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Rapid Changes in Ice Discharge from Greenland Outlet Glaciers

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Using satellite-derived surface elevation and velocity data, we found major short-term variations in recent ice discharge and mass loss at two of Greenland's largest outlet glaciers. Their combined rate of mass loss doubled in less than a year in 2004 and then decreased in 2006 to near the previous rates, likely as a result of fast re-equilibration of calving-front geometry after retreat. Total mass loss is a fraction of concurrent gravity-derived estimates, pointing to an alternative source of loss and the need for high-resolution observations of outlet dynamics and glacier geometry for sea-level rise predictions.

The recent, marked increase in ice discharge from many of Greenland's large outlet glaciers has upended the conventional view that variations in ice-sheet mass balance are dominated on short time scales by variations in surface balance, rather than ice dynamics. Beginning in the late 1990s and continuing through the past several years, the ice-flow speed of many tidewater outlet glaciers south of 72° North increased by up to 100%, increasing the ice sheet's contribution to sea-level rise by more than 0.25 mm/year (*1*). The synchronous and multiregional scale of this change and the recent increase in Arctic air and ocean temperatures suggest that these changes are linked to climate warming. The possibility that ice dynamics are so highly sensitive to climate change is of concern, because the physical processes that would drive such a relationship are poorly understood and are not realistically included in ice-sheet models used to predict rates of sea-level rise.

Current estimates of change in Greenland's ice discharge are based on velocity measurements taken 4 to 5 years apart (*1*). However, 50 to 100% increases in ice speed and thinning of tens of meters over a single year have been documented in Greenland and elsewhere (*2*–*6*). Therefore, discharge should be highly variable as well, even at subannual time scales. Large increases in tidewater glacier speed have been attributed to decreased flow resistance and increased along-flow stresses during retreat of the ice front (*2*, *3*, *7*). This suggests that changes in velocity and discharge are coupled to changes in tidewater glacier geometry and that the observed rapid changes may be a transient response to disequilibrium at the front. Therefore, accurate estimates of current rates of discharge and the potential for near-future change require observations of outlet glacier geometry and speed at high temporal resolution.

To assess short-term variability in outlet glacier dynamics, we examined speed, geometry, and discharge at two of Greenland's three largest outlet glaciers between 2000 and 2006. Located on the central east coast, Kangerdlugssuaq (KL) and Helheim (HH) represent 35% of east Greenland's total discharge (*1*). The calving fronts of both glaciers appeared relatively stable from the mid-20th century (*8*, *9*) until 2002, when HH retreated more than 7 km in 3 years (*2*). This was followed by a 5-km retreat of KL during the winter of 2004 to 2005 (*4*). These retreats are much greater than the 1- to 2-km seasonal fluctuations previously observed (*4*, *5*) and followed a sustained period of low-elevation ice thinning (*8*, *10*). Retreats were concurrent with accelerated ice flow (*1*, *2*). This acceleration increased rates of mass loss by 28 and 15 Gt/year at KL and HH, respectively, between 2000 and 2005, representing >40% of the ice sheet's increase in mass loss (*1*).

We measured summer surface speed and elevation for these glaciers using imagery acquired by the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) sensor aboard the Terra satellite, launched in 1999. We constructed Photogrammetric Digital Elevation Models (DEMs) from ASTER stereobands (3N and 3B) and validated them (Figs. 1D and 2D) using laser altimetry data sets collected by NASA's Airborne Topographic Mapper (ATM) in 2001, 2003, and 2005 (*10*). The root-mean-squared differences between DEM and ATM elevations are 10 m, which is similar to the uncertainty quoted in ASTER DEM validation studies (*11*) (Figs. 1D and 2D). Summer surface velocity was obtained from automated feature tracking between repeat, orthorectified principal component images of bands 1 to 3 (*2*, *12*). Uncertainty in these measurements is ~5 m per image pair, or 0.1 to 0.8 m/day for the data presented here. We determined winter velocities (±3% uncertainty) using radar speckle tracking between Canadian Space Agency Radar Satellite

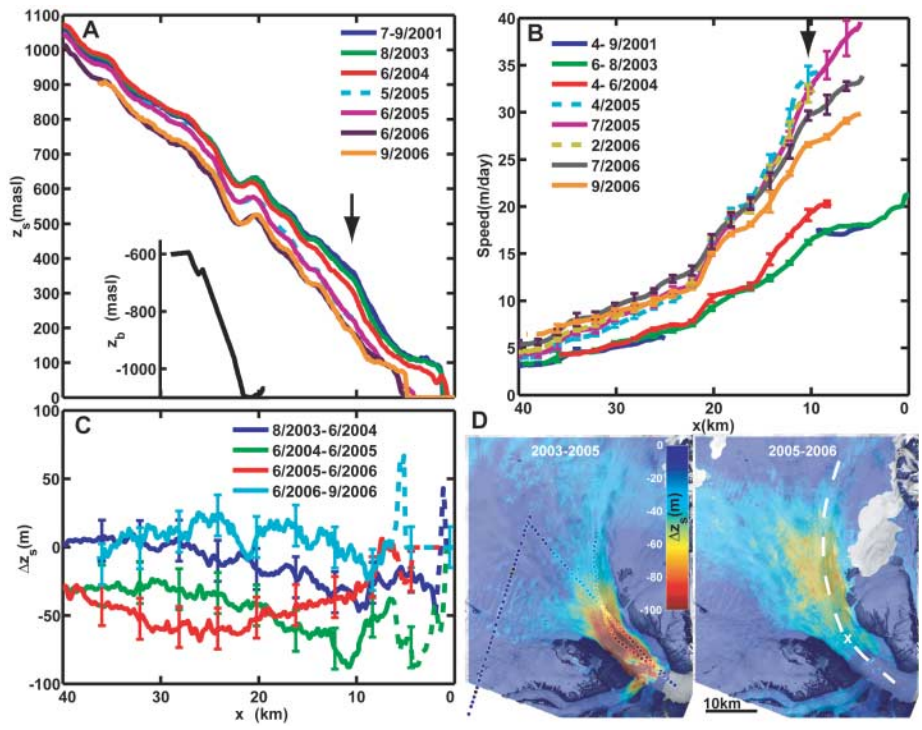

Fig. 1. KL glacier. (**A**) Surface elevation (z_s) from (solid) ASTER DEMs and (dashed) Airborne ATM laser altimetry and bed elevation (z_b) from CoRDS. (**B**) Surface velocity obtained from (solid) optical feature tracking and (dashed) radar speckle tracking along the main flow line, denoted by white dashes in (D). Arrows point to location of flux gate used for discharge calculation. (**C**) Elevation change along the same profile. Dashed segments are changes due to movement of the ice front. (**D**) Maps of elevation change from differenced ASTER DEMs overlaid on the 21 June 2005 image. Circles show repeat ATM altimetry measurements for the same time period and x marks flux-gate location. Error bars in (B) and (C) show means ± SD.

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(RADARSAT) image pairs (24-day separation) (*13*). In some cases, combinations of multiple elevation and speed data sets from the same season improved spatial coverage and reduced errors. The University of Kansas Coherent Radar Depth Sounder (CoRDS) surveyed ice thickness and bed elevation at both glaciers in 2001 (*14*).

From summer 2004 to spring 2005, KL retreated by 5 km (*4*), and its speed increased by 80% near the front and by ~20% at 30 km inland (Fig. 1). Between April and July 2005, the increase in speed migrated rapidly inland with a ~5% decrease in speed close to the front and a ~7% increase in speed in areas farther inland (up-glacier). This upstream propagation continued from July 2005 through July 2006, with the near-front deceleration of ~15% and up-glacier acceleration of ~25%, with the transition between speedup and slowdown at ~15 km. The glacier thinned rapidly during acceleration, with 80 m of thinning near the front and thinning of at least 40 m extending 40 km inland by summer 2005. Thinning moved inland between 2005 and 2006, with a peak thinning of 68 m at about 26 km, but with virtually no thinning at the front. Average thinning over the glacier during the summer of 2006 declined to near zero, with some apparent thickening in areas on the main trunk.

Images from June 2003 are the first to indicate substantial retreat (2.1 km) at HH. During additional retreat over that summer, speedup of 20 to 40% extended at least 20 km up-glacier (Fig. 2). The ice front and speed changed little in 2004, but 4 km of new retreat yielded another major speedup (25%) in the summer of 2005. Many of the earlier data do not extend far inland, but echoing the pattern on KL, speeds from 2006 show a progressive inland acceleration accompanied by deceleration (25%) extending from about 15 km toward the ice front. As with KL, rapid thinning accompanied the large speed increases. By late summer 2006, strain rates indicate a region of compression at about 12 to 15 km. The initial HH acceleration in 2003 produced 40 m of thinning within about 15 km of the ice front. This thinning slowed to 10 m/year when there was little retreat from 2003 to 2004. The 4-km retreat from 2004 to 2005 moved the ice front over a 200-m bathymetric depression, bringing it to or near flotation. Between the summers of 2005 and 2006, the rate of thinning decreased within 20 km of the front, reaching zero at the front and increasing to 50 m/year 25 km from the front. During this period, the glacier advanced 4 km as a floating or near-floating tongue to near the 2003–2004 front position. It appears that the front of this floating tongue may have regrounded in summer 2006, contributing to the deceleration and the region of compression.

On both KL and HH, the data show a markedly similar progression of increasing down-glacier speed and thinning synchronous with retreat, followed by an inland migration of the speed increase. As the front restabilized, speed and thinning increased up-glacier and decreased down-glacier. This progression of dynamic response strongly suggests that the notable increases in acceleration and thinning are related to changes in calving-front position through variations in longitudinal stresses (*2*). Consistent with standard theories of tidewater glacier dynamics (*15*), rapid retreat at HH occurred as the front moved into deeper water and stopped where the bed slope reversed (Fig. 2). At both glaciers, the initial acceleration and thinning after retreat were concentrated within 10 to 20 km of the ice front, which would be the expected range of stress coupling (*16*). Relative thinning down-glacier increases the surface slope and driving stress up-glacier. By this means, thinning and acceleration are advected up-glacier (*17*). This can be seen at KL, where the maximum thinning rates moved ~10 km up-glacier between 2005 and 2006 (Fig. 1). This propagation rate is equal to about five times the distance-integrated 2005 ice speed, which is the approximate rate of advection of a kinematic wave traveling through ice (*18*).

We estimated discharge anomalies relative to the year 2000, when the glaciers were near balance, taking into account the changes in both speed and thickness (Fig. 3). At each glacier, our discharge estimates from 2000 to 2005 agree closely with mass-budget estimates (*1*). At KL, roughly 80% of the total increase in discharge occurred in less than 1 year in 2005, followed by a 25% drop the next year (Fig. 3). At HH, discharge increased 5 Gt/year between 2000 and

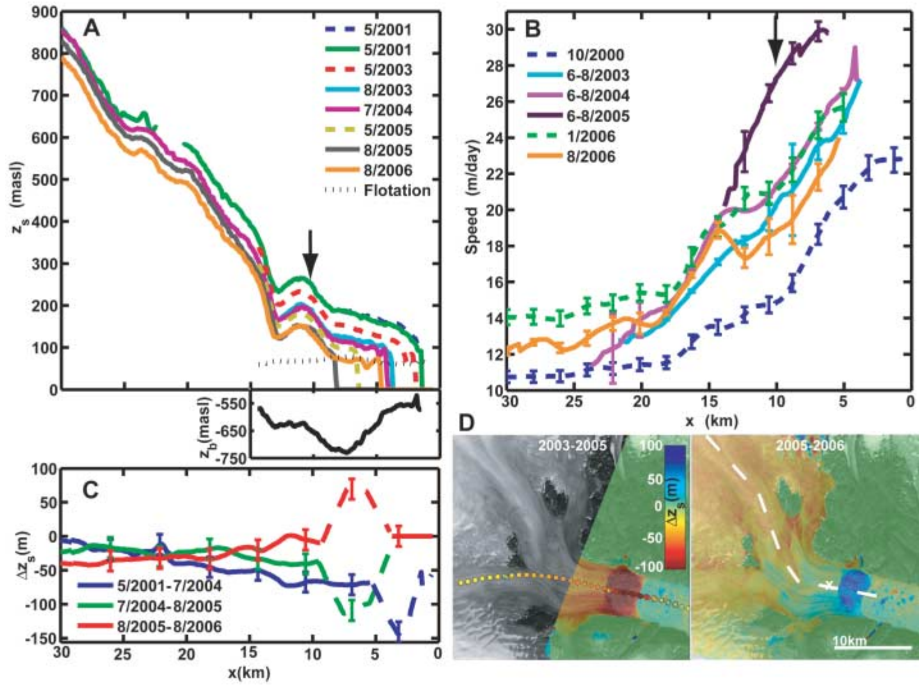

Fig. 2. (**A** to **D**) Same as Fig. 1 for HH, except (D) uses a 29 August 2005 image background.

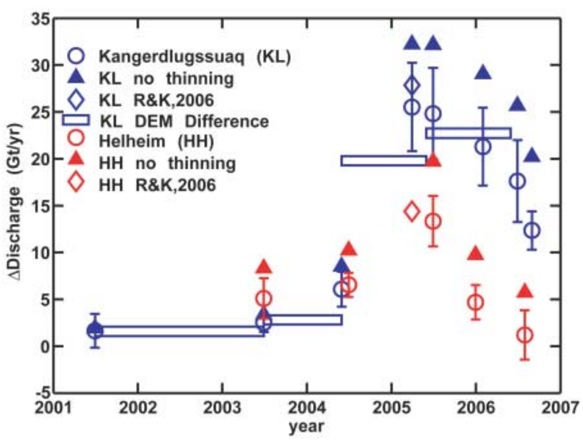

Fig. 3. Discharge anomaly from year 2000. Circles with error bars are calculated from speed and thickness change across flux gates shown in Figs. 1 and 2 with initial ice thickness obtained by dividing the year 2000 flux by the product of glacier width and 2000 speed (*1*). Uncertainties are the combinations of errors in ice elevation and speed. Triangles are the discharge anomaly with ice thickness held constant. Diamonds are the 2000 to 2005 discharge-change values from mass budget (*1*). Rectangles are KL mass-loss estimates from differencing repeat on-ice ASTER DEMs over the area shown in Fig. 1D. Spatial DEM coverage for HH is incomplete, preventing mass-loss calculations. The horizontal ranges in these estimates are the image acquisition dates, and the vertical range is the uncertainty.

2003 and by another 7 Gt/year between 2004 and 2005. It then dropped by more than 13 Gt/year in 2006, returning to near its 2000 value.

Integrating the time series of discharge anomaly from 2000 to 2006 gives totals of 52 Gt at KL and 30 Gt of excess discharge at HH (Fig. 3). Extensive DEM coverage of KL allows for a direct estimate of volume change over the lower basin (47 Gt), excluding any additional thinning at higher elevation. This loss estimate (47 Gt) agrees well with the KL discharge anomaly. When the existing imbalances from 2000 are factored in, the combined net loss of ice from 2000 to 2006 is 90 Gt, with 63 Gt of this loss in the interval from summer 2004 to summer 2006. The sharp increase in mass loss through these glaciers between 2004 and 2005 (32 Gt) can explain about 30% of the mass loss indicated by Gravity Recovery and Climate Experiment (GRACE) gravity observations for southeast Greenland (*19*).

Other GRACE observations suggest a 450 Gt ice loss from south Greenland between May 2004 and April 2006 that the authors mostly attribute to increased discharge from HH and KL (*20*). Although the timing of the increased loss agrees well with the KL and HH acceleration, our results suggest that the combined loss from these glaciers over this period can only account for 13% of this loss. Absent an extensive but unobserved acceleration elsewhere, measurements for other south Greenland glaciers suggest a loss increase from 2000 to 2005 of roughly 23 Gt/year (*1*). This suggests that despite large dynamic changes, much of the loss between 2004 and 2006 estimated from GRACE may be related to surface balance anomalies or other causes.

Our results indicate that large variations in outlet glacier discharge can produce large discharge anomalies in a span of a few years. Although the initial triggering for the recent changes is unclear, it is well known that very small perturbations to thickness can induce retreat in calving glaciers (*15*). In the cases we examined, large imbalances appear to have caused rapid adjustments in the glacier geometry, leading to a quick (~2-year) return to near balance, though some degree of moderate thinning may persist. The surface drawdown of 100 m or more at low elevations within the outlets may have substantial effects on summertime surface melt rates, potentially predisposing them to further ice thinning and retreat. However, prediction of near-future change will require detailed data on bed elevation and ice thickness. This is not yet available for most of the outlet glaciers.

Dynamic re-equilibration after a perturbation in geometry may not always be as rapid as observed here. For example, Jakobshavn Isbrae has maintained high speeds for several years after retreat and acceleration (fig. S1) (*3*). In this case, retreat from the fjord increased inflow from the sides, potentially resulting in lower thinning rates (~15 m/year) (*5*, *10*). Likewise, many glaciers along Greenland's northwest coast have retreated into the ice sheet with sustained thinning at rates of a few meters per year but show no apparent change in speed (*1*). This suggests that geometry and other characteristics unique to each glacier may determine the time scale over which discharge anomalies occur.

The highly variable dynamics of outlet glaciers suggest that special care must be taken in how mass-balance estimates are evaluated, particularly when extrapolating into the future, because short-term spikes could yield erroneous long-term trends. Rather than yielding a well-defined trend, our results are notable in that they show that Greenland mass balance can fluctuate rapidly. If these changes are the result of recent warm summers (*21*), continued warming may cause a long-term drawdown of the ice sheet through a series of such discharge anomalies, perhaps with a similar degree of variability. Therefore, accurate estimates of ice-sheet mass balance will require subannual observations of outlet glacier dynamics to avoid aliasing this rapidly varying signal.

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Fig. S1
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Conformationally Controlled Chemistry: Excited-State Dynamics Dictate Ground-State Reaction

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Ion imaging reveals distinct photodissociation dynamics for propanal cations initially prepared in either the cis or gauche conformation, even though these isomers differ only slightly in energy and face a small interconversion barrier. The product kinetic energy distributions for the hydrogen atom elimination channels are bimodal, and the two peaks are readily assigned to propanoyl cation or hydroxyallyl cation coproducts. Ab initio multiple spawning dynamical calculations suggest that distinct ultrafast dynamics in the excited state deposit each conformer in isolated regions of the ground-state potential energy surface, and, from these distinct regions, conformer interconversion does not effectively compete with dissociation.

From stereoselective synthesis to protein folding, conformational dynamics lie at the heart of chemistry (*1*). Molecular conformers typically interconvert via hindered rotations about single bonds, and the low energy barriers to these processes lead to equilibration even at low temperatures. Recent efforts to explore the detailed conformational energy landscapes of molecules have relied on stimulated emission pumping in jet-cooled beams, exciting then re-trapping molecules in different local minima to probe the interconversion barriers (*2*, *3*). Single-molecule methods have also been used to investigate conformational heterogeneity: Otherwise identical molecules exhibit vastly different rates in key steps of enzymatic processes (*4*, *5*). Conformational selectivity has been suggested as a means of achieving laser control of chemical outcomes (*6*). However, the low barriers for intercon-

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