21st-Century Evolution of Greenland Outlet Glacier Velocities

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Science **336**, 576 (2012);
DOI: 10.1126/science.1219985

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Acknowledgments: This research was carried out for the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Supplementary Materials
www.sciencemag.org/cgi/content/full/336/6081/570/DC1
Figs. S1 and S2
References (*43*–*96*)

13 February 2012; accepted 3 April 2012
10.1126/science.1220476

21st-Century Evolution of Greenland Outlet Glacier Velocities

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Earlier observations on several of Greenland's outlet glaciers, starting near the turn of the 21st century, indicated rapid (annual-scale) and large (>100%) increases in glacier velocity. Combining data from several satellites, we produce a decade-long (2000 to 2010) record documenting the ongoing velocity evolution of nearly all (200+) of Greenland's major outlet glaciers, revealing complex spatial and temporal patterns. Changes on fast-flow marine-terminating glaciers contrast with steady velocities on ice-shelf–terminating glaciers and slow speeds on land-terminating glaciers. Regionally, glaciers in the northwest accelerated steadily, with more variability in the southeast and relatively steady flow elsewhere. Intraregional variability shows a complex response to regional and local forcing. Observed acceleration indicates that sea level rise from Greenland may fall well below proposed upper bounds.

Changes in glacier dynamics contribute to roughly half of the Greenland Ice Sheet's current mass loss (~250 Gt/year, equivalent to 0.6 mm/year sea level rise) (*1*, *2*), largely through thinning and increased calving as glaciers have sped up. Large changes in ice dynamics have been observed (*3*), but were not accounted for in early models and led to the inability to quantify uncertainty of 21st-century sea level rise in the Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment (*4*). Although multiglacier speedups have been linked to recent warming in Greenland (*5*–*7*), the exact connection to climate change is poorly known, but may be related to processes controlled by ice-ocean interaction (*8*–*10*). A firm understanding of the processes driving recent change, which is needed to improve predictions of sea level rise, requires a better characterization of the temporal and spatial patterns of ice flow across the ice sheet.

Despite the need for comprehensive data, recent studies of glacier velocity in Greenland are limited in spatial and temporal resolution. For Jakobshavn Isbræ, Helheim Gletscher, and Kangerdlugssuaq Gletscher, three of Greenland's fastest outlet glaciers, velocity is relatively well documented (*3*, *11*, *12*). For most of Greenland's other 200+ outlet glaciers, however, observation has been limited to ~5-year sampling on an ice-sheet–wide scale (*13*, *14*) or smaller regions with more frequent sampling (*7*). Where comprehensive records exist, they have been used to focus on aggregate discharge rather than regional variability (*2*). We present a decade-long record, with annual sampling for the latter half, to examine decadal-scale trends and regional and local interannual variation, and to inform predictions of sea level rise.

To create this record, we produced velocity maps for winter 2000 to 2001 (referred to as 2000) and annually for each winter from 2005 to 2006 through 2010 to 2011 (referred to using the earlier year for the map), using synthetic aperture radar data from the Canadian Space Agency's RADARSAT-1, German TerraSAR-X, and Japanese Advanced Land Observation Satellite (ALOS) (table S1). We used a combination of speckle-tracking and interferometric algorithms to estimate ice-flow velocity (*14*, *15*). Coverage for each year is almost complete, with some unavoidable gaps, primarily in the south, due to satellite acquisition limits.

Of the 206 largest Greenland outlet glaciers, 178 have adequate temporal coverage for 2000 to 2005, and 195 have sufficient data for 2005 to 2010 (Fig. 1) (*16*). We divided these glaciers into several categories. First, we identified land-terminating, ice-shelf–terminating (ice shelf >10 km long), and low-velocity marine-terminating (mean velocity <200 m/year) glaciers (55 total). Next, glaciers with highly variable behavior were separated to avoid misrepresenting large variations as consistent trends (*16*). This included glaciers such as Harald Moltke Bræ (fig. S1), where apparent surge behavior produces erratic changes (*17*). The final group consisted of fast-flow marine-terminating glaciers that we fit with linear regressions for all available data for 2000 to 2005 (111 glaciers) and 2005 to 2010 (123 glaciers) to evaluate trends and fill data gaps (figs. S2 and S3).

Our record reveals the complexity of Greenland's ice flow. Greenland's largest land-terminating glaciers are located primarily along the southwest coast, with a few in the northeast (Fig. 1). Nearly all flow at peak velocities between 10 and 100 m/year, so that annual changes of 10 to 30 m/year produce large long-term trends (>15% change over 5 years). Most (70%) of the land-terminating glaciers with a notable trend slowed during 2005 to 2010—a continuing trend for half of them. The scale of these changes, however, is close to the measurement error and seasonal variability (*11*) and orders of magnitude smaller than changes seen on many fast-flowing glaciers. The one outlier, Frederikshab Isblink (fig. S1), has a large lobe-shaped terminus that is primarily land-terminating, but with one segment of lake-terminating ice front. The velocity field suggests that this segment helps the glacier maintain a higher peak velocity (~270 m/year) than other land-terminating glaciers and hints at the importance of a calving terminus in maintaining fast ice flow.

Ice-shelf–terminating glaciers (Fig. 1) have mean velocities (300 to 1670 m/year) that are generally slower than those of other marine-terminating glaciers (total mean: 1890 m/year), but most show negligible change for 2000 to 2010. The most notable change occurred on Hagen Bræ (from 50 m/year in 2000 to 650 m/year in 2007), a previously identified surge-type glacier (*18*).

Surge-type glaciers occur mostly in the northwest, north, and east (*18*, *19*). In several cases, 1- or 2-year velocity changes suggest surge-type behavior, as observed on Harald Moltke Bræ (high speed in 2005), where surges have been recorded before, and Adolf Hoel Gletscher (low speed in 2007) (fig. S1) and Kangilerngata sermia (low speed in 2005), where earlier surges have not been recorded. Other glaciers where surges have been observed previously, including Storstrommen and L. Bistrup Bræ (*18*) and Sortebræ (*20*), maintained quiescent speeds over the past decade.

Most glaciers in east Greenland are marine-terminating, but have substantially slower mean velocities (1040 m/year) relative to southeast (2830 m/year) or northwest (1630 m/year) marine-terminating glaciers. This is consistent with the lower regional discharge from this low accumulation area (*21*). As a group, eastern glaciers showed only negligible changes from 2000 to

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2010. The low decadal-scale variability may be related to colder surface and subsurface ocean temperatures north of ~69°N (*22*). Of the few glaciers where we did detect a trend, at least half were slowing in each period (Fig. 1). The predominance of surge-type glaciers in the east (*19*) also suggests that the few notable trends may result from surge-related dynamics, which represent velocity changes that are not necessarily linked to climate (*23*, *24*).

Fast-flow marine-terminating glaciers are the dominant type in the northwest, and regional speed increased there by 8% from 2000 to 2005 (Fig. 2). This was followed by a larger increase (18%) from 2005 to 2010, with most of the speedup during 2007 to 2010 (14%). This trend results from a number of glaciers speeding up and is not driven by the acceleration of any particular glacier (supplementary materials). Despite the overall increase, however, there is not a uniform pattern of synchronous intraregional acceleration (fig. S2). A third of northwest glaciers steadily increased over the whole decade, whereas ~15% slowed from 2000 to 2005 and then accelerated substantially from 2005 to 2010. Another third of the glaciers showed no trend, and a quarter of the region's glaciers slowed over the decade (Fig. 1).

Greenland's southeast sector also has a high concentration of marine-terminating glaciers. Satellite coverage is more limited in this region, which allowed us to sample 35 of 47 glaciers for the whole decade (Fig. 1). Many (43%) of these glaciers sped up substantially over the first half of the decade, but most did not maintain their rate of acceleration to 2010, and a third dropped below their 2005 speed. Across the region, a quarter of the glaciers slowed by more than 15% from 2005 to 2010 (none did during 2000 to 2005). As a result, the southeast's mean velocity in 2010 (3120 m/year) was less than 200 m/year higher than its 2005 mean (2980 m/year) (Fig. 2)—the result of a 2005 to 2006 slowdown followed by a sluggish 2006 to 2010 speedup (50 to 110 m/year average annual speedup). The pattern is similar when excluding the three fastest 2010 glaciers, though the annual speedup after 2005 is lower (20 to 60 m/year average annual speedup). Like the northwest, however, the regional trend in the southeast does not describe most individual glaciers (fig. S3). Instead, large speedups on many glaciers during 2005 to 2010 are balanced by considerable slowing on others (Fig. 1).

Despite some consistency in regional trends, the data show a marked degree of overall variability. Substantial acceleration (28%) in the southeast and on Jakobshavn Isbræ (32%) from 2000 to 2005 garnered much attention (*7*, *13*, *25*) and raised concern about the climate sensitivity of the Greenland Ice Sheet, particularly because these changes were not included in IPCC sea level rise predictions (*4*). Subsequent studies found that acceleration was not sustained on the southeast's largest glaciers, but continued on Jakobshavn (*3*). Our expanded record shows

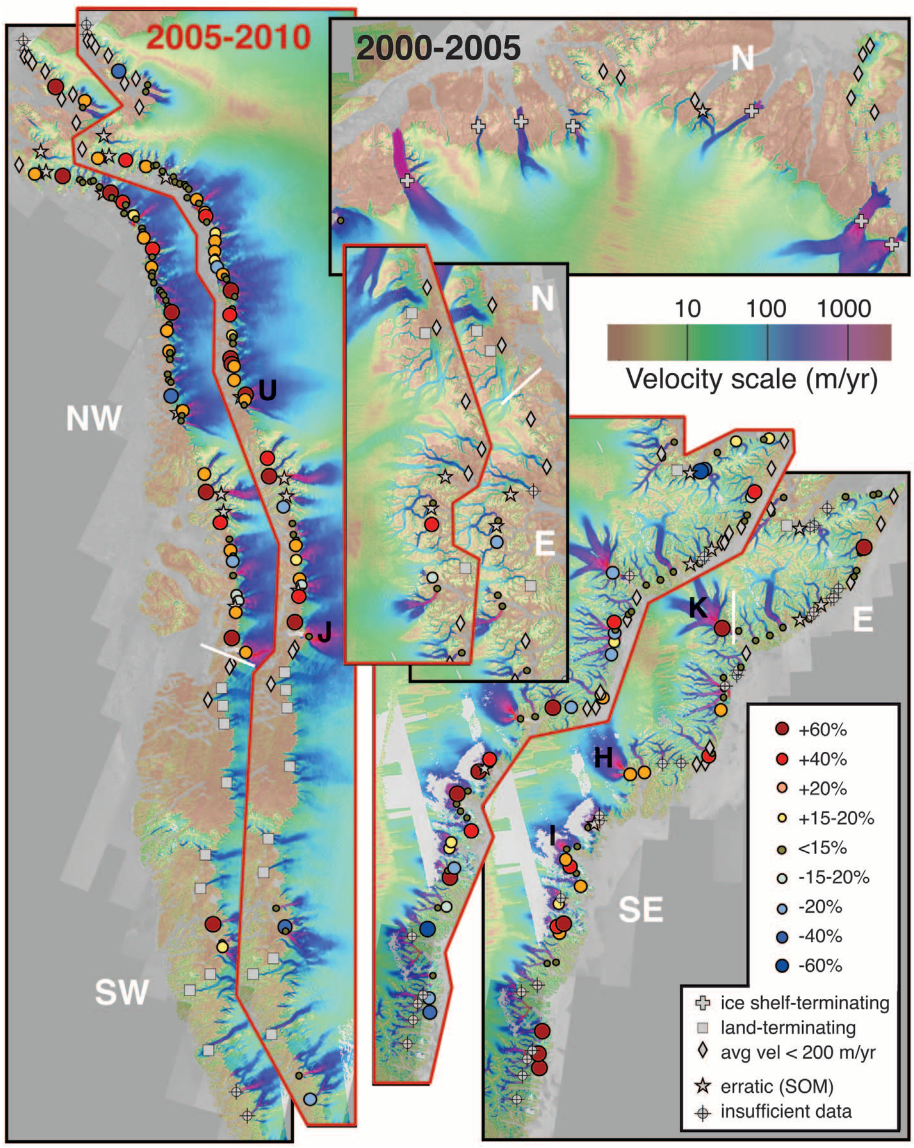

Fig. 1. Outlet glacier categories and rates of velocity change (percentage change from beginning of 5-year period). Black-outlined images show 2000 to 2005 results, and red-outlined images are 2005 to 2010 results. The background velocity map for both periods is a 2007 to 2010 composite, with the five ice-sheet regions indicated: north (N), northwest (NW), southwest (SW), southeast (SE), and east (E). There was no change for the north during 2005 to 2010. Jakobshavn (J), Upernavik North (U), Helheim (H), Kangerdlugssuaq (K), and Ikeq Fjord (I) glaciers are indicated.

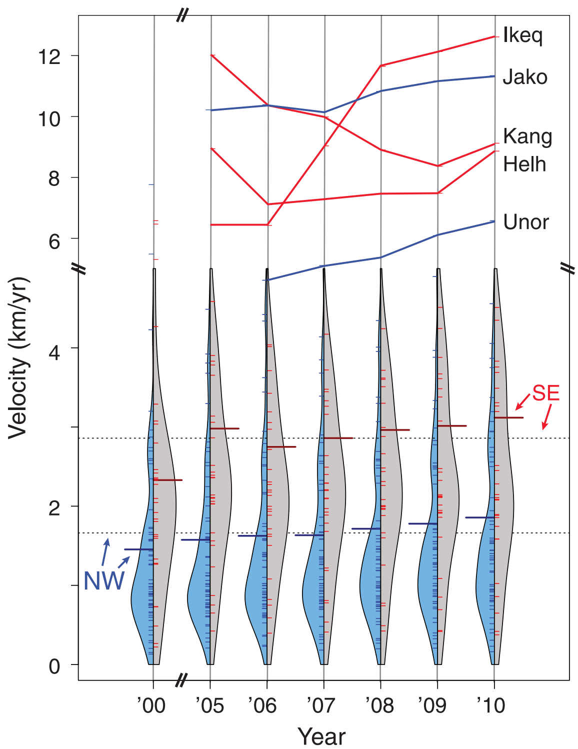

Fig. 2. Bottom: Distribution of glacier speeds (short ticks), smoothed speed density (colored bars), and mean speeds (long ticks) for 7 years' data. The northwest region is shown in blue with blue tick marks (left side) and the southeast region in gray with red tick marks (right side). Dashed black lines indicate regional mean speed over the entire decade (top for southeast, bottom for northwest). Only glaciers with sufficient data for both 2000 to 2005 and 2005 to 2010 are included. **Top:** Velocity plots for Jakobshavn (Jako), Upernavik North (Unor), Kangerdlugssuaq (Kang), Helheim (Helh), and Ikeq Fjord (Ikeq).

that these patterns are truly region-wide: Early acceleration in the southeast decreased, with little change from 2005 to 2010, whereas the northwest overall maintained relatively steady acceleration throughout the decade. As a result, 2000 to 2010 acceleration in the northwest (28%) is comparable to that in the southeast (34%).

Differences in the regional velocity patterns for the northwest and southeast may be connected to ice-sheet environment; many northwest glaciers are embedded within the surrounding ice sheet so that strongly convergent flow may limit rapid thinning, whereas southeast glaciers tend to flow through long fjords where along-flow stretching can produce rapid thinning as a glacier speeds up, potentially creating faster and larger fluctuations in speed (*3*). Ocean water characteristics may also affect regional trends. Both southeast and northwest glaciers respond to changes in warm North Atlantic waters, but geography and atmospheric and ocean circulation patterns control when and how these warm waters reach the separate sectors (*8*, *26*, *27*).

Although ocean and climate factors seem to exert a regional influence (*7*, *22*, *26*), the effect on any particular glacier is highly variable and may be primarily affected by a wide range of local factors (*28*, *29*). We observe many instances of asynchronous behavior on neighboring glaciers on annual (fig. S2 and S3) and decadal (Fig. 1) time scales. Influencing factors likely include fjord, glacier, and bed geometry (*3*); local climate (*30*); and small-scale ocean water flow and terminus sea ice conditions (*31*, *32*). The scale of many of Greenland's glaciers (<5 km width) suggests that high-resolution models with detailed topography and local conditions may be necessary to resolve this complex behavior—a challenge that remains for individual glacier to full ice-sheet simulations. Despite the extent of our observations, this remains a glaciologically short record, and efforts in modeling and statistical extrapolation will benefit as the period of observation lengthens.

Finally, our observations have implications for recent work on sea level rise. Earlier research (*33*) used a kinematic approach to estimate upper bounds of 0.8 to 2.0 m for 21st-century sea level rise. In Greenland, this work assumed ice-sheet–wide doubling of glacier speeds (low-end scenario) or an order of magnitude increase in speeds (high-end scenario) from 2000 to 2010. Our wide sampling of actual 2000 to 2010 changes shows that glacier acceleration across the ice sheet remains far below these estimates, suggesting that sea level rise associated with Greenland glacier dynamics remains well below the low-end scenario (9.3 cm by 2100) at present. Continued acceleration, however, may cause sea level rise to approach the low-end limit by this century's end. Our sampling of a large population of glaciers, many of which have sustained considerable thinning and retreat, suggests little potential for the type of widespread extreme (i.e., order of magnitude) acceleration represented in the high-end scenario (46.7 cm by 2100). Our result is consistent with findings from recent numerical flow models (*34*).

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Acknowledgments: Velocity products were processed under NASA MEaSUREs (NNX08AL98A). Analysis was funded by an NSF Graduate Research Fellowship (T.M.) and grants NSF ANT-0852697 (I.J.) and NNX08AQ83G (B.S. and I.H.). Velocity data maps are or will be available via the MEaSUREs Earth Science Data Record at the National Snow and Ice Data Center, Boulder, CO (http://nsidc.org/data/nsidc-0478.html). We acknowledge the contributions of synthetic aperture radar data from the Canadian (CSA), German (DLR), and Japanese (JAXA) space agencies. We thank three anonymous reviewers and J. Carmichael for comments that improved the manuscript.

Supplementary Materials

www.sciencemag.org/cgi/content/full/336/6081/576/DC1
Materials and Methods
Figs. S1 to S3
Table S1
Reference (*35*)

2 February 2012; accepted 28 March 2012
10.1126/science.1219985