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LETTERS

Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets

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Many glaciers along the margins of the Greenland and Antarctic ice sheets are accelerating and, for this reason, contribute increasingly to global sea-level rise[1–7]. Globally, ice losses contribute ~1.8 mm yr^{-1} (ref. 8), but this could increase if the retreat of ice shelves and tidewater glaciers further enhances the loss of grounded ice[9] or initiates the large-scale collapse of vulnerable parts of the ice sheets[10]. Ice loss as a result of accelerated flow, known as dynamic thinning, is so poorly understood that its potential contribution to sea level over the twenty-first century remains unpredictable[11]. Thinning on the ice-sheet scale has been monitored by using repeat satellite altimetry observations to track small changes in surface elevation, but previous sensors could not resolve most fast-flowing coastal glaciers[12]. Here we report the use of high-resolution ICESat (Ice, Cloud and land Elevation Satellite) laser altimetry to map change along the entire grounded margins of the Greenland and Antarctic ice sheets. To isolate the dynamic signal, we compare rates of elevation change from both fast-flowing and slow-flowing ice with those expected from surface mass-balance fluctuations. We find that dynamic thinning of glaciers now reaches all latitudes in Greenland, has intensified on key Antarctic grounding lines, has endured for decades after ice-shelf collapse, penetrates far into the interior of each ice sheet and is spreading as ice shelves thin by ocean-driven melt. In Greenland, glaciers flowing faster than 100 m yr^{-1} thinned at an average rate of 0.84 m yr^{-1}, and in the Amundsen Sea embayment of Antarctica, thinning exceeded 9.0 m yr^{-1} for some glaciers. Our results show that the most profound changes in the ice sheets currently result from glacier dynamics at ocean margins.

To quantify ice loss from ice sheets, three different methods have so far been used: calculation of flux imbalance from separate measurements of snow accumulation and ice flow velocity, detection of changing gravitational anomalies and measurement of changing ice-sheet surface elevation. Each approach has limitations: flux-imbalance estimates suffer from inaccuracies in snow accumulation rate[13], and satellite gravity measurements have poor spatial resolution and are prone to problems in modelling crustal rebound[14]. Direct measurement of volume change by satellite radar altimeters is limited to latitudes between 81.5° S and 81.5° N and to surface slopes below ~1°. Resolution is limited to a footprint width of 2–3 km, measurement density is low (being restricted to ground-track crossover points) and radar surface penetration is imperfectly known. Current radar systems perform poorly where change is most rapid, namely along the relatively steep and narrow glaciers fringing the ice sheets[12]. Furthermore, conversion from volume to mass change requires knowledge of the density of snow or ice added or lost. Additional information is needed to distinguish between these in low-resolution radar altimeter measurements[12].

An entirely different experiment, the Geoscience Laser Altimeter System, launched in 2002 on board NASA's ICESat, was designed to overcome several of these issues. Here we report a method of comparing data from near-repeat ICESat tracks. This produces a much greater measurement density than was previously available, revealing the pattern of change from local to continental scales, including the steep ice-sheet margins.

Figure 1 shows two examples demonstrating that our technique provides coherent measurements of change, significant on length scales on the order of 100 m along the satellite ground track. This high resolution allows us, in many areas, to distinguish between changes in elevation that result from dynamical changes associated with fast-flowing ice and those that result from other causes (snowfall, melt and so on), by comparing the rate of change in adjacent slow- and fast-flowing areas in the same climatic setting (Fig. 1b, Supplementary Figs 5, 6, 7, 8, 9 and 10 and Supplementary Tables 2, 4 and 5).

Comparison of Fig. 2 with those produced using the >10-yr records obtained by radar altimetry[12,15,16] shows that our technique successfully reproduces the large-scale patterns of ice-sheet change and, in both Antarctica and Greenland, shows features not previously seen.

Prominent in Greenland is the strong thinning of the southeast and northwest ice-sheet margins (Supplementary Fig. 3); higher areas in the south thickened. These margins have a positive surface mass balance (SMB) and, hence, a high proportion of discharge through tidewater glaciers. Southeastern glaciers accelerated between 1996 and 2005, but those in the northwest showed little change in flow[2]. The widespread dynamic thinning we identify in the northwest therefore implies a sustained period of dynamic imbalance. For the ice sheet as a whole, areas of fast flow[1] (>100 m yr^{-1} (ref. 2)) thinned significantly more rapidly than slow-flowing areas (0.84 m yr^{-1} versus 0.12 m yr^{-1}), a discrepancy that cannot be explained by variability in SMB (Supplementary Table 2). We find that of 111 glaciers surveyed, 81 thinned dynamically at rates greater than twice the thinning rate on nearby slow-flowing ice at the same altitude (Supplementary Tables 5 and 6). Dynamic thickening is scarce but notable on quiescent surge-type glaciers Storstrømmen[17] (Fig. 2, inset; S) and neighbouring L. Bistrup Bræ (Supplementary Fig. 3). For the first time, low-altitude changes are discernible across the slower-flowing, land-terminating ice sheet and on many small, fringing ice caps. North of 80° N, thinning of the slow-flowing margin peaked at 0.15 ± 0.002 m yr^{-1} at an altitude of 900 m but was close to zero at 450 and 1,450 m (Supplementary Fig. 4), with changes most likely driven by SMB anomalies. In contrast, the southwestern margin thickened at all altitudes, at up to 0.44 ± 0.005 m yr^{-1}. Dynamic thinning has penetrated deep into the ice sheet: on Jakobshavn Isbræ, Helheim and Kangerdlugssuaq glaciers (Fig. 2, inset; respectively J, H and K), it is detectable from the snout to 120, 95 and 100 km inland, respectively, at altitudes of 1,600 m to 2,000 m above sea level. If these changes are driven by the reported recent glacier retreat and acceleration[18], this would imply remarkable rates

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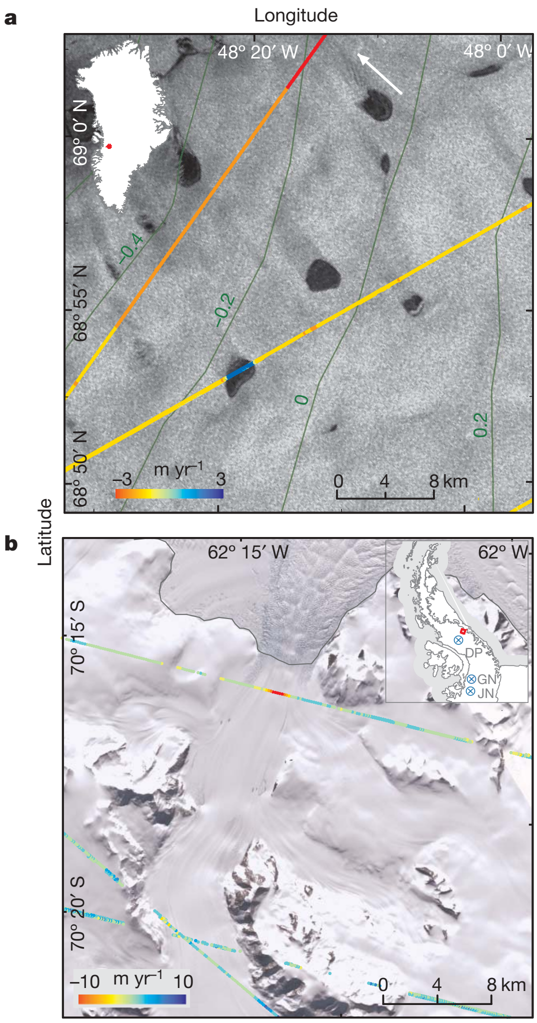

Figure 1 | High-resolution change measurements from along-track interpolation of ICESat data. a, The filling of a melt pond (blue; see colour scale) is resolved against a trend of dynamic thinning (yellow to red) on Jakobshavn Isbræ, Greenland. Thinning increases strongly towards the glacier centre, to the northeast. White arrow, main ice flow direction; green contours, mean SMB (metres water equivalent per year) (after ref. 2); background, synthetic-aperture-radar image. See also Supplementary Fig. 2. **b**, Rapid dynamic thinning (up to 13 m yr^{-1}) of Clifford Glacier, feeding the southern part of the Larsen Ice Shelf, Antarctic Peninsula. Background, Landsat Image Mosaic of Antarctica (grounding line in grey). Data are unfiltered. Inset, global-positioning-system ground-control points from Supplementary Table 1 (JN, Jurassic Nunatak; GN, Gomez Nunatak; DP, Dyer Plateau).

of propagation (Supplementary Fig. 5). Furthermore, deeply penetrating dynamic thinning has spread to high northern latitudes, for example on Tracy Glacier at 77.6° N (Supplementary Table 3 and Supplementary Fig. 6).

In Antarctica, we find significant dynamic thinning of fast-flowing ice at rates greater than plausible through interannual accumulation variability for drainage sectors[19] F′G and GH (Fig. 2), with significant dynamic thickening of sector A′B (Supplementary Table 4). On the glacier scale, thinning is strongest in the Amundsen Sea embayment (ASE), where it is confirmed as being localized on the fast-flowing glaciers and their tributaries (Fig. 3 and Supplementary Fig. 7). The area close to the Pine Island Glacier grounding line thinned in the period 2003–2007 at up to 6 m yr^{-1}, neighbouring Smith Glacier thinned at a rate in excess of 9 m yr^{-1} and Thwaites Glacier thinned at a rate of around 4 m yr^{-1}. These rates are higher than those reported for the 2002–2004 period[20]. Numerous small, independent glaciers feeding the same, rapidly thinning ice shelves, namely the Crosson and Dotson ice shelves[21], are also thinning dynamically, which is strong evidence of a common, ocean-driven cause (Supplementary Fig. 7). Surface lowering is apparent across almost the whole area of the drainage basins of the Kohler, Smith, Pope and Haynes glaciers of the Amundsen Sea embayment, and up to the northern drainage divide of Pine Island Glacier. We calculate the mean elevation rate for sector GH to be -0.139 ± 0.07 m yr^{-1} (whereas a rate of -0.092 ± 0.007 m yr^{-1} was reported for 1995–2003[22]), giving a volume change of -57 ± 29 km^3 yr^{-1}.

Several new features in the pattern of Antarctic elevation change are now visible. The 'polar hole' resulting from the orbital limit of satellites is reduced from the area south of 81.5° S for current radar altimetry to that south of 86° S for ICESat; hence, we now see the full Antarctic grounding line, including the Siple Coast (Fig. 2; SC). This allows us to confirm expectations of previous studies of the shutdown of the Kamb Ice Stream around 130 yr ago[12,23–25]. We see thickening of the ice stream reaching 0.65 ± 0.07 m yr^{-1} close to the transition between its fast-flowing tributaries and stagnant trunk (Fig. 4). The fast-flowing (>200 m yr^{-1}) sections of the neighbouring Whillans Ice Stream are thickening, but this is clearly bounded by the ice-stream shear margins, with the interstream ridges and slower-flowing upper drainage basins conversely thinning at up to 0.25 ± 0.07 m yr^{-1}.

Assuming that these volume changes are of ice with a density of 917 kg m^{-3}, our observations allow an independent assessment of the flux imbalance. For drainage sector E′E′′ as a whole (Fig. 4), the net change was $+36 \pm 16$ Gt yr^{-1} ($+39$ km^3 yr^{-1}), which is substantially greater than estimates based on the partial radar altimetry coverage[12,16], but agrees with estimates from flux imbalance[13,26].

On the Amundsen Sea coast of West Antarctica, our laser altimetry method resolves rapid dynamic thinning along the full length of the grounded ice-sheet margin feeding the Getz Ice Shelf (Fig. 3; GIS) on finer spatial scales than are possible using radar altimetry[12]. This reveals thinning at the grounding line at rates of up to several metres per year over areas of fast flow; this thinning attenuates inland but more than outweighs gains on the interior of the drainage basin. The net volume change for sector F′G is -14 ± 9 km^3, in agreement with flux-imbalance calculations[13,24] (assuming losses are of ice). Here also, the more dynamic glaciers on offshore islands bounded by the Getz Ice Shelf are thinning rapidly on their lower reaches, suggesting that the common cause is the ocean-driven thinning of this shelf at 2–3 m yr^{-1} (ref. 27).

Conversely, for the 400 km of coast feeding the Abbott Ice Shelf (AIS), whose thickness is unchanging[27], the drainage basin thickened strongly down to the grounding line, presumably driven by recent anomalously high snowfall rates (Fig. 3). This is partly offset by dynamic thinning of adjacent Eltanin Bay (EB) glaciers, giving a net volume gain of $+8 \pm 24$ km^3 yr^{-1} (loss of 8 km^3 yr^{-1} plus gain of 16 km^3 yr^{-1}) for sector HH′; hence, we do not find evidence for the large negative flux imbalance (-49 Gt yr^{-1}) reported previously[13].

In East Antarctica, we observe dynamic thinning on some outlets, particularly between 90° and 165° E (Supplementary Figs 8 and 9). Thinning of Totten Glacier, the highest-flux East Antarctic outlet, is three times greater than previously reported[28]. The similar behaviour of its smaller, independent neighbours indicates a common, regional and perhaps ocean-driven cause.

With ICESat, we can view elevation change over the full Antarctic Peninsula for the first time (Fig. 2), and find that slow-flowing ice caps and divides along the Bellingshausen Sea (BS) coast are thickening at up to 1 m yr^{-1} (comparable to radar altimetry measurements of the neighbouring inland ice sheet for the preceding 13 yr (ref. 12)). This signal extends at high altitude to the peninsula's northern tip, contrasting strongly with profound dynamic thinning of collapsed-ice-shelf tributary glaciers flowing from the plateau to both the east and west coasts (see, for example, Supplementary Fig. 10). These glaciers are thinning at some of the highest rates recorded either in Antarctica or Greenland (up to tens of metres per year), and ongoing thinning is detectable right up to the headwalls, or well into the inland ice sheet,

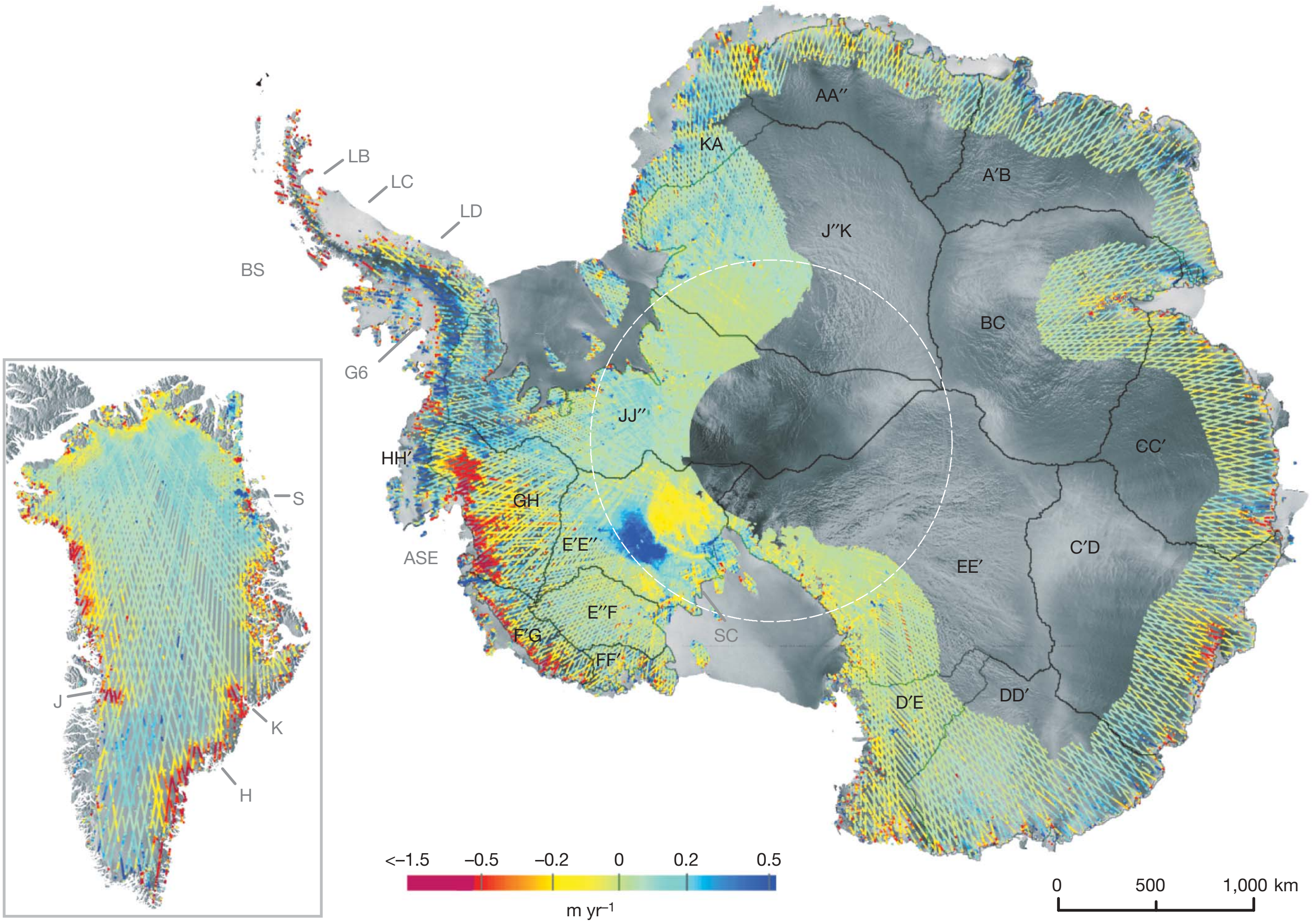

Figure 2 | Rate of change of surface elevation for Antarctica and Greenland. Change measurements are median filtered (10-km radius), spatially averaged (5-km radius) and gridded to 3 km, from intervals (Δt) of at least 365 d, over the period 2003–2007 (mean Δt is 728 d for Antarctica and 746 d for Greenland). East Antarctic data cropped to 2,500-m altitude. White dashed line (at 81.5° S) shows southern limit of radar altimetry measurements. Labels are for sites and drainage sectors (see text).

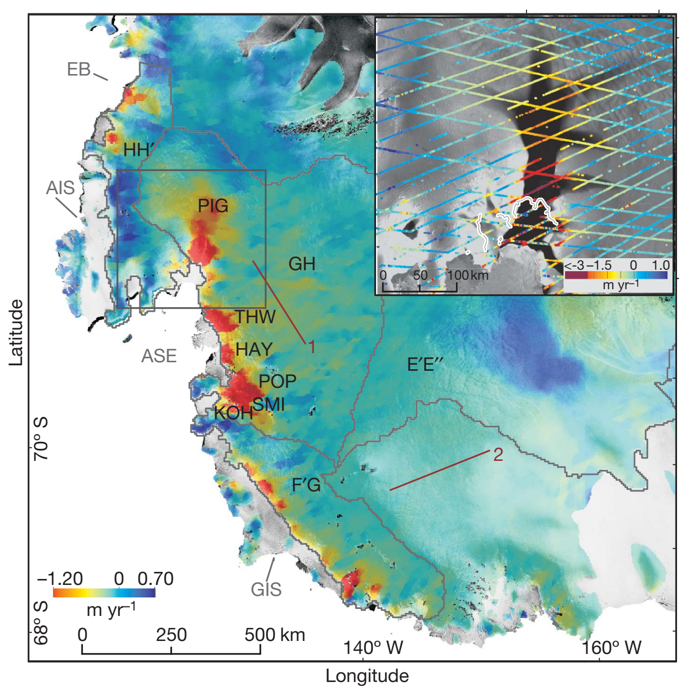

Figure 3 | Rate of elevation change of coastal West Antarctica. Filtered, spatially averaged (10-km radius) $\Delta h/\Delta t$ data (background, Radarsat Antarctic Mapping Project (RAMP) mosaic). We note fast thinning on the Amundsen Sea embayment (ASE) glaciers Pine Island (PIG), Thwaites (THW), Haynes (HAY), Pope (POP), Smith (SMI) and Kohler (KOH) and on tributaries of the thinning Getz Ice Shelf (GIS). Tributaries of the unchanging Abbott Ice Shelf (AIS) thickened. Profiles 1 and 2 are discussed in Supplementary Methods. Inset, high-resolution data over Pine Island Glacier. Dynamic thinning is strongly concentrated on the fast-flowing trunk (dark grey in background[28]). Change becomes highly variable on the floating, fissured ice-shelf downstream of the year-2000 grounding line (outlined in white).

even up to 30 yr after shelf collapse. Glacier tributaries feeding the surviving but thinning parts of the Larsen Ice Shelf (Fig. 2; LC and LB)[29], plus the George VI Ice Shelf (G6) and the little-studied, southern part of the Larsen Ice Shelf (Fig. 2; LD), also thinned at rates of up to several metres per year. This behaviour, similar to that seen on Getz, Crosson and Dotson ice-shelf tributaries, demonstrates an unexpectedly marked dynamic response of glaciers flowing into intact but thinning ice shelves.

To conclude, our simple technique for using ICESat along-track data to measure ice-sheet change is an effective tool for mapping continental and local-scale changes and can deliver two orders of magnitude more measurements than crossover analysis, increasing spatial coverage and resolution. The ICESat data constitute complete, consistent and directly comparable maps of elevation change for the entire grounded margins of the Antarctic and Greenland ice sheets, where rapid change is concentrated. They broadly agree with those from radar altimetry but show changes farther south in Antarctica, closer to the ice-sheet margins, on coastal ice caps and ice rises, and on the mountainous Antarctic Peninsula and Greenland margins. The high spatial resolution allows us in many places to make the distinction between dynamic thinning of faster-flowing ice and other elevation-change signals. Our independent measurements act as arbiter in areas where existing methods fail to agree on the magnitude of ice-sheet volume change: we find support for the results of flux-balance studies on the Siple Coast and Getz Ice Shelf areas of West Antarctica.

The pattern of change now apparent across Antarctica and Greenland is complex, exhibiting the influence of changing precipitation, atmospheric temperature and oceanographic conditions, but the most profound changes clearly result from glacier dynamic effects. Much of the Greenland ice-sheet margin is thinning slowly as SMB becomes more negative, but many coastal glaciers at all latitudes show evidence specifically of rapid dynamic thinning as a result of acceleration of flow. Where strong dynamic thinning has begun, it has spread rapidly, deep into the ice-sheet interior and up to high altitudes. In Antarctica, dynamic thinning has accelerated at the grounding lines of the major glaciers of the Amundsen Sea embayment, and in places has penetrated to within 100 km of the ice divides. Ice-shelf-collapse glaciers show particularly strong thinning that has persisted for years to decades after collapse and in places has penetrated to their headwalls. Although losses are partly offset by strong gains on the spine and western flank of the Antarctic Peninsula, numerous glaciers feeding intact Antarctic Peninsula, West Antarctic and East Antarctic ice shelves are also thinning dynamically. We infer that grounded glaciers and ice streams are responding sensitively not only to ice-shelf collapse but to shelf thinning owing to ocean-driven melting. This is an apparently widespread phenomenon that does not require climate warming sufficient to initiate ice-shelf surface melt. Dynamic thinning of Greenland and Antarctic ice-sheet ocean margins is more sensitive, pervasive, enduring and important than previously realized.

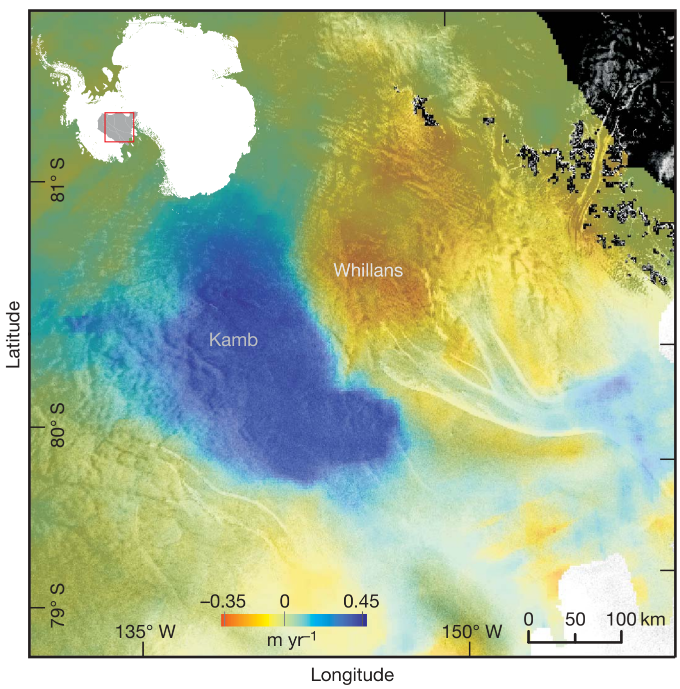

Figure 4 | Rate of elevation change on the Siple Coast, Antarctica. Filtered, spatially averaged (10-km radius) $\Delta h/\Delta t$ data (background, RAMP synthetic-aperture-radar mosaic). The Kamb Ice Stream is thickening, as are the fast-flowing sections of the Whillans Ice Stream. Much of the Whillans catchment and many of the interstream ridges are thinning. Inset, location (red) and drainage sector E′E′′ (grey).

METHODS SUMMARY

ICESat samples surface elevation over 65-m footprints every 172 m along the satellite orbit, and closely repeats ground tracks on the Greenland and Antarctic ice sheets. However, technical issues limit the number of repeated tracks[30], and they are rarely repeated precisely—most are offset by up to a few hundred metres. This has made height-change measurement difficult without knowledge of the cross-track slope[3]. Attention has therefore focused on measuring change at relatively sparse ground-track crossovers, discarding the bulk of along-track data.

Our approach maximizes coverage by using the along-track data, allowing us to resolve ice-sheet change in greater detail. We applied our method to the entire grounded Greenland ice sheet and its fringing ice caps (6,700,000 measurements of height change rate, $\Delta h/\Delta t$), and to the grounded Antarctic ice sheet below 2,500 m, including islands and ice caps (43,500,000 $\Delta h/\Delta t$ measurements).

We used ICESat Release 28 GLA12 data[31] from between February 2003 and November 2007. We fitted planar surfaces to parallel tracks of point height and date measurements that are close in space (< 300 m) and time (< 2 yr). We then subtracted the height and date of later point measurements that overlap these interpolated surfaces, giving us $\Delta h/\Delta t$ (Supplementary Figs 1 and 2). We repeated this process for all possible combinations of interpolated and overlapping tracks that fit our criteria. This approach sacrifices temporal resolution to gain spatial coverage. We estimate the uncertainty in our spatially averaged $\Delta h/\Delta t$ values to be ± 0.07 m yr^{-1} at the 1σ level.

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1. Joughin, I. *et al.* Continued evolution of Jakobshavn Isbrae following its rapid speedup. *J. Geophys. Res.* **113**, doi:10.1029/2008JF001023 (2008).
2. Rignot, E. & Kanagaratnam, P. Changes in the velocity structure of the Greenland ice sheet. *Science* **311**, 986–990 (2006).
3. Scambos, T. A., Bohlander, J. A., Shuman, C. A. & Skvarca, P. Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophys. Res. Lett.* **31**, doi:10.1029/2004GL020670 (2004).
4. Krabill, W. *et al.* Greenland ice sheet: increased coastal thinning. *Geophys. Res. Lett.* **31**, doi:10.1029/2004GL021533 (2004).
5. Pritchard, H. D. & Vaughan, D. G. Widespread acceleration of tidewater glaciers on the Antarctic Peninsula. *J. Geophys. Res.* **112**, doi:10.1029/2006JF000597 (2007).
6. Sole, A., Payne, T., Bamber, J., Nienow, P. & Krabill, W. Testing hypotheses of the cause of peripheral thinning of the Greenland Ice Sheet: is land-terminating ice thinning at anomalously high rates? *Cryosphere* **2**, 205–218 (2008).
7. Scott, J. B. T. *et al.* Increased rate of acceleration on Pine Island Glacier strongly coupled to changes in gravitational driving stress. *Cryosphere* **3**, 125–131 (2009).
8. Meier, M. F. *et al.* Glaciers dominate eustatic sea-level rise in the 21st century. *Science* **317**, 1064–1067 10.1126/science.1143906 (2007).
9. Vieli, A., Funk, M. & Blatter, H. Flow dynamics of tidewater glaciers: a numerical modelling approach. *J. Glaciol.* **47**, 595–606 (2001).
10. Schoof, C. Ice sheet grounding line dynamics: steady states, stability and hysteresis. *J. Geophys. Res.* **112**, doi:10.1029/2006JF000664 (2007).
11. Bindoff, N. L. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 385–432 (Cambridge Univ. Press, 2007).
12. Wingham, D., Shepherd, A., Muir, A. & Marshall, G. J. Mass balance of the Antarctic ice sheet. *Phil. Trans. R. Soc. A* **364**, 1627–1636 (2006).
13. Rignot, E. *et al.* Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geosci.* **1**, 106–110 (2008).

14. Velicogna, I. & Wahr, J. Acceleration of Greenland ice mass loss in spring 2004. *Nature* **443,** 329–331 (2006).
15. Zwally, H. J. *et al.* Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. *J. Glaciol.* **51,** 509–527 (2005).
16. Davis, C. H., Yonghong, L., McConnell, J. R., Frey, M. M. & Hanna, E. Snowfall-driven growth in East Antarctic ice sheet mitigates recent sea-level rise. *Science* **308,** 1898–1901 (2005).
17. Reeh, N., Mohr, J. J., Madsen, S. N., Oerter, H. & Gundestrup, N. S. Three-dimensional surface velocities of Storstrømmen glacier, Greenland, derived from radar interferometry and ice-sounding radar measurements. *J. Glaciol.* **49,** 210–219 (2003).
18. Howat, I. M., Joughin, I. R. & Scambos, T. A. Rapid changes in ice discharge from Greenland outlet glaciers. *Science* **315,** 1559–1561 (2007).
19. Liu, H. X., Jezek, K. C. & Li, B. Development of Antarctic DEM by integrating cartographic and remotely sensed data: a GIS-based approach. *J. Geophys. Res.* **104,** 23199–23213 (1999).
20. Thomas, R. *et al.* Accelerated sea-level rise from West Antarctica. *Science* **306,** 255–258 (2004).
21. Rignot, E. & Jacobs, S. S. Rapid bottom melting widespread near Antarctic ice sheet grounding lines. *Science* **296,** 2020–2023 (2002).
22. Helsen, M. M. *et al.* Elevation changes in Antarctica mainly determined by accumulation variability. *Science* **320,** 1626–1629 (2008).
23. Smith, B. E., Bentley, C. R. & Raymond, C. F. Recent elevation changes on the ice streams and ridges of the Ross Embayment from ICESat crossovers. *Geophys. Res. Lett.* **32,** doi:10.1029/2005GL024365 (2005).
24. Rignot, E. & Thomas, R. H. Mass balance of polar ice sheets. *Science* **297,** 1502–1506 (2002).
25. Joughin, I. & Tulaczyk, S. Positive mass balance of the Ross Ice Streams, West Antarctica. *Science* **295,** 476–480 (2002).
26. Joughin, I., Tulaczyk, S., Bindschadler, R. & Price, S. F. Changes in west Antarctic ice stream velocities: observation and analysis. *J. Geophys. Res.* **107,** doi:10.1029/2001JB001029 (2002).
27. Shepherd, A., Wingham, D. & Rignot, E. Warm ocean is eroding West Antarctic ice sheet. *Geophys. Res. Lett.* **31,** doi:10.1029/2004GL021106 (2004).
28. Rignot, E. Changes in ice dynamics and mass balance of the Antarctic ice sheet. *Phil. Trans. R. Soc. Lond. A* **364,** 1637–1655 (2006).
29. Shepherd, A., Wingham, D., Payne, T. & Skvarca, P. Larsen ice shelf has progressively thinned. *Science* **302,** 856–859 (2003).
30. Abshire, J. B. *et al.* Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: on-orbit measurement performance. *Geophys. Res. Lett.* **32,** doi:10.1029/2005GL024028 (2005).
31. Zwally, H. J. *et al.* GLAS/ICESat L2 Antarctic and Greenland Ice Sheet Altimetry Data V028. *Boulder, CO: National Snow and Ice Data Center* ⟨http://nsidc.org/data/gla12.html⟩ (2007).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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