REVIEW

Recent Sea-Level Contributions of the Antarctic and Greenland Ice Sheets

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After a century of polar exploration, the past decade of satellite measurements has painted an altogether new picture of how Earth's ice sheets are changing. As global temperatures have risen, so have rates of snowfall, ice melting, and glacier flow. Although the balance between these opposing processes has varied considerably on a regional scale, data show that Antarctica and Greenland are each losing mass overall. Our best estimate of their combined imbalance is about 125 gigatons per year of ice, enough to raise sea level by 0.35 millimeters per year. This is only a modest contribution to the present rate of sea-level rise of 3.0 millimeters per year. However, much of the loss from Antarctica and Greenland is the result of the flow of ice to the ocean from ice streams and glaciers, which has accelerated over the past decade. In both continents, there are suspected triggers for the accelerated ice discharge—surface and ocean warming, respectively—and, over the course of the 21st century, these processes could rapidly counteract the snowfall gains predicted by present coupled climate models.

Antarctica and Greenland hold enough ice to raise global sea levels by some 70 m (*1*) and, according to the geological record (*2*), collapses of Earth's former ice sheets have caused increases of up to 20 m in less than 500 years. Such a rise, were it to occur today, would have tremendous societal implications (*3*). Even a much more gradual rise would have great impact. Accordingly, one goal of glaciological survey [e.g., (*4*, *5*)] is to determine the contemporary sea-level contribution due to Antarctica and Greenland. For much of the 20th century, however, the size of these ice sheets hindered attempts to constrain their mass trends, because estimating whole–ice sheet mass change could be done only by combining sparse local surveys, with consequent uncertainty. For example, a 1992 review (*6*) concluded that the available glaciological measurements allowed Antarctica to be anything from a 600 Gt year^{-1} sink to a 500 Gt year^{-1} source of ocean mass [500 Gt of ice equals 1.4 mm equivalent sea level (ESL)], accounting for nearly all of the 20th-century sea-level trend of 1.8 mm year^{-1} (*1*) or, in the other direction, leaving a mass shortfall of some 1000 Gt year^{-1}. Even the 2001 Intergovernmental Panel on Climate Change (IPCC) report (*1*) preferred models to observations in estimating Antarctic and Greenland sea-level contributions.

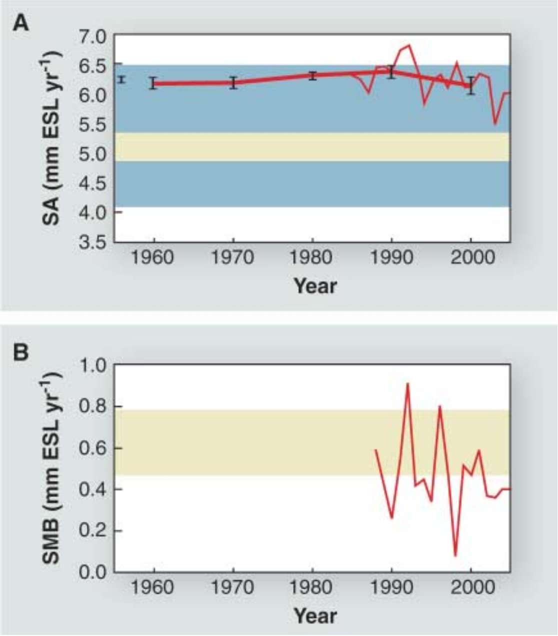

Fig. 1. Fluctuations in (**A**) the rate of snow accumulation (SA) of Antarctica [redrawn from (*38*)] and (**B**) the net surface mass balance (SMB) of Greenland [drawn from the data of (*32*)], determined from model reanalyses of meteorological observations expressed as ESL rise. Also shown are the ranges of published mean accumulation rates determined from glaciological observations (yellow) and climate models (blue).

However, in the past decade, our knowledge of the contemporary mass imbalances of Antarctica and Greenland has been transformed by the launch of a series of satellite-based sensors. Since 1998, there have been at least 14 satellite-based estimates (*7*–*20*) of the mass imbalance of Earth's ice sheets (Table 1). At face value, their range of some –366 to 53 Gt year^{-1}, or 1.0 to –0.15 mm year^{-1} sea-level rise equivalent, explains much of the eustatic component of 20th-century sea-level rise [1.5 mm year^{-1} in (*21*)], but we argue that the contribution is smaller and the problem of closing the 20th-century sea-level budget remains. Equally, the new observations provide a picture of considerable regional variability and, in particular, the long-predicted [e.g., (*1*)] snowfall-driven growth [e.g., (*10*, *22*)] is being offset by large mass losses from particular ice stream and glacier flows [e.g., (*12*, *23*)]. There is, moreover, evidence in Greenland and Antarctica of recent accelerations in these flows (*12*, *24*, *25*). It is apparent that the late 20th- and early 21st-century ice sheets at least are dominated by regional behaviors that are not captured in the models on which IPCC predictions have depended, and there is renewed speculation (*26*, *27*) of accelerated sea-level rise from the ice sheets under a constant rate of climate warming.

Although the observations in Table 1 have narrowed the uncertainty in estimates of the eustatic contribution to sea level, the range of values is notably wider than their stated uncertainties. Accordingly, we give consideration to the limitations of the three methods—accounting the mass budget [e.g., (*9*)], altimetry measurement of ice-sheet volume change [e.g., (*7*)], and observing the ice sheets' changing gravitational attraction [e.g., (*11*)]—used to calculate the estimates in Table 1. In light of these limitations, we discuss the recent changes in the Antarctic and Greenland ice sheets (AIS and GIS), and we conclude with some remarks on the future evolution of the ice sheets.

Methods and Their Sensitivity to Accumulation Rate

The mass-budget method [e.g., (*9*, *12*)] compares the mass gain due to snowfall to mass losses due to sublimation, meltwater runoff, and ice that flows into the ocean. It has been given new impetus by the capability of interferometric synthetic aperture radar (InSAR) to determine ice surface velocity. This has improved earlier estimates of the ice flux to the ocean (*5*) and provides a capability to identify accelerations of ice flow. The method is hampered by a lack of accurate accumulation and ice thickness data. For Antarctica, where surface melting is negligible, accumulation may be determined by spatially averaging the history of accumulation recorded in ice cores, or from meteorological forecast models. Estimates of the temporally averaged accumulation or "mean" accumulation range, respectively, from 1752 to 1924 Gt year^{-1} (*1*) and from 1475 to 2331 Gt year^{-1} (*28*). The meteorological data are acknowledged to be of inferior accuracy (*28*), and their wide range can perhaps be discounted. The range of the core-based estimates, which use substantially the same core records, arises from differences in their spatial interpolation. Recent compilations have used the satellite-observed microwave temperature, which is correlated with accumulation, to guide the interpolation, and a careful study (*29*) placed the

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error of individual drainage-basin accumulation at 5%. The extent to which this error may average out over the entire sheet is not known: The microwave interpolation field [see (*29*)] depends on factors other than accumulation (e.g., temperature) that may bias the outcome. There is also the difficulty that, although accumulation is averaged over decades or centuries, the ice-flux measurements are limited to those of the satellite measurements [1995 to 2000 in (*9*)]. This complicates comparison of the estimated mass imbalance with altimetry estimates whose interval [e.g., 1992 to 2003 in (*14*)] is precisely defined. To date, 58% of Antarctica has been surveyed, although the method may in principle be extended to the remainder. Some 70% of Greenland has also been surveyed, but the impact of the satellite observations in determining the time-averaged imbalance is lessened because runoff from land-terminated ice, which in Greenland accounts for some 60% of the mass loss, remains largely unmeasured. The range of estimates of net accumulation and runoff [169 to 283 Gt year^{-1} in (*1*), about 20% of the total accumulation] has complicated mass imbalance estimates for some time [e.g., (*30*, *31*)] and will continue to do so.

Satellite and aircraft, radar, and laser altimetry provide a detailed pattern of change in the ice sheets' interior (*7*, *10*, *14*, *17*, *18*) and have played a key role in distinguishing changes related to accumulation and ice dynamics. The longest records to date span 1992 to 2003 (*10*, *14*), and imbalances estimated from them differ from longer averages estimated by other methods as a result of fluctuations in accumulation and ablation. Ice cores [see (*7*)] and model reanalyses (*28*, *32*) show fluctuations in accumulation, relative to their temporal means, on the order of 15% in individual years, and a similar variability in rates of ablation (*32*, *33*) (Fig. 1). The problem is exacerbated because the density of snow differs from that of ice by a factor of three, and decadal fluctuations in snowfall mass are exaggerated in the observed volume fluctuations over those due to ice dynamics in the same ratio. A correction is possible if the snowfall fluctuation is independently known, but the only estimates available today are from meteorological forecast models, and a recent study (*14*) of Antarctica concluded that there was too little correspondence between the altimeter and meteorological data sets for this method to be reliable. Differences between estimates of mass change made from the same observations of volume change (*10*, *14*, *18*) arise largely through different approaches to the conversion of volume to mass. To give an idea of the uncertainty, Wingham *et al.* (*14*) showed that, in the absence of other data, an altimeter estimate covering 73% of the Antarctic interior could vary by 90 Gt year^{-1} without contradicting the observed volume change. ERS-1 and -2 radar altimetry (for which the longest records are available) has been limited to latitudes between 81.5°N and 81.5°S and to terrain of low slope. Because these regions lie in the ice sheet's interior, which is characterized by growth in Greenland in general and in Antarctica in some places, there is a tendency for these estimates to be more positive (Table 1). These difficulties may be overcome with the satellite laser altimeter records initiated by ICESat (Ice, Cloud, and land Elevation Satellite) in 2003 or, in the future, with the high-resolution radar altimeter of CryoSat-2.

Although differences in the time-averaged imbalances from the interferometric and altimetry methods are to be expected, the methods are highly complementary. For example, the retreat of the West Antarctic Pine Island Glacier grounding line observed by InSAR (*34*) is in close agreement with the drawdown of the inland ice observed with satellite altimetry (*23*). More recently, a combination of the two methods has provided considerable insight into the unstable hydraulic connection between subglacial lakes in East Antarctica (*35*).

The GRACE (Gravity Recovery and Climate Experiment) satellites have permitted the changing gravitational attraction of the ice sheets to be estimated (*11*, *13*, *15*, *16*, *19*, *20*). These estimates (Table 1) are more negative than those provided by mass budget or altimetry, but care is needed in making comparisons. The method is new, and a consensus about the measurement errors has yet to emerge [e.g., (*36*)], the correction for postglacial rebound is uncertain [e.g., (*37*)], contamination from ocean and atmosphere mass changes is possible [e.g., (*16*)], and the results depend on the method used to reduce the data [compare, e.g., (*20*) and (*16*)]. The GRACE record is also short (3 years) and, as was the case with early altimeter time series [e.g., (*7*)], is particularly sensitive to the fluctuations in accumulation described above. For example, whereas (*13*) puts the total 2002 to 2005 Antarctic Ice Sheet mass loss at 417 ± 219 Gt, a subsequent meteorological study (*38*) has put the 2002 to 2003 snowfall deficit at 309 Gt, a value that explains most of the observed change.

East Antarctica

Although the East Antarctic Ice Sheet (EAIS) is the largest reservoir of ice on Earth, it exhibits the smallest range of variability among recent mass balance estimates (Table 1). Since 1992, altimetric (*7*, *10*, *14*, *17*, *18*), interferometric (*9*), and gravimetric (*13*, *19*) surveys have put the EAIS annual mass trend in the range –1 to 67 Gt year^{-1}. Growth of the EAIS mitigates the current sea-level rise. Gains are limited to Dronning Maud Land and

Table 1. Mass balance (MB) of the East Antarctic (EAIS), West Antarctic (WAIS), Antarctic (AIS), and Greenland (GIS) ice sheets as determined by a range of techniques and studies. Not all studies surveyed all of the ice sheets, and the surveys were conducted over different periods within the time frame 1992 to 2006. For comparison, 360 Gt of ice is equivalent to 1 mm of eustatic sea-level rise.

Study	Survey period	Survey area 10^6 km^2 (%)	EAIS MB Gt year^{-1}	WAIS MB Gt year^{-1}	AIS MB Gt year^{-1}	GIS MB Gt year^{-1}
Wingham *et al.* (*7*)*	1992–1996	7.6 (54)	–1 ± 53	–59 ± 50	–60 ± 76	
Krabill *et al.* (*8*)*	1993–1999	1.7 (12)				–47
Rignot and Thomas (*9*)†	1995–2000	7.2 (51)	22 ± 23	–48 ± 14	–26 ± 37	
Davis and Li (*17*)*	1992–2002	8.5 (60)			42 ± 23	
Davis *et al.* (*10*)*	1992–2003	7.1 (50)	45 ± 7			
Velicogna and Wahr (*11*)‡	2002–2004	1.7 (12)				–75 ± 21
Zwally *et al.* (*18*)*	1992–2002	11.1 (77)	16 ± 11	–47 ± 4	–31 ± 12	11 ± 3
Rignot and Kanagaratnam (*12*)†	1996	1.2 (9)				–83 ± 28
	2000					–127 ± 28
	2005					–205 ± 38
Velicogna and Wahr (*20*)‡	2002–2005	12.4 (88)	0 ± 51	–136 ± 19	–139 ± 73	
Ramillien *et al.* (*19*)‡	2002–2005	14.1 (100)	67 ± 28	–107 ± 23	–129 ± 15	–169 ± 66
Wingham *et al.* (*14*)*	1992–2003	8.5 (60)			27 ± 29	
Velicogna and Wahr (*13*)‡	2002–2006	1.7 (12)				–227 ± 33
Chen *et al.* (*15*)‡	2002–2005	1.7 (12)				–219 ± 21
Luthcke *et al.* (*16*)‡	2003–2005	1.7 (12)				–101 ± 16
Range			–1 to 67	–136 to –47	–139 to 42	–227 to 11

*Altimetry. †InSAR mass budget. ‡Gravimetry.

Wilkes Land, and their spatial distribution (Fig. 2A) is strongly suggestive of snowfall-driven growth. Two glaciers in East Antarctica are losing mass (Fig. 2B). From 1992 to 2003, the fast-flowing trunks of the Totten and Cook glaciers deflated by 5.0 ± 0.5 and 2.4 ± 0.2 km^3 year^{-1}. Although these figures are only in rough coincidence with those determined from interferometry [0 ± 2 and –8 ± 5 km^3 year^{-1}, respectively, in (*9*)], the signals are clear and the trends definitely established.

West Antarctica and the Antarctic Peninsula

The West Antarctic Ice Sheet (WAIS) contains enough ice to raise global sea levels by more than 5 m and, according to altimetry and interferometry, one key sector is in a state of rapid retreat (*23*, *34*). Glaciers draining into the Amundsen Sea (Fig. 2A) are losing mass because of an ice-dynamic perturbation. During the 1990s, for example, the Pine Island Glacier retreated by up to 1.2 km year^{-1} (*34*), thinned by up to 1.6 m year^{-1} (*23*), and accelerated by around 10% (*39*); the ice loss has been implicated in the freshening of the Ross Sea some 1000 km away (*40*). Throughout the 1990s, independent altimeter (*7*, *14*, *17*, *18*) and interferometer (*9*) surveys of the WAIS as a whole were in notable, possibly fortuitous, agreement (Table 1), placing its annual losses in the range 47 to 59 Gt year^{-1}. The mass balance of the WAIS has been dominated by the losses from glaciers of the Amundsen sector, canceled to a degree by some snowfall-driven coastal growth and growth arising from the well-established shutdown of the Kamb Ice Stream (*41*).

There has been a report of an accelerated recent sea-level contribution (*42*) based on satellite and aircraft altimetry, and the gravimetric surveys have also estimated a rate of mass loss since 2002 of between 107 and 136 Gt year^{-1} (Table 1). Such an acceleration (an increase in sea-level trend of 0.2 mm year^{-1}, or about 10%) would be a cause for considerable concern. However, the altimeter data from which accelerated mass losses were derived in (*42*) span less than 5% of the WAIS area and use three altimeters with markedly different measurement errors. Furthermore, both data sets span a short time interval in which forecast models indicate that a 309-Gt accumulation deficit occurred (*38*). Taking these factors into account, it is unlikely that the WAIS mass loss has altered substantially since the 1990s.

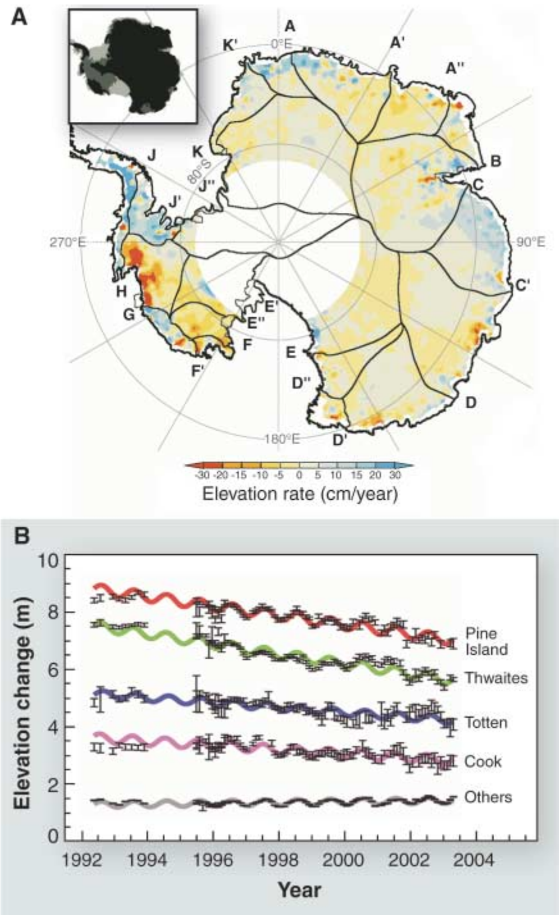

Fig. 2. (**A**) Rate of elevation change of the Antarctic Ice Sheet, 1992 to 2003, from ERS satellite radar altimetry [redrawn from (*14*)]. Also shown (inset) is the bedrock geometry, highlighting floating (light gray), marine-based (mid-gray) and continental-based (black) sectors. (**B**) Elevation change of the trunks (flow in excess of 50 m year^{-1}) of the Pine Island [Basin GH in (A)], Thwaites (Basin GH), Totten (Basin C′D), and Cook (Basin DD′) glaciers. All the deflating glaciers coincide with marine-based sectors of the ice sheet. An ice-dynamic origin of the thinning of the East Antarctic glaciers has yet to be confirmed by interferometry. However, the correlation of the thinning with flow velocity and the fact that the thinning rate is secular make ice dynamics the likely cause of all Antarctic mass losses.

During the past decade, there have been notable glaciological changes at the Antarctic Peninsula (AP): The Larsen Ice Shelf thinned (*43*) and sections collapsed (*44*), accelerating ice discharge into the oceans by some 0.07 mm year^{-1} ESL rise (*45*). However, the majority of AP ice forms the continental ice cap of Dyer Plateau. This exhibits snowfall-driven growth (Fig. 2A) that is sufficient to cancel the accelerated flow from the Larsen-A and -B catchments. The AP contribution to sea level is negligible.

Greenland

Since the most recent IPCC report, there have been seven estimates of Greenland mass imbalance based on satellite altimetry (*18*), interferometry (*12*), and gravimetry (*11*, *15*, *16*, *19*, *20*). There is consensus that during the 1990s the interior underwent modest snowfall-driven growth, which appears to be associated with a precipitation trend present in the meteorological record (*32*), offset by losses from lower altitude regions (Fig. 3, A and B). The decadal imbalance is not accurately determined. The more positive satellite altimeter estimate (*18*) is affected by signal loss in the steeper coastal margins; the aircraft laser measurements (*8*) are relatively sparse, although more sensitive to losses from marginal glaciers; and the mass-budget estimate (*12*) is undermined by the uncertainty of some 50 Gt year^{-1} in the accumulation. Nonetheless, the consensus of these measurements suggests a net loss in the 1990s of some 50 Gt year^{-1}.

Satellite interferometry (*12*, *24*) has also established that from 1996 to 2005, mass losses through flow increased by 102 Gt year^{-1}, and meteorological estimates (*32*) (Fig. 1B) of the surface-mass imbalance decreased some 20 Gt year^{-1} in the same period because of increased melting. Gravimetric surveys too support an increased mass loss (*11*, *15*, *16*, *19*, *20*). However, the interferometric and gravimetric records are short and reflect the considerable variability in the mass flux of tidewater glaciers and the surface mass balance. For example, the ice fluxes of two glaciers that by 2005 were responsible for 43 Gt year^{-1} of the increased discharge had by late 2006 declined to within 10 Gt year^{-1} of their level in 2000 (*46*), whereas in the past 14 years, the 3-year variability in surface mass imbalance has ranged from –130 to 120 Gt year^{-1} (Fig. 1B). In addition, not all gravimetric estimates capture the known spatial distribution of change; one that does (*16*) (Fig. 3B) is some 120 Gt year^{-1} more positive than other estimates, and some understanding of the cause of these discrepancies is needed. Increased mass loss from Greenland has occurred, but the decadal change is probably modest.

Implications for the Future

It is reasonable to conclude that, today, the EAIS is gaining some 25 Gt year^{-1}, the WAIS is losing about 50 Gt year^{-1}, and the GIS is losing about 100 Gt year^{-1}. These trends provide a sea-level contribution of about 0.35 mm year^{-1}, a modest component of the present rate of sea-level rise of 3.0 mm year^{-1}. Because 50 Gt year^{-1} is a very recent contribution, the ice sheets made little contribution to 20th-century sea-level rise. However, what has also emerged is that the losses are dominated by ice dynamics. Whereas past assessments (*47*) considered the balance between accumulation and ablation, the satellite observations reveal that glacier accelerations of 20 to 100% have occurred over the past decade. The key question today is whether these accelerations may be sustained, or even increase, in the future.

The question is difficult because the causes of the instabilities have yet to be established. The geological record (*48*) suggests that some 10,000 years ago, the Amundsen sector of the WAIS extended only 100 km farther than today, confining the present rate of retreat to more recent times, and the drawdown of the Amundsen sector ice streams has been linked (*49*) to a recent trigger in the ocean. A comparable argument may be extended to the thinning glaciers in East Antarctica and Greenland, which are also marine terminated. Equally, there is no direct evidence of a warming of the Amundsen Sea, and it has long been held possible that the marine-terminated WAIS, and the Amundsen sector in particular, may be geometrically unstable (*50*), and the retreating East Antarctica streams have a similar geometry (Fig. 2A). In Greenland, where summer melting is widespread and increasing, Global Positioning System measurements have shown the melting to affect flow velocity in the ice sheet interior (*26*), introducing the possibility that increased surface meltwater is reaching the bed and accelerating the ice flow to the ocean.

The discovery that particular ice streams and glaciers are dominating ice sheet mass losses means that today our ability to predict future changes is limited. Present numerical models capture neither the details of actual ice streams nor, in Greenland, those of hydraulic connections between the surface and the bed. In addition, the detailed mechanics at the grounding line still remain to be fully worked out. In consequence, the view that the changing sea-level contribution of the Antarctic and Greenland ice sheets in the 21st century will be both small and negative as a result of accumulating snow in Antarctica [e.g., –0.05 mm year^{-1} in (*1*)] is now uncertain.

Because our predictive ability is limited, continued observation is essential. The satellite record clearly identifies the particular ice streams and glaciers whose evolution is of greatest concern. The causes of their instability need to be identified. Their detailed basal topography, their basal hydrology, and the details of the interaction with their surrounding shelf seas need to be established. Numerical models that capture the detailed dynamics of these glaciers and their hydrology are required. Of equal importance are meteorological and ice core measurements that will increase confidence in forecast models of accumulation and ablation fluctuations, because to a considerable extent these limit interpretations of the short satellite records. There is a great deal that the International Polar Year may achieve.

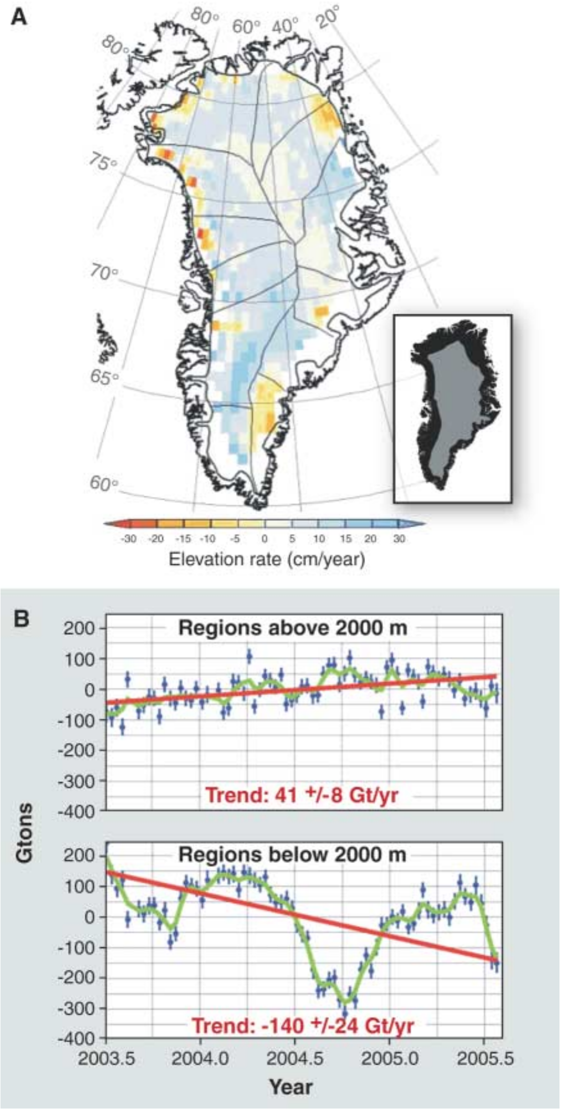

Fig. 3. (**A**) Rate of elevation change of the Greenland Ice Sheet, 1992 to 2003, determined from satellite radar altimetry [from (*22*)], and (**B**) time series of elevation change of individual sectors, 2003 to 2005, determined from satellite gravimetry [from (*16*)]. Also shown (inset) is the ice surface geometry, highlighting areas above (gray) and below (black) 2000 m elevation. Both instruments concur that high elevation areas are growing and low elevation areas are losing mass. According to gravimetry (*16*) and repeat InSAR measurements of ice discharge (*12*), the rate of mass loss at low elevations has increased over the past decade (see Table 1).

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