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Seasonal Speedup Along the Western Flank of the Greenland Ice Sheet

Ian Joughin, *et al.*

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across their surface, supporting the fracture-based mechanism for rapid drainage that we have described for our study lake.

Thus, we have shown that water-driven fracture enabled by the large volume of water stored in supraglacial lakes provides a means by which hydrologic surface-to-bed connections are established through thick ice. Climate warming would lead to earlier and expanded surface lake formation and, as a result, connections to the bed may occur earlier in the melt season and over a larger area, although further work is needed to constrain the limits of this area. This would increase the annual subglacial throughput of meltwater and may substantially impact Greenland Ice Sheet dynamics (*1*).

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Supporting Online Material

www.sciencemag.org/cgi/content/full/1153360/DC1
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Seasonal Speedup Along the Western Flank of the Greenland Ice Sheet

Ian Joughin,[1]* Sarah B. Das,[2] Matt A. King,[3] Ben E. Smith,[1] Ian M. Howat,[1]† Twila Moon[1]

It has been widely hypothesized that a warmer climate in Greenland would increase the volume of lubricating surface meltwater reaching the ice-bedrock interface, accelerating ice flow and increasing mass loss. We have assembled a data set that provides a synoptic-scale view, spanning ice-sheet to outlet-glacier flow, with which to evaluate this hypothesis. On the ice sheet, these data reveal summer speedups (50 to 100%) consistent with, but somewhat larger than, earlier observations. The relative speedup of outlet glaciers, however, is far smaller (<15%). Furthermore, the dominant seasonal influence on Jakobshavn Isbrae's flow is the calving front's annual advance and retreat. With other effects producing outlet-glacier speedups an order of magnitude larger, seasonal melt's influence on ice flow is likely confined to those regions dominated by ice-sheet flow.

Along its western margin, the Greenland Ice Sheet melts at rates that can exceed 2.5 m/year (*1*) as ice flows seaward at speeds of roughly 100 m/year. Embedded within the ice sheet are faster-flowing (200 to 12,000 m/year) outlet glaciers that discharge ice directly to the ocean. When the combined loss from melt and ice discharge, which now act in roughly equal proportions, removes more ice than is replaced by annual snowfall, the excess ice lost to the ocean contributes to sea-level rise.

Glacial motion results from a combination of internal deformation of ice under its own weight, sliding at the ice-bed interface, and deformation of underlying sediments. Basal sliding over a well-lubricated bed is often the source of fast (e.g., >100 m/year) ice motion (*2*). Seasonal fluctuation in the drainage of rainfall and surface meltwater to the bed modulates the sliding speed of many alpine glaciers (*3*–*5*). Greenland's large coastal melt rates have prompted widespread speculation both in the popular media (*6*) and in the scientific literature (*7*, *8*) that a warmer climate will increase melting, which in turn will enhance basal lubrication and hasten ice-sheet retreat. Poor knowledge of this process is one of the limitations on prediction of future ice-sheet contributions to sea-level rise that was noted by the Intergovernmental Panel on Climate Change (*9*).

The few studies of seasonal speedup in Greenland are equivocal about the importance of this lubrication effect. An early study of western Greenland's largest outlet glacier, Jakobshavn Isbrae, found no measurable seasonal speedup (*10*). One outlet glacier in northern Greenland, however, did undergo a short-term speedup, apparently in response to the drainage of a supraglacial lake (*11*). On the slow-moving ice sheet at Swiss Camp (Fig. 1), located just north of Jakobshavn Isbrae, a time series of Global Positioning System (GPS) observations showed seasonal speedups of 5 to 28% that correlated well with summer melt rates (*7*).

To better determine the influence of surface melting on ice-sheet flow, we have assembled a comprehensive set of interferometric synthetic aperture radar (InSAR) and GPS observations (*12*). These data include 71 (September 2004 to August 2007) InSAR velocity maps along two partially overlapping RADARSAT tracks that include Jakobshavn Isbrae, several smaller marine-terminating outlet glaciers, and a several-hundred-kilometer-long stretch of the surrounding ice sheet. We also collected GPS observations from July 2006 to July 2007 at sites near two supraglacial lakes (Fig. 1) south of Jakobshavn Isbrae.

Figure 1 shows the August 2006 speedup measured with InSAR speckle tracking. Although there are coverage gaps, the data show a relatively uniform speedup extending over the bare-ice zone. To simplify the analysis, we used a 150-m/year threshold to partition the area into slower-moving "ice-sheet" and faster-moving "outlet-glacier" regions. Under this rough classification, the ice sheet sped up by 36 m/year (48%) above its 76-m/year mean speed, demonstrating increases over a broad area that are substantially larger than measured earlier at Swiss Camp (28%) (*7*). On the outlet glaciers, the 51-m/year speedup was larger, but this was only 8.6% faster than the 594-m/year mean. Although the InSAR coverage (not shown) is less complete, mid-July 2006 speedups were 71 (97%) and 77 m/year (14%) for the ice-sheet and outlet-glacier regions, respectively. Similar speedups occurred in summer 2007 (e.g., fig. S1).

Although RADARSAT provides good spatial coverage, its temporal resolution (24 days) is limiting. Two-day temporal resolution is available with GPS observations (Fig. 2) from two locations (North Lake and South Lake, Fig. 1). These data reveal periods of generally higher speeds (~50%) during two melt seasons, punctuated by several additional short-term speedups (~100%). The minimum velocity occurs with the late-summer cessation of melt, and speed then slowly increases through the winter before the late-spring large melt-induced speedup.

The GPS sites at both lakes show similar short- and long-term variation in speed, consistent with

[1]Polar Science Center, Applied Physics Lab, University of Washington, 1013 NE 40th Street, Seattle, WA 98105–6698, USA. [2]Department of Geology and Geophysics, Woods Hole Oceanographic Institute, Woods Hole, MA 02543, USA. [3]School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK.

*To whom correspondence should be addressed. E-mail: ian@apl.washington.edu

†Present address: The Ohio State University, 1090 Carmack Road, Columbus, OH 43210–1002, USA.

the spatial uniformity visible at longer time scales (Fig. 1). A notable exception is the local speedup on day 210 at the North Lake site (Fig. 2), which coincides with this lake's rapid drainage to the bed (*13*). Another local speedup occurred when a moulin, a surface-to-bed conduit, likely opened along the South Lake's overflow channel and began draining on day 217. Other than these local lake-drainage events, the velocity peaks coincide well with high-melt periods inferred from positive-degree-days recorded at each site.

We also examined InSAR-measured speed at 10 locations (Fig. 1) on eight marine-terminating outlet glaciers (Fig. 3A), which cover a range of flow speeds. We selected these points to sample the full range of variability for fast-flowing regions (e.g., areas both near and far from the calving front). Eight of these locations showed coincident speedups of 40 to 200 m/year during the 2006 and 2007 melt seasons. Speed at locations 6 and 8, which were near their respective calving fronts, fluctuated erratically without a distinct seasonal pattern. Speed was considerably more regular at location 9, several km upstream on the same glacier as location 8, suggesting the anomalous behavior seen at locations 6 and 8 was driven by the dynamics near the calving front.

Figure 3A does not include the region of Jakobshavn Isbrae flowing faster than 1500 m/year, which continues to evolve following its speedup that began in 1998 (*14*, *15*). To evaluate seasonal variation in speed on this glacier's fast-moving region, we have removed a linear trend with time at three locations designated A through C (Fig. 1). At location A, 4 to 10 km behind the seasonally varying calving front, the speed varies by ±1000 m/year from its 8500-m/year mean (Fig. 3B). Farther upstream (location B), the annual variation diminishes to roughly ±400 m/year (around a 5200-m/year mean). The seasonal variation at these two sites is distinctly different from the melt-related speedup visible elsewhere (Fig. 3A). Instead, peak speeds occur near the melt season's end, after seasonal speedups on other glaciers have ended. In addition, the main trunk's elevated speeds persist past the end of the melt season, taking several months to reach their mid-winter lows. This variation appears negatively correlated with the calving front's position, which fluctuated annually by ~6 km from 2004 to 2007 (Fig. 3B). At location C, the variation (±200 m/year) is an apparent mixture of melt- and ice-front–driven effects.

The InSAR data indicate that seasonal speedup is widespread across much of the bare-ice zone. When averaged over 24 days, the speedup is spatially uniform to a notable degree, particularly given the expected variation in melt intensity with elevation. This spatial uniformity is consistent with motion over a well-distributed drainage network rather than a network of sparsely distributed large tunnels (*4*, *16*).

On Jakobshavn Isbrae's fastest-moving parts (>4000 m/year), the seasonal speedup is in phase with changes in the ice-front position rather than surface meltwater. This region accelerates through spring and summer likely in response to a decline in back-stress as the calving front retreats [e.g., (*17*)]. Conversely, minimum speeds occur as the ice front extends to form a short floating ice tongue each winter. This apparent back-stress modulation of speed is consistent with the initial speedup in ~2000, which was about a factor of 3 larger than the current annual variation and coincided with the disintegration of a much larger section of the ice tongue (*14*, *17*). The current large seasonal variation also is consistent with earlier observations of little or no seasonal variation (*10*, *15*) when the ice-front position was much less variable (*18*).

Although our observations indicate substantial (≥50%) ice-sheet speedup, the melt-induced speedup averaged over a mix of several tidewater outlet glaciers is relatively small (<10 to 15%). When factoring in the short melt-season duration, the total additional annual displacement attributable to surface meltwater amounts to a few percent on glaciers moving at several hundred meters per year. Although conditions might yield a greater sensitivity to melt for some glaciers outside our study area, the limited seasonal observations elsewhere in Greenland suggest a low sensitivity to summer melt similar to that which we observe (*19*–*21*). Because of this low sensitivity, it is unlikely that recent outlet-glacier speedups (*14*, *19*–*21*) were directly caused by increased surface meltwater lubrication during recent warmer summers. Instead, these large speedups were likely driven by processes that caused ice-front retreat and reduced back-stress (*17*, *19*, *20*, *22*), such as declining sea-ice extent near calving fronts (*18*). The recent period of warmer summers (*23*) might also enhance ice-front retreat through increased hydro-fracturing in water-filled crevasses near the calving front (*18*), which represents a process whereby surface meltwater influences glacial flow through means other than directly enhancing basal lubrication.

Smoother beds beneath outlet glaciers, caused by strong erosion, should yield less sensitivity to water-pressure variation (*3*), which may explain some of the insensitivity of outlet-glacier flow to surface meltwater. Additionally, basal shear-heating under the outlet glaciers produces a steady source of

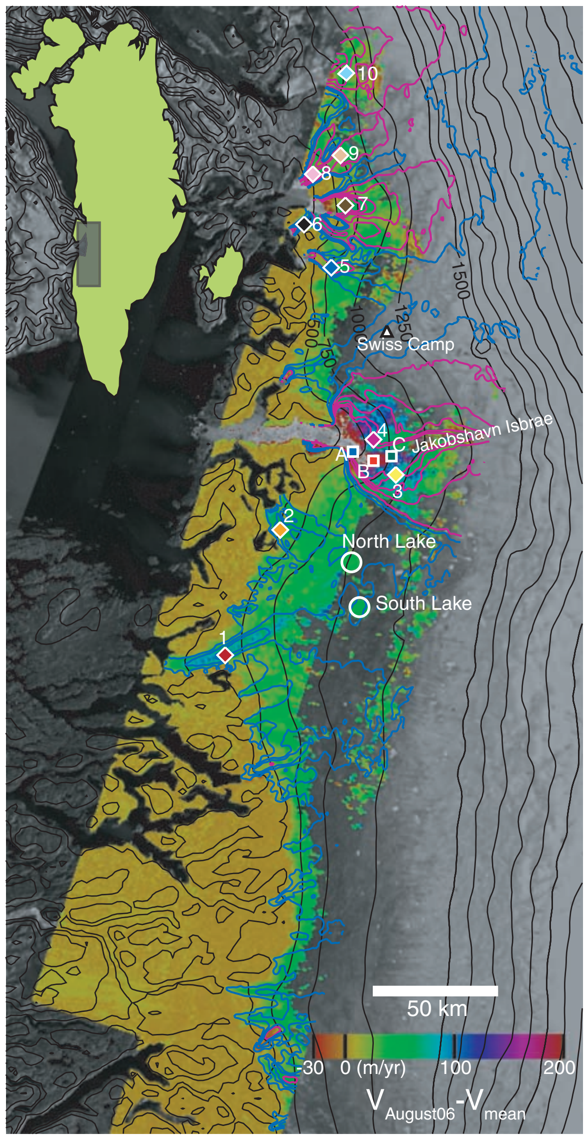

Fig. 1. The August 2006 speedup (color) relative to the September 2004 to December 2006 mean speed displayed over SAR imagery (gray scale). Speeds are determined using overlapping tracks that span two 24-day intervals centered on 5 and 13 August. Mean annual speed is shown with blue, 50-m/year (50 to 150 m/year), and magenta, 200-m/year (200 to 1000 m/year) contours. Contours for speeds greater than 1000 m/year are omitted. Colored/numbered symbols indicate the locations referenced in Fig. 3. We situated our GPS receivers next to two supraglacial lakes at the locations indicated with white circles. The colors within these circles correspond to the values from the GPS observations to allow comparison with the surrounding InSAR speedup values for the same period. Surface elevation is contoured at 250-m intervals (black).

meltwater that could maintain water-filled cavities year-round. In contrast, the water-filled cavities under the ice sheet may drain and collapse over the winter, resulting in a more pronounced speedup once spring melt reaches the bed [e.g., (*24*)]. Another contributor may be that the outlet glaciers are narrow and deep so that their lateral margins have comparable area to their beds. With this geometry, the lateral resistive stresses should be comparable to or even greater than the basal resistive stresses, potentially making outlet glaciers less sensitive to variations in basal lubrication.

Surface meltwater–enhanced basal lubrication has been invoked previously as a feedback that would hasten the Greenland Ice Sheet's demise in a warming climate (*6*–*8*). Our results show that several fast-flowing outlet glaciers, including Jakobshavn Isbrae, are relatively insensitive to this process. Previously reported acceleration and near-doubling of speed of many outlet glaciers from other effects such as back-stress reduction are more than an order of magnitude greater (*14*, *19*–*21*) than the observed melt-induced acceleration. South of Jakobshavn, however, the ice sheet's western flank is comparatively free of outlet glaciers, and ice loss is largely due to melt. Numerical models appropriate to this type of sheet flow and that include a parameterization of surface meltwater–induced speedup predict 10 to 25% more ice loss in the 21st century than models without this feedback (*8*). Thus, surface meltwater–induced speedup may influence large regions of the ice sheet in a warming climate. Although our data provide the most comprehensive observations to date, more data are needed to quantify the relative importance of melt- and calving-front–induced changes in ice flow in controlling near-future ice-sheet mass balance. Our results thus far suggest that surface meltwater–enhanced lubrication likely will have a substantive but not catastrophic effect on the Greenland Ice Sheet's future evolution.

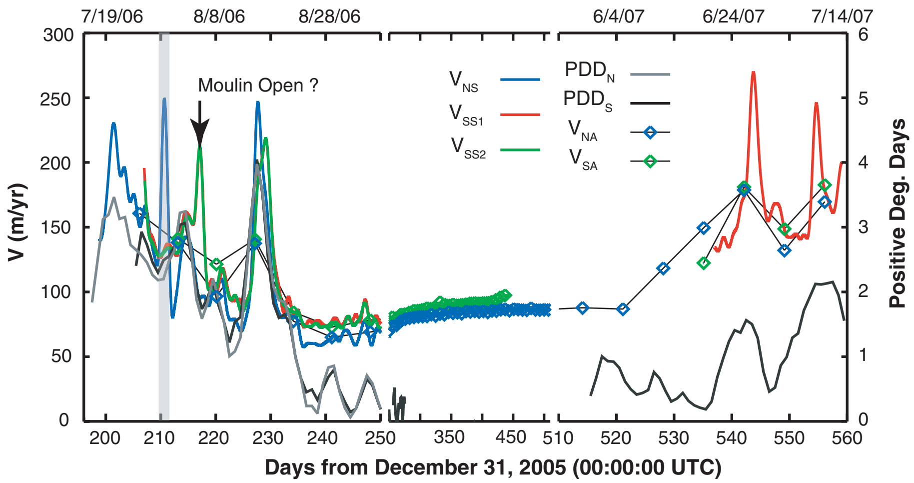

Fig. 2. Speed from GPS stations located south of Jakobshavn Isbrae (Fig. 1). At the North Lake, we installed one summer continuous (15-s sample rate) GPS receiver (NS) and one annual (operating 12 hours/week) GPS receiver (NA). The South Lake had one annual (SA) and two summer (SS1 and SS2) receivers. In summer 2007, NS and SS2 did not resume logging and SA lost power for 3 months. The summer-station data have been smoothed to 2-day resolution, and the year-round estimates are based on weekly positions. Positive-degree-day (PDD) values are included for both sites in 2006 and for the South Lake in 2007. Gray shading indicates when the North Lake drained in 2006 (*13*).

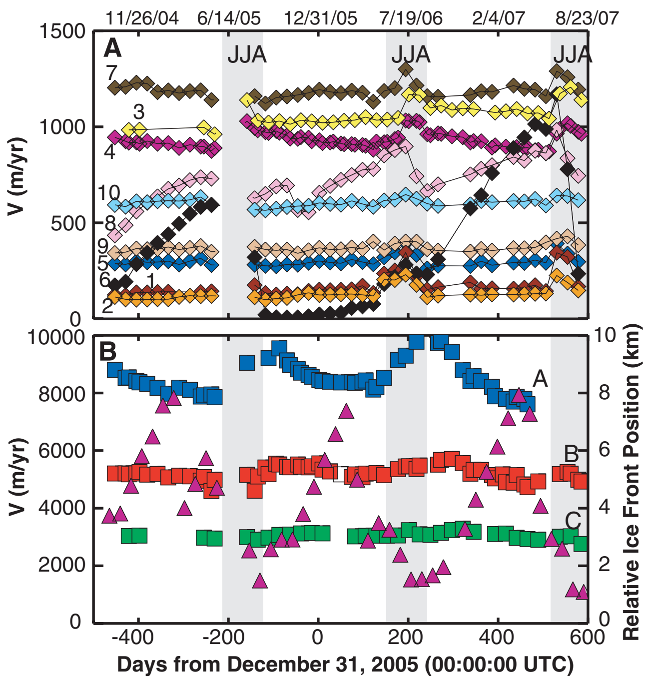

Fig. 3. (**A**) InSAR-determined speed from September 2004 through August 2007 at 10 outlet-glacier locations. The gray shading indicates the months of June, July, and August (JJA). (**B**) Detrended (*12*) speeds (squares) at three locations (A, B, and C) on Jakobshavn Isbrae and relative ice-front position (triangles). Figure 1 shows sampled locations with corresponding colored and numbered/lettered symbols.

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Methods
Fig. S1
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Ian Joughin,* Sarah B. Das, Matt A. King, Ben E. Smith, Ian M. Howat, Twila Moon

*To whom correspondence should be addressed. E-mail: ian@apl.washington.edu

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This PDF file includes:

Supporting Online Material

Methods

InSAR Data

Velocities were determined by applying standard speckle-tracking techniques to 71 RADARSAT image pairs acquired from September 2004 through August 2007 (S*1*). On the fastest moving regions, where motion may introduce strong decorrelation of the speckle patterns, we also applied the algorithm after smoothing the images with a 3-by-3 moving average filter to suppress speckle and enhance matching on features (e.g., crevasses). These results were merged with the speckle-tracked (unfiltered) results in a way that selected the best estimate at each point. Because of the effect of uncompensated surface slopes (S*2*), absolute errors may be as large as 3% where local slopes are high. These errors cancel, however, when making comparisons between InSAR estimates. Relative errors when comparing estimates are spatially and temporally variable, and typically fall in the range of 1-20 m/yr.

GPS Data

The GPS 15-s data, collected in one 12-hour interval each week, from the year-round stations (NA and SA) were processed with the GIPSY software using the Precise Point Positioning (PPP) strategy at 5-minute intervals (S*3*), which were then averaged to produce a weekly position. These positions were used to calculate weekly estimate of velocity.
The continuous GPS summer stations (NS, SS1 and SS2) were processed at the full the 15-s resolution using PPP processing. During some periods when our stations were operating, data were available from a station on bedrock (Kaga) located 55-to-74 km from our sites. When data were available, we also processed our summer sites relative to the Kaga bedrock position, using the Track software (S*4*). In both the PPP and relative data processing, site motion was constrained on an epoch-by-epoch basis to suppress noise without damping the signal. We computed velocities using the PPP data and smoothed the results to 2-day temporal resolution using a finite impulse response (FIR) filter (Fig. 2).

Removal of Secular Trends from InSAR Data

The fast moving regions of Jakobshavn are accelerating at a steady rate of a few percent per year. For this study we are concerned with seasonal variation, so we have removed this trend from data in the area surrounding Jakobshavn. At each grid point, we performed a linear fit to all the estimates over the 3-year span for that location. Using the results from this fit, we removed the spatially-varying linear trend at each grid point (Fig. 3b).

InSAR GPS Comparison

We have compared the InSAR and GPS data for the North Lake location as shown in Figure S1. The lake lies just at the edge of the region of overlap for the two satellite tracks, so we sampled the InSAR data a few kilometers to the west of the GPS location

where there was overlap, doubling the number of estimates. For the period from Day 270 to 500, when the speed was varying slowly, we compared the InSAR data (15 points) to a linear fit to the
GPS data. This yielded a mean difference of 2.1 m/yr and a standard deviation of 6.1 m/yr. The mean difference is well within the difference expected due to the different sampling locations and the standard deviation is consistent with the expected errors.

Figures

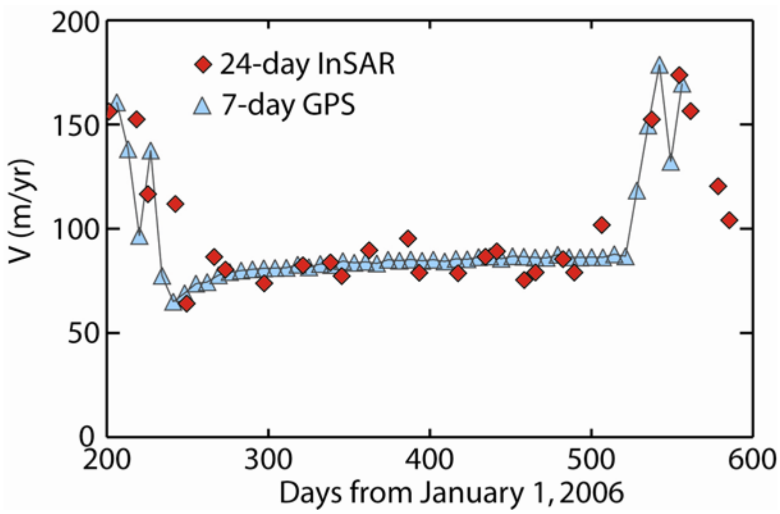

Figure S1. Speed measured with GPS (NA) and InSAR in the vicinity of the North Lake at the location shown in Fig. 1.

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