Calving at Ryder Glacier, Northern Greenland

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Abstract Recent evidence has shown increasing mass loss from the Greenland ice sheet, with a general trend of accelerated mass losses extending northwards. However, different glaciers have been shown to respond differently to similar external forcings, constituting a problem for extrapolating and upscaling data. Specifically, whilst some outlet glaciers have accelerated, thinned, and retreated in response to atmospheric and oceanic warming, the behavior of other marine terminating glaciers appears to be less sensitive to climate forcing. Ryder glacier, for which only a few studies have been conducted, is located in North Greenland and terminates with a floating ice tongue in Sherard Osborn Fjord. The persistence or disintegration of floating ice tongues has impacts on glacier dynamics and stability, with ramifications beyond, including sea level rise. This study focuses on understanding the controls on calving and frontal ablation of the Ryder glacier through the use of time-lapse imagery and satellite data. The results suggest that Ryder glacier has behaved independently of climate forcing during recent decades, with fjord geometry exerting a first order control on its calving.

Plain Language Summary Many glaciers around the world are losing ice at an accelerating rate as a result of global climatic changes. The Greenland ice sheet, an important contributor to sea-level rise, is losing increasing amounts of mass, with regions in the North has become impacted. However, each glacier is responding differently to the climatic changes due to different local settings. All glaciers can lose mass due to surface melt. On top of this, marine terminating glaciers lose mass as a result of submarine melt and calving (the breaking off of icebergs at the front). With increasing ocean temperatures, marine terminating glaciers can be particularly sensitive to climatic changes and be important contributors to sea-level rise. This article focuses on the Ryder glacier, a marine terminating glacier in North Greenland, to investigate controls on glacier behavior in this region. The results show that the Ryder glacier has been stable over recent decades, with periodic large calving events controlled by the shape of the fjord.

1. Introduction

The Greenland ice sheet has had an increasingly negative mass balance during recent decades (Mouginot et al., 2019), and has been responsible for ∼0.76 ± 0.1 mm/yr of global sea level rise (SLR) between 2005 and 2018 (Cazenave et al., 2018). Greenland was the most important cryospheric contributor to SLR during this period, above Mountain glaciers (0.74 ± 0.1 mm/yr) and Antarctica (0.42 ± 0.1 mm/yr) (Cazenave et al., 2018). Mass losses in Greenland are driven by climatic and oceanographic warming (Christoffersen et al., 2011; Cowton et al., 2016; Millan et al., 2018; Moon et al., 2012; Rignot et al., 2012) but show considerable spatial variation. The greatest mass losses (during 1972–2018) have been observed in the South East and North West sectors as defined by Mouginot et al. (2019) and shown in Figure 1. In these areas, mass loss was so far dominated by discharge at numerous tidewater glaciers, as opposed to surface melt and runoff (Mouginot et al., 2019). In the Northern sector, however, where Ryder glacier is located, mass loss during 1972–2018 was dominated by surface melt rather than discharge. Yet, the neighboring Petermann and Ryder glaciers have the first and third largest discharges in the sector respectively, with the Humboldt glacier having the second largest (Hill et al., 2017; Mouginot et al., 2019). An increased understanding of the controls on northern Greenland’s glacier behavior is of importance because there is a potential for rapid mass loss if remaining large ice tongues, (i.e., those of Ryder and Petermann glaciers), are lost, as this could lead to a significant increase in ice discharge through a reduction in buttressing. This chain of events has been previously observed at Jakobshavn Isbrae, where ocean thermal forcing likely caused the breakup...
of its floating ice tongue and initiated significant acceleration and retreat (Bondzio et al., 2018; Joughin et al., 2008). At Petermann Glacier, previous studies have documented retreat due to large calving events in 2010 and 2012 reducing the length of the floating ice tongue from c. 70 km to c. 45 km. The associated reduction in buttressing has led to an acceleration of the floating and grounded parts of the glacier (Rückamp et al., 2019). During the period 1948–2015, Petermann experienced a net retreat of, on average, 311 m a\(^{-1}\) (Hill et al., 2018).
The behavior of individual glaciers, even within a similar setting, is often not uniform. At the neighboring Tracy and Heilprin glaciers (Inglefield Gulf, North West Greenland), a significant retreat of Tracy has been observed since 1982, whereas Heilprin has been relatively stable (Porter et al., 2014). This discrepancy has been attributed to differences in the grounding line depth and the exposure and sensitivity of the grounding line and the submerged part of the glacier to cold, polar, near surface waters (for shallow grounding lines), or warmer deeper water of Atlantic origin (for deeper grounding lines) (Porter et al., 2014).

Similar explanations have been provided for the differing behavior of Ryder and Petermann glaciers; Petermann glacier has retreated in recent decades whilst Ryder glacier has been relatively stable (e.g., Hill et al., 2017, 2018; Rückamp et al., 2019) In Sherard Osborn Fjord, a recently mapped shallow bathymetric sill in front of Ryder glacier substantially reduces the intrusion of warm water of Atlantic origin into the cavity beneath the floating glacier tongue so that cool water temperatures prevail at the grounding line (Jakobsson et al., 2020). In Petermann Fjord, the situation is different: a deeper sill in front of the Petermann glacier (Jakobsson et al., 2018) allows for the inflow of deep, warm water which has the potential to reach the Petermann glacier’s grounding line and contribute to melting in the cavity beneath the ice tongue (Johnson et al., 2011). Results from a plume-model indicate that, at Ryder glacier, the colder water temperatures (as a result of the sill) could result in basal melt rates that are 15% lower (Jakobsson et al., 2020). These differences in fjord geometry, that is, seafloor bathymetry, likely are a part of the explanation as to why the Petermann glacier has retreated whilst Ryder glacier has been reasonably stable during recent decades. At the same time, such variability of glacier behavior presents problems for up-scaling and extrapolating current data sets of mass balance, leading to uncertainties with regards to future projections of SLR.

Here, we focus on calving and frontal dynamics at Ryder glacier, Northern Greenland, and its relation to glacier dynamics. Ryder glacier’s overall stability during recent years makes the glacier an interesting site to study and compare to retreating marine-terminating glaciers in Greenland. This study aims to investigate controls of Ryder glacier’s behavior and to attribute external forcings or site specific characteristics such as geometry to it. To do this, time-lapse imagery (hours/days) collected during the Ryder 2019 expedition is used to study glacier behavior on short time scales, while satellite imagery (years/decades) is used to investigate glacier dynamics on long time scales. The resulting data are related to a range of variables that may exert an influence on the Ryder glacier including meteorological data, tidal patterns, and supraglacial lakes. Ryder glacier’s velocities, margin change trends, and climatic setting will also be compared to the nearby Petermann glacier.

2. Ryder Glacier

Ryder glacier is located in Northern Greenland at c. 81.8°N, 51.5°W terminating in Sherard Osborn Fjord with a c. 25–29 km long and c. 10 km wide ice tongue seaward of the grounding line, which is located at c. 500 m below sea level (see Figure 1) (Hill et al., 2017; Wilson et al., 2017). Ryder glacier drains ~1.7% of the Greenland ice sheet by area (Joughin et al., 1996). Early observations from Ryder glacier (Davies & Krinsley, 1962; Higgins, 1991; Koch, 1928) focused on the ice-tongue margin and calved icebergs, as well as their drift in Sherard Osborn Fjord. Reported flow velocities are around 500 m/yr during 1959–1978 (Higgins, 1991), and 100–500 m/yr during the 1990s, except for a short-term acceleration to threefold speed in 1995 raising the possibility that Ryder glacier may be of surge type, with the surge initiated by supra-glacial lake drainage (Joughin et al., 1996).

Ryder glacier has displayed cyclic behavior with periods of steady advance interrupted by abrupt and substantial retreats (Hill et al., 2018; Murray et al., 2015). Ice flux across the grounding line is estimated to be 1.9–2.4 km³/yr (Joughin et al., 1999), and is approximately in balance with satellite-derived figures of combined aerial and submarine melt (Wilson et al., 2017). Notably, little was known about the thermal state and bathymetry of Sherard Osborn Fjord before the Ryder 2019 Expedition with Swedish Icebreaker Oden (Jakobsson et al., 2020). This is in contrast to other Greenland sites for which warming fjord temperatures and subsequent increased subglacial melt rates at glaciers have been reported (Johnson et al., 2011; Rignot et al., 2012; Xu et al., 2012), often in connection with the discussion of bathymetric features (Catania et al., 2018; Rignot et al., 2015; Schaffer et al., 2020). The high-resolution bathymetric data from the previously unmapped inner part of Sherard Osborn Fjord acquired during the Ryder 2019 expedition shows the
presence of a shallow sill in front of the Ryder glacier (193–390 m deep), suggesting its floating tongue and grounding line is shielded from the intrusion of warm Atlantic waters (Jakobsson et al., 2020).

3. Methods

3.1. Glaciological Variables

3.1.1. Long Term

To create a record of margin change at Ryder glacier 1995–2019, satellite archives were used. Specifically, ERS-1 images were used for the period 1995–1999, Landsat 7 for the period 1999–2013, and Landsat 8 for the period 2013–2019. Margin positions were manually delineated once per year during the time period 1995–2019, with images as close to 1 July as possible chosen to provide consistency. Margin change was then calculated using the multi centerline method, with the Margin Change Quantification Tool (MaQiT) (Lea, 2018). Margin change was calculated separately for the different satellites but, as there are overlaps between the time periods each satellite was used for, the margin change records could be combined.

3.1.2. Medium Term

A more detailed analysis of Ryder glacier’s behavior was conducted for the period 2015–2019, investigating front position data, velocities, and supra-glacial lake data. For margin positions, 126 Sentinel 1 SAR images were retrieved from the ESA Open Access Hub, covering the period January 2015–December 2019. The time elapsed between subsequent images is most often 12 days, although the availability of data means there are some longer time periods. The longest period between images was 108 days, but this only occurred once from May 01, 2019 to August 17, 2019. The mean period is 14 days.

Margins were manually digitized from these images using the Google Earth Engine Digitization Tool (Lea, 2018). Margin change was calculated using MAQiT (Lea, 2018). Velocities were calculated via offset tracking using the software package SNAP. The images used were Ground Range Detected (GRD) with each image pair co-registered using the ACE30 DEM. The processing chain followed is the same as described in Holmes et al. (2019). Velocities were then extracted across a flux gate close to the calving front and a mean was taken to yield a single figure for frontal velocity. In addition, grounding line velocities were extracted for Ryder glacier by taking the mean value from the area bounded by the two lines shown in Figure 1c and the fjord walls. The frontal ablation rate, \(\dot{a}\), is then computed from the terminus speed \(U_T\) and the change in ice front position with time \(\frac{dl}{dt}\), where \(dl\) is the retreat of the calving front in m between two successive satellite images and \(dt\) is the period between two successive satellite images (Holmes et al., 2019; Luckman et al., 2015).

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\dot{a} = U_T - \frac{dl}{dt}. \tag{1}
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The presence of supra-glacial lakes on Ryder glacier was investigated through manually digitizing lakes across Ryder glacier’s tongue and inland ice using Google Earth Engine. This was only done for the summer seasons of 2015–2019, using Sentinel 2 (optical) data. One image per month in the period March–September was used. Cloud cover made finding more than one image per month with a good view of the whole glacier almost impossible. The number of lakes in each image was recorded, as well as the total area of the lakes. The supra-glacial lake data was compared to velocities, in order to look for a connection between lake drainage and frontal velocity/surge behavior.

Velocities and margin positions were also collated for the Petermann glacier during this period, using the same methods as used for the Ryder glacier. Sentinel one images were used for velocities, but margin positions were digitized from Landsat eight imagery, and only one image per year was used (early July in each year).

3.1.3. Short Term

To create a short (12 days) but high-resolution log of calving events, a time-lapse camera system was set up overlooking the calving front of Ryder glacier between August 14 and August 25, 2019, inclusive (see Figures 1c and 1d for camera location). The system consisted of a Canon T6 camera with an 18–55 mm lens,
controlled by a Digisnap Pro intervalometer. The system was placed on a tripod, in weatherproof housing, and power from a 12 V lead-acid battery. The camera took photos every 5 s, 24 h a day, and operated in shutter-priority mode in order to maintain the 5 s intervals accurately (How et al., 2019; Vallot et al., 2018). In total, around 140,000 photos were taken. Heavy fog made observations of calving events impossible between August 17 and August 21. Images from August 14–17 and August 21–25 were turned into videos, which were then viewed multiple times to identify and time-stamp a total of 45 calving events. Their locations were first mapped onto the glacier front as seen from the camera and then translated onto a satellite image, by matching distinctive features between the camera and satellite imagery (see Figure 1b). The style of each calving was described adopting classifications used by How et al. (2019). These classifications were chosen as, first, the calving events observed fitted well into the categories. In addition, the classifications provide a way of linking the events to calving mechanisms; for example, sheet collapse events are related to waterline weaknesses and thus can be connected to undercutting from submarine melting (one of the mechanisms presented by Benn et al. [2007]).

### 3.2. Atmospheric and Oceanic Conditions

#### 3.2.1. Medium Term

In order to situate the behavior of the Ryder and Petermann glaciers within the context of local conditions, meteorological data sets were compiled. Modeled hourly meteorological data (air temperature, wind speed, wind direction, precipitation, sea-surface temperature, and sea-ice concentration) was retrieved from the ERA-5 re-analysis data set, and compared to the data recorded by Oden’s shipmounted instrumentation during August 14–25 (Figure 2).

Sea-surface temperature and sea-ice concentration were also retrieved from the JPL Multi-scale Ultra-high Resolution (MUR) sea-surface temperature (SST) observational data set. This data is a blend of infrared...
sensor data (from MODIS and AVHRR) and microwave data (from AMSR-E). For consistency, both the ERA5 and JPL-MUR data were extracted from within Sherard Osborn fjord at 82°N, 51.5°W. This point was chosen as it was as close to the front of Ryder glacier as possible where the land/sea masks identified the grid cell as water.

### 3.2.2. Short Term

For the short term part of the study, meteorological data (air temperature, true wind speed, true wind direction, sea-surface temperature, and precipitation [type and amount]) was collected once per minute using shipmounted instrumentation onboard Icebreaker Oden during its bathymetric survey of Sherard Osborn Fjord, at distances of c. 0.3 km to c. 60 km to the calving front.

Tidal phase data were also acquired as previous studies have identified elevated calving rates during certain parts of the tidal cycle (How et al., 2019). Tidal phase variations were accessed by running a regional barotropic tide model with a grid spacing of 1 km for the Greenland coastline. The model is a beta version of the coarser AOTIM-5 model (Padman et al., 2003). The tidal data were plotted alongside the calving data to investigate if there was a correlation. The output from the tidal model was verified by visually comparing output for the nearby Petermann and Bessel fjords with RTK-corrected GPS data collected as part of the Ryder 2019 expedition. While the RTK data do not cover a full tidal cycle, correspondence was shown to be reasonably good, with the recorded time intervals not dismissing the use of the tidal model in this area.

### 3.3. Statistical Tests

#### 3.3.1. Medium Term

To investigate the relationship between frontal ablation and the aforementioned climatic variables, simple linear regression analysis was conducted with frontal ablation rate as the dependant variable. The possible predictors were air temperature, precipitation, wind speed, wind direction, sea-surface temperature (from both ERA-5 and JPL-MUR), and sea-ice fraction. Supra-glacial lake count and supra-glacial lake area were instead regressed against frontal and grounding line velocity. This was done as a relationship between supra-glacial lakes and velocity (surging) has been previously suggested (Joughin et al., 1996), which we wanted to explicitly investigate further. A satisfactory $p$-value was defined for the analysis as <0.05. Plots showing the regression results, including $R^2$ and $p$-values, can be found in the supplementary information (Figure S1).

#### 3.3.2. Short Term

To analyze whether the timing of calving events was triggered by meteorological conditions, superposed epoch analysis (or "compositing") was conducted. This type of analysis has been used for many applications, for example, (Sear et al., 1987), and was adapted for this analysis by only looking at meteorological conditions preceding the calving events. The analysis was done by first defining a time window of interest (e.g., 1 h before calving) and a variable of interest (e.g., air temperature). Then, the air temperatures for the hour period preceding each calving event were extracted. As there were 45 calving events and hourly air temperature values, this would create 45 matrices, each containing 60 air temperature values. The mean of these matrices would be taken, resulting in one single matrix with 6° air-temperature values. This would then be plotted, along with the standard deviation. If, for example, air temperatures consistently peaked 5 min before a calving event then this would be visible on the resulting graph and indicate that calving events were triggered by an increase in air temperatures - but no such pattern was found. The above steps were then repeated for different variables and for different time window lengths (15 min–24 h). For the analysis at Ryder, no evidence was found for any of the environmental variables investigated (air temperature, wind speed, wind direction, sea surface temperature, precipitation) triggering calving. An example output is shown in Figure S2).
4. Results

4.1. Long Term

The pattern of margin change at Ryder glacier 1995–2019 shows a linear and gradual advance, interspersed with significant calving events, as shown in Figure 3. Ryder glacier advances to approximately the same position in the fjord each time, before calving. Each large calving event corresponds to an average retreat of $\sim 3$ km. The position to which Ryder glacier advances to before calving corresponds to the location of the inner bathymetric sill, as well as to a widening of the fjord, as can be seen in Figure 4. The duration of the cycles is c.10 years, with three full cycles included in the data analyzed here.

During the cycle extending from 2007 to 2016, there are two notable calving events (2011 and 2014) occurring at roughly the same location along the front. As these calving events only occur across a portion of the glacier front, whilst the rest of the terminus advances, they show up in the data as a slowdown in advancement (see Figure 3). These correspond to reasonably large calving events which only occur across a c. 2.7 km portion of the 9 km glacier front. These calving events correspond to c. 1 km of retreat, around one third of the retreat caused by full-length calving events.

4.2. Medium Term

4.2.1. Glaciological Variables

The margin position data shows a pattern of gradual advance interrupted with a sudden 3 km retreat during 2016, representing a large calving event (Figure 5). The frontal velocities do not show seasonal behavior over this time but start high (c. 0.75 m d$^{-1}$, decrease to around 0.1 m d$^{-1}$ at the end of 2015 and then increase again to c. 0.7 m d$^{-1}$ in early-mid 2017. The increase in frontal velocity occurs around 6 months after the large calving event identified from the margin change data. The grounding line velocities remain reasonably constant throughout the entire study period at around 0.5 m d$^{-1}$. They are generally higher than the frontal velocities 2015–2017, after which both the frontal and grounding line velocities become similar. The frontal ablation rate is reasonably consistent throughout 2015–2019 with a mean value of $-1.1$ m d$^{-1}$. A negative $dl/dt$ that is larger than the velocity will give a positive ablation rate, meaning the glacier is losing mass at its front. A notable exception to the consistent frontal ablation rate occurs in July 2016, corresponding to the large calving event.

4.2.2. Meteorological Data

The air temperature, wind speed, and wind direction variables from ERA-5 show a clear seasonal signal (see Figure 6). Air temperatures during summer reach somewhere between 7 and 12°C, with the highest temperatures being recorded in 2019. There is, however, no clear directional trend; peak temperatures were lowest in 2017 and 2018 where they lay just below 8°C. Winter temperatures drop to lows of $\sim -35$°C.

Wind speeds are low (c. 0.2–0.8 m s$^{-1}$) and North-easterly/Easterly during summer. In contrast, winds are most often South-Easterly during the winter, corresponding with higher wind speeds of up to 3.5 m s$^{-1}$ and lower air temperatures. Precipitation also shows a seasonal signal, with higher precipitation during summer. However, there is more variation between years compared to the aforementioned variables, for example with low precipitation during 2015. Sea-ice, too, shows a seasonal signal, with a lower sea-ice concentration during summers. Like precipitation, this is also variable between years. For example, sea-ice completely disappears during the summer of 2015, but during 2016 only goes down to a minimum of 80%.
The sea-surface temperature data from ERA-5 during 2015–2019 shows a constant temperature, apart from a short period where it drops by nearly 2 degrees centigrade during 2015, at the same time as the sea-ice minimum. The sea-surface temperature from the JPL-MUR data set shows some differences. It is also relatively constant throughout 2015–2019, though slightly lower compared to the ERA-5 dataset and it shows short periods of increased temperatures during some of the summer periods.

When the simple linear regression was run between the meteorological variables and the frontal ablation rate, none of the results were statistically significant at the 95% level (see Figure S1).

### 4.2.3. Supra-Glacial Lakes

Both the count and area of supra-glacial lakes on Ryder glacier peak in July every year, and show a steep rise and fall in the spring and late summer/autumn (Figure 5). There appears to be a small increase in the number of lakes each year, with 37 lakes identified at the peak in 2015 compared with 48 at the peak in 2019. The peak lake area was consistent in 2015–2018, ranging between 43 and 46 km², but dropped in 2019 to a peak area of 35 km². The peak lake area occurred after the peak lake count in some years, notably
Through plotting the lake data alongside the velocity data, no evidence was found for a connection between the presence and subsequent disappearance of supra-glacial lakes and velocities at Ryder glacier. Part of the reason for the lack of correlation could be that the lake data has a monthly resolution, whilst the velocity data is extracted every 12 days.

### 4.2.4. Petermann Glacier Comparison

The meteorological data for Petermann and Ryder glaciers are very similar but, despite this, the velocity patterns are different. The Petermann glacier velocities appear to increase at the end of 2016, but as the data for this time period was reasonably scarce, it is the velocities 2017–2020 which are preferred for the comparison here. Unlike Ryder, the velocities at Petermann glacier show a seasonal signal with defined minima during summer. These minima may be related to the development of a channelized subglacial hydrological system as a result of increased meltwater inputs from the surface (Nienow et al., 2017; Williams et al., 2020). A channelized basal hydrological system is more efficient, reducing water pressures at the bed of the glacier and so leading to a reduction in sliding (Hewitt, 2013). The Petermann glacier velocities are consistently higher than those at Ryder glacier, oscillating at around 2.3 m d⁻¹ compared to 0.5 m d⁻¹ (Figure 5). The front of the Petermann glacier advanced steadily during the period 2015 to 2019, with an average total advance of 3.5 km (see Figure S3). This is in contrast to Ryder glacier, which experienced an average retreat of c. 1 km over the same time period (see Figure 5).
4.3. Short Term

4.3.1. Calving Styles and Locations

We deployed a time-lapse camera for 12 days during August 2019 and identified 45 calving events. These events were classified according to calving style (How et al., 2019), with events left unclassified when the view of the calving front was obscured—these events were often identified by large splashes. Some events exhibited characteristics of more than one calving style. For instance, a small waterline event may have triggered a larger sheet collapse event. Without any clear gap between these occurrences, this type of situation would be recorded as one event and classified as a combination of two calving styles for example, “sheet collapse and waterline.” In total there were 160 h of usable data and 45 recorded calving events, yielding an average calving rate of 0.28 events/h.

The calving event classification yielded the following percentages (summing to 99 due to rounding): sheet collapse 51%, ice fall 9%, submarine 4%, waterline 2%, sheet collapse and ice fall 11%, sheet collapse, and waterline 9%, unclassified 13%. Examples of calving styles, as well as locations, are shown in Figure 1. Some calving events were likely missed in areas far from the camera set up, or where the front of the glacier faced away from the camera. As can be seen in Figure 1d, the section of the glacier front facing away from the camera has no recorded events. Sheet collapse is the most common event overall and this trend is evident even along the section of the front closest to the camera, where events are easily identified. This suggests that missing data due to areas without a clear view does not significantly impact the overall results.

4.3.2. Meteorological and Oceanographic Data

Meteorological data from I/B Oden is shown in Figure 2. The wind speed data show a gradual increase from 2 ms\(^{-1}\) on the August 14 to peaks of over 16 ms\(^{-1}\) on August 24, followed by a rapid decrease back to 2 ms\(^{-1}\) by August 26. Wind directions also change, from being predominantly northerly August 14 until August 20, to being predominately southerly August 21 until August 25. Air temperatures increase slowly from August 14 until August 15, after which they fall gradually to lows of −1.3°C on August 20. After this, air temperatures rise quickly until August 24 where they hit a peak of nearly 11°C, after which they fall steeply up until August 26. Precipitation was variable but shows a general trend of reducing with time. The type of precipitation is predominantly rain, but there is a period of snow between 17 August 17 and August 21. Sea-surface temperatures drop throughout the observation period from c. 4°C to c. −1°C, but are variable throughout.

The superposed epoch analysis was run numerous times to look for connections between different calving styles and the meteorological parameters. However, no evidence was found for calving events being meteorologically triggered.

The tidal data was plotted alongside the calving events, which enabled the counting of the number of events occurring on a falling tide (43%), rising tide (32%), and on the turn of the tide (25%).

5. Discussions

Ryder glacier shows a consistent pattern of general advance interspersed with a large, sudden retreat during the period 1995–2019. The results of the linear regression (for the 2015–2019 period) show no links between meteorological parameters and frontal ablation at Ryder glacier. Whilst comparisons made between the ERA-5 data and observational data show generally good correspondence, there is some uncertainty over the validity of the sea-surface temperatures. The sea-surface temperature from the JPL-MUR source varied considerably from the ERA-5 data, whilst the sea-ice concentration showed good correspondence. Despite this, the regression result did not vary much when run against the different sea-surface temperature data-sets, with results always suggesting that Ryder glacier seems to be unaffected by seasonal meteorological fluctuations. This provides evidence to back up the assertion that the dynamics of the Ryder glacier are internally controlled, rather than externally forced (at least on time scales of years). It is of note that the large calving event in 2016 occurred around the time of a pronounced sea ice minima, raising the possibility that a reduction in buttressing due to reduced sea ice influenced the occurrence of the event. Previous studies found that increasing ocean temperatures around Greenland have led to increased ablation and, often, acceleration, for example, (Johnson et al., 2011; Moon et al., 2012). Often ocean warming impacts glaciers in conjunction with atmospheric warming, with increased surface melt driving subglacial plumes...
which entrain the warm Atlantic water and enhance subglacial melting (Slater et al., 2018). Earlier work has shown that Northern Greenland has experienced increasing air temperatures in recent decades (Orsi et al., 2017) and that this atmospheric warming has led to enhanced surface melt and run-off in Northern Greenland (Noël et al., 2019). This can be exemplified by the fact that the ablation area in North Greenland has expanded by 46% since the early 1990s (Noël et al., 2019). Climatic warming has been linked to the collapse of ice tongues at other Greenlandic glaciers (e.g., Kangerlussuaq glacier), but with local bathymetric settings leading to differences in the timing of ice tongues break-up (Vermassen et al., 2020). Assuming Ryder glacier is impacted by increased surface melt capable of producing plumes that enhance subglacial melt at the grounding line, then the lack of an obvious correlation between frontal ablation and climate variability may in part be due to the fact that warm Atlantic waters are modified (and become cooler via mixing) before reaching the grounding line. This is most likely a consequence of the shallow sill that is present in the inner part of Sherard Osborn fjord, shielding Ryder glacier’s grounding line from deep, warmer waters (Jakobsson et al., 2020). On the glacier side of the sill, the water temperatures from about 350 m water depth do not exceed 0.2°C, while they are greater than 0.3°C in the main fjord (Jakobsson et al., 2020). However, until better knowledge of the properties and dynamics of the water masses beneath the floating glacier tongue is gained, arguments remain speculative and it is unclear if Atlantic water reaches Ryder glacier.

No evidence was found for surge-type behavior at Ryder glacier, although frontal velocities at Ryder glacier do increase in early 2017. The sustained nature of the elevated velocities is in contrast to the previously identified 1995 surge, where velocities were only elevated for up to 7 weeks (Joughin et al., 1996). Supra-glacial lakes drainage was the proposed mechanism for the 1995 surge (Joughin et al., 1996), but we did not find any correlation between supra-glacial lakes and frontal or grounding line velocities during 2015–2019.

An alternative explanation for the 2017 frontal acceleration is that the large calving event which occurred in July 2016 may have increased frontal velocities through a loss in buttressing. Another period of elevated frontal velocity can be seen at the beginning of the study period (early 2015), which may be related to a large calving event that occurred in August 2014. This calving event was smaller than that in 2016, only spanning approximately one third of the glacier front (see Figure 4). This smaller size may explain why the frontal velocities decreased after ~1 year. In contrast, the 2017 acceleration could indicate a sustained calving-induced speed-up of the ice tongue—but uncertainty remains due to the lag between the calving event and the acceleration. Previous work has highlighted the importance of buttressing for grounding line dynamics at confined glaciers (Haseloff & Sergienko, 2018) but, at Ryder glacier, grounding line velocities did not increase after the large calving events. This suggests that discharge losses from the Ryder glacier did not rise as a result of the calving events. The monitoring of the Ryder glacier and its behavior in response to future calving events will be necessary to provide more clarity on how large calving events impact the glacier dynamics.

The partial-width calving events which have been identified during the 2006–2016 cycle suggest that Ryder glacier is beginning to feel the impacts of external forcings. These calving events both span the same, northern proportion of the front, with the boundary coinciding with a supra-glacial stream (see Figure 4). The calving likely occurs at this specific point as the stream constitutes a line of weakness which promotes calving, either by hydrofracture or by being a line of weakness on which buoyancy forces can act. This may not have occurred during previous cycles due to cooler air temperatures resulting in lower levels of surface melt, meaning that this stream was not so well defined. A potential compounding factor is that the calving is occurring at a line of weakness created by a sub-glacial channel that runs along the same line as the subglacial stream. Although there is no direct evidence for this at Ryder glacier, these features have been found at the nearby Petermann glacier (Rignot & Steffen, 2008).

On the scale of individual calving events, timing appears to be stochastic with no apparent link between calving and meteorological variables or tidal fluctuations. It should be noted that the tidal model uses Bedmachine bathymetry (Morlighem et al., 2017), which can be seen to have some significant errors through comparison with the high-resolution bathymetric data acquired during the Ryder 2019 expedition and presented by Jakobsson et al. (2020). This highlights the tidal amplitude data unusable, but the phase should still be accurate. The lack of a connection between tidal cycles and calving found at Ryder glacier is in contrast to previous short-term studies (Bartholomaus et al., 2015; How et al., 2019). One example, also using time-lapse imagery, focused on Tunabreen in Svalbard (How et al., 2019). At Tunabreen, which differs from
the Ryder glacier in that it has a grounded front and lacks a floating ice tongue, 68% of the calving events observed during a 28 h period occurred during a falling tide. The lack of an obvious link between calving events and tidal cycles found in this study compared to How et al. (2019) may be due to the differences in tidal amplitude or the glacier systems; Tunabreen is grounded and calves frequently (12.8 events/hour) whilst the floating tongue at Ryder glacier has a much lower calving rate of 0.28 events/hour. At this lower calving frequency, more data points would be needed in order to establish if there is a statistically significant trend.

The most prominent calving style at Ryder glacier (sheet collapse), as well as the presence of waterline events, suggests that calving is often instigated by waterline weaknesses (How et al., 2019). Close observation of some of the time-lapse images provides further evidence for this, as a waterline notch can be seen. These two facts together suggest that these calving events are related to submarine melting and undercutting, rendering ocean temperatures in the fjord a potentially important driver of calving—even if the precise timing of events remains stochastic.

There is some evidence from the time lapse imagery for larger, tabular icebergs being produced when Ryder glacier’s lateral margins are not fastened to the fjord walls. Specifically, after the fog clears on the August 21, a section of ice along the lateral margin on Ryder glacier has detached from the main glacier but is prevented from floating away by the complex geometry of Ryder glacier’s lateral margin. The iceberg is tabular and ~200 m long and 60 m wide, in contrast to all the other identified calving events. The fact that the iceberg cannot drift away from the front suggests that complex calving fronts can interpret calving events from satellite imagery difficult, thus making it harder to correctly attribution external factors to calving patterns.

The Petermann glacier has retreated during the period Ryder glacier has been stable, despite experiencing similar meteorological forcings. One possible explanation is bathymetry; there is a sill in Petermann Fjord, but it does not prevent warm, subsurface Atlantic water from reaching the grounding line of the Petermann glacier (Münchow et al., 2014). This is because Petermann glacier’s sill has a maximum depth of 443 m (Jakobsson et al., 2018), substantially deeper than the sill in front of Ryder glacier’s ice tongue, which is shallower than 300 m everywhere except one narrow passage which goes down to 390 m (Jakobsson et al., 2020).

At Petermann glacier, a previous study reported acceleration of both the ice tongue and grounded ice after large calving events in 2010 and 2012, but with a less pronounced velocity increase in the grounded section (Rückamp et al., 2019). The differences in the amount of upstream propagation of velocity increase between glaciers may be related to variations in the reduction of buttressing (this can be also variable between events at the same glacier for example, Petermann glacier (Rückamp et al., 2019)) or in glacier geometry (Felikson et al., 2017).

The different behavior of Ryder and Petermann glaciers with regards to large calving events suggests that different mechanisms are at play. This could point to a hierarchy of controls on ice-tongue behavior; bathymetry exerts a first order control by modulating the amount of warm Atlantic waters reaching the glaciers. Under circumstances where warm Atlantic waters can intrude to the grounding line, large calving events occur irrespective of fjord geometry (e.g., Petermann glacier). In locations where bathymetry shields the glacier from warm Atlantic waters, then another factor—which we propose to be fjord geometry—becomes a key determinant of calving occurrence (e.g., Ryder glacier).

The suggestion that large calvings at Ryder glacier are geometrically controlled is derived from the fact that Ryder fjord widens at the point where the large calving events occur. The proposed mechanism is that, when the fjord widens, the lateral margins of the ice tongue begin to detach from the fjord walls. This detachment may make the front of the ice tongue more susceptible to tidally induced water level fluctuations or create a velocity gradient between the front of the ice tongue and the grounding line through a reduction in lateral friction. Both of these mechanisms have the potential to enhance rift propagation and promote calving (Benn & Åström, 2018). Tidal fluctuations have been linked to ice tongue fracture before, for example at Langhovde glacier, Antarctica (Minowa et al., 2019). The cyclic nature of tidal fluctuations can cause fatigue of the ice and lead to softening (Hulbe et al., 2016). These tidally induced fractures and strand cracks are usually observed at the grounding line (Hulbe et al., 2016; Padman et al., 2018), but we suggest that the same mechanisms may operate to enlarge existing fractures at the point the fjord widens, triggering calving.
6. Conclusions

To summarize, the frontal dynamics of the Ryder glacier appear to have been reasonably stable over recent decades and little evidence is found of externally forced changes. This suggests that the frontal dynamics of the Ryder glacier (a cyclic pattern of slow advance interspersed with rapid retreat) are controlled by local factors, most notably fjord geometry. However, there is some evidence of changing behavior in the most recent data. Specifically, the occurrence of a speed-up of the floating ice tongue following the 2016 calving event and the development of weakness along the Northern side of the glacier. Further observation will be needed to tease out any directional trend, and a time series of water temperatures at depth would allow quantification of whether warm Atlantic waters can reach the glacier.

Data Availability Statement

The use of freely available Copernicus Sentinel data, ERA-5 re-analysis data, and JPL-MUR data allowed this study to take place. The meteorological data used for this study is available at https://doi.org/10.17043/ryder-2019-metobs-oden-sherard-osborn-fjord and the time-lapse images at https://doi.org/10.17043/ryder-2019-glacier-front-imagery.

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