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Totten Ice Shelf history over the past century interpreted from satellite imagery

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Abstract: Totten Glacier is currently the largest source of mass loss in the East Antarctic Ice Sheet and it is projected to be a large source of sea-level rise over the coming century. The glacier has been losing mass for decades and inland thinning was detected in the earliest satellite-altimetry observations in the early 1990s, but when the glacier first started losing mass remains unknown. We calculate decadal ice-speed anomalies to confirm that Totten Glacier has not undergone sustained acceleration since at least 1973. Together with observations of grounding-line retreat from 1973-1989, we confirm that the glacier was already out of balance in the 1970s. Surface undulations form on the Totten Ice Shelf adjacent to an ice rumple near the grounding line in response to time-varying melt rates and are preserved downstream for several decades. From utilizing the full suite of Landsat imagery, we produce a century-long record of surface-undulation formation that we interpret as a qualitative record of basal-melt-rate variability. An anomalous ~20-year absence of undulations associated with the mid-20th century manifests a period when ice passing over the ice rumple was pervasively thinner, and may represent an anonymously warm period that triggered the onset of modern-day mass loss at Totten Glacier. Our results highlight that the currently available ~30-year satellite altimetry records are not long enough to capture the full scale of decadal variability in basal-melt rates and mass-loss patterns.

1. Introduction

Aurora Subglacial Basin (ASB), located in Wilkes Land, East Antarctica, is drained by five major outlet glaciers: Holmes, Moscow University, Totten, Vanderford and Denman glaciers (Fig. 1). Oceanographic observations have confirmed the presence of warm modified Circumpolar Deep Water (mCDW) on the continental shelf adjacent to each of these outlet glaciers (Ribeiro et al., 2021; Rintoul et al., 2016; Silvano et al., 2017; van Wijk et al., 2022). This is accompanied by ongoing grounding-line retreat (Brancato et al., 2020; Li et al., 2023b; Li et al., 2015; Picton et al., 2023), detachment of the ice shelf from pinning points (Miles and Bingham, 2024), and ice-front retreat (Baumhoer et al., 2021; Miles et al., 2016) identified from satellite observations. The rate of mass loss of ASB between 2003 and 2019 is estimated at -20 Gt yr^{-1} (Smith et al., 2020), meaning that mass loss from ASB has accounted for just under 2% of global sea-level rise over this period. Paleo-reconstructions from a variety of geological evidence show that ASB may have made multi-metre contributions to global sea-level rise during the warm periods of the mid-Pliocene (Aitken et al., 2016; Cook et al., 2014)

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when CO_2 concentrations were comparable to the present day (Martínez-Botí et al., 2015). Therefore, indications from the past and observations of current mass loss suggest that ASB has the potential to make globally significant contributions to sea-level rise in the coming decades to centuries (Stokes et al., 2022).

Ice discharge from Totten Glacier (Fig. 1) is estimated to be between 65 and 85 Gt yr^{-1} (Davison et al., 2023; Rignot et al., 2019), and it is the single largest source of mass loss from both ASB and the entire East Antarctic Ice Sheet (Mohajerani et al., 2018; Nilsson et al., 2022; Rignot et al., 2019; Schröder et al., 2019; Smith et al., 2020). Inland thinning of Totten Glacier was detected in the early 1990s (Nilsson et al., 2022; Schröder et al., 2019), hinting that the catchment may have been losing mass decades before the earliest satellite-altimetry observations, but the onset date of this current bout of mass loss is unclear. Recent evidence shows that enhanced intrusion of mCDW is the most likely forcing of the mass loss at Totten Glacier. The warm ocean water can flow over the continental shelf (Rintoul et al., 2016) and travel beneath Totten Ice Shelf towards the grounding line via a network of deep bathymetric troughs (Hirano et al., 2023), leading to significant basal melting. However, whether and how this oceanic forcing has varied over time is unknown, and contributing to large uncertainties in quantifying sea-level rise contributions from Totten Glacier over the coming century and beyond under a variety of different climate warming scenarios (Jordan et al., 2023; McCormack et al., 2021; Pelle et al., 2021).

Outlet glaciers can lose mass through a dynamical acceleration in ice discharge into the ocean, a reduction in snowfall, or a combination of both. Unequivocal evidence shows that major outlet glaciers in West Antarctica that have consistently been losing mass since the onset of satellite observations are doing so in response to a dynamic-thinning-induced acceleration in ice-flow speed, forced initially by thinning to the impounding ice shelves (Kim et al., 2024). However, despite its significant mass loss across the satellite era, existing studies show no clear widespread acceleration in ice-flow speed across the Totten system (Li et al., 2023a; Li et al., 2015; Rignot et al., 2019; Roberts et al., 2018). Therefore, the absence of a clear shelf-wide acceleration at Totten could be explained by two possibilities: 1) Sparse and lower quality satellite images pre-2000s are not of sufficient quality to capture ice-flow acceleration, or 2) Totten accelerated before the onset of the satellite era, meaning the Totten catchment was already out of balance at the onset of satellite observations.

Here, we analyse ARGON and Landsat optical imagery to investigate the behaviour of the Totten glacier and ice-shelf system over the past century. We calculate decadal ice-speed anomalies and grounding-line migration back to 1973. We also produce a century-long record of surface-undulation formation that can be taken as a qualitative record of basal-melt anomalies. We use all three datasets to determine the likely timing for the onset of mass loss at Totten Glacier.

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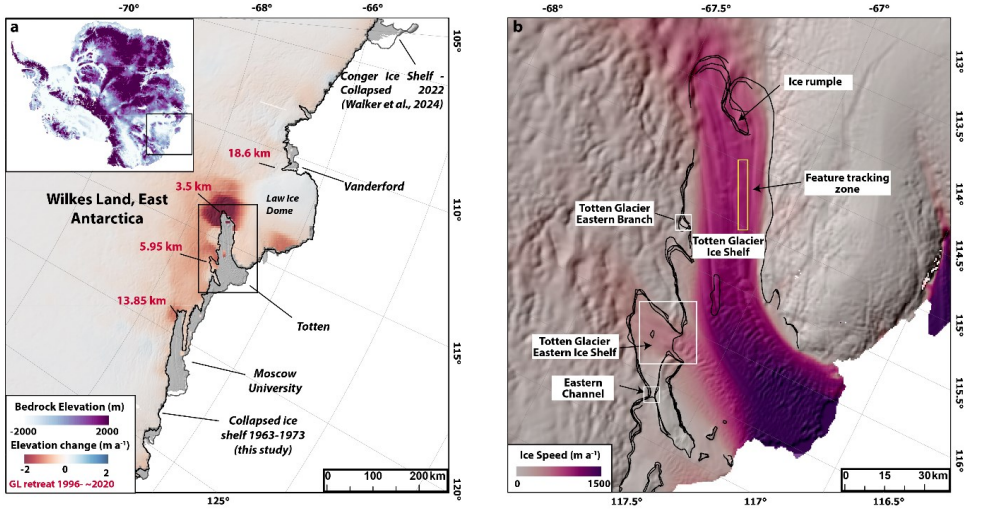

Figure 1: a) Ice-surface elevation change in Wilkes Land, East Antarctica between 2003 and 2019 (Smith et al., 2020), and rate of grounding-line retreat of key outlet glaciers from published studies referenced in the main text. The black line on both images is the MODIS 2009 grounding line (Haran, 2021; Scambos et al., 2007). The inset is bed topography from BedMachine (Morlighem et al., 2020). **b)** Ice speed of Totten system with various InSAR derived grounding lines (Floricioiu, 2021) overlain. The yellow box represents the region of manual feature tracking. The white boxes are the regions where grounding line migration is mapped. The background image in both panels is the REMA DEM (Howat et al., 2019).

2. Methods

2.1 Satellite imagery

The earliest available satellite imagery of Totten glacier system including the ice shelf comprises a pair of ARGON images from 1963 (Fig. 2a). We use the orthorectified and enhanced ARGON imagery of Totten Ice Shelf developed in previous studies (Li et al., 2023a; Ye et al., 2017). The image covering the lower half of the ice shelf and the ice front is of high quality, thus enabling us to identify larger crevasses and surface features. However, the image covering the upper half of the ice shelf and grounding line is of relatively poor quality and the identification of surface features is more challenging (Fig. 2a). For 1973 and 1989, we use the geo-corrected, cloud-free scenes of Totten Ice Shelf acquired respectively by Landsat-1 and Landsat-4 (Miles and Bingham, 2024). Throughout the 2000s, we were able to exploit more regular imagery from Landsat 7, 8 and 9 (Fig. 2). Sporadic SAR imagery is available throughout the 1990s (e.g. ERS), but was not used in this study because we are mainly interested in surface features on Totten Ice Shelf which can express very differently between SAR and optical imagery.

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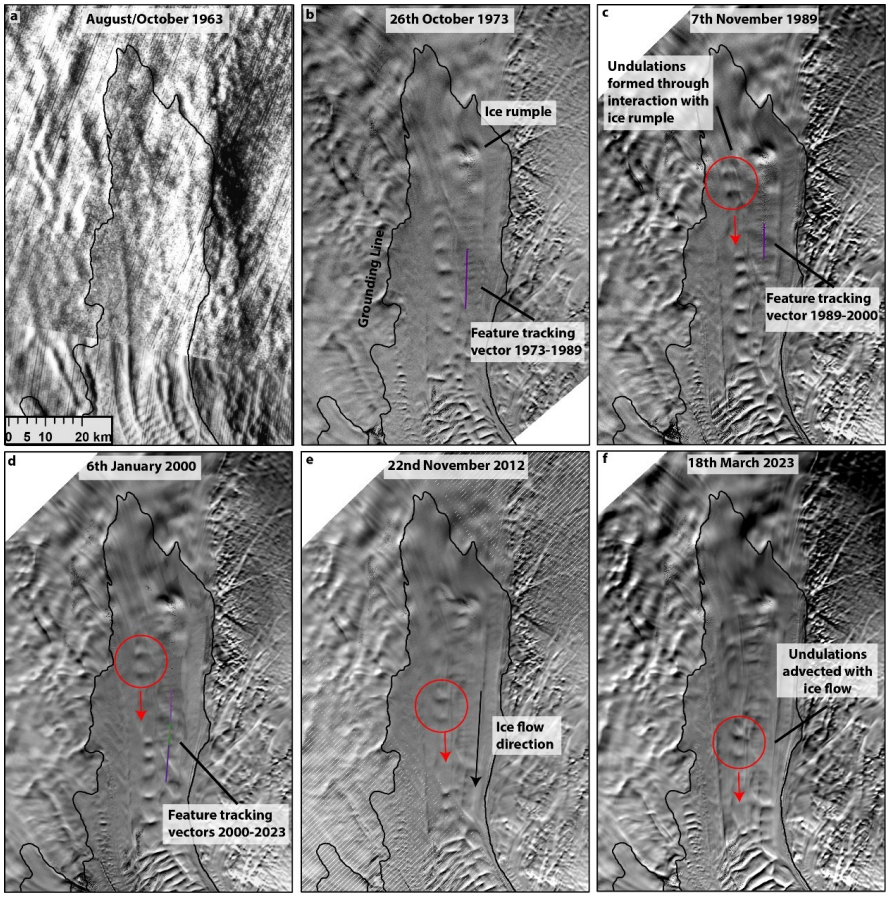

Figure 2: Six decades of satellite imagery over Totten Ice Shelf. The red circles highlight surface undulations forming near the ice rumple in 1989, before being advected downstream with ice flow. Feature tracking vectors used to calculate ice-speed anomalies are shown. ARGON (a) and Landsat (b-f) images are courtesy of the U.S. Geological Survey. Black line shows MODIS 2009 grounding line (Haran, 2021; Scambos et al., 2007).

2.2 Ice Speed

Sporadic and lower quality satellite imagery from before 2000 makes it difficult to determine long-term trends in ice speed at the Totten system. There are two principal reasons for this: Firstly, post-2000 ice-speed records show large interannual variability, with ice speeds varying by ~10% over the course of a few years (Greene et al., 2017; Miles et al., 2022). In the absence of continuous observations in the past, it is difficult to determine whether any apparent changes in ice speed from isolated observations in the past (e.g. 1973, 1989) are related to long-term trends or part of this cyclic interannual variability. Secondly, sparse image availability means that uncertainties can be very high. For example, the only pair of Landsat images covering Totten Glacier between 1975 and 1998 comprises Landsat-4 images from 28th March 1989 and 7th November 1989. During this relatively short period, ice in the yellow box (Fig. 1b) may have only flowed ~700 m and, assuming a displacement uncertainty of ±60 m or 2 pixels (1 for

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co-registration; 1 for feature tracking), this equates to uncertainties of around ±9%. This very high uncertainty could partly explain the vast range (>20%) of ice-speed anomaly estimates for Totten Glacier in 1989 reported in previous studies (Li et al., 2023a; Li et al., 2015; Rignot et al., 2019; Roberts et al., 2018).

To address both of these issues, we manually track surface features on Totten Ice Shelf using image pairs separated by much longer periods of time (>10 years), which both smooths the impact of interannual variability and reduces relative feature tracking uncertainties because surface features are travelling much greater distances. For example, between 1973 and 1989 we track a 16.07 km displacement of a surface feature and, assuming a displacement uncertainty of two pixels or 120 m (60 m pixel size for Landsat-1), this equates to a smaller uncertainty of ±0.74% (Fig. 3). The disadvantage of this method is that very few surface features remain visible over this length of temporal separation and the process of tracking features over long periods of time can systematically overestimate ice-flow speed if ice does not flow in a straight line (Li et al., 2022). After a careful inspection of the imagery, we focus our feature tracking on one prominent feature that repeatedly forms around 20 km downstream (Location; yellow box, Fig. 1b) of the grounding line, the only feature that unambiguously maintains its shape and structure for multiple decades (Fig. 3). The close proximity to the grounding line of the surface feature and the confined nature of Totten Ice Shelf means the relative speed anomalies likely provide a good proxy for changes in ice speed across the grounding line, as well as the changes in ice discharge of Totten Glacier. Secondly, because ice flows in a straight line in this region, velocity overestimate corrections are not required. We report changes in ice speed in each epoch as an anomaly with respect to the MEaSUREs ice-velocity reference mosaic of Antarctica (Rignot et al., 2011). This is because, in each epoch, the location of the feature that is tracked starts in a slightly different position. All relative anomalies are calculated along the same flowline and the maximum distance between the centre point of any two anomalies is <20 km. Therefore, given their close proximity it is reasonable to infer that the anomalies are closely comparable to each other through time. In total we measure decadal ice-speed anomalies from 10 epochs detailed in Table 1.

Table 1: Feature tracking - decadal ice-speed anomalies

Image 1	Image 2	Days	Distance (km)	Average speed (m a^{-1})	MEaSUREs speed (m a^{-1})	Anomaly (%)	Uncertainty (km)	Uncertainty (%)
26/10/1973	07/11/1989	5856	16.07	1002	976	2.7	0.12	0.75
07/11/1989	06/01/2000	3712	9.54	938	947	-1.0	0.06	0.63
06/01/2000	03/12/2010	3984	10.70	980	974	0.6	0.03	0.28
22/12/2002	22/11/2012	3623	10.01	1008	981	2.8	0.03	0.30
22/11/2006	25/11/2016	3656	10.07	1005	997	0.8	0.03	0.30
09/11/2007	25/09/2017	3608	9.89	1003	999	0.4	0.03	0.30
29/12/2008	17/12/2018	3640	9.98	1001	1005	-0.4	0.03	0.30
14/11/2009	30/08/2019	3576	9.83	1003	1009	-0.6	0.03	0.31
03/12/2010	19/10/2020	3608	9.88	999	1015	-1.6	0.03	0.30
17/11/2013	24/03/2023	3414	8.86	947	959	-1.3	0.03	0.34

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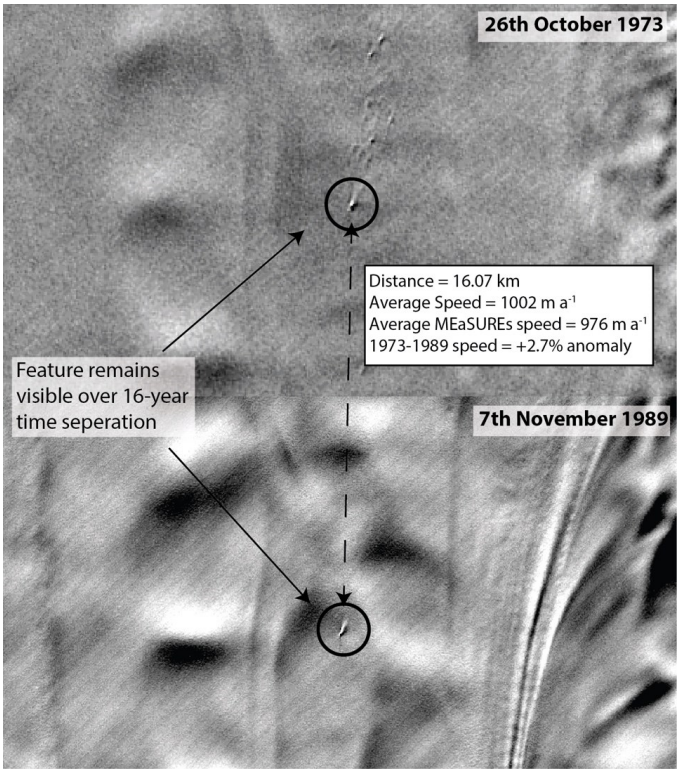

Figure 3: Image split showing an example of manual feature tracking from a Landsat-1 image from 26th October 1973 to a Landsat-4 image from 7th November 1989. Landsat images are courtesy of the U.S. Geological Survey.

In addition to decadal ice-speed anomalies, we also calculate interannual ice-speed anomalies at Totten Ice Shelf from 1989 to 2023 where there is a greater availability of satellite imagery. We calculate interannual ice-speed anomalies by manually tracking the same surface feature used in decadal ice-speed anomalies. We chose this method instead of using the existing ITS_LIVE and MEaSUREs annual mosaics because a preliminary analysis showed these two datasets have large differences in the magnitude of ice speed and interannual trends. In total, we measure interannual ice-speed anomalies from 11 epochs detailed in Table 2.

Table 2: Feature tracking - interannual ice speed anomalies

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Image 1	Image 2	Days	Distance (km)	Average speed (m a^{-1})	MEaSUREs speed (m a^{-1})	Anomaly (%)	Uncertainty (km)	Uncertainty (%)
28/03/1989	07/11/1989	224	0.69	1124	1004	12.0	0.06	8.70
06/01/2000	22/12/2002	1081	2.76	931	963	-3.3	0.03	1.09
22/12/2002	22/11/2006	1431	3.85	981	971	1.0	0.03	0.78
22/11/2006	29/12/2008	768	2.14	1017	980	3.8	0.03	1.40
29/12/2008	03/12/2010	704	1.98	1029	985	4.5	0.03	1.51
03/12/2010	22/11/2012	720	2.00	1014	1000	1.4	0.03	1.50
22/11/2012	19/10/2014	696	1.85	972	1005	-3.3	0.03	1.62
19/10/2014	25/11/2016	768	2.10	998	1016	-1.8	0.03	1.43
25/11/2016	17/12/2018	752	2.06	1001	1024	-2.2	0.03	1.45
17/12/2018	19/10/2020	672	1.89	1026	1034	-0.8	0.03	1.59
19/10/2020	18/03/2023	880	2.52	1046	1044	0.2	0.03	1.19

2.3 Grounding Line

We use Landsat imagery to map the break-in-slope (Christie et al., 2016; Fricker et al., 2009), a proxy for the grounding-line location. Our analysis is limited to three locations where we observe clear breaks-in-slope, which are the Totten Glacier Eastern Branch, Totten Glacier Eastern Ice Shelf and the Eastern Channel (Fig. 1b). In these regions, break-in-slopes are a good representative for the true grounding line and have been previously used in analysing the basal melting regimes in Totten Ice Shelf due to warm ocean water intrusions (Greenbaum et al., 2015; Li et al., 2023b). We did not map the grounding line at the main glacier trunk of the Totten Ice Shelf featured by fast ice flow, where the break-in-slope is an unreliable proxy for the actual grounding line and the grounding line detection is challenging using DInSAR interferograms or satellite altimetry datasets (Li et al., 2015; Li et al., 2023b). We map the break-in-slope in each location in 1973, 1989, 2000 and 2023. Based on previous studies, we prescribe a mapping uncertainty of 1 pixel (Christie et al., 2016), along with an additional 1 pixel uncertainty associated with image co-registration.

2.4 Surface Undulations

Surface undulations downstream of bedrock obstacles on floating ice shelves are common features observed across several ice shelves, with prominent examples expressed on Filchner-Ronne (Brunt et al., 2011), Pine Island (Bindschadler et al., 2011), Thwaites (Kim et al., 2018), Totten (Roberts et al., 2018), and Ross (Lee et al., 2012) ice shelves. As ice flows over bedrock obstacles, the topographic variability of the bedrock surface is transmitted to the glacier surface (De Rydt et al., 2013; Gudmundsson, 2003). If the thickness of floating ice varies over time in response to time-varying basal-melt rates, the degree of contact with the underlying bedrock obstacle will also change, resulting in variable imprints on the surface topography of the ice shelf that are subsequently transported downstream with ice flow (Fig. 4).

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Sporadic trains of surface undulations form on Totten Ice Shelf adjacent to a large ice rumple near the grounding line (Roberts et al., 2018); Fig. 2; Animation S1). An inspection of our cloud-free Landsat imagery spanning 50 years reveals that the trains of undulations persist relatively unchanged in shape for ~45 km downstream of the ice rumple as they are advected with ice flow. Therefore, in our earliest cloud-free image from 1973, visible surface undulations at the furthest point downstream of the ice rumple formed decades earlier and our full time series provides a near century-long insight into surface-undulation formation.

To investigate the surface undulations on Totten Ice Shelf, we first measure surface-elevation anomalies from ICESat-2 repeat tracks across the ice shelf to capture the dimensions of the undulations as they are advected downstream with ice velocity (Li et al., 2023b). We use the ICESat-2 ATL06 dataset for Track 26 between May 2019 and November 2023. The ICESat-2 data are applied using the 'ATL06_quality_summary' flag to remove poor-quality elevation measurements possibly caused by clouds or high surface roughness (Smith et al., 2019). They are further corrected for the ocean tide and ocean-loading tide, as well as inverted barometer effects (DAC). Instead of using the ocean-tide correction values generated from the GOT4.8 model that are provided in the ATL06 data product, we use the CATS2008 tidal model to estimate the ocean-tide corrections (Padman et al., 2002). Elevation anomalies are calculated by subtracting a reference elevation profile, defined as the average elevation, from each individual repeat track elevation profile.

We then create a time series of surface-undulation formation by estimating the date on which each undulation formed at the ice rumple. This is estimated by calculating the average flow speed from the MEaSUREs ice-velocity mosaic of Antarctica along a flowline from the ice rumple to 45 km downstream, which represents the region where surface undulations are visible before they are lost to a crevasse field. However, because melt rates are highest near the grounding line (Adusumilli et al., 2020), it is the cumulative melt as ice travels downstream from the grounding line that determines the thickness of ice as it flows over the ice rumple. Therefore, we also estimate the date on which ice flowed over the grounding line by calculating the average flow speed from the MEaSUREs ice-velocity mosaic of Antarctica along a flowline from the grounding line to the ice rumple.

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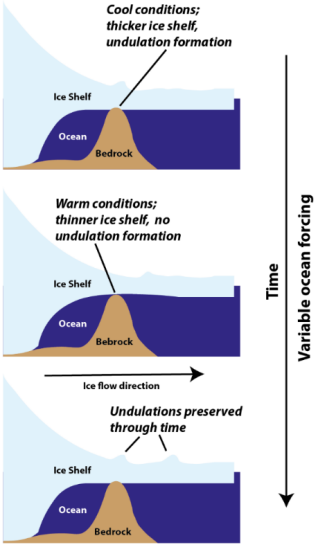

Figure 4: Schematic showing the formation of surface undulations from time-varying melt rates.

3. Results

3.1 Ice Speed

We observe no clear trend in multidecadal ice-speed anomalies at Totten Ice Shelf between 1973 and 2023, with ice-speed anomalies ranging from -1.6 ±0.3% from 2010-2020 to +2.8 ±0.3% from 2002-2012 (Fig. 5). We observe a much greater range of ice-speed anomalies over interannual timescales. We record a maximum ice speed anomaly of +12 ±8.7% in 1989 and a minimum ice speed anomaly of -3.3 ±1.1% from 2000-2002 (Fig. 5). Regular ice-speed measurements between 2000 and 2023 reveal oscillatory behaviour in speed anomalies of up to ~8% over the course of 6-7 year cycles (Fig. 5).

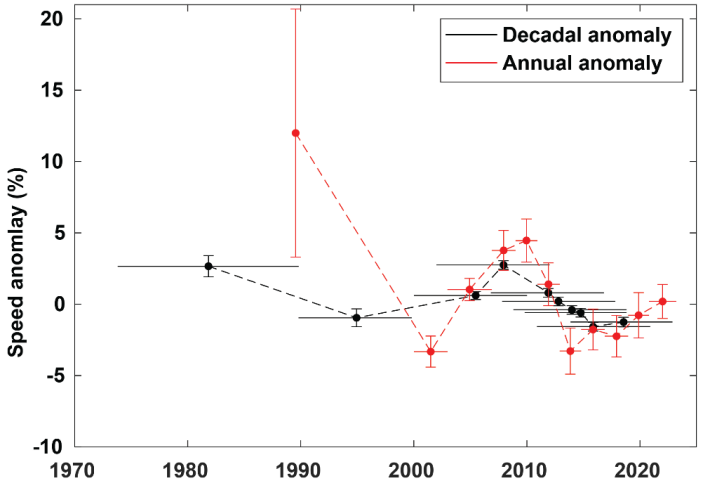

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Figure 5: Ice-speed anomalies at Totten Ice Shelf. Black data points represent decadal ice-speed anomalies; red data points represent the interannual ice-speed anomalies. Horizontal lines represent the time gap between the two images used to track surface features.

3.2 Grounding Line

At the Totten Glacier Eastern Branch we observe a maximum 4.1 ± 0.12 km grounding-line retreat between 1973 and 2023, that includes a 0.8 ± 0.12 km maximum retreat between 1973 and 1989 (Fig. 6a). The width of the mouth of the Totten Glacier Eastern Ice Shelf increased by around 3.8 ± 0.12 km between 1973 and 2023 with retreat on both the northern and southern flanks (Fig. 6b). The rate of retreat is reasonably consistent in each of our three epochs: 1973-1989; 1989-2000 and 2000-2023. At Eastern Channel we observe a gradual widening through each of our 3 epochs, and overall between 1973 and 2023 the channel width approximately doubled (Fig. 6c).

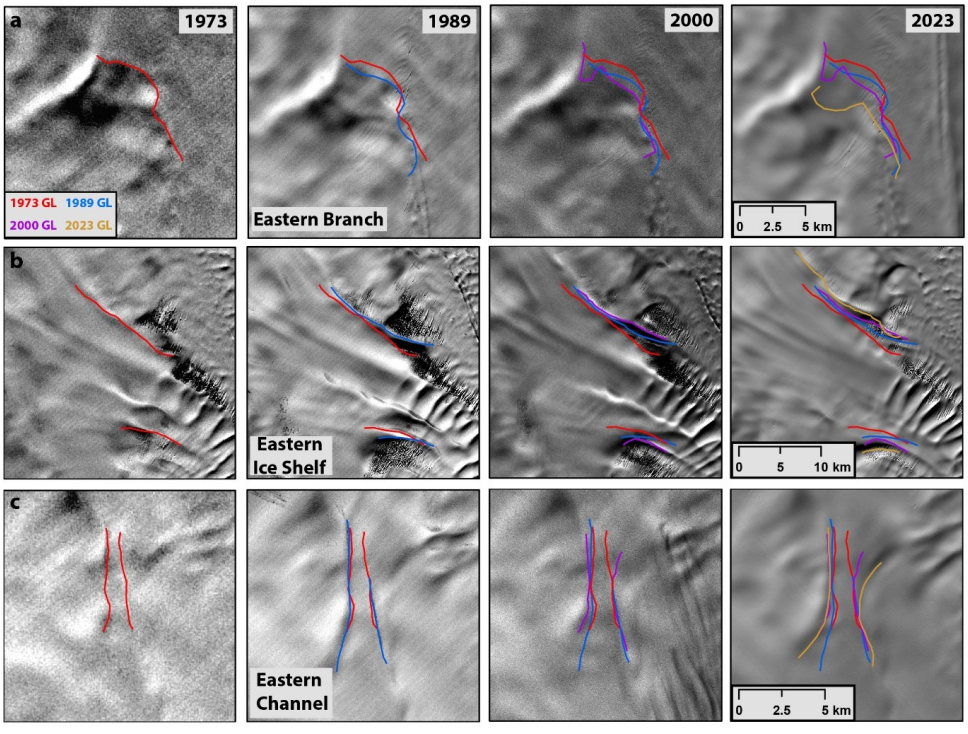

Figure 6: Grounding-line retreat tracked from Landsat imagery for **a)** Eastern Totten Ice Shelf, **b)** Eastern Ice Shelf and **c)** Eastern Channel. See Figure 1b for locations. Landsat images are courtesy of the U.S. Geological Survey.

3.3 Surface Undulations

ICESat-2 repeat tracks across a prominent surface undulation as it flows downstream show a surface height change of up to 25 m (Fig. 7a). Based on the average flow speed of 950 m a^{-1} along the transect of the surface undulations, and assuming ice-flow speed has remained constant through time, the most distant surface undulation 45 km downstream of the ice rumple will have formed ~47 years before the image date (Fig. 7b). We also calculate that it takes

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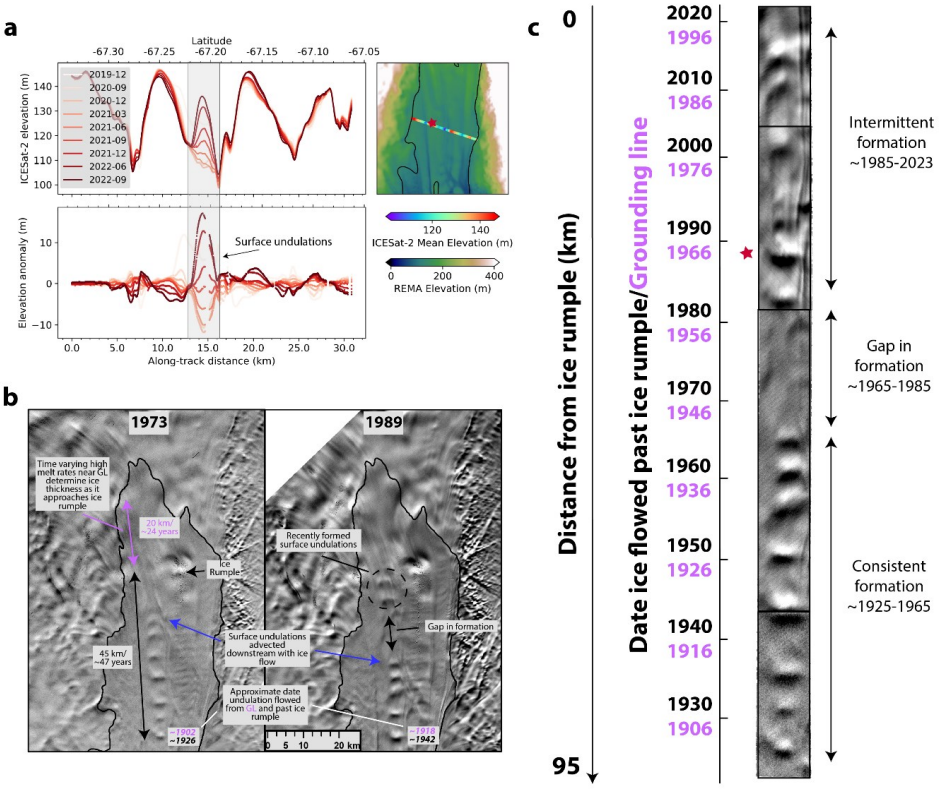
253 approximately 24 years for ice to flow from the grounding line to the ice rumple based on an
254 average flow speed of 850 m a^{-1}. This means that in our earliest Landsat image in 1973, the
255 most distant surface undulation will have formed in approximately 1926, being imprinted into
256 ice that had crossed the grounding line in approximately 1902 (Fig. 7b). The time series of
257 surface-undulation formation reveals three distinct phases of surface undulation formation over
258 the past 100 years (Fig. 7c). The first phase is characterised by regular surface-undulation
259 formation at the ice rumple between 1926 and 1965, imprinted into ice that had flowed across
260 the grounding line from 1902-1941. The second phase is characterised by a gap in surface-
261 undulation formation between 1965 and 1985, for ice that had flowed across the grounding line
262 from 1941-1961. The final phase is characterised by intermittent formation of surface
263 undulations between 1985 and 2023, imprinted into ice that had flowed across the grounding
264 line from 1961-1999. Notably, surface undulations in this final phase appear to reduce
265 progressively in size, possibly implying a progressive thinning of the ice shelf.



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267 **Figure 7: a)** Repeat ICESat-2 tracks over Totten Ice Shelf highlighting the surface-elevation anomalies
268 associated with the surface undulations as they flow downstream. Grey box marks the location of the
269 surface undulations and the height change represents the downstream advection of the undulations **b)**
270 Landsat imagery showing surface-undulation advection downstream. The black line on both images is
271 the MODIS 2009 grounding line (Haran, 2021; Scambos et al., 2007). **c)** Time series of surface-
272 undulation formation comprised of four Landsat images (1973, 1989, 2000 and 2023) stitched together.
273 The red star represents the surface undulation profile depicted in panel a. Landsat images are courtesy
274 of the U.S. Geological Survey.

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4. Discussion

4.1 No speed-up of Totten Glacier since at least 1973

Our results show that there has been no clear multidecadal trend in ice speed at Totten Ice Shelf from 1973-2023 (Fig. 5). Assuming that ice-speed anomalies in the locations we tracked on the ice shelf (Fig. 1a) are good proxies for ice speed at the grounding line, this means that average ice discharge has likely remained relatively unchanged at Totten Glacier over the past 50 years, despite strong interannual variability. Although there exists some interdecadal variability in snowfall (Kim et al., 2024), there is no evidence for any long-term trends in snowfall from the nearby Law Dome ice core (Jong et al., 2022; Roberts et al., 2015) and, because Totten's present ice discharge outweighs input from snowfall, this means that the Totten catchment was likely losing a similar amount of mass from 1973-1989 in comparison to the 2000s. Thus, the trigger for mass loss at Totten catchment predates the onset of the Landsat satellite record.

We note that Li et al. (2023a) reported on a long-term speed up at the Totten grounding line between 1963-1973 and 2022, but with very little change in ice speed 50 km upstream of the ice front over the same time period (Fig.2; Li et al., 2023a). The rate of acceleration in ice speed at the grounding line reported in Li et al. (2023a) was not consistent over this time period, however, with a large ~18% acceleration between 1963-1973 and 1973-1989, then limited change in ice speed between 1973-1989 and 2022. From our methods, we can only reiterate that the Totten system has not experienced any multidecadal acceleration since 1973, because we were unable to track surface features on the 1963 ARGON image near the grounding line.

4.2 Ongoing grounding-line retreat since at least 1973

Our results show consistent grounding-line retreat at Totten Glacier Eastern Ice Shelf and Totten Glacier Eastern Branch between 1973-1989, 1989-2000 and 2000-2023 (Fig. 6). Our observation that the grounding line was already retreating in regions where the break-in-slope is visible between 1973 and 1989 further supports the notion that the Totten Glacier system was already out of balance and losing mass during this period. The Eastern Channel has also been consistently widening from 1973-1989, 1989-2000 and 2000-2023 (Fig. 6c). This channel, first discovered by radio-echo sounding (Greenbaum et al., 2015), has subsequently been shown to be tidally modulated via satellite-radar interferometry (Li et al., 2023b). The Eastern Channel is important because it may provide a direct pathway for warm mCDW to enter the Eastern Ice Shelf cavity (Greenbaum et al., 2015). The expanding width of the channel since at least 1973 would suggest a greater volume of tidally pumped warm mCDW is being progressively funnelled through this trough into the ice-shelf cavity.

4.3 Change in melt pattern in the mid-20th century

At Totten Ice Shelf, high basal-melt-rate variability has been observed from autonomous phase-sensitive radars (Vaňková et al., 2023), variable ocean temperatures have been recorded on the nearby continental shelf (Hirano et al., 2023; Nakayama et al., 2023; Rintoul et al., 2016), and variability has been reported in both ice speed (Greene et al., 2017; Miles et al., 2022) and ice-shelf thickness (Adusumilli et al., 2020; Paolo et al., 2015). The surface undulations that we have tracked along Totten Ice Shelf are large features that result in up to 25 m differential surface-elevation anomalies (Fig. 7a). Roberts et al. (2018) calculated that the wavelength (6-

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7 years) of the surface undulations in a Landsat-7 image from 2010 matched the wavelength of elevation anomalies of the ice shelf observed from satellite altimetry. We estimate that the average length of all visible surface undulations in Landsat imagery dating back to 1973 is similar, at ~5.5 years, based on an average length of ~5 km and an average flow speed of 900 m a^{-1} at the ice rumple where the undulations form. Independent ocean modelling has shown the dominant intrinsic variability in the melt rates of Totten Ice Shelf occurs over ~3 and ~7 years cycles (Gwyther et al., 2018), broadly matching the wavelength of surface-undulation formation. Taken together, along with evidence from similar features on other ice shelves (Bindschadler et al., 2011, Kim et al., 2018), there is substantial theoretical and observational evidence that the surface undulations are formed by time-varying basal-melt rates. Thus, any substantial change in the pattern of surface-undulation formation at Totten Ice Shelf through time likely relates to changes in contact with the underlying pinning point in response to variability in ice-shelf thickness and basal-melt rates.

The abrupt switch from regular surface-undulation formation from 1925-1965 to no surface-undulation formation between 1965 and 1985 implies a change in melt rates and ice-shelf thickness (Fig. 7c). Specifically, because the period from 1965-1985 is characterized by a smoother ice-shelf surface, this suggests warmer conditions and a thinner ice shelf with much more limited interaction with the ice rumple during this period. Surface undulations return sporadically between 1985 and 2023, demonstrating a shift to relatively cooler conditions, but the ice shelf may be thinner compared to 1925-1965 when surface undulations formed on a more regular basis (Fig. 7c).

Modern satellite-altimetry observations of ice-shelf thickness change at Totten Ice Shelf support our hypothesis that the absence of surface-undulation formation between 1965 and 1985 represents a period of higher basal-melt rates and a relatively thinner ice shelf. Observations of ice-shelf thickness change between 2003 and 2019 (Smith et al., 2020) show a conflicting thickness-change signal across the ice shelf (Fig. 8). The upper ice shelf near the ice rumple thickened, while the mid-section of the ice shelf thinned, during this period. This can be explained by waves of ice thickness variations in response to time-varying basal melt rates near the grounding line being advected downstream with ice flow. Notably, the boundary between thinning and thickening ice derived by satellite altimetry (Fig. 8) corresponds to the boundary between the 1985-2023 and 1965-1985 phases in surface-undulation formation (Fig. 7c). That is, the 2003-2019 thickening of the upper section of the ice shelf can be explained by the relatively thinner ice associated with the 1965-1985 period of no surface-undulation formation and high melt rates being advected downstream and being replaced by relatively thicker ice associated with relatively low melt rates and the 1985-2023 period of intermittent surface-undulation formation. The thinning section of the mid-ice shelf is explained by relatively thick ice associated with the 1925-1965 regular phase of surface-undulation formation being advected downstream and being replaced by relatively thin ice associated with the 1965-1985 period of no surface-undulation formation.. Therefore, we are confident that the 1965-1985 gap in surface-undulation formation represents a section of relatively thin ice as it flowed over the ice rumple in response to higher basal-melt rates. However, the timing of this period of high melt rates likely predates the 1965-1985 gap in surface-undulation formation. This is because it takes around 24 years for ice to travel from the grounding line to the ice rumple, and it is the cumulative melt rate during this period that determines the thickness of the ice shelf as it crosses the ice rumple. Thus, we estimate that the switch to higher melt rates

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at the grounding line took place at some point between 1941 and 1965, to which we refer as the mid-20th century.

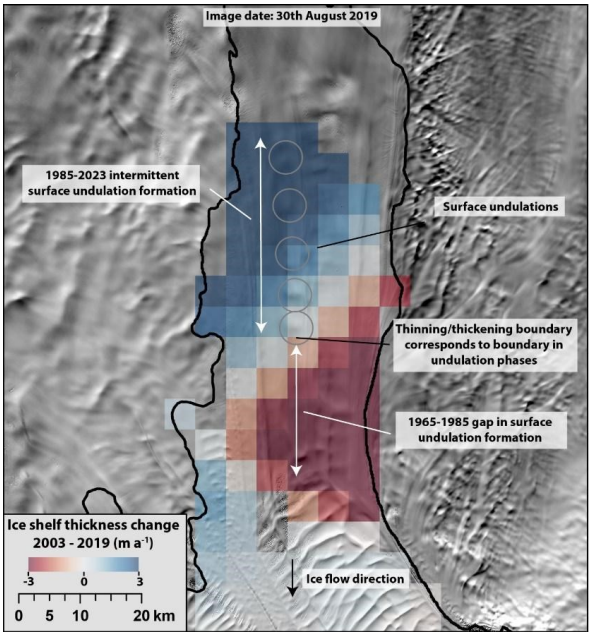

Figure 8: Ice-shelf thickness change between 2003 and 2019 (Smith et al., 2020) overlain on a Landsat-8 image from August 2019. Black line is the MODIS 2009 grounding line (Haran, 2021; Scambos et al., 2007). Landsat images courtesy of U.S. Geological Survey.

4.4 Warm environmental conditions during the mid-20th century trigger mass loss?

We hypothesise that anomalously high basal melt rates in the mid-20th century could have marked the trigger for the current mass loss of Totten Glacier. This could have manifested via anonymously warm conditions causing the ice shelf to detach from a pinning point. A candidate could be the partial detachment from the main ice rumple near the grounding line, where the precise bed topography is still uncertain (Vaňková et al., 2023). At the very least, the period of no surface-undulation formation in the mid-20th century likely marked a period of unusually sustained higher basal-melt rates, with respect to conditions over the past 100 years (Fig. 7c).

The pattern of surface-undulation formation over the past 100 years also supports the notion of a long-term thinning of Totten Ice Shelf since the mid-20th century. Following the period of regular surface-undulation formation in the first half of the 20th century, surface undulations, despite some decadal variability, progressively become less frequent and visibly smaller in size (Fig. 7c). We interpret this as a long-term thinning of the ice shelf in response to increased melt rates, meaning increasingly more extreme cold anomalies are required for undulation formation. This is consistent with ship-based observations of ocean temperature that show a warming of CDW at the continental shelf adject to Totten Glacier between 1930-1990 and 2010-2018, in response to a wind-driven southward shift of the Antarctic Coastal Current (Herraiz-Borreguero and Naveira Garabato, 2022; Yamazaki et al., 2021). However, superimposed on this longer-term trend of CDW warming are the processes that modulate the delivery of mCDW

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onto the continental shelf and then towards ice-shelf cavities that are an important factor in the observed decadal variability in melt rates (Adusumilli et al., 2020; Roberts et al., 2018) and subsequent surface-undulation formation (Fig. 7c). In the case of Totten Glacier and Ice Shelf, several processes have been put forward to explain decadal variability in melt rates including variations in Antarctic Slope Current strength (Nakayama et al., 2021), intrinsic variability (Gwyther et al., 2018), zonal wind strength on the continental-shelf break (Greene et al., 2017) and coastal-polynya activity (Gwyther et al., 2014; Khazendar et al., 2013).

Validating the hypothesised period of anonymously warm conditions in the mid-20th century with reanalysis data is challenging. Outputs from ice-ocean models reconstructing temporal variability in basal-melt rates back to the mid-20th century show conflicting signals (Gwyther et al., 2018; Kusahara et al., 2024), and the reliability of key climatic reanalysis input data throughout much of the early to mid-20th century is unknown. There is also a poor understanding of the sub-ice-shelf bathymetry that is crucial to simulating melt rates (Kusahara et al., 2024). However, modern observations show synchronous ice-speed and ice-shelf thickness anomalies throughout the 2000s at major outlet glaciers across the wider Wilkes Land region (Miles et al., 2022). Therefore, any anonymously warm conditions in the mid-20th century could have been felt regionally and not just at Totten Glacier. We observe the collapse of a previously unreported ice shelf 50 km east of the ice front of Moscow University Ice Shelf between 1963 and 1973 (Fig. 9). The ice shelf is small (250 km^2) and did not buttress any large glaciers, so its collapse is inconsequential for sea-level rise. The unnamed ice shelf was previously adjoined to Voyeykov Ice Shelf through a mixture of fast ice and melange. Voyeykov Ice Shelf periodically collapses and regrows in response to changes in fast ice conditions (Arthur et al., 2021), but at the unnamed ice shelf we observe no signs of regrowth in the following 50 years post-collapse (Fig. 9). The final stages of ice-shelf collapse may be preceded years or even decades of gradual weakening (Walker et al., 2024), meaning the collapse of this unnamed ice shelf at some point between 1963 and 1973 is consistent with relatively warm environmental conditions in the years or decades earlier and is symbolic of environmental change in the mid-20th Century.

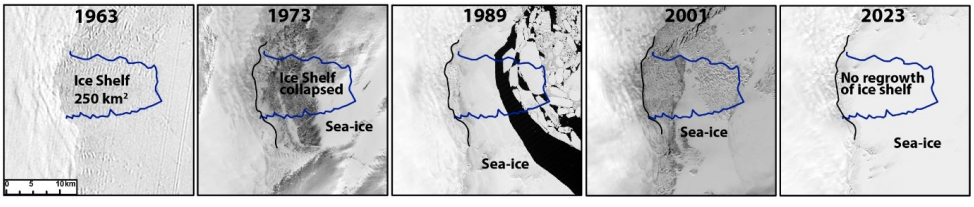

Figure 9: A series of satellite images showing the disintegration of an un-named ice shelf between 1963 and 1973, which has not regrown to a comparable extent in the 50 years since. Satellite images are courtesy of the U.S. Geological Survey. See Figure 1a for location.

The century-long record of surface undulations implies that the ~30-year record of satellite altimetry is not long enough to capture the full extent of the amplitude and wavelength of decadal variability in basal-melt anomalies. Numerical-modelling experiments have shown that forcing Totten Glacier with variable basal-melt rates, at similar amplitudes to those inferred by ~30 years of satellite-altimetry observations, has a net effect of reducing ice discharge and delaying grounding-line retreat in comparison to constant forcing (McCormack et al., 2021).

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Therefore, evidence of prolonged periods of higher sustained melt rates in the recent past raises the possibility of similar episodes in the coming decades accelerating retreat. A greater understanding of the processes and the magnitude of decadal variability is vital to narrowing uncertainties in future sea-level projections from Antarctica (Hanna et al., 2024). It could be that these anomalous periods of warm oceanic conditions play a vital role in kick starting cycles of glacier retreat. Perhaps analogous to this is Pine Island and Thwaites glaciers, where sediment records point to their retreat from stabilizing pinning points in the 1940s (Clark et al., 2024; Smith et al., 2017) in response to anonymously warm environmental conditions (Steig et al., 2012). The key difference here is that bedrock geometry at Pine Island Glacier was conducive for marine ice-sheet instability and a rapid retreat (Reed et al., 2024), whereas the present geometry at Totten Glacier is not favourable for a similar rapid retreat in the near future (Morlighem et al., 2020).

5. Conclusion

Overall, our results have shown that averaged decadal ice speed of Totten Ice Shelf has not accelerated over the past half-century. The combination of observations of inland thinning in the earliest satellite-altimetry records, grounding-line retreat between 1973 and 1989, and the absence of any long-term trends in snowfall, points towards Totten Glacier already being out of balance in the 1970s. Therefore, the initial increase in ice discharge that placed Totten Glacier out of balance must have taken place before 1973. The near century-long record of surface-undulation formation highlights an anomalous ~20-year period in the mid-20th century that we interpret as sustained higher-than-average basal-melt rates causing much more limited interaction between a prominent ice rumple near the grounding line and the ice shelf. This interpretation is supported by satellite-altimetry observations that show waves of ice thickness variations travelling with ice flow that match the gap in surface-undulation formation. We hypothesize that these anonymously warm conditions in the mid-20th century could have marked the onset of the modern-day mass loss of Totten Glacier by accelerating the detachment from a key pinning point, and/or marking a change in environmental conditions represented by more frequent and/or intense intrusions of mCDW onto the continental shelf. Validating this proposed anonymously warm period is challenging because the drivers of interannual variability in melt rates at Totten Ice Shelf over the observational period are not fully understood. Perhaps more importantly, because surface undulations have been forming over the past ~30 years, our observations hint at warmer than present conditions in the recent past. Therefore, basal-melt rates calculated from short satellite-altimetry records that are often used as a baseline in numerical models to project into the future may not be capturing the full variability within the Totten glacier system.

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Data availability: Landsat and ARGON imagery was provided free of charge by the U.S. Geological Survey Earth Resources Observation Science Center (https://earthexplorer.usgs.gov/, USGS, 2022). The MOA grounding line product is available at https://doi.org/10.7265/N5KP8037 (Haran, 2021). The ice shelf thickness change dataset from Smith et al. (2020) is available at http://hdl.handle.net/1773/45388 (last access: April 2022). The REMA DEM is available at https://doi.org/10.7910/DVN/X7NDNY (Howat et al., 2019). ICESat-2 data is available from https://nsidc.org/data/atl06/versions/6. Corrected Landsat imagery of Antarctic ice shelves from 1973 and 1989 is available at https://doi.org/10.7488/ds/3810 (Miles and Bingham, 2023). Corrected Argon imagery was provided by Ron Li. The decadal ice speed tracking vectors and grounding line mapping from this study are available at https://doi.org/10.7488/ds/7853.

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Author Contribution: B.M led the design of the study with input from T.L and R.B. T.L produced figure 7a and carried out the ICESat-2 analysis. B.M led the manuscript writing with input from T.L and R.B

Competing interests: The authors declare that they have no conflict of interest.

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