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# Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing

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**From early 2003 to mid-2013, the total mass of ice in Greenland declined at a progressively increasing rate. In mid-2013, an abrupt reversal occurred, and very little net ice loss occurred in the next 12–18 months. Gravity Recovery and Climate Experiment (GRACE) and global positioning system (GPS) observations reveal that the spatial patterns of the sustained acceleration and the abrupt deceleration in mass loss are similar. The strongest accelerations tracked the phase of the North Atlantic Oscillation (NAO). The negative phase of the NAO enhances summertime warming and insolation while reducing snowfall, especially in west Greenland, driving surface mass balance (SMB) more negative, as illustrated using the regional climate model MAR. The spatial pattern of accelerating mass changes reflects the geography of NAO-driven shifts in atmospheric forcing and the ice sheet's sensitivity to that forcing. We infer that southwest Greenland will become a major future contributor to sea level rise.**

GRACE | GNET | NAO | SMB | mass acceleration

The satellite mission Gravity Recovery and Climate Experiment (GRACE) has been used to monitor ice loss in Greenland by inferring near-surface mass changes from temporal variations in gravity measured in space (1–5). Before mid-2013, these measurements were remarkably consistent with a mass trajectory model (6) consisting of an annual cycle, represented by a four-term Fourier series, superimposed on a quadratic or “constant acceleration” trend with an acceleration rate of  $-27.7 \pm 4.4 \text{ Gt/y}^2$  (Fig. 1). The Greenland Ice Sheet (GrIS) and its outlying ice caps were losing mass at a rate of about  $-102 \text{ Gt/y}$  in early 2003, but 10.5 y later this rate had increased nearly fourfold to about  $-393 \text{ Gt/y}$ , accounting for much of the observed acceleration in sea level rise (7). Then, from mid-2013 onward, mass loss ceased or nearly ceased (Fig. 1 *B* and *E*) for 12–18 mo. Because seasonally adjusted mass loss stalled, we refer to this time interval as the “2013–2014 Pause” (Fig. 1*B*), or just “Pause.”

The abrupt slowdown in deglaciation was also observed by the Greenland GPS Network (GNET), which senses mass changes by measuring the solid earth's response to changing surface loads (8–12). Vertical crustal displacements manifest a combination of (i) glacial isostatic adjustment (GIA), that is, the solid earth's delayed, viscoelastic response to past changes in ice loads, and (ii) instantaneous, elastic adjustment to contemporary changes in ice mass. GIA rates are nearly constant over decadal and shorter timescales—except, perhaps, near Kangerdlugssuaq Glacier where mantle viscosities are extremely low (11). Therefore, the vertical accelerations frequently observed in GNET displacement time series (6, 8, 12) very largely represent elastic adjustments to accelerating changes in ice mass.

For the 5-y time period of 2008.4–2013.4, which excludes the summer of 2013, our estimates of the mean acceleration in uplift were positive at about 75% of GNET stations, and the largest positive accelerations were nearly three times larger in magnitude

than the most negative accelerations (Fig. 2). In contrast, for the 5-y period of 2010.4–2015.4, which includes the summer of 2013, more than 90% of GNET stations sensed negative accelerations, and the most negative accelerations had nearly three times the magnitude of the most positive accelerations. The ubiquity of the shift in mean vertical acceleration rates can be assessed by comparing the cumulative distribution functions for each time period (Fig. 2*C*). Sign reversal is not strongly sensitive to the limits of these time intervals (see *SI Appendix*, Fig. S2 for another example).

The GRACE time series suggests that the  $\sim 10$ -y episode of accelerating mass loss ceased, and the 2013–2014 Pause in the recent deglaciation of Greenland began near the middle of 2013. Given the level of scatter in the GRACE residuals (Fig. 1*D*), it is hard to be more precise. GNET data provide us with an independent means to estimate the onset time of the Pause. In Fig. 3, we define the station uplift anomalies using a reference period that begins in or after 2007.0 and ends at 2013.4—the final epoch was determined a posteriori, after a series of experiments, so as to establish a self-consistent result. We fit the vertical displacement (up) time series for each GNET station during the reference period with the same trajectory model used to model the GRACE data. This model was then projected forward in time. The uplift anomaly is defined as the difference between the observed

## Significance

The recent deglaciation of Greenland is a response to both oceanic and atmospheric forcings. From 2000 to 2010, ice loss was concentrated in the southeast and northwest margins of the ice sheet, in large part due to the increasing discharge of marine-terminating outlet glaciers, emphasizing the importance of oceanic forcing. However, the largest sustained ( $\sim 10$  years) acceleration detected by Gravity Recovery and Climate Experiment (GRACE) occurred in southwest Greenland, an area largely devoid of such glaciers. The sustained acceleration and the subsequent, abrupt, and even stronger deceleration were mostly driven by changes in air temperature and solar radiation. Continued atmospheric warming will lead to southwest Greenland becoming a major contributor to sea level rise.

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The authors declare no conflict of interest.

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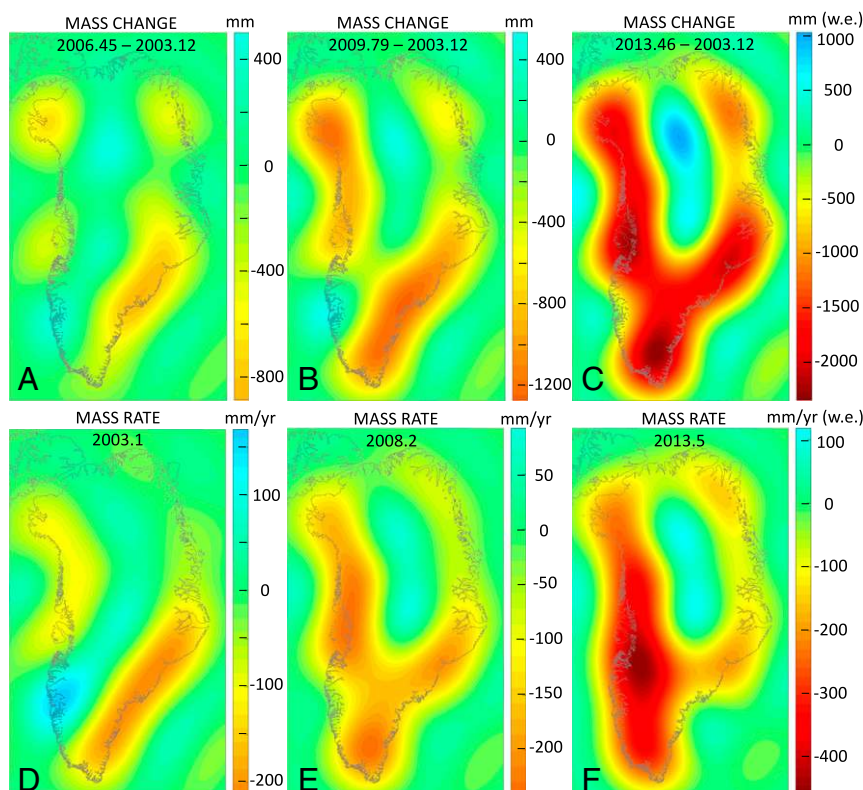
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**Fig. 4.** (A–C) Cumulative mass loss since 2003.12, after the mean seasonal cycle is removed, in millimeters of water equivalent (w.e.), or kilograms per square meter. (D–F) Instantaneous mass rates implied by the quadratic trend model, that is, decycled mass rate, in millimeters per year of water equivalent.

RACMO2 (5). The temporal correlation between summertime SMB and the phase of the NAO is seen in Fig. 1*F*. We estimated the best linear trend in SMB predicted by MAR for the years 2004–2012 (Fig. 5*C*). SMB expressed in water equivalent has units of millimeters per year, so SMB trend has units of millimeters per square year, that is, mass acceleration. The SMB trend field is broadly consistent with the mass acceleration field before 2013, given that the MAR output has much higher resolution ( $\sim 10$  km) than GRACE ( $\sim 334$  km). GRACE's inevitable blurring of the SMB trend field both broadens the zone of negative mass acceleration in southwest Greenland, and lowers its amplitude. The MAR SMB trend in the northeast GrIS is more pronounced than in adjacent areas, but this local feature is a little less pronounced, and slightly displaced, relative to GRACE's secondary peak in mass acceleration (Fig. 5*A*, “ne”) suggesting that in this area changes in ice dynamics also played a role, as discussed later on. Note that both GRACE and MAR agree on near-zero or slightly positive mass accelerations in the east and southeast margins (Fig. 5*A*, “e” and “se”), respectively. MAR's result for the southeast is associated with positive snowfall anomalies. GNET reveals a slightly more complex situation in which accelerations in uplift rates change sign from one major outlet glacier to the next (Fig. 2*A* and *SI Appendix*, Fig. S24). GRACE tends to smooth out these alternating accelerations in dynamic mass change and blends the result with the more subdued SMB trend due to increased snowfall accumulation.

### Topography Modulates the Impact of Atmospheric Warming

The negative phase of the NAO in summertime enhances melting over much of Greenland, but especially in west Greenland (13, 14). The progressive, pre-2013 warming of west Greenland summers was not as spatially focused as the strongest negative mass accelerations (Fig. 5*A* and *C*). The spatial distribution of ablation is largely controlled by the spatial distribution of air temperature and solar

radiation. The ice sheet's sensitivity to surface warming is strongly influenced by surface elevation. If the surface warms from  $-1$  to  $3$  °C, for example, then the impact of  $4$  °C warming is vastly greater than if the surface warms from  $-5$  °C to  $-1$  °C. This is why simple models of melting are often expressed in terms of seasonal sums of positive degree-day (17, 18). The amount of melting induced by a temperature increase is strongly dependent on initial surface temperature, and thus on latitude and elevation (*SI Appendix*, Fig. S11), as well as time of year. The influence that surface elevation has on melting and runoff is enhanced by a powerful positive feedback. The ice exposed in the ablation zone has lower albedo than snow surfaces, leading to greater absorption of solar radiation. Indeed, the largest source of melt energy in the ablation zone is absorbed solar energy, not the transfer of sensible heat from the air (19). Nevertheless, the primary control on the geometry of the ablation zone is air temperature, and, at a given time of year, near-surface temperature is largely controlled by latitude and elevation. In a given latitude zone, lower topographic gradients near the margins of the ice sheet lead to a wider ablation zone, thus acting as primary controls on the spatial extent of the albedo feedback.

Even if the southeast and southwest margins of the GrIS were exposed to similar positive temperature trends, the mass loss trend would be more pronounced at the southwest margin because it has a far greater area of low elevation ice surface per unit length of margin than does the southeast margin (Fig. 5*D*). Similarly, the low elevation and surface slopes prevailing at the northeast margin ensure that it incorporates a far greater area of low elevation ice surface than does a similarly sized segment of the northernmost margin of the ice sheet, or a similarly sized segment of the east margin (region “e” in Fig. 5*A*) where surface elevations  $>2$  km loom over the nearby edges of the ice sheet. This helps us explain the localized center of sustained negative mass acceleration in the northeast (Fig. 5*A*, ne). The locally enhanced sensitivity of the



mechanism will be volumetrically concentrated in thinner portions of ice sheet associated with low surface elevations. Meltwater can also accelerate ice flow by modifying the mechanical conditions at the base of the ice sheet (25–27). In extreme cases, the development of subglacial lakes can lift portions of an ice sheet or an ice cap from its bed (28, 29). The hypothesis that atmospheric warming can promote increases in discharge, dynamic thinning, and glacial retreat has recently been invoked in Prudhoe Land in northwest Greenland (30).

## Discussion

The coverage and quality of our meteorological, glaciological, and geodetic datasets decline as we regress to the mid-1900s, as does our ability to track the relative importance of SMB and DMB as drivers of deglaciation. Even so, it is clear that the sustained acceleration in mass loss recorded by GRACE before mid-2013 was completely unprecedented (31), as was the collapse of seasonally adjusted mass rate from its peak value to nearly zero in the following 12–18 mo. Mass rate scales with SMB and DMB, so mass acceleration scales with the trend or rate of change of SMB and DMB. Greenland's air–sea–ice system crossed one or more thresholds or tipping points near the beginning of this millennium, triggering more rapid deglaciation. The pronounced negative shift in spatially integrated SMB (Fig. 5E and SI Appendix, Fig. S8) was dominated by increased summertime runoff (Fig. 5E and G). Runoff increased over most of the flanks of the GrIS, but most noticeably in southwest Greenland, where the margin was gaining mass in 2003 but strongly losing mass by late 2012 (Fig. 4). Total glacial discharge integrated over southwest Greenland is not only very low ( $9.5 \pm 1.5$  Gt/y) compared with other areas (32), it has been unusually stable as well. South of JI, mass acceleration was dominated by falling SMB from 2000 onward. A little further north, seasonally adjusted discharge rates at JI increased by ~44% from early 2000 to early 2006, but barely changed between early 2006 and early 2012 (32). It was SMB that

was strongly falling in this second 6-y time interval, not DMB (10). Similar considerations apply in southeast Greenland (32).

The decadal acceleration in mass loss in southwest Greenland arose due to the combination of sustained global warming and positive fluctuations in temperature and insolation driven by the NAO. In SI Appendix, we develop an analogy with the global coral bleaching events triggered by every El Niño since that of 1997/1998, but not by any earlier El Niño event. Since 2000, the NAO has worked in concert with global warming to trigger major increases in summertime runoff. Before 2000, the air was too cool for the NAO to do the same. In a decade or two, global warming will be able to drive 2012 levels of runoff with little or no assistance from the NAO. In the shorter term, we can infer that the next time NAO turns strongly negative, SMB will trend strongly negative over west and especially southwest Greenland, just as future warming of the shallow ocean is expected to have its largest impact, via DMB (33, 34), in southeast and northwest Greenland. Because ice sheet topography equips southwest Greenland with greater sensitivity to atmospheric forcing, we infer that within two decades this part of the GrIS will become a major contributor to sea level rise. There is also the suggestion that enhanced summertime melting may induce more sustained increases in discharge rates.

## Materials and Methods

We used the global GRACE solution CSR release RL-05. Our regional GRACE analysis used the methodology of ref. 3. Our GPS data processing followed that of ref. 6, as did our approach to time series analysis, both for GRACE and GNET. We characterized SMB in Greenland using the regional climate models MAR (15) and RACMO2 (5). Further details, and a discussion of data access, can be found in SI Appendix.

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