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Related Dataset

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Synchronous Retreat of Southeast Greenland's Peripheral Glaciers

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Key Points:

- We produced detailed records of glacier length change for 135 marine glaciers in southeast Greenland using an efficient automated method
- 56 (~41%) of the ice-sheet-independent marine glaciers in southeast Greenland underwent synchronous anomalous retreat in 2016
- The widespread retreat anomaly was related to elevated regional surface melting rather than change in subsurface ocean temperatures

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Recently, scientific attention has focused on estimating Greenland's dynamic mass loss through changes to flow speeds, thickness, and length on its marine outlet glaciers. For the ice sheet outlet glaciers, dynamic mass loss has been found to be highly sensitive to changes in climate and individual glacier geometry. For the ice-sheet-independent marine glaciers around Greenland's periphery, dynamic mass loss is presently overlooked. Here, we apply an open-source, automated method of measuring glacier length changes using satellite imagery, to produce highly detailed records of length changes for 135 peripheral marine glaciers in southeast Greenland. We find evidence for anomalous retreat across 56 glaciers coincident with elevated surface melt in 2016, with melt 22% above the 2013–2019 average. Our detailed observations resolve the widespread, rapid, and synchronous response of these independent marine glaciers to increased meltwater input in 2016, indicating that their dynamics may be more sensitive to atmospheric warming than currently thought.

Plain Language Summary Mass loss from Greenland's ice sheet and surrounding glaciers contribute to global sea level rise and the freshening of regional ocean waters, which impacts ocean circulation patterns. Recent attention has turned to Greenland's mass loss through changes to its marine outlet glaciers' flow speeds, thickness, and length (i.e., dynamics). Outlet glacier dynamics are influenced by climate perturbations and glacier geometries, but little is known about the dynamics of the ~600 ice-sheet-independent marine glaciers in Greenland. We use an automated method to measure glacier length changes using satellite imagery, leading to highly detailed records of length changes for 135 independent marine glaciers in southeast Greenland. We find evidence for anomalous retreat across 56 glaciers, which coincided with elevated surface melt in 2016. Our detailed observations and comparison with climate records demonstrate that independent marine glaciers can have a sensitive response to atmospheric warming. It is possible that other independent marine glaciers are also capable of widespread synchronous response to atmospheric forcing, but it may not be resolved with the limited study size and temporal resolution imposed by manual mapping methods.

1. Introduction

Ice mass loss from the Greenland Ice Sheet (GrIS) and surrounding glaciers is one of the largest contributors to global sea level rise. The influx of freshwater from the GrIS and marine glacier melt also impacts marine ecosystems and alters ocean and fjord circulation (Meire et al., 2017; Straneo et al., 2011). Two-thirds of the GrIS total mass loss since 1972 has been caused by changes in ice flux due to perturbations in the forces that govern ice flow (i.e., dynamic change) (Mouginot et al., 2019). Accordingly, numerous studies have focused on understanding the controls on dynamic mass loss from the ice sheet's outlet glaciers (Catania et al., 2018; Howat et al., 2008; King et al., 2018; Moon & Joughin, 2008). For the GrIS outlet glaciers, dynamic mass loss has primarily been attributed to ice flow acceleration driven by the reduction in flow resistance caused by terminus retreat (King et al., 2020).

Meanwhile, the dynamics of the independent glaciers along Greenland's periphery have received little scientific attention. These glaciers are physically separate from the ice sheet or are distinguished from the ice sheet by well-defined divides in their accumulation zone. After Alaska, the Greenland periphery has the greatest rates of total mass loss, with mass losses of ~38 Gt/yr between 2003 and 2009 (Gardner et al., 2013) and ~36 Gt/yr from 2000 to 2019 (Hugonnet et al., 2021) determined from surface elevation change observations. While much of this is due to surface melting, recent regional modeling suggests that dynamic mass loss from Greenland's marine

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peripheral glaciers is on the order of gigatons per year (Recinos et al., 2021). The cause of this dynamic mass loss is unknown, and the abundance of marine glaciers around Greenland's periphery inhibits the manual construction of sufficiently detailed terminus position time series to gain insight into dynamic change.

Here, we use a novel automated method (Liu et al., 2021) for delineating glacier terminus positions to investigate patterns in glacier terminus change for the Greenland peripheral marine glaciers. We focus on southeast Greenland, where the majority (59%) of these glaciers are located and where their GrIS outlet counterparts have been observed to respond sensitively and synchronously to changes in glacier stress balance initiated at their marine margins (Enderlin et al., 2014; Howat et al., 2008; Pritchard et al., 2009). With sub-seasonal resolution time series of terminus position generated from the automated terminus delineation method (Liu et al., 2021), we show that 56 of 135 peripheral marine glaciers in SE Greenland experienced a synchronous retreat anomaly in 2016. Although marine glacier acceleration and retreat have been ubiquitous over the last two decades, individual outlet glaciers in similar climate regimes typically exhibit contrasting retreat patterns (Csatho et al., 2014). Widespread synchronous retreat has only been observed once prior—for the southeast GrIS outlet glaciers from 2000 to 2005, triggered by climate forcing (Howat et al., 2008; Seale et al., 2011). We explored the influence of two major climatic drivers on the 2016 synchronous retreat of the marine peripheral glaciers: ocean thermal forcing and surface meltwater runoff.

2. Methods

2.1. Terminus Position Time Series

We use an automated terminus position delineation method adapted from a gradient-based image segmentation technique used previously in the fields of biomedicine, solar physics, etc., (Khalil et al., 2007; McAteer et al., 2010), to determine changes in the peripheral glacier terminus positions. The adapted method (Liu et al., 2021) applies a continuous wavelet transform to delineate contours in the image brightness gradient at various spatial scales. Thresholds on the brightness contour line properties are used to select the final terminus delineation. The thresholds were calculated using an optimization algorithm that minimized the difference between the automated delineations and a manual validation data set (512 manual delineations). When applied to Landsat 8 panchromatic satellite images over the peripheral glaciers, the method produces delineations that are accurate within one pixel of manual delineations in a variety of image conditions (Liu et al., 2021). The method efficiently generates time series of relative glacier terminus positions at unprecedentedly high temporal resolution, which varies on the order of weekly to monthly, depending on the overlap in Landsat satellite tracks and the image conditions (i.e., cloud cover, shadows, etc.,) for each glacier. Regional-scale analyses are possible with the efficiency of automated terminus position delineation. Furthermore, the terminus position time series are generated at the sub-seasonal temporal scales that are necessary to resolve important terminus dynamics (Enderlin et al., 2018).

To estimate glacier terminus positions where there are data gaps and capture the sinusoidal patterns in seasonal terminus position change typical to marine glaciers (Howat et al., 2010; Moon et al., 2015; Schild & Hamilton, 2013), we fit Fourier Series models to the terminus position data and determine the model uncertainty using the Interquartile Range (IQR) of 500 models generated using a Monte Carlo approach (Text S1 in Supporting Information S1). With these continuous Fourier Series models, we are able to automatically identify the maximum and minimum terminus positions in each year. The maximum and minimum terminus positions each year, excluding partial years of data (i.e., model covered <280 days of the year), are automatically differenced to calculate annual retreat magnitudes. Comparison of the annual retreat magnitudes suggests that the 2016 retreat magnitude was anomalously high compared to 2013–2020 for many glaciers. Furthermore, many time series also show gradual multiyear retreat beginning in 2016, suggesting a shift in terminus stability. We calculate the linear trend in terminus position prior to 2016 and after 2016 for each glacier and compare their slopes to identify those glaciers that lost terminus stability in 2016. We automatically identify glaciers that initiated multiyear retreat in 2016 if they have pre-2016 slopes that were positive or within 5% of 0 and post-2016 slopes that were negative. Using all terminus position models for all 135 glaciers in the study, we categorize those glaciers that anomalously retreated in 2016 corresponding to a step-like change in terminus position (Figure 1, panel C1) or change in stability to multiyear retreat (Figure 1, panel C2 and C3).

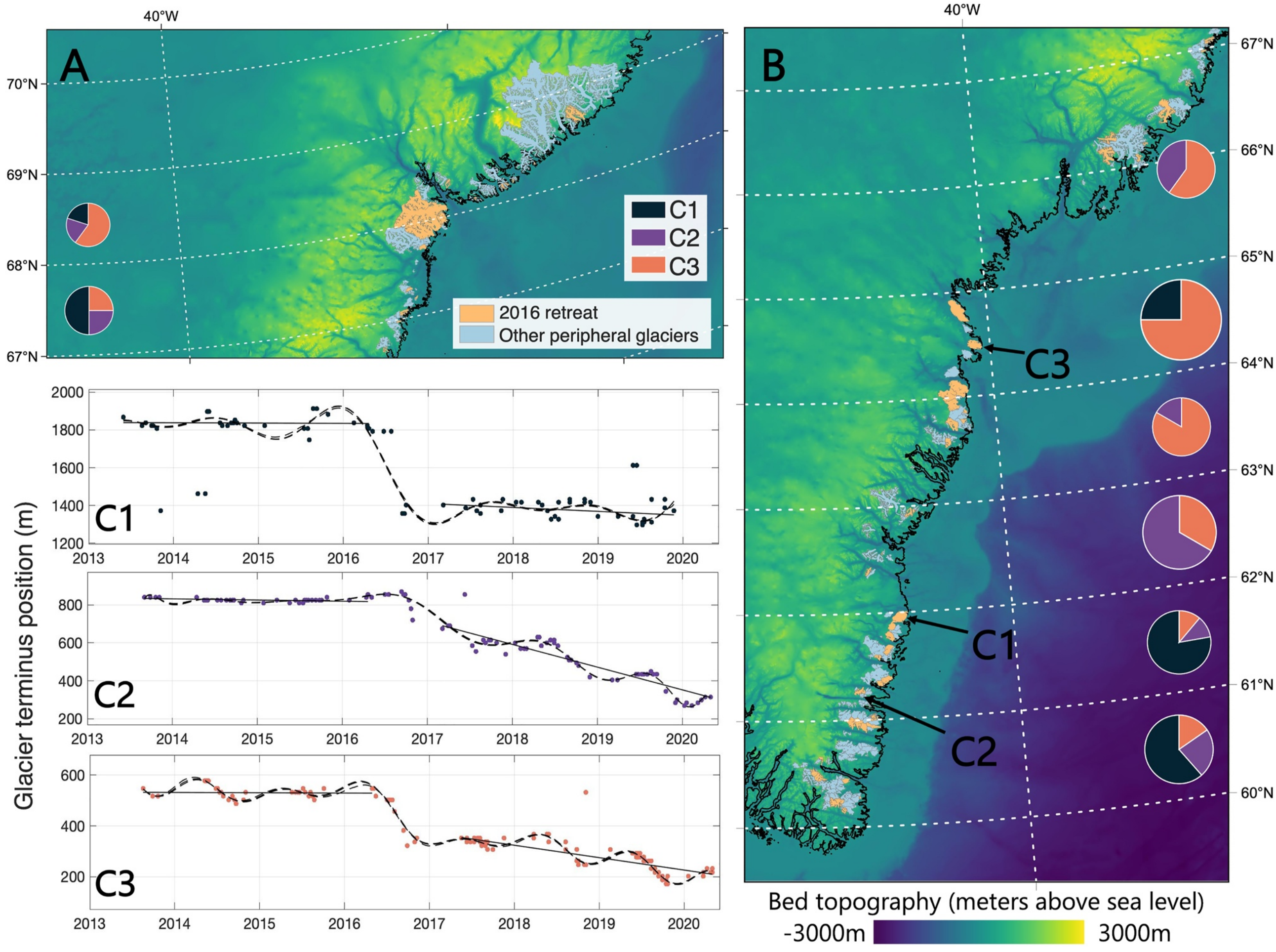

Figure 1. (a) Marine peripheral glaciers in southeast Greenland from 67° to 69°N and (b) 60° to 67°N overlaid on bed topography from BedMachine v3 (Morlighem et al., 2017). Pie charts show the relative distribution of each retreat case (C1–C3) and are size-scaled to the fraction of glaciers in each latitude bin that anomalously retreated in 2016, with the largest pie corresponding to 61.5%. Relative glacier terminus position time series generated from the automated method with modeled Fourier Series showing (C1) step-change retreat in 2016 (C2) stability change to multi-year retreat in 2016, and (C3) a combination of both. Solid lines are linear trendlines fit to pre-2016 and post-2016 terminus positions while dashed curves show the Fourier Series models.

2.2. Surface Runoff

Meltwater generated at the glacier surface can be routed through and beneath the glacier, eventually emerging at the terminus below the sea surface where it melts the submerged ice face (Sutherland et al., 2019). An increase in meltwater production can enhance submarine melting of the terminus, but melt rates cannot be measured remotely for these marine glaciers (How et al., 2017; Sutherland et al., 2019). Therefore, we use surface runoff from a regional climate model RACMO 2.3, as a proxy for subglacial discharge as in Carroll et al. (2016). Daily RACMO 2.3 surface runoff was available from 2013 to 2019, statistically down-sampled to 1-km spatial resolution over all of Greenland (Noël et al., 2019). The total runoff for each glacier is calculated as the sum of surface runoff within Randolph Glacier Inventory (RGI) glacier outline, obtained from the Global Land Ice Measurements from Space (GLIMS) database (RGI Consortium, 2017). Surface runoff on these glaciers is close to zero m water equivalent (m w. e.) throughout the winter (i.e., October–April), increases rapidly in late spring, and peaks annually in the summer.

From these runoff time series, we calculate the annual cumulative surface runoff over 2013–2019. To evaluate the 2016 runoff anomaly, we calculate the ratio of the cumulative runoff in 2016 to the average cumulative runoff from 2013 to 2019 (excluding 2016) for each of the SE Greenland peripheral glaciers. We use the two-sample *t*-test to statistically compare the mean of the 2016 runoff anomaly ratios for the glaciers that anomalously retreated to the mean of the ratios for the glaciers that did not anomalously retreat in 2016. We use a two-sample

Kolmogorov-Smirnov test to the likelihood that they came from the same underlying distribution. Additionally, we separate the cumulative runoff in 2016 from the cumulative runoff for the other years for the glaciers that anomalously retreated and those that did not anomalously retreat in 2016. We use a Monte Carlo approach to calculate the mean runoff from 1,000 random samples of 90% of the data from both groups. We then compare the two groups' distributions of mean cumulative runoff using a two-sample *t*-test to evaluate whether they are statistically different.

2.3. Subsurface Ocean Temperatures

Warming of ocean temperatures at depth may also promote retreat by driving submarine melt of the submerged portion of the terminus. The peripheral glaciers in this study are located along the outer coast of SE Greenland and inside the fjords. NASA Oceans Melting Greenland (OMG) TerraSond Conductivity, Temperature, and Depth (CTD) measurements made near these peripheral glaciers' termini indicate depths of 300 m below sea level or more within the fjord (Figures S1 and S2 in Supporting Information S1). The available vertical temperature profiles demonstrate that warm subsurface waters can enter the majority of these fjords (Figures S1 and S2 in Supporting Information S1). Some of the peripheral glaciers are potentially grounded above the depth of the warm subsurface water implicated as a driver of GrIS terminus retreat (e.g., Rignot et al., 2012; Wood et al., 2021), but no near-terminus radar-derived thickness estimates are available for these glaciers, so we cannot rule out the impact of ocean forcing on glacier retreat.

Although a comparison of repeat CTD casts from the inner fjords would be ideal to evaluate change in ocean temperature over time and investigate ocean forcing on the 2016 retreat, TerraSond fjord CTD measurements were only available in 2016. Therefore, we use measurements from OMG Airborne eXpendable Conductivity Temperature Depth instruments (AXCTDs) made from 2016 to 2018 in SE Greenland (OMG Mission, 2020) and modeled ocean temperatures from 2013 to 2017 from the global Estimating the Circulation and Climate of the Ocean (ECCO) v4r4 model (ECCO Consortium et al., 2020) for our analysis. OMG AXCTD measurements were acquired each year between August and October and were spatially distributed across all latitudes along the SE Greenland continental shelf (Figure S1 in Supporting Information S1). The global ECCO model resolves ocean temperatures along the continental shelf and monthly temperatures are provided on a regular 0.5° by 0.5° grid (ECCO Consortium et al., 2020). The ECCO temperatures are extracted from all grid cells with center points located within a bounding area that extended ∼100 km offshore (Figure S1 in Supporting Information S1).

The warm subsurface Atlantic Water that has been implicated as a driver of outlet glacier submarine melt is generally found at least 150–200 m below the sea surface around Greenland (Straneo et al., 2012; Rignot et al., 2012). On the continental shelf of SE Greenland, previous in situ observations (Sutherland et al., 2013) and the OMG data (Figure S3 in Supporting Information S1) indicate that seasonal variations in surface temperatures reach down to 200–250 m below the surface. To minimize the impact of seasonal heating effects and cooler surface water (Straneo et al., 2010), we calculate the depth-averaged temperature between 250 and 350 m below the surface for both the OMG measurements and the ECCO model outputs. We spatially average the ocean temperatures at depth within each latitude band in SE Greenland, from 60° to 69°N, corresponding to the documented extent of influence of the Irminger Current along the SE coast (Seale et al., 2011). We compare these ocean temperature changes by latitude band to the fraction of peripheral glaciers that anomalously retreated in each latitude band.

2.4. Glacier Surface Slopes

We calculate the peripheral glacier surface slope near their termini using elevations from the ArcticDEM release 7 100-m mosaic (C. Porter et al., 2018; D. F. Porter et al., 2018) produced by the Polar Geospatial Center. We extract the elevation values along the glacier centerlines, which are drawn manually following flow vectors generated from the MEaSUREs 1995–2015 Greenland Ice Sheet Velocity Mosaic (Joughin et al., 2016). Each glacier's slope is calculated using the elevation at the manually traced terminus in 2015/2016, prior to the 2016 retreat period, and the elevation at a point 0.5 km up-glacier of the manually traced terminus. Surface slopes are also extracted using the elevation 1 km up-glacier of the termini, yielding similar results (Figure S7 in Supporting Information S1). The surface slopes for the glaciers that anomalously retreated in 2016 ($n = 56$) are clustered lower than the slopes for glaciers that did not anomalously retreat in 2016 ($n = 79$). We use a Kolmogorov-Smirnov test on the two slope distributions to determine the likelihood that they were drawn from the same underlying distribution.

3. Evidence of Widespread Retreat in 2016

Out of 135 peripheral marine glaciers in SE Greenland, 56 glaciers spanning all degrees of latitude from 60°N to 69°N anomalously retreated in 2016 (Figure 1). These peripheral glaciers vary in size (IQR of 21.9–105.7 km^2) and setting, from the inner fjords to directly along the outer coast (Table S1 in Supporting Information S1). Three retreat types were observed: Step change in terminus position in 2016 corresponding to a retreat magnitude of ≥1.25 times the glacier's average retreat magnitude over 2013–2020 (Figure 1, panel C1), shift from either a stable or advancing trend to multiyear retreat after 2016 (Figure 1, panel C2), or a combination of both (Figure 1, panel C3). The normalized terminus position time series for the 56 glaciers that retreated anomalously in 2016 show a marked retreat from the 2013–2015 terminus position (Figure S5 in Supporting Information S1).

We group the peripheral glaciers by latitudinal band from 60° to 69°N for comparison with climatic data. The 65° to 66°N and the 66° to 67°N data were combined for all variables, since 65° to 66°N only contained six peripheral glaciers which was too small of a sample size to interpret independently. The fraction of peripheral glaciers that anomalously retreated in 2016 varied with latitude, with more glaciers that anomalously retreated in the southerly latitudinal bands (Figure 1b). The majority of peripheral glaciers underwent large step changes in terminus position (37%) or a step change combined with multiyear retreat after 2016 (42%). Loss of terminus stability in 2016 indicated by post-2016 multiyear retreat only dominated at the middle latitudinal bands (Figure 1b).

The observed 2016 retreat anomaly for 56 peripheral glaciers across all latitudes of SE Greenland indicates a widespread, synchronous glacier response in this region. GrIS outlet glaciers, sourced from and therefore interconnected to the ice sheet, have responded synchronously and sensitively on seasonal to centennial time scales to climate factors (Howat et al., 2008; Moon & Joughin, 2008; Seale et al., 2011). For example, up to 30 outlet glaciers in SE Greenland were observed to respond sensitively and synchronously from 2000 to 2006 to changes in atmospheric conditions (Howat et al., 2008; Moon & Joughin, 2008) and enhanced advection of warm Atlantic Water carried by the Irminger Current (Howat et al., 2008; Seale et al., 2011). While ice-sheet-independent glaciers have undergone widespread synchronous retreat in response to drastic climate changes over decades to centennial time scales, such as the end of the Little Ice Age in the 19th century (e.g., Bjork et al., 2018; Lowell, 2000), no prior evidence suggests that they respond on shorter timescales to environmental perturbations. Our observations represent the first evidence of rapid synchronous response of independent marine glaciers across glacier catchments. Below we consider oceanic and atmospheric drivers of the widespread synchronous retreat of the peripheral glaciers in the southeast.

4. Drivers of Synchronous Retreat

Studies of submarine melt on marine glacier termini indicate that both ocean thermal forcing and subglacial discharge control melt rates (Cowton et al., 2018; Jenkins, 2011; Sutherland et al., 2019) and affect the near-terminus strain rates to promote calving (Benn et al., 2007). Numerical modeling indicates that subglacial discharge and ocean thermal forcing scale with submarine melt rates on marine glaciers, following the parameterization

$$q_{\mathrm{m}} \propto Q_{\mathrm{sg}}^{a} \cdot T_f \tag{1}$$

where q_{m} is the submarine melt rate, Q_{sg} is the subglacial discharge, T_f is the thermal forcing, and a is the exponent scaling the subglacial discharge that has a typical range from 1/3 to 1 (Cowton et al., 2018; Jenkins, 2011; Xu et al., 2012). To evaluate the ocean thermal forcing, we use observations and models of the subsurface water temperatures in SE Greenland. Surface meltwater runoff impacts the subglacial discharge flux that drives submarine melt, as well as the subglacial water pressures that influence sliding (How et al., 2017), controlling retreat through melt and terminus dynamics. Since we are not able to measure subglacial discharge directly on marine glaciers, we assume that all runoff reaches the glacier bed and use glacier surface runoff to investigate the impact of subglacial discharge on glacier retreat.

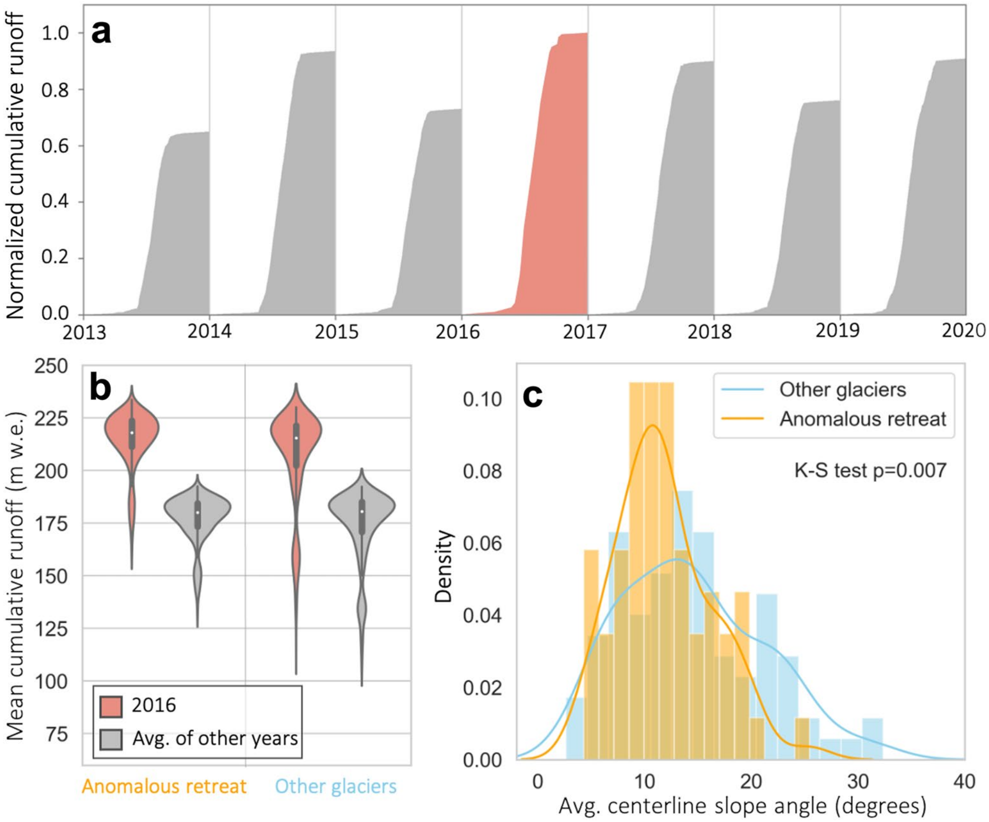

Figure 2. (a) Cumulative surface runoff from RACMO2.3 for all the peripheral glaciers in SE Greenland normalized over the 2013–2019 period. (b) Violin plots show the distributions of mean cumulative runoff values in meters water equivalent (m w. e.) calculated for the two groups of glaciers (2016 anomalous retreat vs. other glaciers) from 1,000 random samples of 90% of the data. Box plots inside the violins show the 25th, 50th, and 75th quartiles and extend to the minimum and maximum data values. (c) Distributions of the average glacier centerline slope angles for the two groups of glaciers, indicating that glaciers that experienced anomalous retreat in 2016 are more gently sloped.

Subsurface ocean temperatures averaged over 250–350 m below sea level from the OMG measurements did not indicate anomalous warmth in 2016, though the ability to evaluate the 2016 anomaly is limited by the temporal resolution, coverage, and seasonal timing of the *in situ* observations. The differences in timing of the OMG AXCTD measurements (August vs. October) may cause differences in temperatures even at depth (Grist et al., 2014). The ECCO data suggest that temperatures on the SE Greenland continental shelf were fairly stable over the study period (Figure S4 in Supporting Information S1). We also considered temperatures in the 200- to 300-m and the 300- to 400-m depth ranges, none of which indicated anomalous warmth in 2016. Therefore, it is unlikely that ocean thermal forcing drove the widespread, synchronous glacier retreat in 2016.

Changes in meltwater runoff can also strongly influence dynamics at marine glacier termini. Modeled estimates of elevated meltwater runoff and our new observations of pronounced retreat indicate the strong sensitivity of marine glacier retreat magnitude and timing to meltwater input for these relatively small marine glaciers. In contrast with the stable ocean forcing, the impacts of regional atmospheric forcing varied considerably between years, with fluctuations in cumulative glacier surface runoff of up to one-third of the maximum over the time period (Figure 2a). Surface runoff appears to influence annual magnitudes of retreat. For all of the glaciers that anomalously retreated in 2016, the 2016 cumulative surface runoff was greater than the mean from 2013 to 2019 (excluding 2016) by 5%–40% (Figure 2b). The mean normalized cumulative runoff in 2016 was 22% larger than the mean of the other years, indicating elevated meltwater delivery to glacier termini that year. To assess the significance of the 2016 runoff anomaly, we calculate the mean cumulative runoff in 2016 and the mean cumulative runoff for the other years of analysis for random 90% samples of the glaciers in the study 1,000 times. The resulting two distributions of mean cumulative runoff, 2016 means and means of the other years, are significantly different (Figure 2b). A two-sample t-test indicated that the 2016 means (n = 1,000) were significantly different

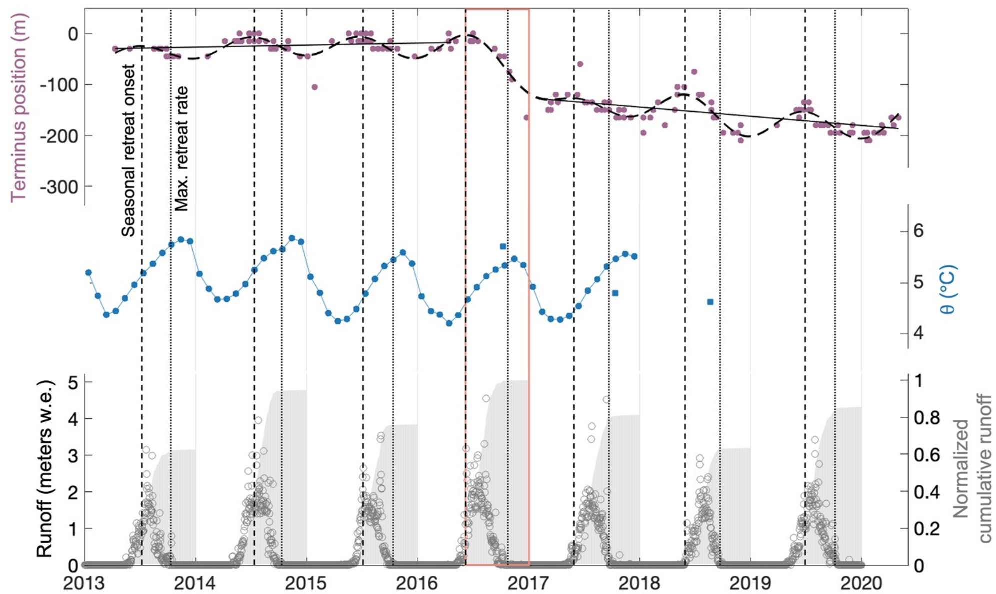

Figure 3. Example time series of peripheral glacier (60.9779°N, 43.3386°E) terminus position, runoff and annual cumulative runoff (normalized between 0 and 1), and subsurface ocean temperatures (θ) for the corresponding latitude band 60 to 61°N. The pink box bounds the time period of the 2016 terminus retreat. Vertical dashed lines indicate the timing of the onset of seasonal retreat (long dash) and the maximum retreat rate based on the mean terminus position model (short dash).

from the means of all other years ($n = 1{,}000$), yielding $p << 0.01$. The dominance of meltwater-driven retreat for these peripheral glaciers contrasts with the ocean forcing implicated for GrIS outlet glacier retreat that began in the 1990s (Wood et al., 2021).

Cumulative runoff in 2016 was significantly greater than the mean cumulative runoff over the other years. Applying the 2016 mean runoff anomaly (1.22) as the subglacial discharge anomaly to the submarine melt rate parameterization in Equation 1 using the typical range of scaling values (a = 1/3 to 1), with no ocean thermal forcing anomaly, produces a submarine melt rate increase of 7%–22%. Given that enhanced subglacial discharge may further encourage retreat through buoyancy-driven fjord circulation (Slater et al., 2018; Straneo & Cenedese, 2015) and that submarine melt-driven undercutting enhances calving, the increased submarine melt may have a substantial impact on retreat.

Time series of terminus position and surface runoff for the SE peripheral glaciers also indicate that the seasonal timing of meltwater input may modulate the timing of terminus retreat. Retreat onset approximately coincides with runoff onset and maximum retreat rate coincides with peak runoff for some of these peripheral glaciers (Figure S6 in Supporting Information S1), while retreat onset approximately coincides with peak runoff for other glaciers (e.g., in Figure 3). The difference is likely due to the influence of the subglacial hydrological system. The glaciers that exhibit synchronous runoff and retreat onset may efficiently route meltwater to the bed while the delayed retreat response would result from a less efficient, distributed subglacial drainage system. These peripheral glaciers may contain a variety of subglacial drainage systems, as has been inferred for the GrIS outlet glaciers (Vijay et al., 2021), which would influence the surface meltwater-driven retreat response.

Our analysis of the 2016 surface runoff anomaly indicated that meltwater input was elevated for the glaciers that exhibited anomalous retreat in 2016 as well as the glaciers that did not (Figure 2b). Both the difference in the mean runoff anomaly and the difference in the distributions of the two groups are not statistically significant. Furthermore, with no clear trend in ocean warming, these peripheral glaciers appear to have been subjected to similar environmental forcing in 2016 despite exhibiting varied magnitudes of retreat and subsequent stability. We expect that the physical setting and geometry of these glaciers ultimately controls the retreat magnitude and response type. Analysis of near-terminus glacier surface slopes indicated that the glaciers that anomalously retreated in 2016 had lower surface slopes than those that did not (Figure 2c). A Kolmogorov-Smirnov test on the two slope distributions yielded a p-value of 0.007 for the 0.5-km slopes and 0.017 for the 1-km slopes, indicating that they are significantly different. For the more gently sloped glaciers, melt-driven thinning may bring a larger portion of the near-terminus region closer to flotation, promoting calving at the terminus. Furthermore, greater areas of these low-slope glaciers are situated at lower elevations where surface melt rates are highest. Thus, the 2016 melt anomaly could strongly enhance terminus retreat for these glaciers, promoting high retreat magnitudes and loss of terminus stability. Other glacier-specific factors such as glacier and fjord geometry and bed topography control the stress distribution near glacier termini and also exert important controls on glacier retreat (Catania et al., 2018). Individual glacier and fjord geometry is likely to have influenced whether glaciers lost stability in 2016 (Figure 1, panel C2) or underwent pronounced retreat and re-stabilized (Figure 1, panel C1). Glacier bed topography also influences the configuration of the subglacial hydrological system, which may modulate the impact of increased surface meltwater. Further exploration of geometric controls on these glaciers' stability will be important for predicting their future changes.

5. Conclusions

Our observations demonstrate that the independent marine glaciers around Greenland's periphery are capable of synchronous and rapid dynamic response linked to atmospheric forcing. We provide the first indication that marine glaciers outside of the ice sheets may retreat and destabilize *en masse* at short timescales. We found that anomalously high cumulative meltwater input coincided with a synchronous and anomalous 2016 retreat of the peripheral marine glaciers in southeast Greenland and likely was a major driver of retreat for glaciers with less stable geometries. Accounting for the rapid retreat of marine glaciers is critical to obtaining accurate estimates of their frontal ablation, mass loss through calving and submarine melt (McNabb et al., 2015). Consequently, measuring their dynamic changes and understanding controls on their dynamics will be necessary to obtain accurate estimates of their mass loss. Furthermore, the abrupt retreat in the absence of an obvious ocean forcing suggests that peripheral marine glacier stability can be extremely sensitive to subglacial discharge-driven terminus retreat. Thus, continued atmospheric warming may drive greater glacier mass loss than currently predicted, due to meltwater runoff-driven terminus retreat, acceleration, and dynamic mass loss.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The glacier terminus position time series produced in this study are submitted to the Boise State University data repository (https://doi.org/10.18122/cryogars_data.1.boisestate). The code used for the automated terminus delineations is available as a GitHub repository (https://doi.org/10.5281/zenodo.6646787). Access the latest version of the code at https://github.com/julialiu18/automated-glacier-terminus. The Regional Atmospheric Climate Model (RACMO) data set authors provided the surface runoff data (https://doi.org/10.1126/sciadv.aaw0123). All other data used in the analysis are publicly available. The Oceans Melting Greenland and Estimating the Circulation and Climate of the Ocean v4r4 temperature data are available from https://omg.jpl.nasa.gov/portal/data/OMGEV-AXCTD and https://ecco-group.org/products-ECCO-V4r4.htm, respectively. Glacier outlines used to extract glacier surface runoff were downloaded through the Global Land Ice Measurements from Space (GLIMS) Randolph Glacier Inventory (https://doi.org/10.7265/N5-RGI-60). The ArcticDEM used for glacier surface slope analysis is available through the Polar Geospatial Center (https://doi.org/10.7910/DVN/OHHUKH). The MEaSUREs Multi-year Greenland Ice Sheet Velocity Mosaic used for the construction of glacier centerlines was retrieved from the National Snow and Ice Data Center (https://doi.org/10.5067/QUA5Q9SVMSJG).

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