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Helheim Glacier Poised for Dramatic Retreat

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Key Points:

- Helheim Glacier is more retreated and the near-terminus region is up to 100 m thinner than during its much-reported dramatic retreat in 2005
- Helheim, one of Greenland's largest ice dischargers, is now more vulnerable than at any point since the Little Ice Age
- Helheim's new configuration offers potential for sustained dynamic instability and a major contribution to global sea-level rise

Supporting Information:

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

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Abstract

Helheim Glacier, one of the largest marine-terminating outlet glaciers draining the Greenland Ice Sheet, underwent significant retreat and acceleration in the early 2000s, accounting for an appreciable proportion of the ice sheet's mass loss during that period. Using a range of remotely sensed datasets, we show that despite a subsequent readvance, the glacier has continued to lose mass and thin, and has retreated inland of the retracted position occupied in 2005. Critically, the near-terminus is up to 100 m thinner than during 2005, and the front 5 km is within 25–50 m of flotation, with retrograde bed slopes extending several kilometers inland of the terminus. The neighboring Fenris and Midgard Glaciers have both undergone recent large-scale and rapid retreat once their near-terminus regions began to float, suggesting that under projected climate warming and associated glacier thinning, Helheim Glacier is poised to pass a threshold whereby the near-terminus region will retreat rapidly.

Plain Language Summary

A significant proportion of the Greenland Ice Sheet's contribution to global sea-level rise is as a result of mass loss from its marine-terminating glaciers. Helheim Glacier, located in southeast Greenland, is one of the largest and fastest-flowing glaciers draining the Greenland Ice Sheet. During the early 2000s, Helheim Glacier underwent dramatic retreat and acceleration, but subsequently readvanced during relatively cooler conditions in 2006. However, persistently high ocean and atmospheric temperatures have meant that Helheim Glacier has in fact been continuously losing mass since 2003, despite this readvance. Here, we use a range of remotely sensed data to show that since 2014, Helheim Glacier has accelerated and retreated to a greater extent than occurred in 2003–2005. More importantly, as the glacier has been losing mass over the past two decades, it is currently much thinner than during its peak retreat in 2005. As the glacier continues to lose mass, it will pass a threshold whereby the ice will float and rapidly disintegrate. We observe that this process has already occurred at the glaciers neighboring Helheim Glacier, which are subject to the same climate forcing and thus provide an analogue for the future response of Helheim Glacier to continued warming.

1. Introduction

The Greenland Ice Sheet (GrIS) is a major contributor to global sea-level rise (Bamber et al., 2018; van den Broeke et al., 2016). Approximately 50% of Greenland's mass loss is due to increasing ice loss from its marine-terminating outlet glaciers (The IMBIE Team, 2020). This is particularly prominent in the southeast where ice discharge increased from an average of 136 ± 6 Gt yr^{-1} during 1972–1980 to an average of 160 ± 2 Gt yr^{-1} during 2010–2018 (Mouginot et al., 2019), totaling ~25% of the ice-sheet-wide mass loss due to ice discharge since 1990. Located at the head of Sermilik Fjord, Helheim Glacier (66.4°N, 38°W) is one of the largest and fastest-flowing glaciers in Greenland, contributing 6–7% of the total ice discharge from the GrIS (Mankoff et al., 2020).

After several decades of stability (Bevan et al., 2012; Bjørk et al., 2012; Miles et al., 2016), Helheim Glacier underwent dramatic retreat, near-front acceleration and dynamic thinning between 2003 and 2005 (Howat et al., 2005, 2008; Luckman et al., 2006; Stearns & Hamilton, 2007), thought to be driven by increased oceanic and/or atmospheric temperatures (Andresen et al., 2012; Cowton et al., 2018; Joughin et al., 2008; Straneo et al., 2011), followed by stabilization and readvance from 2006 (Bevan et al., 2012; Howat et al., 2011; Kehrl et al., 2017; Miles et al., 2016). Recent estimates, however, show a large increase in Helheim's ice discharge from ~2014 to 2019, such that it is now at least the second-largest discharging Greenlandic glacier (Mankoff et al., 2020) and one of the sectors of the GrIS losing mass the fastest (Mouginot et al., 2019). It remains unclear, however, how the dynamics of Helheim Glacier have changed during this recent period of enhanced ice discharge, as well as what this recent change means for its' future evolution.

Here, we combine satellite-derived measurements of ice velocity, terminus position and surface elevation alongside estimates of bed topography and mass balance to examine recent dynamical change at Helheim Glacier. The same analyses are undertaken for the neighboring Fenris and Midgard Glaciers in order to contextualize the observed change at Helheim Glacier and provide analogs for its future evolution.

2. Data and Methods

To determine near-terminus ice velocity, we use the MEaSUREs Selected Glacier Site Velocity from Optical Images V3 (Howat, 2020) for the period 2014–2019 and extract velocities from an area of interest near the terminus of each glacier. As the velocity data coverage near the front of Midgard South is poor, we are unable to plot a velocity time series for this site.

Terminus positions were digitized from all available Landsat 8 and Sentinel-2 satellite imagery from 2014 to 2020 using the Google Earth Digitization Tool (GEEDiT) (Lea, 2018). Annual terminus positions were mapped for the period 2000–2020 using Landsat 7, Landsat 8, and Sentinel-2 imagery, using images as close to August 31 as possible. We estimate an RMSE of ±4.8 and ±3.1 m for Landsat-8 and Sentinel-2 imagery, respectively, both of which are less than the respective pixel sizes (see Supporting Information S1). Changes in terminus position were assessed using the curvilinear box method along a glacier centerline using MaQiT (Lea, 2018).

To assess surface elevation change, we use 50-m resolution DEMs for the period 2016–2019 from the Oceans Melting Greenland (OMG) L3 GLISTIN-A product (OMG Mission, 2020). To evaluate decadal change in surface elevation at each glacier, we sample the 2016–2019 OMG elevation data along a Pre-IceBridge Airborne Topographic Mapper (ATM) flightline over the near-terminus region (Thomas & Studinger, 2010). The sampled OMG elevation data are then compared to the Pre-IceBridge ATM L2 Icessn elevation data collected along the same flightline, with these flights flown on 19 May 2005 at Helheim Glacier, 11 May 2007 at Fenris Glacier and Midgard South Glacier, and 31 July 2008 at Midgard North Glacier.

We also generate surface elevation change across the wider glacier catchments (see Figures S6–S8 in Supporting Information S1) between 2010 and 2020 using CryoSat-2 radar altimetry. CryoSat-2 time-dependent surface elevations are processed following Gourmelen et al. (2018). Monthly time series of height change for each of the three glaciers are then generated following the approach described in Malczyk et al. (2020), with uncertainty obtained from the standard deviation (calculated as 1.48 * median absolute deviation) of multiple realizations of the time series (Malczyk et al., 2020). The pixels across which these elevation measurements were collected are displayed in the Supporting Information S1. For each glacier, we also include mass balance data from Mouginot et al. (2019, their Data Set S2).

For each of the surface elevation data profiles, we extract bed topography and ice thickness from BedMachineV3 (Morlighem et al., 2017). We calculate the flotation elevation at each point along the profile as follows:

$$h_f = H * \left(1 - \frac{\rho_{ice}}{\rho_{ocean}}\right)$$

where H is the ice thickness, ρ_{ice} is the density of ice (917 kg m^{-3}) and ρ_{ocean} is the density of seawater (1,025 kg m^{-3}).

Relative changes in submarine melt rate are estimated following Slater et al. (2019) by assuming submarine melt rates scale as $Q^{0.4}$TF, in which Q is subglacial discharge and TF is ocean thermal forcing. Subglacial discharge is estimated by summing surface runoff volumes from RACMO2.3p2 (Noël et al., 2018) over the hydrological catchment for the glacier in question. Ocean thermal forcing is estimated by extrapolating ocean properties on the continental shelf (from EN4; Good et al., 2013) into the fjord. Melt rates are calculated monthly and then averaged over each year.

We direct the reader to the Supporting Information S1 should they require a more detailed explanation of any of the methods described herein.

3. Results

3.1. Helheim Glacier

Helheim Glacier has been characterized by a persistently negative mass balance ranging between −5.0 and −13.2 Gt yr^{-1} since 2003/04 (Figure 1c, Mouginot et al., 2019) and a long-term negative trend in glacier-wide surface elevation initiated in the mid-2000s (The IMBIE Team, 2020) and averaging ∼10 m of thinning between late 2010 and early 2020 (Figure 1c). Within 5 km of the terminus, we observe surface thinning of >50 m between 2016 and 2019, and a strong reduction in surface slope reaching to near-horizontal by 2018 and 2019 (Figure 1d). The 2019 surface in the near-terminus region is up to 100 m thinner than during 2005 and is only 25–50 m above flotation. While the bed topography in the center of the glacier is largely flat with a 100 m elevation gain between 2 and 4 km inland, the northern and southern sectors are underlain by retrograde slopes, extending 1–2 and 3–4 km inland of the 2019 terminus respectively (Figures 1a and 1e).

During 2014–2020, we observe a near-terminus acceleration of 2.5–3 km yr^{-1} and concomitant terminus retreat of 4 km from summer 2014 to summer 2019, with retreat beyond the 2005 extent in 2017 and 2019 (Figure 1f). The observed pattern of retreat and acceleration shows some seasonality, with large readvances (2–3 km) during the winters of 2015/16 and 2017/18, limited readvance (∼1 km) during the winters of 2016/17, 2018/19, and 2019/20, and no readvance during the winter of 2014/15.

3.2. Fenris Glacier

Fenris Glacier has had a negative mass balance since 2003/04, ranging from −0.6 to −2.0 Gt yr^{-1} (Figure 2c, Mouginot et al., 2019), and an average surface thinning of 15 m across the wider glacier area (Figure S7 in Supporting Information S1) between late 2010 and mid-2020 (Figure 2c). The near-terminus region thinned by >50 m between 2007 and 2016, with the terminal 1 km of the glacier floating in early 2016 and early 2017 (Figure 2d). Thinning continued through 2018 such that by early 2019, the front ∼2.5 km of the glacier was floating. This is supported by the presence of large tabular icebergs within the proglacial fjord that have not overturned (see Figure S10 in Supporting Information S1). Fenris Glacier is underlain by a steep retrograde bed slope characterized by an ∼300–400 m decrease in bed elevation over a 6 km distance inland of the 2007 terminus (Figures 2a and 2e), and the surface elevation data (Figure 2d) indicates that by 2019, the grounding line had retreated down this slope to a region of stable topography.

Fenris Glacier was characterized by relatively stable ice velocity during the period 2014–2017 before an initial acceleration of ∼1 km yr^{-1} near the front from early 2017 to 2018, coincident with the absence of a 2016/17 winter readvance of the terminus (Figure 2f). This preceded a rapid acceleration to 4.5 km yr^{-1} and terminus retreat of 3 km beginning in early 2019.

3.3. Midgard Glacier

Midgard Glacier has been characterized by a persistently negative mass balance between 2000 and 2018 (Figure 3c) with a minimum of −5.1 Gt yr^{-1} in 2012. The surface of Midgard Glacier has thinned by an average of >10 m across the wider glacier area during the period 2010–2020 (Figure 3c).

Midgard North Glacier thinned by 100–300 m and retreated by >6 km between 2008 and 2016, and the glacier has been grounded on a steep prograde slope since at least 2016 (Figure 3e). We observe a subsequent thinning of 20 m between 2016 and 2017, after which the surface elevation has remained stable (Figure 3d). During the period 2014–2020, Midgard North Glacier has been characterized by terminus stability, with seasonal advance of ∼1 km in winter and retreat back to its stable position in summer (Figure 3f). The near-terminus ice velocity underwent a gradual slow-down during this period from ∼3.5 km yr^{-1} in early 2014 to ∼2.2 km yr^{-1} in late 2019.

In contrast to the other glaciers studied, Midgard South Glacier underwent gradual thinning of its surface alongside a consistent terminus retreat from 2014 to 2020. The terminus retreat totaled ∼1.5 km and exhibited only limited evidence of seasonality (Figures 3d and 3f), indicating that the glacier may have become essentially land-terminating.

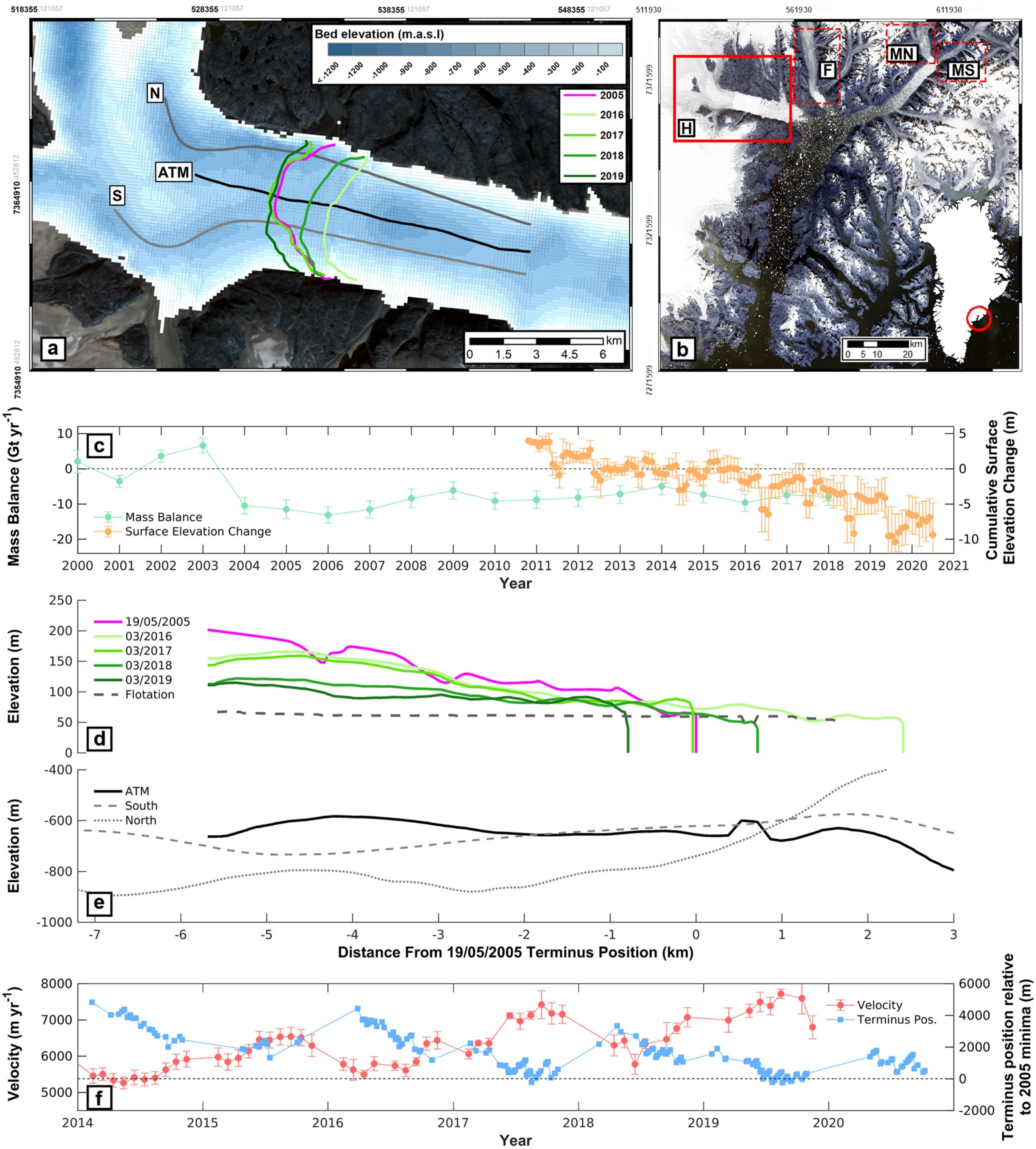

Figure 1. (a) Helheim Glacier bed topography overlain with summer minimum terminus positions for the indicated years. The Airborne Topographic Mapper (ATM) profile follows a Pre-IceBridge flightline, and the northern (N) and southern (S) profiles were drawn manually to illustrate the bed topography in these regions of the glacier. (b) Map of Sermilik Fjord with red rectangles showing the locations of Helheim Glacier (H), Fenris Glacier (F), Midgard North Glacier (MN), and Midgard South Glacier (MS). (c) Glacier total mass balance (green, Gt yr^{-1}) and cumulative surface elevation change (orange, m) from CryoSat-2 altimetry (averaged across the wider glacier area [Figure S6 in Supporting Information S1]) with associated uncertainty. (d) Surface elevation along the ATM profile. The dashed line represents the surface elevation at which the ice will float. (e) Bed topography along the profiles displayed in (a). (f) Near-terminus ice velocity (red) with associated uncertainty and terminus position (blue), plotted relative to the 2005 minima.

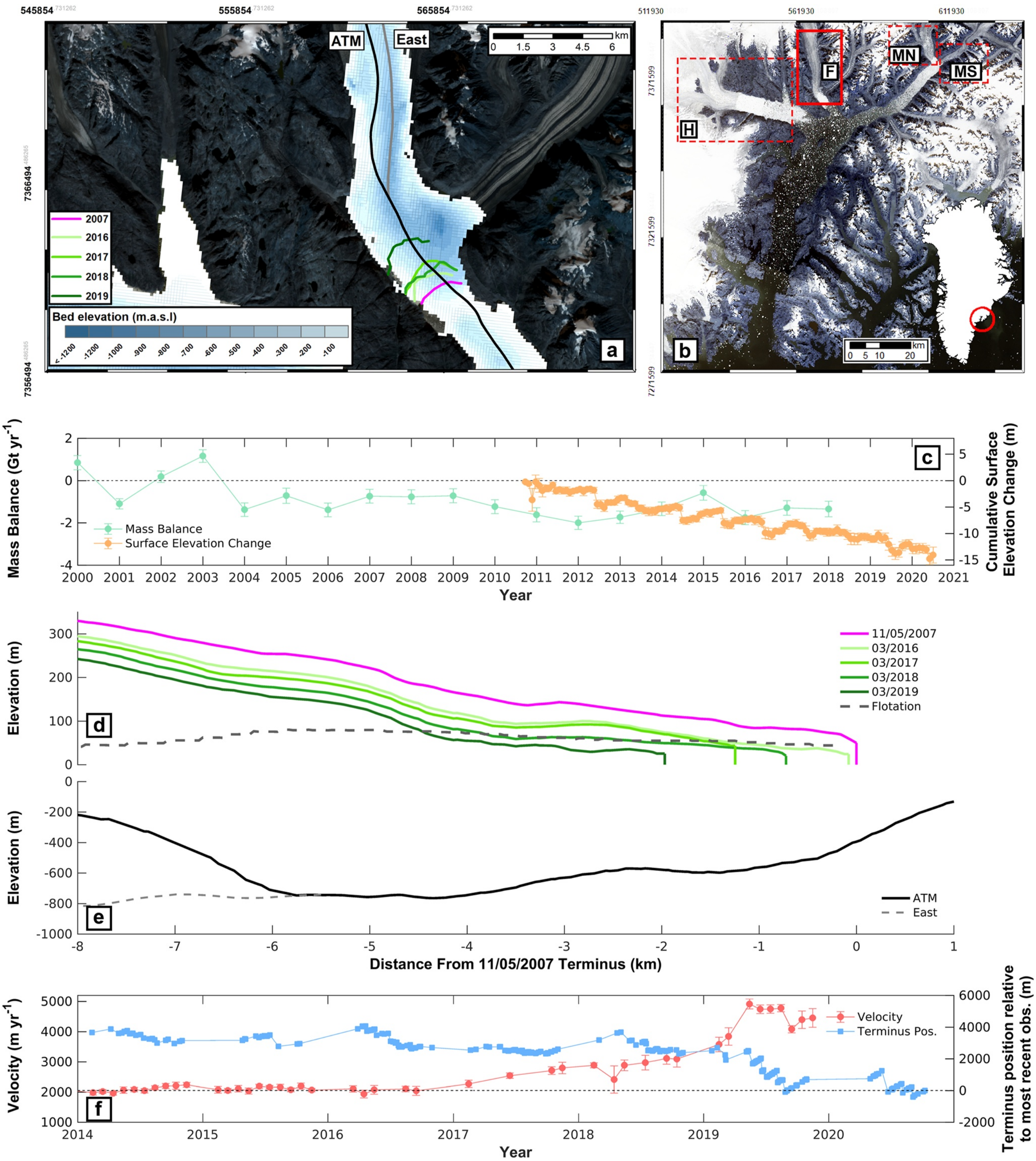

Figure 2. Equivalent to Figure 1 for Fenris Glacier. The ATM elevation data and associated summer minimum terminus position are from 2007, and an eastern (East) profile was drawn manually to illustrate the bed topography in this region of the glacier. Terminus positions in (f) are plotted relative to the most recent observation.

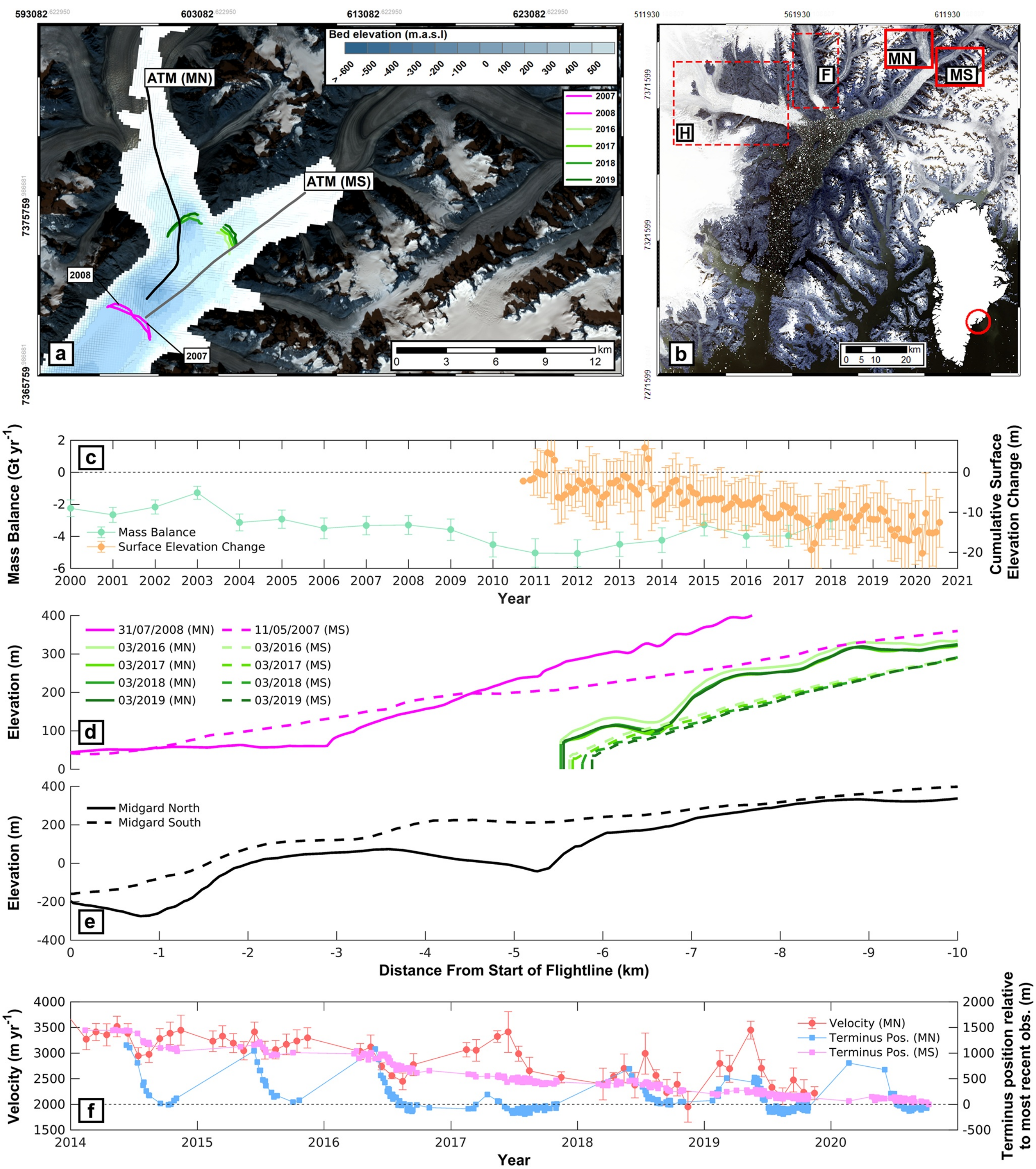

Figure 3. Equivalent to Figure 1 for Midgard North Glacier and Midgard South Glacier. The Airborne Topographic Mapper (ATM) elevation data and associated summer minimum terminus position are from 2007 for Midgard South, and 2008 for Midgard North. Terminus positions in (f) are plotted relative to the most recent observation.

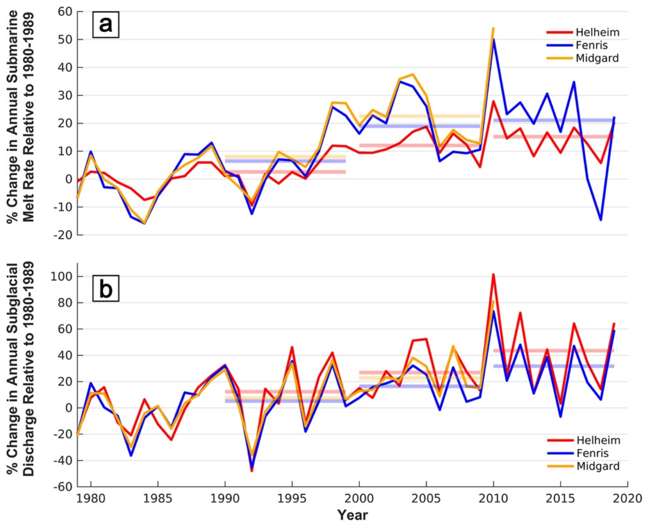

Figure 4. (a) Change in annual mean submarine melt rate (% relative to 1980–1989) and (b) annual mean subglacial runoff (% relative to 1980–1989) at the termini of Helheim, Fenris, and Midgard Glaciers for the period 1979–2019. Data for Midgard Glacier stops in 2010 when the glacier split into two distinct branches. The horizontal lines represent 10-year means.

3.4. Ocean and Atmospheric Forcing

Submarine melt rates and subglacial runoff (Figures 4a and 4b) exhibit considerable interannual variability with a multidecadal increase at all three glaciers. At Helheim Glacier, the annual mean submarine melt rate during 2010–2019 was 15% greater than during 1980–1989. Between 2010 and 2019, submarine melt rates have been at least as great as, if not greater than, those during the mid-2000s period of retreat, acceleration, and thinning. We also estimate consistent increases in submarine melt rates at Fenris and Midgard glaciers, with an increase of 21% between the 1980–1989 and 2010–2019 means at Fenris Glacier and an increase of 23% between the 1980–1989 and 2000–2009 means at Midgard Glacier. Annual mean subglacial runoff increased by 43% and 32% between 1980–1989 and 2010–2019 at Helheim Glacier and Fenris Glacier, respectively, and increased by 23% between 1980–1989 and 2000–2009 at Midgard Glacier.

4. Discussion

The three glaciers have continuously lost mass between 2003 and 2018, with 2003 characterized by a large, quasi-synchronous increase in mass loss at all three sites (Figures 1c, 2c, and 3c; Mouginot et al., 2019), suggesting a sensitivity to a regional environmental forcing, driven by warming of the atmosphere and/or ocean (Howat et al., 2008; Luckman et al., 2006; Moon & Joughin, 2008; Seale et al., 2011). While it has proven difficult to disentangle the relative importance of particular oceanic and atmospheric processes in driving terminus retreat (i.e., Bevan et al., 2012; Moon et al., 2015; Murray et al., 2015), significant relationships have been found between oceanic and atmospheric warming and southeast Greenland tidewater glacier retreat over multiple decades (Cowton et al., 2018). We observe a step increase in both mean modeled submarine melt rates and subglacial discharge rates at all three sites between the periods 1990–1999 and 2000–2010 (Figure 4), which remained elevated during 2010–2019, driving the persistently negative mass balance observed at all three glaciers (Mouginot et al., 2019).

Helheim Glacier last underwent a period of sustained retreat between 2003 and 2005, during which the front retreated by >7 km, and the near-terminus region accelerated by 5 km yr^{-1} (Howat et al., 2005, 2008), an almost doubling of its flow velocity, and dynamically thinned by 100 m (Stearns & Hamilton, 2007). While Helheim Glacier slowed and underwent some readvance between 2006 and 2014 (Bevan et al., 2012; Howat et al., 2011; Kehrl et al., 2017; Miles et al., 2016), during the past 6 years we observe an acceleration (2.5–3 km yr^{-1}) and retreat (3–4 km) similar in magnitude to those of the early 2000s. This is supported by recent measurements of an ~10 Gt yr^{-1} increase in ice discharge from Helheim Glacier between 2014 and 2019 (Mankoff et al., 2020). The total retreat measured is less than that in 2003–2005; however, this is because the glacier did not readvance to its pre-2003 extent between 2006 and 2014, and we observe retreat further inland than its 2005 minimum extent during the summers of 2017 and 2019 (Figure 1f). Moreover, the near-terminus region is up to 100 m thinner than during 2005 and much closer to flotation, indicating that the glacier is currently in a more unstable configuration than during its peak retreat in 2005. While the bed topography data from BedMachineV3 (and thus the calculated flotation elevation) is subject to various uncertainties (see Text S4, Figures S11–S13 in Supporting Information S1), we argue that Helheim Glacier must be at or close to flotation due to the regular calving of tabular icebergs that do not rotate (e.g., Figure S9 in Supporting Information S1). Furthermore, the key observation is that Helheim Glacier has thinned by up to 100 m between 2005 and 2019, and is therefore moving closer to flotation, irrespective of how well-constrained the flotation elevation is. These results challenge the contemporary understanding of Helheim Glacier as relatively stable, having recovered from similar retreats in the 1930s and 2005. Here, we show that Helheim Glacier is now much thinner and thus more vulnerable to continued oceanic and atmospheric warming, due to its continued thinning and mass loss since 2005.

The broad trends in behavior at Helheim Glacier are also observed at the neighboring Fenris and Midgard Glaciers. Fenris Glacier slowly retreated by <3 km between 1972 and 2011 (Mernild et al., 2012), and exhibited little dynamic change during the 2000s, with a decadal area change of −0.3 km^2 a^{-1} (Box & Decker, 2011) and maximum retreat of −1.6 km (Walsh et al., 2012) during 2000–2010. Between 2000 and 2018, the glacier gradually retreated by 2 km (Figures S1 and S2 in Supporting Information S1), before the ice front thinned to flotation in early 2018, leading to a rapid retreat of 3–4 km (Figure 2e) that is unprecedented in at least the last 50 years. Midgard Glacier retreated by 5–6 km between 1972 and 1999 (Mernild et al., 2012), before undergoing a major retreat of nearly 10 km during the mid-2000s (Box & Decker, 2011; Walsh et al., 2012; Figures S1 and S2 in Supporting Information S1), likely a result of thinning to flotation. This is supported by the very low surface elevations (<50 m a.s.l.) extending down-fjord during 2007 and 2008 (Figure 3d). While the precise timing and magnitude of retreat differ between the glaciers studied, the fundamental mechanism, thinning to flotation as a result of a persistent negative mass balance, is the same. As such, the changes observed at Fenris and Midgard Glaciers support our suggestion that Helheim Glacier is poised for dramatic retreat.

The precise timing of acceleration and retreat in response to the long-term climate forcing differs between the glaciers studied, likely reflecting the different morphological settings and characteristics of the three glaciers (Catania et al., 2018). Glaciers overlying deeper bed topography and/or with wider trunks are likely to be closer to flotation such that less thinning is required to initiate a rapid, unstable retreat following a given perturbation (Enderlin et al., 2013). This influence of glacier geometry contributes to the likely instability of Helheim Glacier, as it is characterized by a wide glacier trunk (~6 km), where the northern and southern sections of the glacier are underlain by retrograde bed slopes (Figures 1a and 1e). With continued mass loss, thinning, and retreat down these reverse slopes, the near-terminus region of Helheim Glacier will move rapidly toward flotation and thus rapid retreat beyond what has previously been observed.

During the 1930s, warmer air temperatures (Box et al., 2009) were coincident with retreat at Helheim Glacier (Bjørk et al., 2012; Khan et al., 2014, 2020) with the terminus reaching approximately the same glacier extent as 2011/12. However, following this retreat during the 1930s, Helheim Glacier gained mass and readvanced such that during the period 1900–1983, it was in near-balance (Khan et al., 2014, 2020; Kjeldsen et al., 2015) and recent data shows that between 1972 and 2003, it was characterized by an almost consistently positive mass balance (Mouginot et al., 2019). Consequently, between 1875 and 2012, Helheim Glacier lost only 31 ± 21 Gt of mass (Khan et al., 2020), orders of magnitude less than the mass loss from Jakosbhavn Isbrae (1,518 ± 189 Gt) and Kangerlussuaq (1,381 ± 178 Gt).

In contrast to the post-1930s readvance, Helheim Glacier's mass balance has remained negative since 2003 (Mouginot et al., 2019), such that the glacier has continued to thin and lose mass despite readvancing and decelerating. Therefore, we argue that while the glacier has readvanced following its last two periods of major retreat, it is currently in a far more precarious position than during either of these past retreats as a result of sustained thinning toward flotation over the past two decades. Moreover, not only is the near-terminus region much closer to flotation, but dynamic thinning (Csatho et al., 2014; McMillan et al., 2016; Pritchard et al., 2009) and a prolonged negative surface mass balance (Khan et al., 2014, 2020; Mouginot et al., 2019; Sørensen et al., 2018) mean that the ice inland is also much thinner (Figure 1c). The current surface topography thus points to a different future dynamic trajectory when compared with the 2005 retreat. Consequently, while Helheim Glacier has made only a small contribution to global sea-level rise during the period 1875–2012 (0.1 ± 0.1 mm, Khan et al., 2020), our results suggest that its new configuration offers the likelihood of imminent dynamic instability and thus the trajectory to join Kangerlussuaq and Jakobshavn Isbrae as a major contributor to global sea-level rise over the coming decades.

It is nevertheless possible that the fjord geometry may exert a stabilizing influence on the future evolution of Helheim Glacier. Within the central region of ice flow there is a bedrock high (Figure 1a) that may act as a pinning point should the glacier retreat this far inland. Similarly, strong lateral flow convergence from Helheim Glacier's three branches of ice flow may stabilize the terminus, even in regions with a reverse-sloping bed (Frank et al., 2021; Gudmundsson et al., 2012). However, both the bedrock high and the convergence of Helheim Glacier's flow branches are located >6 km inland of the 2019 terminus, and thus the glacier would already have retreated significantly should it reach this point.

Readvance has been observed at other major tidewater glaciers draining the GrIS following large-scale retreat. Jakobshavn Isbrae has readvanced since 2016/17 following an extended period of retreat (Joughin et al., 2020; Khazendar et al., 2019), and Kangerlussuaq readvanced from 2019 following a transient retreat (Bevan et al., 2019), with both of these readvances occurring up retrograde bed slopes. These events have both been linked to localized cooling of ocean waters and the associated presence of a rigid winter ice melange, facilitating greater winter advance (Bevan et al., 2019; Joughin et al., 2020). However, while Helheim Glacier may undergo some readvance should the local climate cool, analogous to that which occurred in 2006 (Bevan et al., 2012; Howat et al., 2011; Kehrl et al., 2017; Miles et al., 2016), unless local air and ocean temperatures cool to levels sufficient to facilitate mass gain for an extended period, this will only be a transient readvance as the glacier will continue to thin and lose mass. Air and ocean temperatures are projected to continue to rise, driving greater rates of surface (Hofer et al., 2020) and submarine melting (Slater et al., 2020). Under continued climate warming, we argue that a critical threshold will be reached at Helheim Glacier through thinning to flotation, which would drive a dramatic retreat analogous to those observed at Fenris and Midgard Glaciers. Such a retreat event is inferred to have occurred during the Holocene, beginning between 10.5 and 9.6 ka BP, after which Helheim Glacier remained retreated for most of the Holocene, despite cold events at 9.3 and 8.2 ka and during the early Neoglacial, until a readvance beginning at 0.3 ka BP (Bjørk et al., 2018). These observations support our suggestion that should Helheim Glacier continue to thin to flotation, a much larger retreat is possible than has been observed since the end of the Little Ice Age. Given that Helheim Glacier is one of the largest ice dischargers in Greenland (Mankoff et al., 2020), such a retreat and associated loss of mass would likely result in Helheim Glacier becoming a major sea-level rise contributor over the coming decades, and thus a glacier of global importance.

5. Conclusion

We have shown that Helheim Glacier has recently retreated and accelerated to an extent similar to that observed during its well-studied dynamic change in the early 2000s. Critically, however, the near-terminus region is up to 100 m thinner than during its previous maximum retreat in 2005, such that the terminus within ~5 km of the ice front is within up to 50 m of flotation. Thinning and retreat have been driven by a persistent negative mass balance since 2003 as a result of anomalously warm atmospheric and oceanic temperatures which have shown a sustained increase since 1980. Although temporary readvance is possible, with further oceanic and atmospheric warming we expect that Helheim Glacier will continue to thin and lose mass, eventually passing a threshold whereby the near-terminus region floats and rapidly accelerates and retreats. Such a retreat would be the most extensive within the observational record, exceeding that which occurred in the 1930s and the early 2000s. Moreover, Holocene records (Bjørk et al., 2018) indicate that after a similar retreat occurred beginning between 10.5 and 9.6 ka, Helheim Glacier remained retreated until 0.3 ka despite several cold events, suggesting that readvance would be difficult. As such, we argue Helheim Glacier is poised for a rapid retreat that may represent a tipping point into a new dynamic state.

Data Availability Statement

MEaSUREs selected glacier site velocity maps from optical images (https://nsidc.org/data/NSIDC-0646) and Pre-IceBridge ATM L2 Icessn elevation data (https://nsidc.org/data/BLATM2/versions/1) are freely available through the NSIDC. The Oceans Melting Greenland glacial elevations from GLISTIN-A are freely available through NASA (https://podaac.jpl.nasa.gov/dataset/OMG_L3_ICE_ELEV_GLISTINA). Links to GEEDiT and downloads for MaQiT are accessible via University of Liverpool Google Earth Engine Tools (www.liverpool-GEE.wordpress.com). Landsat imagery is freely available from the USGS (https://earthexplorer.usgs.gov/) and ESA (https://landsat-diss.eo.esa.int/oads/access/), and Sentinel-2 imagery and CryoSat-2 data are freely available from ESA and at https://cryo2ice.org/.

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