the summer retreat and SST monthly for six glaciers

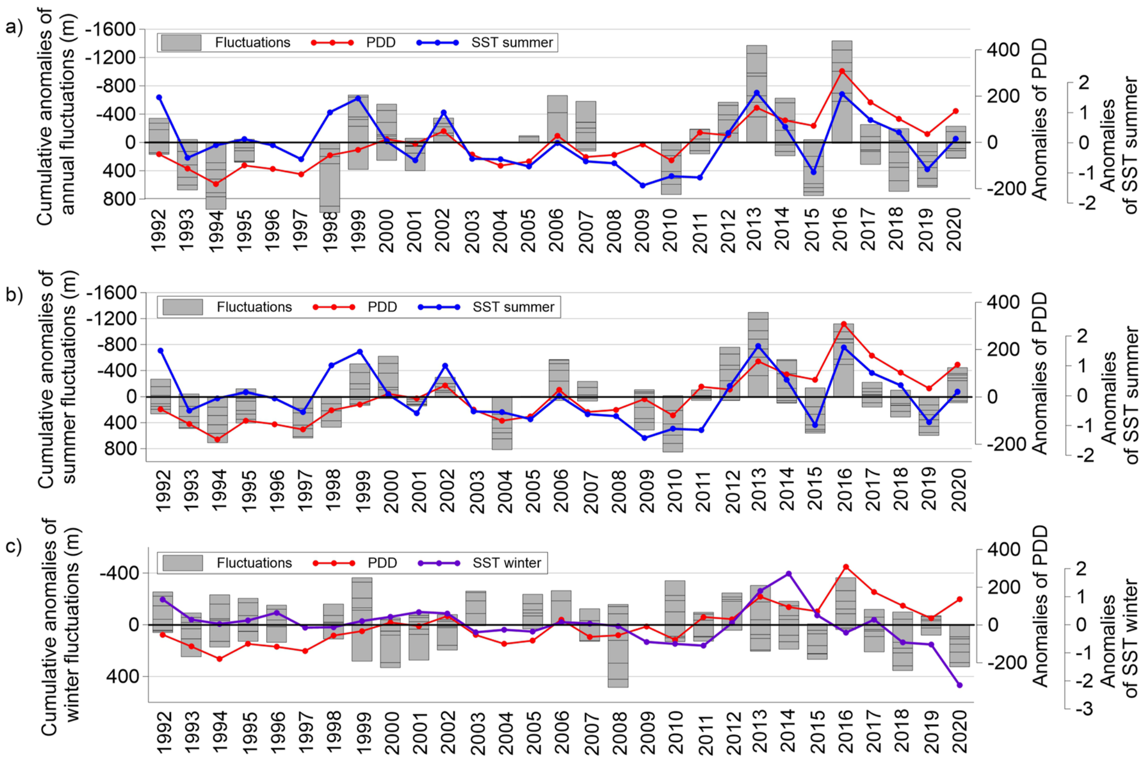

Figure 4. Cumulative anomalies of glacier fluctuations (the horizontal lines inside the bar denotes the individual glaciers contribution), anomalies of positive degree-day index (PDD) and sea surface temperature (SST) from the multiyear average (1992–2020). The *y* axes are inverted to facilitate reader's reception.

($r > 0.48$) and PDD monthly for five out of seven glaciers ($r > 0.39$). There is also a significant and cointegrated correlation between summer retreat and liquid precipitation for the three glaciers. Regarding velocities, we found a significant correlation between summer velocity and PDD and SST only for Hornbreen. There is no statistically significant correlation between the velocity and liquid precipitation resolved at the monthly time scale.

Periods of switching between retreat and advance (Figure 5c) are further compared with fast ice cover and AOF. The average daily air temperature (T air daily) in Hornsund begins to rise from 0°C in May and peaks in June/August (Figure 5d). An increase in daily SST during the summer (Figure 5e) resembles air temperature. With some exceptions, glaciers begin to retreat in early summer around June/July, when the air temperature reaches 4–5°C and SST over 3°C. After the onset of summer retreat, depth-averaged sea temperature from CTD measurement (Temp. CTD; Figure 5e) is around 1–3°C lower than the observed SST as colder fresh waters from the active surface and frontal ablation with runoff cause mixing of seawater. Additionally, surface water is warmed by solar insolation during summer. The retreat continues until December and even January. There are exceptions to the general pattern, for example, Mendelejevbreen and Mühlbacherbreen commenced retreating much earlier in April/May 2016. The retreat of Hornbreen, Mühlbacherbreen and Svalisbreen ended earlier in November 2017, and September or October 2019. Nevertheless, the remaining glaciers retreated further until the end of the year.

In the period 2016–2019, we observed relatively high SST values at the entrance to the fjord even in January and February (Figure 5e) and fast ice coverage at the glacier termini was present only for 2 to 3 months, beginning in February/March (Figure 5c). In 2016, ice cover was not present at Paierlbreen. In 2020, when water at the fjord was extremely cold during winter, fast ice coverage persisted at all glaciers as late as June. In some cases, the onset of terminus retreat follows the disappearance of the ice cover, with some days of delay; while the termination of the seasonal retreat is not related to ice cover.

4.3. Glacier Fluctuations v. Bathymetry

The largest average water depths are at the glaciers in the main basin of Hornsund, Paierlbreen, Mühlbacherbreen and Samarinbreen, at over 150, 90, and 86 m, respectively (Figure 1, Table 1). The average depth of the glaciers

10.1029/2022JF006911

Table 2
Pearson's Correlation Coefficients of Terminus Fluctuations Against Climate Factors for Individual Glaciers

	Terminus fluctuations	Climate factors	Pa	Mu	St	Ho	Sv	Me	Sa	Sum
1992–2020	**Annual fluctuations**	PDD annual	**−0.63 (−0.51)**	−0.23	**−0.63**	−0.26	0.28 (0.06)	−0.38 (−0.34)	**−0.74**	**−0.64**
		SST annual	**−0.42 (−0.55)**	−0.40	**−0.52**	**−0.55**	−0.23 (−0.03)	−0.18 (**−0.56**)	−0.33	**−0.55**
		SST summer	**−0.54 (−0.66)**	−0.37	**−0.53**	**−0.71**	−0.10 (−0.13)	−0.04 (−0.43)	**−0.44**	**−0.58**
		Liquid precip.	−0.34 (−0.38)	−0.08	−0.34	−0.17	0.08 (−0.05)	−0.26 (0.02)	−0.35	−0.33
	Summer fluctuations	PDD annual	**−0.74 (−0.73)**	−0.28	**−0.74**	−0.23	−0.18 (−0.36)	**−0.63 (−0.63)**	**−0.71**	**−0.77**
		SST annual	**−0.44 (−0.54)**	−0.34	**−0.46**	**−0.55**	**−0.43** (−0.41)	−0.43 (**−0.50**)	**−0.42**	**−0.54**
		SST summer	**−0.60 (−0.69)**	−0.33	**−0.42**	**−0.64**	−0.43 (−0.47)	−0.34 (−0.43)	**−0.57**	**−0.62**
		Liquid precip.	−0.38 (−0.40)	−0.15	−0.31	−0.10	−0.11 (−0.17)	−0.11 (−0.10)	−0.33	−0.34
	Winter fluctuations	SST winter	−0.19 (−0.24)	−0.06	0.06	−0.01	−0.10 (0.40)	−0.03 (−0.40)	−0.07	−0.18
2016–2020	**Monthly summer fluctuations**	PDD monthly	**0.41**	**0.63**	0.16	**0.53**	**0.65**	**0.39**	0.11	n/a
		SST monthly	**0.52**	**0.67**	**0.43**	**0.69**	**0.74**	**0.57**	**0.48**	n/a
		Liquid precip. monthly	**0.52**	0.25	**0.47**	**0.49**	0.28	0.18	**0.59**	n/a
	Monthly summer velocity	PDD monthly	0.32	−0.03	−0.20	**0.40**	0.08	0.03	0.29	n/a
		SST monthly	0.12	0.11	0.16	**0.36**	0.08	0.07	0.24	n/a
		Liquid precip. monthly	−0.12	0.33	0.27	−0.05	0.04	0.11	0.18	n/a

Note. Statistically significant correlations ($p_{correlation} < 0.05$) are shown in bold. Underlined values indicate that time series are cointegrated ($p_{cointegration} < 0.05$). Correlations estimated without surge episodes in the studied period 1992–2020 are presented in brackets. Abbreviated names for glaciers: Pa, Paierlbreen; Mu, Mühlbacherbreen; St, Storbreen; Ho, Hornbreen; Sv, Svalisbreen; Me, Mendelejevbreen; Sa, Samarinbreen; Sum, sum of termini fluctuations.

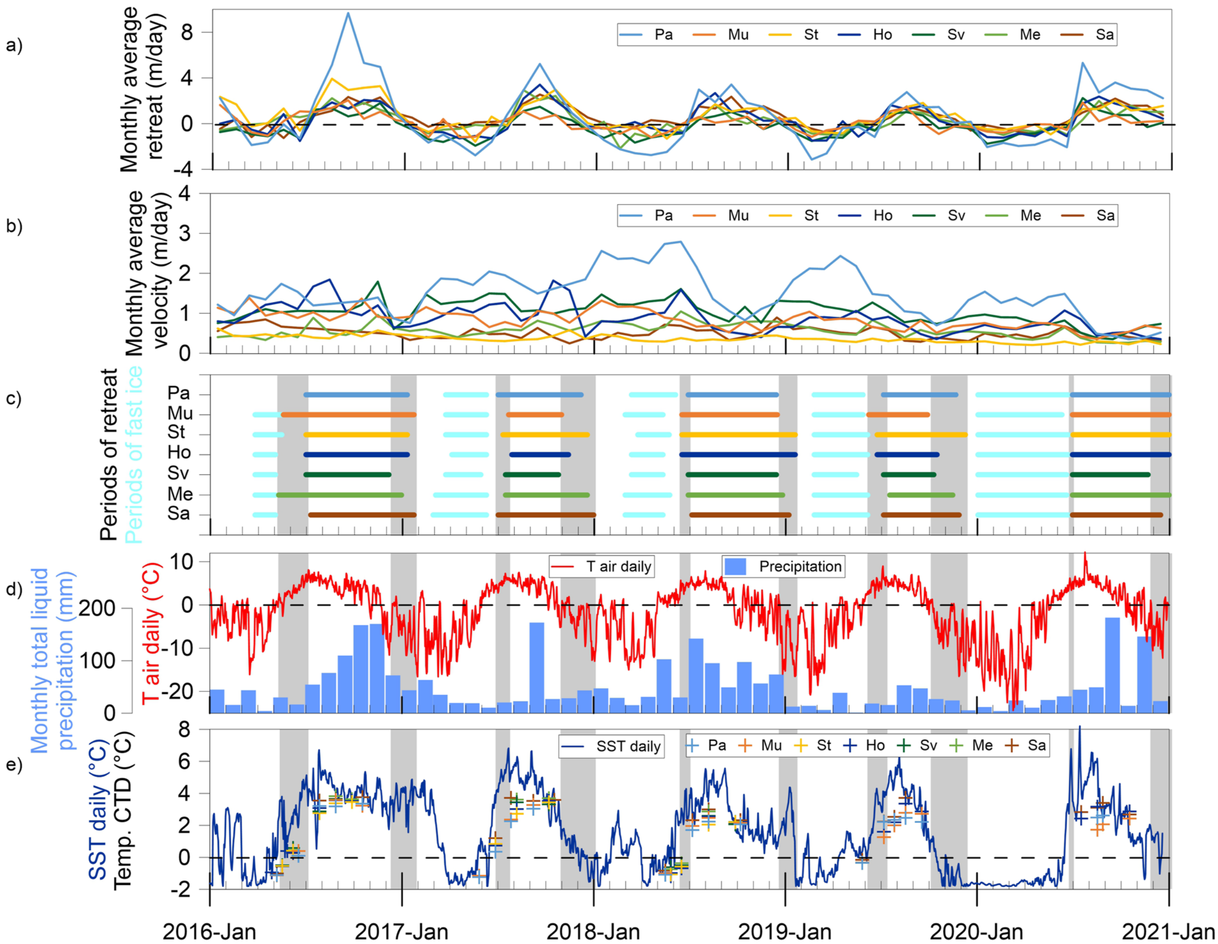

Figure 5. Retreat and velocity of the glaciers termini and atmospheric and oceanic factors: (a) monthly average retreat and (b) monthly average velocity near the terminus position are estimated as averages for each month. Periods of (c) retreat and fast ice cover are determined for each glacier separately. Meteorological data at (d): air temperatures (T air daily) and monthly total liquid precipitation were recorded at the PPS weather station. Panel (e) show Sea Surface Temperature (SST daily) and Temp. CTD, which is an averaged temperature in the water column from CTD measurements at the front of each glacier. The shadowed fields in panels (c–e) indicate the periods when the glaciers change their mode between retreat and advance.

in the Brepollen area is significantly shallower, between 42 and 52 m. To quantify the role of the water depth at the termini on a regional scale, we compared average depths at the termini with average annual fluctuations of all glaciers determined for the period 1992–2020. We found no statistically significant correlation between the retreat and water depth in a decadal timescale. However, it is worth noting that seasonal fluctuations at Paierlbreen are twice as large as those at the other glaciers (Figure 3). The terminus of Paierlbreen terminates in significantly deep water (c. 170 m in the central part) and is the only glacier in the Hornsund fjord where we noticed occasional large-scale calving events, sometimes preceded by deep surface crevasses.

5. Discussion

5.1. Front Fluctuations in Hornsund

On a regional scale, temporal variations in termini positions show a largely synchronous pattern, suggesting that there is a common external driver in the studied region (Table 2, Figure 4). Our findings show that the sum of TWG annual or summer fluctuations in Hornsund can be explained by one or two AOFs. In warmer years, higher air temperatures increase surface melt and runoff. That, with the presence of relatively warm seawater, drives increased submarine melting, frontal calving and retreat (Motyka et al., 2003, 2013; Nick et al., 2010; Slater et al., 2015). Further, higher amount of meltwater in warm years may influence glacier dynamics through moderating basal sliding (Moon et al., 2014), through thinning the glacier to flotation followed by increased calving

(Pfeffer, 2007) or by driving increased calving by hydrofracture (Otero et al., 2017). Also, warmer seawater affects melting at the waterline, stimulating calving, as was shown for Svalbard glaciers (How et al., 2019; Pętlicki et al., 2015). Oppositely, in colder years, reduced subglacial discharge and/or lower heat supplied by the ocean to the terminus may decrease submarine melting, calving and frontal retreat. As we do not estimate the amount of surface meltwater and subglacial melt in this study, further research is needed to answer which of these processes driven by air and sea temperature is the most responsible for the terminus positions of glaciers in Hornsund.

Further investigation for spurious regression between climate variables and monthly termini change of particular glaciers for the period 2016–2020 revealed that the correlation between summer terminus fluctuations and one or more climate forcings occurs for six out of seven glaciers (Table 2). However, the identification that annual and summer fluctuations in the period 1992–2020 exhibit cointegration with one or more climate forcings in only four out of seven glaciers highlights the complexity of ice–ocean–atmosphere interactions on a local scale, showing that even neighboring TWG might respond differently to climate (Cowton et al., 2018). Variations in PDD and sea temperature can explain most seasonal termini fluctuations of glaciers; however, some exceptions exist, for example, in 2000, 2006, 2007, 2012, and 2018 (Figure 4). Also, the pattern of terminus fluctuation differs at individual glaciers regardless of their location (main basin or Brepollen), suggesting that other processes affect the terminus position. Such variables include among others: water depth at the front (Brown et al., 1982), sea-depth/glacier-thickness ratio (Meier & Post, 1987; Post, 1975), terminus height above buoyancy (Van der Veen, 1996), seasonal and interannual changes in subglacial drainage configuration translating into changes in frontal ablation (Bunce et al., 2021) and bathymetry which controls the access of seawater to calving fronts (Rignot, Fenty, et al., 2016; Truffer & Motyka, 2016). However, as the studied glaciers retreated, they exposed new areas where the bathymetry data is limited. This is a source of uncertainty and does not allow quantifying detailed linkages between ice front retreat and water depth in the fjord, as was found in Greenland (Rignot, Fenty, et al., 2016). Another parameter affecting the terminus position is a surge history, which by changes in the accumulation area ratio (AAR) influence glacial runoff variations (Meier, 1962). For example, on the decadal scale, the highest and steady retreat rate has been noticed for Storbreen, which surged before the analyzed period. The second largest retreat has been detected for Mendelejevbreen since 2002, after a significant advance due to the surge episode (Figure 2). The surge caused a decrease in AAR and in consequence a higher runoff in comparison to other glaciers. That can support the high importance of surface melting in frontal ablation and evolution of glaciers' termini. Also, a highly crevassed surface after the surge may intensify hydrofracture-driven calving (Otero et al., 2017). Further, although we have not found a correlation between frontal changes and bathymetry for TWG, we noticed that annual and seasonal changes of Paierlbreen termini are double that observed at other glaciers. This can be directly linked to the extreme depth at the termini susceptible to buoyant flexure, which results in sporadically full ice thickness calving events (Fried et al., 2018) driven by amplified submarine melting (O'Leary & Christoffersen, 2013). Also, the surge in the 1990s would reduce the AAR ratio of the glacier, which intensified the front retreat.

We found that in the last four consecutive years, 2017–2020, the majority of glaciers underwent a period of annual or multiannual advance (Figures 2a and 3), despite relatively high air and water temperature (Figures 2b, 2d, 4a, and 4b). Only Samarinbreen and Storbreen continued their multiyear retreat. The advance followed the year 2016 with the highest records of PDD, SST and liquid precipitation, when frontal ablation was extremely large, resulting in a significant annual and summer retreat. A similar effect of terminus advance or reduced retreat occurred periodically in colder years (e.g., 2010, 2015; Figures 3 and 4), sometimes following an extreme retreat in warmer years. Results from 2017 to 2018 show that this adjustment is independent of climatic conditions, as glaciers were advancing despite relatively high air and sea temperatures.

Błaszczyk et al. (2021) found a similar pattern of front fluctuations driven by AOF for Hansbreen in Hornsund. The largest values of annual and summer retreat of Hansbreen were noticed mainly in the warm years 1999–2000 and 2012–2014, similar to some of the glaciers studied here (Figures 3 and 4). Annual advances of Hansbreen were noticed in the years 1993–1995, 2010, and 2015, as for the other glaciers in the fjord. Despite some differences between glaciers, the synchronicity of the seasonal and interannual fluctuations is observed. Although, the size of the front position changes for Hansbreen (mean annual retreats 38 m a^{-1}) is smaller than for the other Hornsund neighbors. In this context, a comparison of Hansbreen with the behavior of other TWG in Hornsund is interesting, as one can expect that the front of Hansbreen, exposed directly to the influence of the Greenland Sea conditions, will demonstrate more distinct fluctuations than the other glaciers. Further studies taking into account exposure to high ocean waves or submarine moraine sill limiting the effectiveness of the estuarine circulation at

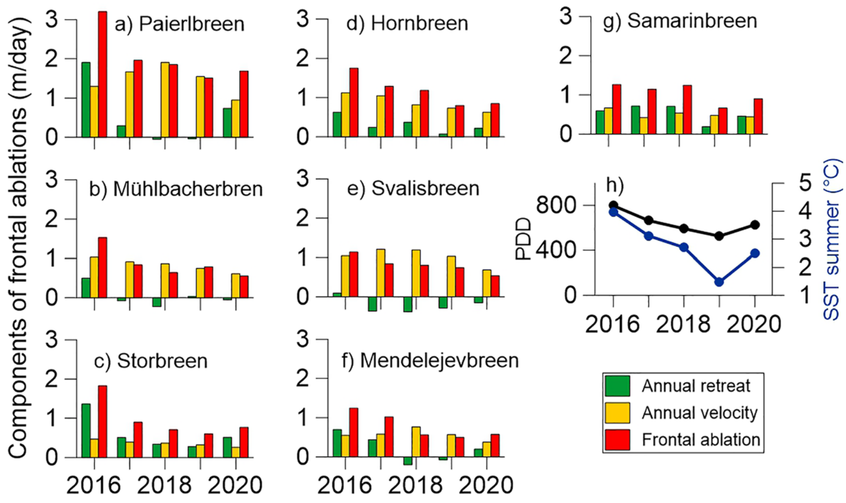

Figure 6. Components of frontal ablation 2016–2020 for (a–g) all glaciers, and (h) positive degree-day index (PDD) and summer sea surface temperature (SST).

the Hansbreen termini (Głowacki et al., 2016) are required to explain the relatively small fluctuations in relation to the other TWG in the fjord.

5.2. Terminus Position Controlled by Frontal Ablation and Ice Motion

The position of a tidewater terminus is controlled by the difference between the frontal ablation and the ice flux into the terminus (Truffer & Motyka, 2016). To quantify the role of both components, we estimated frontal ablation on an annual scale as the sum of annual velocity (ice flux near the calving front) and annual front retreat. Results differ between glaciers and change between years (Figures 6a–6g). Frontal ablation for all glaciers was the highest in 2016, the warmest year in our records, when the air and sea temperatures, as well as precipitation, were extremely high (Figures 2b–2d, 6h). Frontal ablation noticeably decreased during the next 4 years. Besides Mühlbacherbreen and surging Svalisbreen, frontal ablation was the lowest in 2019 when air and sea temperatures were much lower. At the same time, velocities only slightly fluctuated around the average, depending on the glacier.

Frontal ablation during the summers of 2016–2020 varied between around 1.0 m per day and a few meters per day. We do not know the rate of submarine melting for the studied glaciers. Pętlicki et al. (2015) modeled the maximum daily melt rate of the cliff of neighboring Hansbreen between 0.02 and 0.56 m/day in relatively cool August 2011 and between 0.14 and 0.78 m/day in a warmer 2012. Assuming similar values for other glaciers in Hornsund, frontal ablation would be even a few times larger than the submarine melt during summer. Nevertheless, taking into account results of direct observations of subsurface geometry made by Sutherland et al. (2019), we know that melt rates can be up to two orders of magnitude greater than predicted by theory due to near-terminus circulation patterns. Our result is in accordance with the finding of O'Leary and Christoffersen (2013) and De Andrés et al. (2018, 2021) that submarine melting might be a relevant driver of frontal retreat.

The contribution of the retreat rate in frontal ablation changes from year to year (Figure 6). The average terminus retreat in 2016 was around 45% of the mass loss by frontal ablation, varying for individual glaciers between 9% and 75%. That is much higher than the 30% ratio estimated by Błaszczyk et al. (2019) for glaciers in Hornsund from 2006 to 2015. In contrast, between 2017 and 2020, the contribution of the average retreat component to frontal ablation decreased considerably and accounted for only 2%–26% of the mass loss by frontal ablation in the fjord. In many cases, frontal ablation and ice flux were almost exactly balanced, and in some years, the ice flux to the terminus was larger than frontal ablation, resulting in front advance. Similar ranges of ice supply and frontal ablation show that these two quantities are generally not independent of each other (Truffer & Motyka, 2016). Surface melting plays a significant role in front fluctuations, stimulating both ice flux toward the front controlled by subglacial water pressure (Budd et al., 1979; Iken & Bindschadler, 1986; Van der Veen, 1996) and frontal ablation, driven by increased submarine melting due to intensified mixing of runoff with seawater

(Motyka et al., 2013). Overall, these results show that variation in velocity, driven by surface melting or interannual changes in subglacial drainage configuration (Bunce et al., 2021) are significant contribution to frontal ablation, thus also to multiyear and seasonal changes in the termini position in Hornsund. Unfortunately, there is not enough continuous data on glacier velocities before 2016 to compare whether the flow speed of glaciers has markedly accelerated in recent years in the region, driving some frontal advances. Comparing the 5-year averaged velocities with data from Błaszczyk et al. (2019) shows that all glaciers besides Mühlbacherbreen flowed 10%–87% faster than in 2012 and 2014. However, the data used by Błaszczyk et al. (2019) come from two short winter periods, and further studies are needed to assess whether the Hornsund glaciers responded to climate change by increasing velocity, as was noted for Greenland (Moon et al., 2012).

5.3. Comparison of Front Fluctuations to Other Tidewater Glaciers

This study shows that at a regional scale, annual termini positions of the TWG of Hornsund are vulnerable to both atmospheric and oceanic. Our results are in good agreement with the findings by Cowton et al. (2018), Fahrner et al. (2021), Seale et al. (2011), and Wood et al. (2021), who recognized both oceanic and atmospheric warming as a key control of the retreat of TWG in Greenland. Other authors highlight significant variations in retreat rates in different parts of the Arctic due to the sea ice and ice melange condition (Carr et al., 2017; Moon et al., 2015; White & Copland, 2019). This study shows that the onset of retreat depends on fast ice conditions for some glaciers. Further, the advance period in Hornsund extends to June or even July, while a minimal position can be reached up to December. In contrast, many glaciers in Alaska and Greenland reach their maximal position in the late winter or spring and their minimal position in the late summer or autumn (e.g., Bartholomaus et al., 2013; Fried et al., 2018; Ritchie et al., 2008; Seale et al., 2011). We noted positive air temperatures and increased liquid precipitation in Svalbard even in December, which significantly prolongs the retreat/ablation season, stimulating submarine melting and calving even during winter.

The average annual retreat rate of TWG in Hornsund (100 ma^{-1}) is two times higher than the retreat rate of glaciers along the east coast (48 ma^{-1}; Kavan et al., 2022). However, the results of Kavan et al. (2022) relate to the period 1970–2019 and it needs further studies to assess whether the increased heat transport to the Arctic Ocean by Atlantic Water (Merchel & Walczowski, 2020; Piechura & Walczowski, 2009; Strzelewicz et al., 2022; Walczowski & Piechura, 2011) plays a significant role in the pattern of termini position in western Spitsbergen. Taking into account the earlier timing of spring melt (Vickers et al., 2022), and an increasing trend of warmer winter periods (Osuch & Wawrzyniak, 2017), increased water input to the glacier drainage system is expected, as the models predict that runoff from glaciers in Svalbard will double during the 21st century (Geyman et al., 2022; van Pelt et al., 2021) and the AAR of the glaciers will reach zero in southern Svalbard in the 2030s (van Pelt et al., 2021). However, it remains unclear how changes in atmospheric and oceanic temperatures will translate into changes in frontal ablation (Bunce et al., 2021), especially in the lack of bathymetry recently exposed by retreating glaciers' terminus. Our results can help answer the key questions raised by Schuler et al. (2020) concerning how the dynamics and geometry of Svalbard glaciers will respond to climate change. Future research in Svalbard should address the drivers of the front position of TWG to understand the relation between near terminus hydrology and frontal ablation on a regional scale.

6. Conclusions

We assess the seasonal fluctuations of the ice fronts of seven marine-terminating glaciers in the inner part of Hornsund based on satellite data, meteorological data, sea surface temperature observations and bathymetry. The long observational record, from 1992 to 2020, allowed the investigation of TWG behavior on a multiyear scale. Results show the general synchronous pattern of glacier retreat in the period 1992–2020, punctuated in a few cases by surges. The resulting regional depiction was compared with air temperature, positive degree day index, sea surface temperature, sea ice condition and liquid precipitation. We show that at a regional scale multiyear termini changes are sensitive to PDD and SST and summer fluctuations are linked to PDD. The highest retreat occurred in the warm years. Glaciers slowed their retreat or advanced periodically in colder years, following an extreme retreat in warmer years. There was no clear relationship between the terminus position and liquid precipitation on a decadal timescale. At the scale of individual glaciers, a relationship between terminus position and one or more environmental forcings was found for four out of seven glaciers, identifying potentially different drivers of TWG frontal change even among neighboring glaciers. The divergent behavior in the case of some glaciers may be linked to water depth, but continued bathymetry is necessary to study its role in driving tidewater glaciers into a retreat. However, the largest seasonal fluctuations were noted for Paierlbreen, which terminates in water two to three times deeper than the other six glaciers.

With some exceptions, glaciers showed seasonal retreat initiated between June and early July following a rise in air and sea temperature, which supports the influence of meltwater availability and submarine melting on the glacier front position. A relationship between the onset of retreat and the presence of fast ice was found for some glaciers. Glacier retreat terminated between October and December, driven in some cases by a decrease in sea surface temperature.

Additionally, we present 5-year records (2016–2020) of detailed seasonal and annual variations in front positions, ice flux, and frontal ablation to evaluate potential processes responsible for termini positions. Frontal ablation for all glaciers was the highest in 2016, the warmest year in our records, with the highest sum of liquid precipitation, and much lower in colder 2019. But the ratio of annual ice flux to retreat rate, that is, components of frontal ablation, varies from year to year, indicating changing contributions from the two competing factors. We found a similarity between ice supply and frontal ablation rate, which supports couplings between the atmosphere, ocean, and ice supply to the glacier front (Truffer & Motyka, 2016) and highlights the significance of variation of velocity for terminus positions in the fjord.

As in Greenland (Bunce et al., 2021), the expected increases in meltwater runoff in Svalbard as well as an increase in the input of warm water to the fjord may have implications for changes in near-terminus subglacial hydrological characteristics and frontal ablation. Further research is needed to assess whether the Svalbard glaciers will respond to climate change by increasing velocity and frontal ablation, influencing the front position of tidewater glaciers.

Data Availability Statement

Terminus positions of glaciers can be accessed from the Polish Polar DataBase directly via this URL: http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search#/metadata/4a6a5fcb-07dc-472e-8901-9fb63ec541d9. Meteorological data are derived from https://doi.pangaea.de/10.1594/PANGAEA.909042 (Wawrzyniak & Osuch, 2019) and from the IGF PAS data portal https://monitoring-hornsund.igf.edu.pl/. SST data are available at: https://www.ncei.noaa.gov/products/optimum-interpolation-sst (Huang et al., 2020). CTD data are derived from IGF PAS data portal: https://dataportal.igf.edu.pl/dataset/inter-calibrated-temperature-and-salinity-in-depth-profiles-in-hornsund-fjord. Surface velocity of glaciers is available at: https://doi.org/10.5880/fidgeo.2021.016 (Friedl et al., 2021).

Acknowledgments
The study and publication were financed from the funds of the Leading National Research Centre (KNOW-Krajowy Naukowy Osrodek Wiodacy) received by the Centre for Polar Studies for the period 2014–2018 and partially by the Institute of Geophysics PAS statutory activities No. 3841/E-41/S/2022 of the Ministry of Science and Higher Education of Poland. Publication co-financed by the funds granted under the Research Excellence Initiative of the University of Silesia in Katowice. Glaciological, hydrological and meteorological data have been processed under assessment of the University of Silesia data repository within the project Integrated Arctic Observing System (INTAROS). This work was supported by the Research Council of Norway under the project Svalbard Integrated Arctic Earth Observing System—Infrastructure development of the Norwegian node (SIOS-InfraNor Project No. 269927). Satellite data from ASTER © METI and NASA [2003–2010]. Landsat data from the USGS. The SPOT-5 image and DEM data © CNES 2008, distribution Spot Image S.A. ERS SAR images provided by ESA (Project No. C1P.9630). TerraSAR-X data was provided by DLR (project LAN2787). Sentinel-1 from Copernicus Sentinel data (2014–2020). Radarsat data provided by NCS/KSAT under the Norwegian-Canadian RADARSAT-2 agreement 2012–2022. Thanks are directed to the staff of the Institute of Geophysics PAS, the Polish Polar Station Hornsund and participants of the University of Silesia's expeditions to Spitsbergen for establishing and maintaining the meteorological, glaciological, and LONGHORN oceanographic monitoring and for assistance during field campaigns. The research and logistic equipment of the Polar Laboratory of the University of Silesia in Katowice was used during the fieldwork. We would like to thank the three anonymous reviewers who provided very thoughtful and constructive feedback that helped improve the paper.

References

Amundson, J. M., Fahnestock, M., Truffer, M., Brown, J., Lüthi, M. P., & Motyka, R. J. (2010). Ice mélange dynamics and implications for terminus stability, Jakobshavn Isbræ, Greenland. *Journal of Geophysical Research*, *115*(F1), F01005. https://doi.org/10.1029/2009JF001405

Arntsen, M., Sundfjord, A., Skogseth, R., Błaszczyk, M., & Promińska, A. (2019). Inflow of warm water to the inner Hornsund fjord, Svalbard: Exchange mechanisms and influence on local sea ice cover and glacier front melting. *Journal of Geophysical Research: Oceans*, *124*(3), 1915–1931. https://doi.org/10.1029/2018JC014315

Bartholomaus, T. C., Larsen, C. F., & O'Neel, S. (2013). Does calving matter? Evidence for significant submarine melt. *Earth and Planetary Science Letters*, *380*, 21–30. https://doi.org/10.1016/j.epsl.2013.08.014

Błaszczyk, M., Ignatiuk, D., Uszczyk, A., Cielecka-Nowak, K., Grabiec, M., Jania, J., et al. (2019). Freshwater input to the Arctic fjord Hornsund (Svalbard). *Polar Research*, *38*(0). https://doi.org/10.33265/polar.v38.3506

Błaszczyk, M., Jania, J. A., Ciepły, M., Grabiec, M., Ignatiuk, D., Kolondra, L., et al. (2021). Factors controlling terminus position of Hansbreen, a tidewater glacier in Svalbard. *Journal of Geophysical Research: Earth Surface*, *126*(2), e2020JF005763. https://doi.org/10.1029/2020JF005763

Błaszczyk, M., Jania, J. A., & Kolondra, L. (2013). Fluctuations of tidewater glaciers in Hornsund fjord (southern Svalbard) since the beginning of the 20th century. *Polish Polar Research*, *34*(4), 327–352. https://doi.org/10.2478/popore-2013-0024

Braithwaite, R. J. (1985). Calculation of degree-days for glacier-climate research. *Zeitschrift Fuer Gletscherkunde Und Glazialgeologie*, *20*(1984), 1–8.

Brown, C. S., Meier, M. F., & Post, A. (1982). *Calving speed of Alaska tidewater glaciers, with application to Columbia glacier USGS professional paper 1258-C* (pp. 1044–9612). USGS.

Budd, W. F., Keage, P. L., & Blundy, N. A. (1979). Empirical studies of ice sliding. *Journal of Glaciology*, *23*(89), 157–170. https://doi.org/10.3189/S0022143000029804

Bunce, C., Nienow, P., Sole, A., Cowton, T., & Davison, B. (2021). Influence of glacier runoff and near-terminus subglacial hydrology on frontal ablation at a large Greenlandic tidewater glacier. *Journal of Glaciology*, *67*(262), 343–352. https://doi.org/10.1017/jog.2020.109

Carr, J. R., Stokes, C. R., & Vieli, A. (2013). Recent progress in understanding marine-terminating Arctic outlet glacier response to climatic and oceanic forcing: Twenty years of rapid change. *Progress in Physical Geography*, *37*(4), 436–467. https://doi.org/10.1177/0309133313483163

Carr, J. R., Stokes, C. R., & Vieli, A. (2017). Threefold increase in marine-terminating outlet glacier retreat rates across the Atlantic Arctic: 1992–2010. *Annals of Glaciology*, *58*(74), 72–91. https://doi.org/10.1017/aog.2017.3

Christoffersen, P., O'Leary, M., Van Angelen, J. H., & Van Den Broeke, M. (2012). Partitioning effects from ocean and atmosphere on the calving stability of Kangerdlugssuaq Glacier, East Greenland. *Annals of Glaciology*, *53*(60), 249–256. https://doi.org/10.3189/2012AoG60A087

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., et al. (2011). *Glossary of glacier mass balance and related terms*. United Nations Educational, Scientific and Cultural Organization, International Hydrological Programme.

Cook, A. J., Copland, L., Noël, B. P., Stokes, C. R., Bentley, M. J., Sharp, M. J., et al. (2019). Atmospheric forcing of rapid marine-terminating glacier retreat in the Canadian Arctic Archipelago. *Science Advances*, *5*(3), eaau8507. https://doi.org/10.1126/sciadv.aau8507

Cottier, F. R., Nilsen, F., Inall, M., Gerland, S., Tverberg, V., & Svendsen, H. (2007). Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation. *Geophysical Research Letters*, *34*(10), L10607. https://doi.org/10.1029/2007GL029948

Cowton, T. R., Sole, A. J., Nienow, P. W., Slater, D. A., & Christoffersen, P. (2018). Linear response of east Greenland's tidewater glaciers to ocean/atmosphere warming. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(31), 7907–7912. https://doi.org/10.1073/pnas.1801769115

Dahlke, S., Hughes, N. E., Wagner, P. M., Gerland, S., Wawrzyniak, T., Ivanov, B., & Maturilli, M. (2020). The observed recent surface air temperature development across Svalbard and concurring footprints in local sea ice cover. *International Journal of Climatology*, *40*(12), 5246–5265. https://doi.org/10.1002/joc.6517

De Andrés, E., Otero, J., Navarro, F., Promińska, A., Lapazaran, J., & Walczowski, W. (2018). A two-dimensional glacier–fjord coupled model applied to estimate submarine melt rates and front position changes of Hansbreen, Svalbard. *Journal of Glaciology*, *64*(247), 745–758. https://doi.org/10.1017/jog.2018.61

De Andrés, E., Otero, J., Navarro, F. J., & Walczowski, W. (2021). Glacier–plume or glacier–fjord circulation models? A 2-D comparison for Hansbreen–Hansbukta system, Svalbard. *Journal of Glaciology*, *67*(265), 797–810. https://doi.org/10.1017/jog.2021.27

Dowdeswell, J. A., & Benham, T. J. (2003). A surge of Perseibreen, Svalbard, examined using aerial photography and ASTER high resolution satellite imagery. *Polar Research*, *22*(2), 373–383. https://doi.org/10.3402/polar.v22i2.6466

Dowdeswell, J. A., Hamilton, G. S., & Hagen, J. O. (1991). The duration of the active phase on surge-type glaciers: Contrasts between Svalbard and other regions. *Journal of Glaciology*, *37*(127), 388–400. https://doi.org/10.3189/S0022143000005827

Enderlin, E. M., O'Neel, S., Bartholomaus, T. C., & Joughin, I. (2018). Evolving environmental and geometric controls on Columbia glacier's continued retreat. *Journal of Geophysical Research: Earth Surface*, *123*(7), 1528–1545. https://doi.org/10.1029/2017JF004541

Engle, R. F., & Granger, C. W. J. (1987). Co-Integration and error correction: Representation, estimation, and testing. *Economic Journal Economic Society*, *55*(2), 251–276. https://doi.org/10.2307/1913236

Fahrner, D., Lea, J. M., Brough, S., Mair, D. W., & Abermann, J. (2021). Linear response of the Greenland ice sheet's tidewater glacier terminus positions to climate. *Journal of Glaciology*, *67*(262), 193–203. https://doi.org/10.1017/jog.2021.13

Flink, A. E., Noormets, R., Kirchner, N., Benn, D. I., Luckman, A., & Lovell, H. (2015). The evolution of a submarine landform record following recent and multiple surges of Tunabreen glacier, Svalbard. *Quaternary Science Reviews*, *108*, 37–50. https://doi.org/10.1016/j.quascirev.2014.11.006

Fried, M., Catania, G., Stearns, L., Sutherland, D., Bartholomaus, T., Shroyer, E., & Nash, J. (2018). Reconciling drivers of seasonal terminus advance and retreat at 13 Central West Greenland tidewater glaciers. *Journal of Geophysical Research: Earth Surface*, *123*(7), 1590–1607. https://doi.org/10.1029/2018JF004628

Friedl, P., Seehaus, T., & Braun, M. (2021). Sentinel-1 ice surface velocities of Svalbard. V. 1.0 [Dataset]. GFZ Data Services. https://doi.org/10.5880/fidgeo.2021.016

Geyman, E. C., van Pelt, W. J. J., Maloof, A. C., Aas, H. F., & Kohler, J. (2022). Historical glacier change on Svalbard predicts doubling of mass loss by 2100. *Nature*, *601*(7893), 374–379. https://doi.org/10.1038/s41586-021-04314-4

Gjelten, H. M., Nordli, Ø., Isaksen, K., Førland, E. J., Sviashchennikov, P. N., Wyszynski, P., et al. (2016). Air temperature variations and gradients along the coast and fjords of western Spitsbergen. *Polar Research*, *35*(1), 29878. https://doi.org/10.3402/polar.v35.29878

Glowacki, O., Moskalik, M., & Deane, G. B. (2016). The impact of glacier meltwater on the underwater noise field in a glacial bay. *Journal of Geophysical Research: Oceans*, *121*(12), 8455–8470. https://doi.org/10.1002/2016JC012355

How, P., Schild, K., Benn, D., Noormets, R., Kirchner, N., Luckman, A., et al. (2019). Calving controlled by melt-under-cutting: Detailed calving styles revealed through time-lapse observations. *Annals of Glaciology*, *60*(78), 20–31. https://doi.org/10.1017/aog.2018.28

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., et al. (2020). Improvements of the daily optimum interpolation sea surface temperature (DOISST) version 2.1 [Dataset]. Journal of Climate, *34*, 2923–2939. https://doi.org/10.1175/JCLI-D-20-0166.1

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. https://doi.org/10.3189/S0022143000006936

IPCC. (2019). *IPCC special report on the ocean and cryosphere in a changing climate* In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, et al. (eds.). (pp. 755). Cambridge University Press. https://doi.org/10.1017/9781009157964

IPCC. (2021). Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Retrieved from https://www.ipcc.ch/report/ar6

Jakacki, J., Przyborska, A., Kosecki, S., Sundfjord, A., & Albretsen, J. (2017). Modeling of the Svalbard fjord Hornsund. *Oceanologia*, *59*(4), 473–495. https://doi.org/10.1016/j.oceano.2017.04.004

Jania, J. (1988). Dynamiczne procesy glacjalne na południowym Spitsbergenie (w świetle badań fotointerpretacyjnych i fotogrametrycznych). Dynamic glacial processes in South Spitsbergen (in the light of photointerpretation and photogrammetric research). Prace Naukowe Uniwersytetu Śląskiego w Katowicach. (in Polish).

Kavan, J., Tallentire, G. D., Demidionov, M., Dudek, J., & Strzelecki, M. C. (2022). Fifty years of tidewater glacier surface elevation and retreat dynamics along the south-east coast of Spitsbergen (Svalbard Archipelago). *Remote Sensing*, *14*(2), 354. https://doi.org/10.3390/rs14020354

Luckman, A., Benn, D. I., Cottier, F., Bevan, S., Nilsen, F., & Inall, M. (2015). Calving rates at tidewater glaciers vary strongly with ocean temperature. *Nature Communications*, *6*(1), 1–7. https://doi.org/10.1038/ncomms9566

Lydersen, C., Assmy, P., Falk-Petersen, S., Kohler, J., Kovacs, K. M., Reigstad, M., et al. (2014). The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. *Journal of Marine Systems*, *129*, 452–471. https://doi.org/10.1016/j.jmarsys.2013.09.006

Małecki, J. (2016). Accelerating retreat and high-elevation thinning of glaciers in central Spitsbergen. *The Cryosphere*, *10*(3), 1317–1329. https://doi.org/10.5194/tc-10-1317-2016

Marsz, A. A., & Styszyńska, A. (2013). The principal climatic parameters. In A. A. Marsz & A. Styszyńska (Eds.), *Climate and climate change at Hornsund, Svalbard*. Gdynia Maritime University.

McNabb, R., & Hock, R. (2014). Alaska tidewater glacier terminus positions, 1948–2012. *Journal of Geophysical Research: Earth Surface*, *119*(2), 153–167. https://doi.org/10.1002/2013JF002915

Meier, M., & Post, A. (1987). Fast tidewater glaciers. *Journal of Geophysical Research*, *92*(B9), 9051–9058. https://doi.org/10.1029/JB092iB09p09051

Meier, M. F. (1962). Proposed definitions for glacier mass budget terms. *Journal of Glaciology*, *4*(33), 252–263. https://doi.org/10.3189/S0022143000027544

Meier, M. F., & Post, A. (1969). What are glacier surges? *Canadian Journal of Earth Sciences*, *6*(4), 807–817. https://doi.org/10.1139/e69-081

Merchel, M., & Walczowski, W. (2020). Increases in the temperature and salinity of deep and intermediate waters in the West Spitsbergen Current region in 1997—2016. *Oceanologia*, *62*(4), 501–510. https://doi.org/10.1016/j.oceano.2020.08.001

Moon, T., & Joughin, I. (2008). Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007. *Journal of Geophysical Research*, *113*, F02022. https://doi.org/10.1029/2007JF000927

Moon, T., Joughin, I., & Smith, B. (2015). Seasonal to multiyear variability of glacier surface velocity, terminus position, and sea ice/ice mélange in northwest Greenland. *Journal of Geophysical Research: Earth Surface*, *120*(5), 818–833. https://doi.org/10.1002/2015JF003494

Moon, T., Joughin, I., Smith, B., & Howat, I. (2012). 21st-Century evolution of Greenland outlet glacier velocities. *Science*, *336*(6081), 576–578. https://doi.org/10.1126/science.1219985

Moon, T., Joughin, I., Smith, B., van den Broeke, M. R., van de Berg, W. J., Noël, B., & Usher, M. (2014). Distinct patterns of seasonal Greenland glacier velocity. *Geophysical Research Letters*, *41*(20), 7209–7216. https://doi.org/10.1002/2014GL061836

Moskalik, M., Grabowiecki, P., Tęgowski, J., & Żulichowska, M. (2013). Bathymetry and geographical regionalisation of Brepollen (Hornsund, Spitsbergen) based on bathymetric profiles interpolations. *Polish Polar Research*, *34*(1), 1–22. https://doi.org/10.2478/popore-2013-0001

Motyka, R. J., Dryer, W. P., Amundson, J., Truffer, M., & Fahnestock, M. (2013). Rapid submarine melting driven by subglacial discharge, LeConte Glacier, Alaska. *Geophysical Research Letters*, *40*(19), 5153–5158. https://doi.org/10.1002/grl.51011

Motyka, R. J., Hunter, L., Echelmeyer, K. A., & Connor, C. (2003). Submarine melting at the terminus of a temperate tidewater glacier, LeConte Glacier, Alaska, USA. *Annals of Glaciology*, *36*, 57–65. https://doi.org/10.3189/172756403781816374

Muckenhuber, S., Nilsen, F., Korosov, A., & Sandven, S. (2016). Sea ice cover in Isfjorden and Hornsund, Svalbard (2000–2014) from remote sensing data. *The Cryosphere*, *10*(1), 149–158. https://doi.org/10.5194/tc-10-149-2016

Nick, F. M., Van Der Veen, C. J., Vieli, A., & Benn, D. I. (2010). A physically based calving model applied to marine outlet glaciers and implications for the glacier dynamics. *Journal of Glaciology*, *56*(199), 781–794. https://doi.org/10.3189/002214310794457344

Nilsen, F., Cottier, F., Skogseth, R., & Mattsson, S. (2008). Fjord–shelf exchanges controlled by ice and brine production: The interannual variation of Atlantic Water in Isfjorden, Svalbard. *Continental Shelf Research*, *28*(14), 1838–1853. https://doi.org/10.1016/j.csr.2008.04.015

Nilsen, F., Skogseth, R., Vaardal-Lunde, J., & Inall, M. (2016). A simple shelf circulation model: Intrusion of Atlantic water on the West Spitsbergen shelf. *Journal of Physical Oceanography*, *46*(4), 1209–1230. https://doi.org/10.1175/JPO-D-15-0058.1

Nordli, P. Ø., & Kohler, J. (2003). Met. no-REPORT ISSN 0805-9918.

Nuth, C., Kohler, J., Aas, H., Brandt, O., & Hagen, J. (2007). Glacier geometry and elevation changes on Svalbard (1936–90): A baseline dataset. *Annals of Glaciology*, *46*, 106–116. https://doi.org/10.3189/172756407782871440

Nuth, C., Kohler, J., König, M., Von Deschwanden, A., Hagen, J., Kääb, A., et al. (2013). Decadal changes from a multi-temporal glacier inventory of Svalbard. *The Cryosphere*, *7*(5), 1603–1621. https://doi.org/10.5194/tc-7-1603-2013

Ohmura, A. (2001). Physical basis for the temperature-based melt-index method. *Journal of Applied Meteorology*, *40*(4), 753–761. https://doi.org/10.1175/1520-0450(2001)040<0753:PBFTTB>2.0.CO;2

O'Leary, M., & Christoffersen, P. (2013). Calving on tidewater glaciers amplified by submarine frontal melting. *The Cryosphere*, *7*(1), 119–128. https://doi.org/10.5194/tc-7-119-2013

Osuch, M., & Wawrzyniak, T. (2017). Inter- and intra-annual changes in air temperature and precipitation in western Spitsbergen. *International Journal of Climatology*, *37*(7), 3082–3097. https://doi.org/10.1002/joc.4901

Osuch, M., Wawrzyniak, T., & Majerska, M. (2022). Changes in hydrological regime in high Arctic non-glaciated catchment in 1979–2020 using a multimodel approach. *Advances in Climate Change Research*, *13*(4), 517–530. https://doi.org/10.1016/j.accre.2022.05.001

Otero, J., Navarro, F. J., Lapazaran, J. J., Welty, E., Puczko, D., & Finkelnburg, R. (2017). Modeling the controls on the front position of a tidewater glacier in Svalbard. *Frontiers of Earth Science*, *5*. https://doi.org/10.3389/feart.2017.00029

Pętlicki, M., Ciepły, M., Jania, J. A., Promińska, A., & Kinnard, C. (2015). Calving of a tidewater glacier driven by melting at the waterline. *Journal of Glaciology*, *61*(229), 851–863. https://doi.org/10.3189/2015JoG15J062

Pfeffer, W. T. (2007). A simple mechanism for irreversible tidewater glacier retreat. *Journal of Geophysical Research*, *112*(F3), F03S25. https://doi.org/10.1029/2006JF000590

Piechura, J., & Walczowski, W. (2009). Warming of the West Spitsbergen Current and sea ice north of Svalbard. *Oceanologia*, *51*(2), 147–164. https://doi.org/10.5697/oc.51-2.147

Post, A. (1975). *Preliminary hydrography and historic terminal changes of Columbia Glacier, Alaska* (Vol. 559). USGS Hydrologic Investigations Atlas.

Promińska, A., Falck, E., & Walczowski, W. (2018). Interannual variability in hydrography and water mass distribution in Hornsund, an Arctic fjord in Svalbard. *Polar Research*, *37*(1), 1495546. https://doi.org/10.1080/17518369.2018.1495546

Rignot, E., Fenty, I., Xu, Y., Cai, C., & Kemp, C. (2015). Undercutting of marine-terminating glaciers in West Greenland. *Geophysical Research Letters*, *42*(14), 5909–5917. https://doi.org/10.1002/2015GL064236

Rignot, E., Fenty, I., Xu, Y., Cai, C., Velicogna, I., Cofaigh, C. Ó., et al. (2016). Bathymetry data reveal glaciers vulnerable to ice-ocean interaction in Uummannaq and Vaigat glacial fjords, west Greenland. *Geophysical Research Letters*, *43*(6), 2667–2674. https://doi.org/10.1002/2016GL067832

Rignot, E., Xu, Y., Menemenlis, D., Mouginot, J., Scheuchl, B., Li, X., et al. (2016). Modeling of ocean-induced ice melt rates of five west Greenland glaciers over the past two decades. *Geophysical Research Letters*, *43*(12), 6374–6382. https://doi.org/10.1002/2016GL068784

Rignot, E., Koppes, M., & Velicogna, I. (2010). Rapid submarine melting of the calving faces of West Greenland glaciers. *Nature Geoscience*, *3*(3), 187–191. https://doi.org/10.1038/ngeo765

Ritchie, J. B., Lingle, C. S., Motyka, R. J., & Truffer, M. (2008). Seasonal fluctuations in the advance of a tidewater glacier and potential causes: Hubbard Glacier, Alaska, USA. *Journal of Glaciology*, *54*(186), 401–411. https://doi.org/10.3189/002214308785836977

Saloranta, T. M., & Svendsen, H. (2001). Across the Arctic front west of Spitsbergen: High-resolution CTD sections from 1998–2000. *Polar Research*, *20*(2), 177–184. https://doi.org/10.1111/j.1751-8369.2001.tb00054.x

Schild, K. M., & Hamilton, G. S. (2013). Seasonal variations of outlet glacier terminus position in Greenland. *Journal of Glaciology*, *59*(216), 759–770. https://doi.org/10.3189/2013JoG12J238

Schuler, T. V., Kohler, J., Elagina, N., Hagen, J. O. M., Hodson, A. J., Jania, J. A., et al. (2020). Reconciling Svalbard glacier mass balance [original research]. *Frontiers of Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00156

Seale, A., Christoffersen, P., Mugford, R. I., & O'Leary, M. (2011). Ocean forcing of the Greenland Ice Sheet: Calving fronts and patterns of retreat identified by automatic satellite monitoring of eastern outlet glaciers. *Journal of Geophysical Research*, *116*(F3), F03013. https://doi.org/10.1029/2010JF001847

Sevestre, H., & Benn, D. I. (2015). Climatic and geometric controls on the global distribution of surge-type glaciers: Implications for a unifying model of surging. *Journal of Glaciology*, *61*(228), 646–662. https://doi.org/10.3189/2015JoG14J136

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

Strzelewicz, A., Przyborska, A., & Walczowski, W. (2022). Increased presence of Atlantic Water on the shelf south-west of Spitsbergen with implications for the Arctic fjord Hornsund. *Progress in Oceanography*, *200*, 102714. https://doi.org/10.1016/j.pocean.2021.102714

Sund, M., Lauknes, T. R., & Eiken, T. (2014). Surge dynamics in the Nathorstbreen glacier system, Svalbard. *The Cryosphere*, *8*(2), 623–638. https://doi.org/10.5194/tc-8-623-2014

Sutherland, D. A., Jackson, R. H., Kienholz, C., Amundson, J. M., Dryer, W. P., Duncan, D., et al. (2019). Direct observations of submarine melt and subsurface geometry at a tidewater glacier. *Science*, *365*(6451), 369–374. https://doi.org/10.1126/science.aax3528

Szafraniec, J. E. (2020). Ice-cliff morphometry in identifying the surge phenomenon of tidewater glaciers (Spitsbergen, Svalbard). *Geosciences*, *10*(9), 328. https://doi.org/10.3390/geosciences10090328

Truffer, M., & Motyka, R. J. (2016). Where glaciers meet water: Subaqueous melt and its relevance to glaciers in various settings. *Reviews of Geophysics*, *54*(1), 220–239. https://doi.org/10.1002/2015RG000494

Tverberg, V., Nøst, O. A., Lydersen, C., & Kovacs, K. M. (2014). Winter sea ice melting in the Atlantic Water subduction area, Svalbard Norway. *Journal of Geophysical Research: Oceans*, *119*(9), 5945–5967. https://doi.org/10.1002/2014JC010013

Van der Veen, C. (1996). Tidewater calving. *Journal of Glaciology*, *42*(141), 375–385. https://doi.org/10.3189/S0022143000004226

van Pelt, W. J. J., Schuler, T. V., Pohjola, V. A., & Pettersson, R. (2021). Accelerating future mass loss of Svalbard glaciers from a multi-model ensemble. *Journal of Glaciology*, *67*(263), 485–499. https://doi.org/10.1017/jog.2021.2

Vickers, H., Malnes, E., & Eckerstorfer, M. (2022). A synthetic aperture radar based method for long term monitoring of seasonal snowmelt and wintertime rain-on-snow events in Svalbard. *Frontiers of Earth Science*, *10*, 868945. https://doi.org/10.3389/feart.2022.868945

Vieli, A., Jania, J., Blatter, H., & Funk, M. (2004). Short-term velocity variations on Hansbreen, a tidewater glacier in Spitsbergen. *Journal of Glaciology*, *50*(170), 389–398. https://doi.org/10.3189/172756504781829963

Vieli, A., Jania, J., & Kolondra, L. (2002). The retreat of a tidewater glacier: Observations and model calculations on Hansbreen, Spitsbergen. *Journal of Glaciology*, *48*(163), 592–600. https://doi.org/10.3189/172756502781831089

Walczowski, W., & Piechura, J. (2011). Influence of the West Spitsbergen Current on the local climate. *International Journal of Climatology*, *31*(7), 1088–1093. https://doi.org/10.1002/joc.2338

Wawrzyniak, T., & Osuch, M. (2019). A consistent high Arctic climatological dataset (1979-2018) of the polish polar station Hornsund (SW Spitsbergen, Svalbard) [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.909042

Wawrzyniak, T., & Osuch, M. (2020). A 40-year high Arctic climatological dataset of the polish polar station Hornsund (SW Spitsbergen, Svalbard). *Earth System Science Data*, *12*(2), 805–815. https://doi.org/10.5194/essd-12-805-2020

White, A., & Copland, L. (2019). Loss of floating glacier tongues from the Yelverton Bay region, Ellesmere Island, Canada. *Journal of Glaciology*, *65*(251), 376–394. https://doi.org/10.1017/jog.2019.15

Wood, M., Rignot, E., Fenty, I., An, L., Bjørk, A., van den Broeke, M., et al. (2021). Ocean forcing drives glacier retreat in Greenland. *Science Advances*, *7*(1), eaba7282. https://doi.org/10.1126/sciadv.aba7282

Wood, M., Rignot, E., Fenty, I., Menemenlis, D., Millan, R., Morlighem, M., et al. (2018). Ocean-induced melt triggers glacier retreat in Northwest Greenland. *Geophysical Research Letters*, *45*(16), 8334–8342. https://doi.org/10.1029/2018GL078024

Ziaja, W. (2001). Glacial recession in Sorkappland and Central Nordenskiolöland, Spitsbergen, Svalbard, during the 20th century. *Arctic Antarctic and Alpine Research*, *33*(1), 36–41. https://doi.org/10.1080/15230430.2001.12003402

Ziaja, W., & Ostafin, K. (2015). Landscape–seascape dynamics in the isthmus between Sørkapp Land and the rest of Spitsbergen: Will a new big Arctic island form? *Ambio*, *44*(4), 332–342. https://doi.org/10.1007/s13280-014-0572-1