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Retreat of Northern Hemisphere Marine-Terminating Glaciers, 2000–2020

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Key Points:

- There were 1704 marine-terminating glaciers in 2000 in the Northern Hemisphere, of which 85.3% retreated and 2.5% advanced from 2000 to 2020
- Tidewater glaciers lost a total area of 7,527 ± 31 km^2 from 2000 to 2020, with the Greenland Ice Sheet responsible for 61.9% of total losses
- Variations in retreat are best explained by glacier characteristics: ice shelves/tongues, surging, basal geometry, and calving width

Supporting Information:

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

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Abstract We mapped the terminus position for every marine-terminating glacier in the Northern Hemisphere for 2000, 2010, and 2020, including the Greenland Ice Sheet, to provide the first complete measure of their variability. In total, these 1,704 glaciers lost an average of 389.7 ± 1.6 km^2 a^{-1} (total 7,527 ± 31 km^2) from 2000 to 2020 with 123 glaciers becoming no longer marine-terminating over this period. Overall, 85.3% of glaciers retreated, 2.5% advanced, and the remaining 12.3% did not change outside of uncertainty limits. Outlet glaciers of the Greenland Ice Sheet are responsible for 61.9% of total area loss, although their rate of retreat was 34% less in 2010–2020 than 2000–2010. Glaciers with the largest area loss terminate in ice shelves or ice tongues, are surge-type, have an unstable basal geometry, or have an unusually wide calving margin.

Plain Language Summary North of the equator, 1,704 glaciers touched the ocean in 2000. Here, we present the first analysis to document the frontal position of every one of these glaciers in 2000, 2010, and 2020. We found that 85.3% retreated and are now reduced in area. Only 2.5% of glaciers advanced or increased in area. The remaining 12.3% did not change within uncertainty limits. Total area losses were 389.7 ± 1.6 km^2 per year (total 7,527 ± 31 km^2) over the 20-year period. Glaciers flowing from the Greenland Ice Sheet accounted for over 60% of total area losses. We found wide variations in the response of glaciers to similar changes in air and ocean temperature and sea ice concentrations, showing that environmental conditions alone cannot explain why some glaciers retreated more than others. Instead, unique glacier characteristics are the most important factor in controlling the variability of terminus retreat. Glaciers with floating ice at their front (ice shelves or ice tongues), those that undergo periodic changes in their flow velocity (surges), those which have a weak connection to their beds, and glaciers that are unusually wide, experienced the largest area loss from 2000 to 2020.

1. Introduction

Globally, average air temperatures for 2001–2020 are 0.99°C higher than they were in 1850–1900 (IPCC, 2021), with enhanced warming in the polar regions driven by polar amplification (Stuecker et al., 2018). Glaciers, ice caps, and ice sheets are increasingly losing mass, with mass loss rates for the Greenland Ice Sheet, for example, increasing from being approximately in balance in the 1990s, to 222 ± 30 Gt a^{-1} for 2013–2017 (Shepherd et al., 2020). To maintain equilibrium with their mass throughput, glaciers, both marine and land terminating, have exhibited terminus retreat (Zemp et al., 2015).

Marine-terminating glaciers, also known as tidewater glaciers, are defined as ice masses which contact the ocean along a grounded terminus, floating terminus, or ice shelf (Cogley et al., 2011). While all glaciers contribute to sea level rise through surface melt, marine-terminating glaciers also contribute via frontal ablation, or the calving of icebergs (Cogley et al., 2011). Quantification of their terminus position provides an essential climate variable (Bojinski et al., 2014) and important information to better understand glacier mass balance, natural hazards, ice-ocean interactions, and the impacts of climate change. Marine-terminating glacier retreat can lead to instabilities at the calving front that further increase glacier velocity and decrease glacier thickness (Meier & Post, 1987; Nick et al., 2009; Schoof, 2007). Changes in terminus position can be non-linear, although over decadal timescales there is evidence that regional retreat is linear (Fahrner et al., 2021). Terminus change is not fully considered in glacier mass balance measurements, as gravimetric (Ciracì et al., 2020) and geodetic (Hugonnet et al., 2021) methods are not able to quantify glacier mass loss below sea level. To first differentiate the mass losses above and below sea level, we need to map the glacier area change that is also a change in ocean area.

There are several ways to measure the changes of marine-terminating glaciers. Most studies have focused on quantifying length changes, using either a box or centerline approach. This has identified the retreat of most, but

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not all, marine-terminating glaciers in Alaska from 1948 to 2012 (McNabb et al., 2015), the retreat of 94% of marine-terminating glaciers in the Canadian Arctic between 1958 and 2015 (Cook et al., 2019), and widespread losses in Greenland (King et al., 2020; McFadden et al., 2011; Moon & Joughin, 2008; Murray et al., 2015), Atlantic Arctic (Carr et al., 2017), and the Russian Arctic (Carr et al., 2014). The centerline or box methods rely on a line or multiple lines to calculate length change (Lea et al., 2014). The main problem with quantifying the retreat along a line is that most glaciers have complex terminus shapes, which are difficult to accurately capture with centerline measurements. Thus, the best way to assess glacier terminus change is to directly measure changes in terminus area. However, no study has identified all northern hemisphere marine-terminating glaciers and evaluated their terminus change over a consistent period with a consistent methodology. Here, we manually digitize the terminus region of every marine-terminating glacier in the Northern Hemisphere to quantify their change in terminus area in approximately 2000, 2010, and 2020, and investigate the patterns and causes of those changes.

2. Methods

2.1. Glaciers Included in This Study

We manually identified every glacier, regardless of size, in the Northern Hemisphere that contacted the ocean between 2000 and 2020 using Landsat 5, Landsat 7, Landsat 8, and ASTER satellite imagery. We differentiate between: (a) the Greenland Ice Sheet, and (b) glaciers and ice caps (GICs), which include the peripheral glaciers of Greenland outside of the ice sheet. We used Randolph Glacier Inventory version 6 (RGI6; RGI Consortium, 2017) to help identify marine terminating GICs and to provide a unique identifier for each glacier. For the Greenland Ice Sheet we used outlines from Mouginot and Rignot (2019) for a unique identifier. We used Rastner et al.'s (2012) classification for glaciers that have a weak (CL1) or no (CL0) hydrological connection to the Greenland Ice Sheet to define periphery glaciers, while those with a strong (CL2) hydrological connection are defined as part of the ice sheet.

The number of glaciers reported here may differ from other studies due to the variable treatment of single glaciers that have multiple termini, or single termini that are fed by several tributaries. Various studies split or group such glaciers or termini in different ways, including RGI6, where, for example, low-lying ice caps with little or no outlet definition are inconsistently divided in the Russian Arctic. However, while different inventories may report different numbers of glaciers in a region, it will not impact regional area change totals.

2.2. Glacier Terminus Area Change

We manually digitized polygons of the terminus region for every glacier in approximately 2000, 2010, and 2020, primarily based on summer (July and August), cloud-free, true-color Landsat 5, 7, and 8 imagery (30 m resolution). When Landsat imagery was not available, we first attempted to fill the gap with summer true-color ASTER imagery (15 m resolution), particularly for northern Greenland and Arctic Canada North for ~2000 and ~2010. Where no cloud-free optical data was available, we used summer Radarsat-1 fine beam imagery (8 m resolution) for Northern Greenland in ~2000, and fine beam ALOS PALSAR imagery (10 m resolution) for Northern Ellesmere Island in ~2010, available from the Alaska Satellite Facility. Images were selected as close as possible to the target dates, based on image availability and minimum cloud and snow cover. The exact date for every glacier outline can be found in Data Set S1 and is almost always within 1 year of the target date. Rates of area change are standardized to annual and decadal values to account for these temporal biases.

We drew a polygon around each terminus to capture the portion of the area that changed from ocean to ice (advance), or ice to ocean (retreat; Figure S1 in Supporting Information S1). For glaciers that either advanced from land into the ocean, or retreated from the ocean onto land, we only include the area that was or became ocean at the surface. We then differenced the polygons to determine the area change for each glacier for 2000–2010, 2010–2020, and 2000–2020. The glaciers were mapped using QGIS version 3.10 in the WGS84 Arctic Polar Stereographic projection (EPSG 3995). To eliminate area distortions in the area change calculations, we reprojected each terminus into a unique local orthographic coordinate system to perform the area and error calculations. While we report decadal rates here, many area losses can be sudden, caused by large calving events, which are not captured in our decadal average observations. This is likely most important for ice shelf breakup events (Copland et al., 2007), and glaciers which have a basal instability (Fahrner et al., 2021). It is beyond the scope of this study to determine more precise timing for these breakup events.

Table 1
Number and Change in Area of Marine-Terminating Glaciers Across the Northern Hemisphere Between 2000, 2010, and 2020, by Region

Region	Number of glaciers	Net area change 2000–2010 (km^2 a^{-1})	Net area change 2010–2020 (km^2 a^{-1})	Net area change 2000–2020 (km^2 a^{-1})	Net area change 2000–2020 (km^2)
Alaska	42	−2.46 ± 0.14	−4.51 ± 0.21	−3.52 ± 0.10	−60.4 ± 1.8
Arctic Canada North	252	−28.96 ± 0.79	−28.78 ± 0.82	−29.09 ± 0.40	−545.7 ± 7.6
Arctic Canada South	86	−1.02 ± 0.08	−0.85 ± 0.07	−0.93 ± 0.04	−16.9 ± 0.7
Asia North	1	0.00 ± 0.01	−0.01 ± 0.01	0.00 ± 0.00	−0.1 ± 0.1
Greenland Ice Sheet	208	−287.54 ± 2.45	−190.99 ± 1.81	−241.47 ± 1.19	−4773.7 ± 23.4
Greenland Periphery	537	−37.10 ± 0.63	−20.32 ± 0.63	−29.92 ± 0.34	−558.2 ± 6.6
Iceland	1	−0.21 ± 0.03	−0.49 ± 0.04	−0.32 ± 0.02	−5.7 ± 0.3
Russian Arctic	411	−49.75 ± 1.38	−69.14 ± 1.63	−57.67 ± 0.74	−1091.5 ± 14.1
Svalbard and Jan Mayen	166	−27.33 ± 0.98	−26.34 ± 1.10	−26.79 ± 0.54	−475.0 ± 9.7
Greenland total	745	−324.63 ± 2.52	−211.30 ± 1.91	−271.39 ± 1.24	−5331.9 ± 24.3
Glacier and ice cap total	1,496	−146.83 ± 1.97	−150.44 ± 2.23	−148.24 ± 1.06	−2753.6 ± 20.0
Northern Hemisphere total	1,704	−434.37 ± 3.14	−341.42 ± 2.87	−389.71 ± 1.59	−7527.3 ± 30.7

Note. See Figure 1 for location of regions.

We assume that area gain/loss uncertainty is one pixel, with total uncertainty derived by multiplying the length of the perimeter of the changed terminus area by the width of a pixel (30 m for Landsat, 15 m for ASTER, ∼10 m for SAR imagery; Krumwiede et al., 2014).

2.3. Climate and Ocean Data

To investigate potential causes of observed changes in terminus position, we assessed ocean and air temperatures, and sea ice concentrations, on or adjacent to each glacier terminus. We derived ocean temperatures from the EC-MWF ORAS5 model from 2000 to 2018 (Zuo et al., 2017, 2019), for the ocean surface and 300 m depth. We used ERA5 modeled 2 m air temperature from 2000 to 2020 (Copernicus, 2019). Both the ocean and air temperature datasets have 0.25° spatial resolution and monthly temporal resolution, which we averaged by decade. We used sea ice concentrations derived from passive microwave observations from 2000 to 2020 (Meier et al., 2017; Peng et al., 2013), with a 25 km spatial resolution and monthly temporal resolution, which we averaged seasonally and annually.

3. Results

3.1. Hemispheric Patterns of Marine-Terminating Glacier Change

We identified 1,704 Northern Hemisphere glaciers that contacted the ocean between 2000 and 2020 (Table 1; Figure 1; see Data Set S1 for details of every glacier). Collectively, these glaciers experienced a net loss of 7,527.3 ± 30.7 km^2 (389.7 ± 1.6 km^2 a^{-1}) over this period, with 1,453 (85.3%) retreating, 42 (2.5%) advancing, and 209 (12.3%) not changing within the uncertainty of our methods (Table S1; Figure S2 in Supporting Information S1). In total, 123 glaciers (7.2%) that were in contact with the ocean in 2000 had retreated enough by 2020 to terminate on land; 52 of these occurred between 2000 and 2010, and 71 between 2010 and 2020.

Very few glaciers are responsible for most of the terminus change, with only 23 glaciers, or 1.3% of the total, accounting for 50.3% of total terminus area loss over the period 2000–2020. The top 10 glaciers with the highest rate of terminus area loss are all in Greenland, with only five glaciers outside of Greenland in the top 21 (one in Russia, one in Alaska, three in Svalbard). This is reflected in the fact that Greenland experienced more terminus

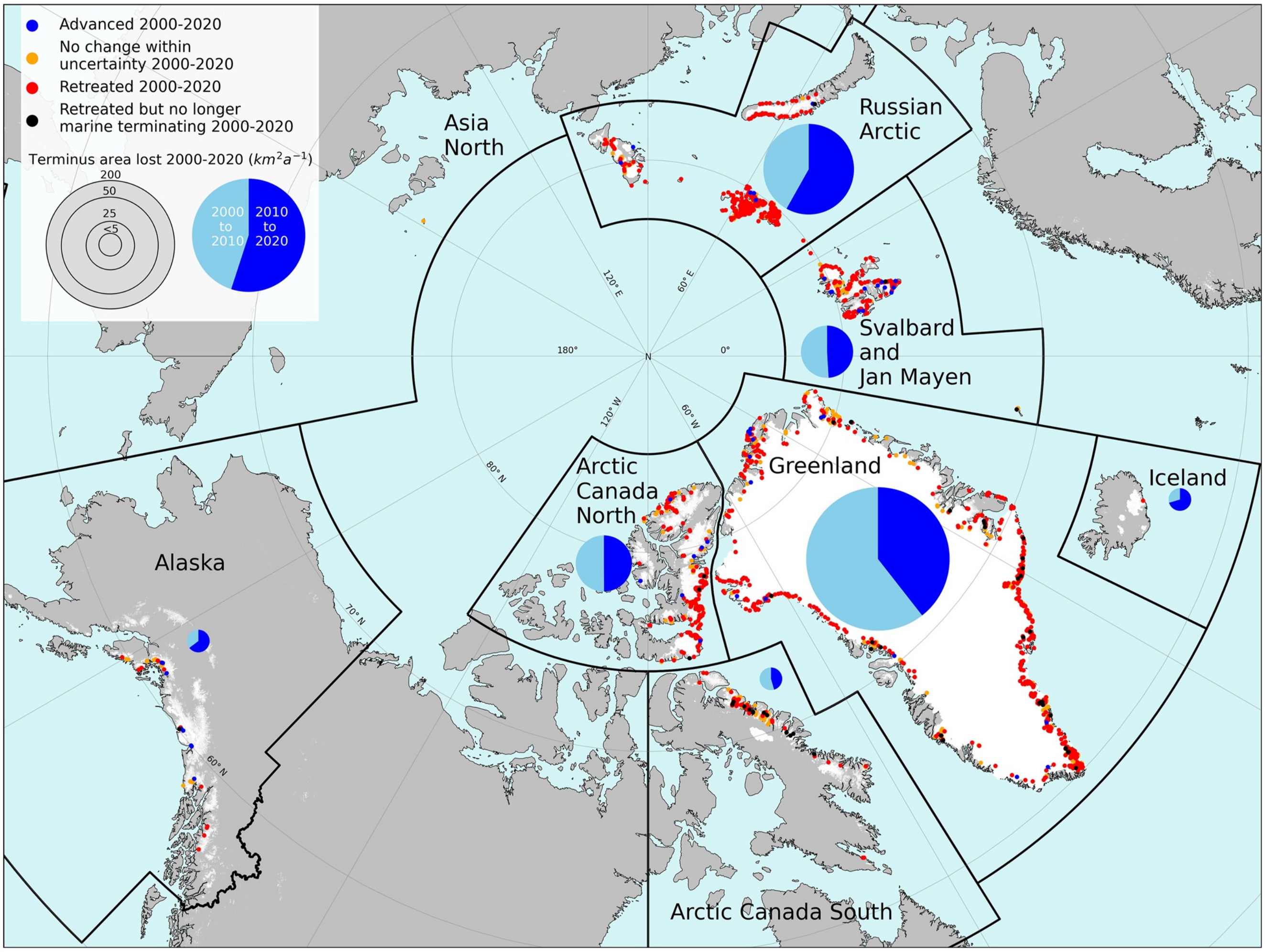

Figure 1. Distribution and change of marine-terminating glacier terminus area for 2000–2020. Circles are scaled (non-linearly) to the area loss of each major region in the Randolph Glacier Inventory.

area loss than any other region, with ice sheet and periphery glaciers combined accounting for 69.6% of total Northern Hemisphere tidewater ice loss from 2000 to 2020 (Table 1; Figure 1).

The rate of terminus loss decreased by 21.4% from 2000–2010 (434.4 ± 3.1 km^2 a^{-1}) to 2010–2020 (341.4 ± 2.87 km^2 a^{-1}), primarily due to a 33.6% decrease in the retreat rate of Greenland Ice Sheet outlet glaciers. In contrast, GICs lost area at a rate 2.5% higher during 2010–2020 than 2000–2010.

3.2. Greenland Ice Sheet Change

Marine-terminating glaciers of the Greenland Ice Sheet lost an average total area of 241.5 ± 1.2 km^2 a^{-1} from 2000 to 2020 (total area loss of 4,774 ± 23 km^2), which accounts for 62.0% of the Northern Hemisphere total. The four glaciers with the largest terminus losses from 2000 to 2020 were Zachariae Isstrøm (total 1452.7 ± 14.4 km^2; mean 72.6 ± 0.72 km^2 a^{-1}: Figure 2a), Humboldt (total 236.1 ± 7.9 km^2; mean 13.0 ± 0.44 km^2 a^{-1}: Figure 2b), Petermann (total 272.6 ± 4.5 km^2; mean 12.9 ± 0.22 km^2 a^{-1}: Figure 2c), and Nioghalvfjerdsbrae (total 206.3 ± 7.3 km^2; mean 10.8 ± 0.38 km^2 a^{-1}). Together, these four glaciers, all of which are in Northern Greenland, accounted for 45.3% of the tidewater glacier terminus area loss from the Greenland Ice Sheet, with Zachariae Isstrøm accounting for 30.1% alone. With the addition of Ostenfeld Harder and Hagen Bræ, this group of six glaciers accounted for 53.3% of total ice sheet area loss.

Only six outlets of the Greenland Ice Sheet (out of 207) had a net advance from 2000 to 2020 (Ryder, Qajuuttap Sermia, Ukaasosuaq, Vestfjord, Store, Heimdal). Of these, the largest advance occurred at Ryder Glacier for a

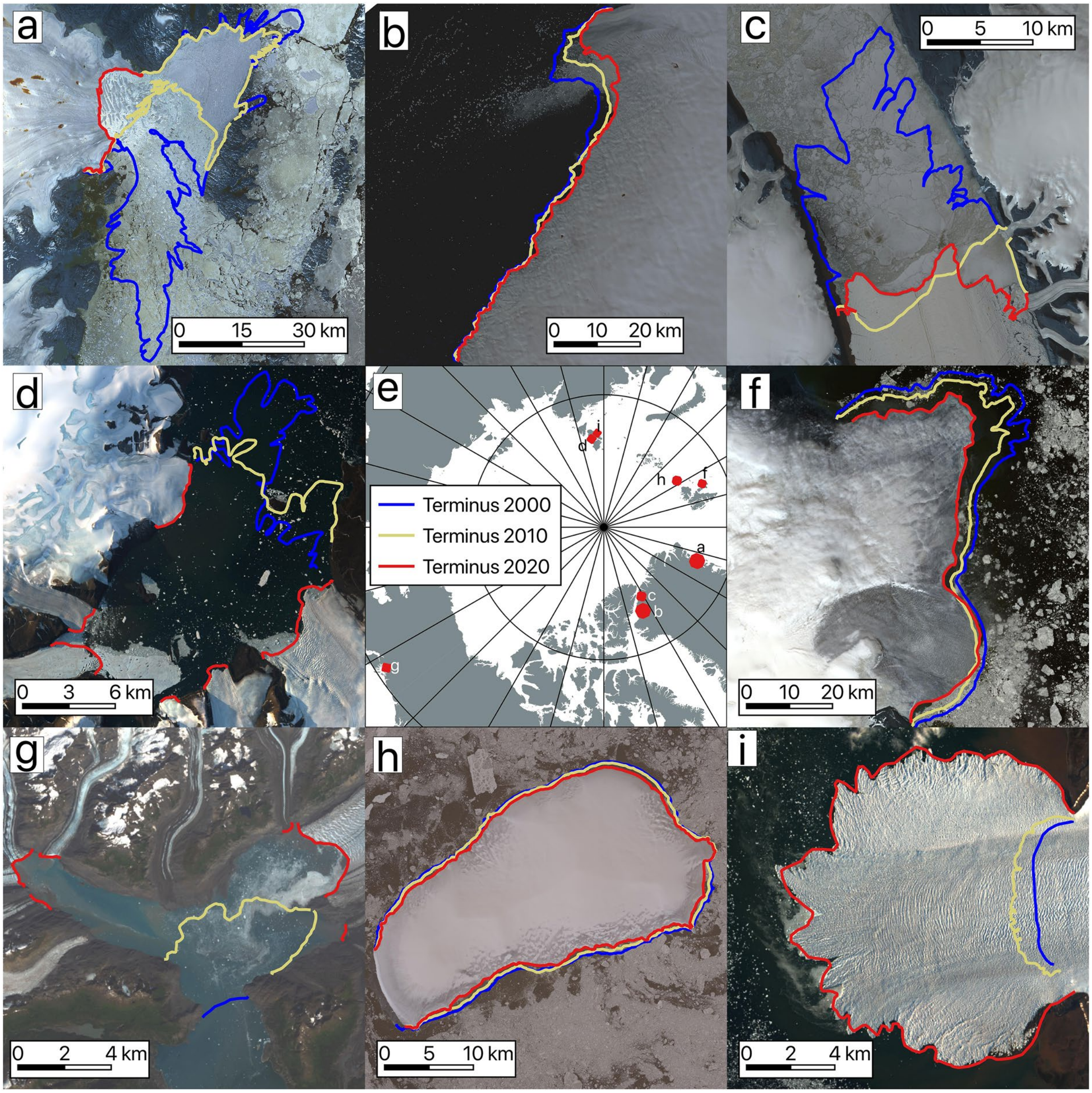

Figure 2. Examples of glaciers with major changes from 2000 to 2020: (a) Zachariae Isstrøm, loss after ice shelf collapse (base image: Landsat 8, 24 August 2019); (b) Humboldt, loss due to unstable basal geometry (Landsat 8, 17 August 2020); (c) Petermann, loss after ice tongue collapse (Landsat 8, 8 July 2020); (d) Matusevich, loss after ice shelf collapse (Landsat 8, 26 August 2019); (e) Location of glaciers shown in other subplots; (f) Stonebreen, loss after surging (Landsat 8, 2 August 2019); (g) Columbia, loss due to unstable basal geometry (Landsat 8, 8 August 2019); (h) Kvitøyjøkulen, loss due to wide calving margin (Landsat 8, 5 August 2019); (i) Vavilov Ice Cap, gain due to surging (Landsat 8, 26 August 2019).

total of 14.6 ± 1.0 km^2 (mean 0.70 ± 0.05 $km^2\ a^{-1}$); the other five glaciers were all at least an order of magnitude less.

The Greenland Ice Sheet experienced a 33.6% decrease in the rate of terminus area loss during the period 2010–2020 compared to 2000–2010 (Table 1). There were five glaciers (Petermann, Zachariae Isstrøm, Hagen Bræ, Ostenfeld Harder, Jakobshavn) that each had a reduction in rate of terminus area loss of more than 10 $km^2\ a^{-1}$ (combined total 82.7 $km^2\ a^{-1}$) during 2010–2020 compared to 2000–2010. Together, these account for 85.7% of the total observed reduction in rate of terminus area loss for the ice sheet between the measurement periods. Excluding these five glaciers, the Greenland Ice Sheet experienced a 10.2% reduction in the rate of terminus area loss during 2010–2020 compared to 2000–2010.

3.3. GIC Change

GICs of the Northern Hemisphere (i.e., those outside of the Greenland Ice Sheet, but including the periphery) lost an average of 148.2 ± 1.1 km^2 a^{-1} from 2000 to 2020 (cumulative total of 2753.6 ± 20.0 km^2; Table 1). The collapse of the Matusevich Ice Shelf (Figure 2d) in the Russian Arctic was the biggest contributor to this loss. In 2000, six glaciers coalesced on Severnaya Zemlya to form this ice shelf, but between 2010 and 2020 the ice shelf collapsed, and the glacier termini separated, resulting in a combined area loss of 157.7 ± 2.8 km^2 (8.3 ± 0.1 km^2 a^{-1}) from 2000 to 2020. The other major GIC terminus area losses from 2000 to 2020 occurred at a northwest outlet of Flade Isblink (Greenland; total 105.1 ± 2.8 km^2, mean 5.0 ± 0.1 km^2 a^{-1}), Stonebreen (Svalbard; total 77.3 ± 3.2 km^2, mean 4.5 ± 0.1 km^2 a^{-1}: Figure 2f), and Columbia Glacier (Alaska; total 49.2 ± 1.4 km^2, mean 2.9 ± 0.1 km^2 a^{-1}: Figure 2g).

Together, changes of 50 termini (out of 1,496 GICs) accounted for 50.1% of total GIC retreat from 2000 to 2020. The region with the most glaciers in this group of 50 was Russia (21 glaciers), followed by Arctic Canada North and Svalbard (11 each), Greenland periphery (6), and Alaska (1).

There were 36 GIC termini that advanced between 2000 and 2020 outside of our uncertainties (Figure 1). Three experienced large advances: Vavilov Ice Cap (Severnaya Zemlya; total 132.6 ± 1.7 km^2, mean 7.0 ± 0.1 km^2 a^{-1}: Figure 2i), Basin-3 of Austfonna (Svalbard; total 88.7 ± 2.4 km^2, mean 4.7 ± 0.1 km^2 a^{-1}), and Nathorstbreen (Svalbard; total 64.9 ± 1.6 km^2, mean 3.4 ± 0.1 km^2 a^{-1}). The fourth largest advance was more than an order of magnitude less than these.

The overall rate of GIC terminus area loss increased by 2.5% between 2000–2010 and 2010–2020 (Table 1). Alaska and the Russian Arctic saw the largest increase in area loss between the two decades, with losses in 2010–2020 being 83.3% and 39.0% higher, respectively, than in 2000–2010 (Table 1; Figure 1). Both Iceland and Asia North also experienced increased area loss between these periods, but there is only one marine terminating glacier in each of these regions and together they account for <0.001% of total losses. Greenland periphery experienced a 45.2% decrease in the rate of area loss between the two time periods, the most of any region. Arctic Canada South also lost less area from 2010–2020 compared to 2000–2010, with a reduction of 16.6%. Svalbard and Arctic Canada North both only had minor differences between the two decades.

4. Discussion

Our measured retreat of 85.3% of Northern Hemisphere marine-terminating glacier termini over the period 2000–2020, with a combined total area loss of 7527.3 ± 30.7 km^2, is consistent with the widespread loss in area and volume of glaciers reported worldwide (Hugonnet et al., 2021; IPCC, 2021). Our analysis of mean annual 2 m air temperatures on glacier termini show that temperatures rose, on average, 1.99°C between 2000–2010 and 2010–2020. The biggest temperature change occurred in Arctic Russia, where the increase was 3.73°C between the two periods. Mean annual ocean temperatures also increased between these decades, by 0.23°C at the surface and by 0.40°C at 300 m depth. Over the same period there was a 3.8% decline in annual sea ice concentration across all regions.

These patterns suggest that pan-Arctic climate and ocean warming over the past two decades is broadly responsible for the reported losses of glacier termini, as has also been reported elsewhere (IPCC, 2021; Zemp et al., 2015). However, it is also clear that there is high local variability in terminus change rates despite similar environmental changes. For example, in Alaska, Columbia Glacier (Figure 2g) retreated 49.2 ± 1.4 km^2 (2000–2020), while 24 km away Meares Glacier gained 0.13 ± 0.1 km^2 (2000–2020). In Arctic Canada North, Mittie Glacier changed the most, losing 34.9 ± 1.2 km^2 (2000–2020), while ~30 km to the east a glacier advanced 0.98 ± 0.2 km^2 (2000–2020). Zachariae Isstrøm lost 1452.7 ± 14.4 km^2 (2000–2020), more than any other glacier in the hemisphere (Figure 2a), while two glaciers ~140 km further north didn't change within uncertainty limits. Stonebreen (Figure 2f), which had the largest terminus area loss of 77.3 ± 3.2 km^2 (2000–2020) in Svalbard, is only 170 km to the south of Basin-3, which had the largest advance of 88.7 ± 2.4 km^2 (2000–2020) in the archipelago. In Russia, the collapse of the Matusevich Ice Shelf (Figure 2d) resulted in the biggest terminus area loss of 157.7 ± 2.8 km^2 (2000–2020), but two glaciers located further within the same fjord, but not connected to the ice shelf, did not change within uncertainty limits.

From this analysis it is evident that changes in climate and ocean conditions alone cannot explain the wide spatial variability in measured terminus change patterns for marine-terminating glaciers, similar to the findings of Carr et al. (2017). Glaciers are retreating at different rates due to unique local circumstances, with each glacier having different thresholds for, and sensitivity to, change at which point they respond to environmental and other forcings in different ways. To further investigate this, we examined the characteristics of glaciers that cumulatively accounted for >50% of measured terminus area losses for the Greenland Ice Sheet (six glaciers), and for GICs (50 glaciers), with reference to previously published literature where possible (Data Set S2). There are four main characteristics of these glaciers that stand out as explanatory causes for their measured changes:

4.1. Ice Shelf and Ice Tongue Collapse

Most of the biggest terminus losses from both GICs and the Greenland Ice Sheet were at least partially due to ice shelf or tongue collapse. When an ice shelf or tongue collapses it is typically lost over a short period, ranging from a few hours to a couple of years (Copland et al., 2007; White & Copland, 2019), as opposed to other glaciers that often retreat more consistently through time. For example, on the Greenland Ice Sheet five of the six outlets responsible for 53.3% of the 2000–2020 reduction in ice sheet terminus area lost part or all of their ice shelves or tongues (Data set S2). Zachariae Isstrøm lost almost its entire ice shelf (Mouginot et al., 2015), although part of it remains but is no longer attached to the glacier (Figure 2a). Petermann (Münchow et al., 2014, Figure 2c), Nioghalvfjerdsbrae (Mayer et al., 2018), and Ostenfeld Brikkerne Harder (Hill et al., 2017) glaciers all lost ice tongues during large calving events.

Of the 50 marine-terminating glaciers that comprise 50.1% of Northern Hemisphere GIC losses, there are 17 glaciers that lost an ice shelf or tongue (Data Set S2). The largest of these losses was the Matusevich Ice Shelf, which broke apart in 2012 (Willis et al., 2015). Flade Isblink, in NE Greenland, has several outlets, three of which lost ice tongues (Bendtsen et al., 2017). Several unnamed glaciers in northern Greenland also lost ice shelves. Arctic Canada North lost large parts of the Serson and Petersen ice shelves, and the Marine and Yelverton ice tongues (White & Copland, 2019). Overall, these patterns highlight the strong sensitivity of ice shelves and ice tongues to changes in external forcing (Copland & Mueller, 2017), and the precarious existence of the few remaining such ice masses in the northern hemisphere.

4.2. Surging

None of the Greenland Ice Sheet outlet glaciers that lost the largest terminus area are surge-type. However, out of the 50 glaciers with the largest GIC terminus losses, 10 are surge-type and another five are possibly surge-type, despite <1% of global glaciers being surge-type (Sevestre & Benn, 2015). Of these glaciers, eight are in Svalbard, six are in the Russian Arctic, and one is in Arctic Canada North (Data Set S2). The largest losses from surge-type glaciers occurred at Stonebreen (Strozzi et al., 2017, Figure 2f), and Braasvellbreen (Moholdt et al., 2010), which retreated 3–5 $km^2\ a^{-1}$ between 2000 and 2020. Stonebreen is the largest outlet from the largest ice cap on Edgøya Island, Svalbard (26 km calving front), although the northern and southern parts of the calving front have different dynamic controls (Strozzi et al., 2017). The northern portion of the glacier (which accounts for nearly all the retreat since 2000) surged between 1936 and 1971, while the southern portion displayed increased velocity and thinning in 2012 followed by a small advance (Strozzi et al., 2017).

Only 42 (of 1,704) glaciers had a net advance between 2000 and 2020. Out of the 42 advances, at least 23 occurred on surge-type glaciers (Sevestre & Benn, 2015), accounting for 91.9% of the total measured increase in area. The three biggest advances were due to surge events at Vavilov Ice Cap, Russia (Willis et al., 2018, Figure 2i; $132.7 \pm 1.7\ km^2$ for 2000–2020), Basin-3, Svalbard (Dunse et al., 2015; $88.7 \pm 2.4\ km^2$ for 2000–2020), and Nathorstbreen Glacier system, Svalbard (Sund et al., 2014; $64.9 \pm 1.6\ km^2$ for 2000–2020). Because few ice shelves or ice tongues still exist in the Northern Hemisphere today (Copland & Mueller, 2017), and surge-type glaciers are relatively common in the Arctic (Sevestre & Benn, 2015), surge-type glaciers are likely to be even more important in future terminus changes.

4.3. Unstable Basal Geometry

Tidewater glaciers can become unstable when resistive stresses are reduced more than driving stresses, such as when a glacier reaches flotation after retreating from a basal pinning point, which can lead to rapid terminus retreat and collapse (Pfeffer, 2007). At least two glaciers on our list retreated primarily due to their basal geometries. Flowing from the Greenland Ice Sheet, Humboldt Glacier has accelerated its retreat since 1999 along a large basal trough in the northern portion of the terminus (Carr et al., 2015). This glacier was the second largest contributor to area change in the Northern Hemisphere since 2000, and has the widest terminus in the hemisphere (90 km), amplifying the impact of even small length changes.

Columbia Glacier is the only GIC that is known to have experienced retreat driven by basal geometry (O'Neel et al., 2005), out of the 50 glaciers that make up 50.1% of GIC terminus area loss. Columbia Glacier lost an average of 2.9 ± 0.1 $km^2\ a^{-1}$ from 2000 to 2020 due to continued long term retreat into deeper water that resulted in higher velocities and calving rates (O'Neel et al., 2005). It is possible that other glaciers have also experienced retreat due to their basal geometries, but the lack of comprehensive ice thickness and bathymetric information close to glacier termini makes this difficult to quantify. We are therefore likely undercounting the importance of unstable basal geometry in causing rapid terminus retreat, and future work should focus on measuring the basal topography of tidewater glaciers to better understand this phenomena.

4.4. Unusually Wide Calving Margins

For GICs, the above explanations account for 33 of the 50 glaciers with the largest area losses. Of the remaining 17 glaciers, four of these are large ice caps. Kvitøyjøkulen is one of these with an area of 600 km^2 in the Barents Sea (Figure 2h), which is undivided and therefore has a calving margin width of 85.4 km, the widest of any GIC. Similarly, there are three ice caps in Franz Josef Land that are not subdivided and have calving widths between 38 and 55 km, which puts them in the 99th percentile of all calving front widths. Ten additional glaciers have a calving front width between 15 and 44 km, which is in the 97th percentile. The remaining three GICs (2 in Arctic Canada North, one in the Russian Arctic) have calving front widths between 6 and 10 km, within the 88th percentile. Ice masses with wide calving margins are likely particularly sensitive to oceanographic changes, while also producing large area losses for relatively short length changes. Although subdivision of large ice caps into smaller basins would reduce the area lost per basin, this connection to calving margin width also highlights the potential influence of oceanographic factors.

5. Conclusions

Our study provides the first complete count of the number of marine-terminating glaciers in the Northern Hemisphere, with a total of 1,704 in 2000 and 1,581 in 2020. There has been widespread loss of their termini, with 85.3% of glaciers retreating from 2000 to 2020 and only 2.5% advancing. However, there have been wide variations in the rate of terminus retreat within fjords, regions, and across the hemisphere. While climate and ocean warming, and associated negative mass balance, has been a dominant factor in global glacier retreat (IPCC, 2021), the high spatial variability in marine-terminating glacier retreat rates is primarily dependent on their local characteristics. Glaciers that terminated in ice shelves or ice tongues retreated the fastest. Surge-type glaciers, glaciers with unstable basal geometries, and those with wide calving margins (e.g., ice caps) showed the next biggest changes. These unique factors to each glacier are more important in determining glacier sensitivity and thresholds to climate change than environmental factors alone.

Greenland, including the ice sheet and periphery glaciers, accounted for 69.6% of total hemispheric marine terminating glacier terminus area loss. Only six outlets of the Greenland Ice Sheet and 50 GICs account for more than 50% of the total terminus area loss in each group. This small number of glaciers has had an outsized impact on the rate of terminus loss in the hemisphere. Monitoring glaciers that have already undergone large changes is important as ice dynamics are tied to terminus retreat, as recent examples from Greenland show (King et al., 2020). We have identified specific glacier characteristics that are conducive to retreat and suggest that future study of similar glaciers is important in predicting the response of ice masses to climate change and their contribution to future sea level rise.

The only remaining ice shelves in the Arctic today are found off the north coast of Arctic Canada North, northern Greenland, and Franz Josef Land (Copland & Mueller, 2017). Given the large losses from ice shelves and ice tongues over the last two decades, these locations may also dominate glacier terminus losses in the coming decades, although exhaustion of supply will be a factor once all ice shelves and ice tongues are lost. Because surge-type glaciers have displayed large retreats in recent decades, and given that surge-type marine-terminating glaciers are common across Arctic Canada North, Greenland, Svalbard, Alaska, and the Russian Arctic (Sevestre & Benn, 2015), these are key places to monitor for large retreats and advances in the future.

Data Availability Statement

All the source data used in this study can be freely downloaded from public repositories. We used Landsat 5, 7, and 8 (https://earthexplorer.usgs.gov), ASTER (https://search.earthdata.nasa.gov/), and Radarsat-1 and ALOS PALSAR SAR (https://asf.alaska.edu) imagery. Environmental data can be downloaded from: ECMWF ORAS5 ocean temperatures (https://www.cen.uni-hamburg.de/en/icdc/data/ocean/easy-init-ocean/ecmwf-oras5.html), ERA5 2 m air temperature (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview), and sea ice concentrations (https://nsidc.org/data/G02202/versions/3). Retreat rates for each glacier are available in Data Set S1. Polygons showing terminus area gained/lost polygons are available in the Polar Data Catalogue (www.polardata.ca/pdcsearch/PDCSearchDOI.jsp?doi_id=13257). All data analysis conducted for this project was undertaken using freely available software in QGIS or Python.

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