Sciencexpress Report

Glaciers Dominate Eustatic Sea-Level Rise in the 21st Century

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Ice loss to the sea currently accounts for virtually all of sea-level rise not attributable to ocean warming; about 60% of the ice loss is from glaciers and ice caps rather than from the two ice sheets. The contribution of these smaller glaciers has accelerated over the last decade, in part due to dramatic thinning and retreat of marine-terminating glaciers associated with a dynamic instability generally not considered in mass balance/climate modeling. This acceleration of glacier melt may cause 0.1–0.25 m of additional sea-level rise by 2100.

Disintegrating glacier ice constitutes a significant and accelerating cause of global sea-level rise. We synthesize results from a variety of recent ice mass change studies in an effort to present a newer picture of changes and trends in ice volume and associated sea-level rise. This synthesis includes current results that update the IPCC Fourth Assessment Report (*1*), stresses the importance of dynamic processes in transporting terrestrial ice to the sea, compares the contributions of glaciers and ice caps with those from the ice sheets, and presents new projections of ice mass change to the end of the 21st century.

We include all glaciers and ice caps, termed here 'Glaciers and Ice Caps' (GIC). We exclude the Greenland and Antarctic ice sheets, but include the glaciers and ice caps that surround and are peripheral to the great ice sheets. We are concerned with present-day behavior (approximately 1996 to 2006) because of its critical importance to society now and its relevance for runoff and sea-level projections to the year 2100.

A significant driver of recent ice loss is the rapid retreat and thinning of marine-terminating glaciers, which are susceptible to a nonlinear dynamic instability when their beds are below sea-level. The increased role of this phenomenon in delivering ice to the ocean during recent warming has been demonstrated for ice sheet outlets [e.g., (*2*–*4*)] but is also important for many GIC. This instability can dramatically raise the sensitivity of glaciers to climate change. It is conventionally assumed that under near-steady state conditions the climatically controlled surface balance (inputs by snow and loss through melt) controls the geometry of an ice mass, and geometric transitions (changes in thickness) are forced by changes in surface mass balance. In contrast, under dynamically forced conditions, changes in ice velocity are forced instead by changes in subglacial mechanics, and geometric transitions are governed by changes in flux divergence rather than surface balance.

The whole-glacier continuity equation for the rate of change of glacier ice mass, *M*, is

$$\dot{M} = \dot{M}_b + \dot{M}_h + \dot{M}_L = \int_A \rho_i \dot{b}\, dA + \int_A (-\nabla q)\rho_i\, dA + \rho_i W_T H_T (u_T - u_c)$$

where dots denote differentiation with respect to time, $\dot{M}_b$ is the glacier-wide net meteorological mass balance, the local surface mass balance, $\dot{b}$, integrated over the glacier area, *A*; $\dot{M}_h$ represents average thickening or thinning associated with the local divergence of ice discharge, *q*, integrated over the glacier area; and $\dot{M}_L$ represents net mass change due to extension or retraction of the terminus governed by the balance between calving at a rate u_c and terminus ice speed, u_T, at a terminus of width W_T and ice thickness H_T. The contribution of mass to the sea from a retreating tidewater glacier ($-\dot{M}$) is therefore the sum of ice losses driven by meteorology ($\dot{M}_b$), by drawdown of the ice reservoir due to ice dynamics ($\dot{M}_h$), and by terminus dynamics ($\dot{M}_L$). We report these as mass fluxes in Gt/year (1 Gt = mass of 1 km^3 water = 1/362 mm sea-level change).

For many marine-terminating outlet and tidewater glaciers, thinning and hence ice loss associated with dynamic instability can be appreciably greater than thinning caused by the local surface mass balance. Alaska's Columbia Glacier provides a useful example. Prior to the onset of rapid retreat ca. 1980, this glacier maintained a nearly steady-state elevation profile (a robust proxy for a steady-state thickness profile), where the positive surface mass balance, estimated at $\dot{M}_b$ =0.37 Gt/year, was closely balanced by dynamic surface lowering. During the late 1970's, however, net thinning began to occur ($\dot{M}_b + \dot{M}_h$ = –0.88 Gt/year), portending dynamic retreat (*5*, *6*); about 15 km of terminus retreat ensued. Columbia Glacier's discharge has since increased. In 2000-2001 the ice flux through the terminus reached 6.6 Gt/year even though the surface mass balance was probably decreasing (*7*). Arendt *et al*. (*8*) point out the critical role of these effects in the wastage of other calving glaciers in the western Chugach Mountains, Alaska. This switch from balance-controlled to dynamically forced modes must be understood in comparing global ice-wastage observations and in predicting future delivery of glacier ice to the oceans. The time scale for extracting large volumes of ice from tidewater glaciers as well as from the margins of the major ice sheets can be dramatically shorter than one would predict from surface mass balance estimates or climate/balance modeling.

Other calculations of losses due to changes in ice dynamics are spotty. Studies in the Russian Arctic (Franz Josef Land, Novaya Zemlya and Severnaya Zemlya) over the period 1952-2001 estimate $\dot{M}_L$ = –1.3 Gt/year and $\dot{M}_b + \dot{M}_h$ = –3.2 Gt/year (*9*). Recent studies on the Devon Island Ice Cap (*10*) indicate that iceberg calving caused up to 30% of the 1960-1999 mass loss. These results suggest that, in areas where tidewater/calving glaciers occur, the errors in estimating ice loss of GIC from classic surface observations are likely to be higher than stated because of the paucity of data on ice dynamic contributions to volume losses.

Rates of ice mass change ($\dot{M}$) from 1995-2005 (Table 1, Fig. 1, and table S1) (*11*) show accelerating rates of mass loss ($\ddot{M}$ > 0) from almost all glacier inventories. The rates are indexed to the common year 2006, and the current accelerations of loss in ice mass ($\ddot{M}$) are obtained by linear regressions of published values of rate of mass loss vs. time, beginning in 2000 or slightly before (*11*). These rates of ice loss include dynamically forced losses where known; as these are not known in many areas, the values reported must be considered underestimates. For comparison, we also present recent results from the Greenland and Antarctic ice sheets in Table 1 and Fig. 2.

The rate of GIC ice loss of 402 ± 95 Gt/year dominates the contributions to sea-level rise from the various ice masses in 2006 (Table 1); the GICs around the Gulf of Alaska contribute significantly (> 100 Gt/year; Fig. 1).
The recent rate of worldwide sea-level rise is about 3.1 ± 0.7 mm/year; of this, ocean warming (the steric effect) accounts for about 1.6 ± 0.5 mm/year (*1*). The results given in Table 1 suggest that glacier and ice sheet wastage currently generates 1.8 mm/year of sea-level rise, accounting for slightly more than the remainder of the non-steric sea-level change. Our results, like those in the IPCC Fourth Assessment (*1*), suggest that GIC contribute about 60% of the eustatic, new water component of sea-level rise (Table 1 and Fig. 2). Our GIC wastage numbers are slightly greater than those reported in a recent consensus statement (*13*) prepared for the IPCC, because the Fourth Assessment reports on an earlier period (1993-2003), and the acceleration of ice loss is very large (Fig. 1).

We explore the future effect of ice wastage for two scenarios in Table 1: (i) the present acceleration of mass loss remains constant ($\ddot{M}$ = present value; figs. S1 to S3), and (ii) the present rate of mass loss remains constant ($\dot{M}$ = present value; $\ddot{M}$ = 0). The surface mass balance contribution to estimates of mass loss would presumably be more accurate if linked to atmospheric models incorporating changes in CO_2 emissions, but our emphasis is on dynamic changes to the glacier mass budget. We include only observed and documented dynamic changes in our assessment, making no attempt to include changes that may be initiated by ice-ocean interaction in the near future. We note that dynamic adjustments can be rapid and may turn on and off asynchronously, as demonstrated in Alaska (*12*) and Greenland (*3*); one should also assume that with further warming these dynamic changes will likely accelerate. These extrapolations suggest that the GIC contribution will exceed or equal that of either ice sheet throughout at least the first half of this century, and perhaps all of this century, and will deplete at most 35% of the available GIC volume, taken here as $250*10^3$ km^3 water equivalent (*14*, *15*), by 2100. These projections appear to be larger than those suggested by the IPCC (*1*), much larger than suggested by some authors, e.g., (*16*), but in close agreement with other recent work (*17*). At the very least, our projections indicate that future sea-level rise may be larger than anticipated, and that the component due to GIC will continue to be substantial.

The values suggested for the GIC contribution to rising sea-level in future years might be questioned because they do not consider the loss of glacier area. Most previous models of GIC discharge begin with a fixed 'reservoir' of GIC ice that decreases in area and volume as global warming progresses. Indeed, many of the smallest glaciers are likely to vanish during the 21st century; however, (i) most of the GIC area on Earth is accounted for by a relatively few large glaciers (e.g., sub-polar ice caps) that will not shrink appreciably in area during the 21st century; and (ii) cold glaciers in the polar regions, which do not now produce runoff to the ocean, will warm to the point where appreciable runoff to the sea can be expected.

Using a global size distribution of glaciers combined with volume/area/thickness scaling (*18*, *19*), we find that more than half of the ice volume in GIC is contained in ice masses individually > 4,000 km^2, with mean thicknesses of ≈300 m (*20*). The current average global thinning rate of all GIC is about 0.55 m (ice equiv.)/year and is increasing at about 0.0164 m/$year^2$ (cf. Table 1). Total projected thinning by the year 2100 is only 50 and 120 m for steady and accelerating wastage scenarios, respectively. While this is heartening, the median area of 34 "benchmark glaciers," which have time-series of glacier mass balance since the 1960s, is only 4.18 km^2, corresponding to a mean thickness of a few tens of meters (~60 m). Thus many of these will likely disappear along with their valuable long-term records.

Our estimates include many possible errors, including measurement errors and area uncertainties, which are difficult to quantify but are likely only a few percent of the global totals. Our neglect of warming of polar firn and subsequent runoff, and of both mass balance-altitude feedback and ill-understood dynamic instabilities, lead to underestimation of sea-level rise. Neglecting area losses, and ignoring the density change correction for ice removed from below sea-level, produce small overestimates. Total errors (Table 1) do not affect significantly our conclusions.

In order to improve our understanding of the ice melt contribution to sea-level, we must recognize that the GIC, not the big ice sheets, are most important today, and will continue to be important throughout this century. Complex processes driving the behavior of glaciers need better characterization. With the growing emergence of dynamically forced thinning and retreat as a dominant mass-loss process on both calving glaciers and ice sheet outlets, rates of volume change have become very non-steady. Studies of retreating tidewater glaciers, completed and underway, are much help in understanding the analogous phenomenon at ice sheet outlet streams. The GIC's around the edges of the big ice sheets, with total area estimated to be more than $200*10^3$ km^2, require detailed examination. Spatial extrapolation to obtain regional averages from representative samples, as well as temporal extrapolation to predict future behavior, requires better knowledge of statistical distributions of glacier area and volume. Glacier volume scales non-linearly with area, thus global grids (e.g., 1° x 1°) must be applied with great care to avoid dividing glacier areas into pieces that do not scale correctly for thickness (*21*).

Ice wastage contributions to sea level rise will likely continue to increase in the future as warming of cold polar and sub-polar glaciers continues, and dynamically forced responses continue to occur. Our results suggest a sea-level rise of about 0.1 to 0.25 m in this century due to GIC wastage alone. This range can be compared with the IPCC projection total sea-level rise (all sources) of about 0.2 to 0.5 m depending on the emission scenario (the full effects of changes in ice sheet flow are not included). While large ice masses may surpass the glacier contribution to sea level rise in the distant future, the GIC contribution is important now and will be for the remainder of this century.

References and Notes

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Supporting Online Material
www.sciencemag.org/cgi/content/full/1143906/DC1
Figs. S1 to S3
Table S1
References

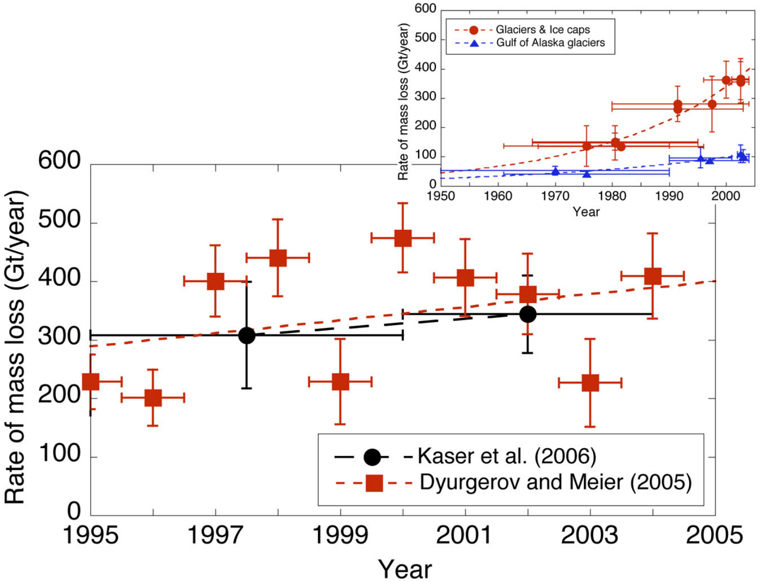
17 April 2007; accepted 10 July 2007
Published online 19 July 2007; 10.1126/science.1143906
Include this information when citing this paper.

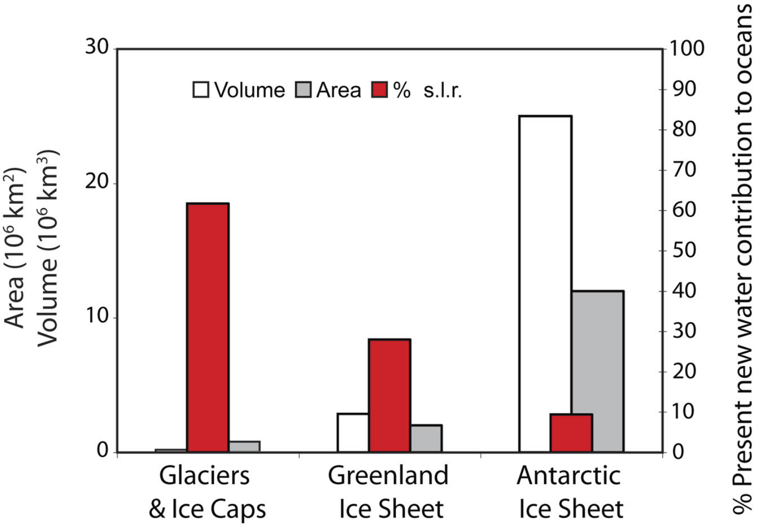
Fig. 1. Rate of ice mass loss from all Glaciers and ice caps (GIC) since 1995. Vertical error bars indicate the published uncertainty; horizontal bars show the years over which the mass balance has been averaged. Inset: Rate of mass loss from all GIC for period 1950-2005. The red curve exponential best fit through the total mass loss; blue curve applies only to the glaciers in the Gulf of Alaska. Data, method, and authorships are given in table S1.

Fig. 2. Contributions of GIC, Greenland, and Antarctic Ice Sheets to present day rate of sea level rise, along with their respective volumes and areas.

Table 1. Present day rate of ice mass loss ($\dot{M}$), its projected rate of change ($\ddot{M}$) and rates of sea-level rise (SLR). The $\dot{M}$ includes surface mass balance, as well as dynamic effects where known. For Greenland and Antarctica, we used published results as in (*4*), but have subtracted GIC mass balances [–26 to –50 Gt/year (*14*), depending on gravity signal leakage pattern] from the Greenland gravity (GRACE) results to avoid double counting the GIC ice losses. We did not make this adjustment for the Antarctic because the known major changes in the Antarctic Peninsula are not necessarily reflected in the gravity results.

	$\dot{M}$ in 2006 Gt/year	$\ddot{M}$ in 2006 Gt/year^2	SLR rate in 2006 mm/year	total SLR to 2050 mm	total SLR to 2100 mm
Glaciers & Ice Caps					
assuming current acceleration	–402±95	–11.9±5.6	1.1±.24	81±43	240±128
assuming no acceleration	–402±95	0.0	1.1±.24	49±12	104±25
Greenland Ice Sheet					
assuming current acceleration	–182±34	–16.2±6.3	0.5±0.1	65±28	245±106
assuming no acceleration	–182±34	0	0.5±0.1	22±4	47±8
West Antarctic Ice Sheet					
assuming current acceleration	–117±15	–7.3±3?	0.32±0.04	34±15?	120±50?
assuming no acceleration	–117±15	0	0.32±0.04	14±2	30±4
East Antarctic Ice Sheet					
assuming current accleration	56±26	3.4±2?	–0.15±0.07	–16±12?	–56±40?
assuming no acceleration	56±26	0	–0.15±0.07	–7±3	15±7
Global Total					
assuming current acceleration	–645±170	–32±10?	1.8±0.5	160±65?	560±230?
assuming no acceleration	–645±170	0	1.8±0.5	78±21	167±44


600
500
400
300
200
100
0
Rate of mass loss (Gt/year)
1995
1997
1999
2001
2003
2005
Year
Kaser et al. (2006)
Dyurgerov and Meier (2005)
Glaciers & Ice caps
Gulf of Alaska glaciers
1950
1960
1970
1980
1990
2000


Volume
Area
% s.l.r.
Area (10^6 km^2)
Volume (10^6 km^3)
% Present new water contribution to oceans
0
10
20
30
0
10
20
30
40
50
60
70
80
90
100
Glaciers
& Ice Caps
Greenland
Ice Sheet
Antarctic
Ice Sheet