The role of subglacial water in ice-sheet mass balance

In the coming decades, significant changes in the polar regions will increase the contribution of ice sheets to global sea-level rise. Under the ice streams and outlet glaciers that deliver ice to the oceans, water and deformable wet sediments lubricate the base, facilitating fast ice flow. The influence of subglacial water on fast ice flow depends on the geometry and capacity of the subglacial hydrologic system: water moving rapidly through a well-connected system of conduits or channels will have little impact on ice-sheet velocities, but water injected into a spatially dispersed subglacial system may reduce the effective pressure at the base of the ice sheet, and thereby trigger increased ice-sheet velocities. In Greenland, the form of the subglacial hydrologic system encountered by increasing surface melt water will determine the influence of changing atmospheric conditions on ice-sheet mass balance. In Antarctica, subglacial lakes have the capacity to both modulate velocities in ice streams and outlet glaciers and provide nucleation points for new fast ice-flow tributaries. Climate models of ice-sheet responses to global change remain incomplete without a parameterization of subglacial hydrodynamics and ice dynamics.

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During the late stages of the Little Ice Age, the glaciers of the Canadian Pacific Northwest had a profound influence on the Tlingit and Athapaskan native communities, changing their trading routes and wrenching the core of their community structure[1]. In this century, the impacts of climate change resulting from the dynamic ice sheets will reach far beyond the populations living in close proximity to ice sheets, extending globally across political and economic boundaries.

Today, 33.5% of the world's population lives within 100 m of the elevation of current sea level and most of the planet's largest cities are close to sea level[2]. Sea level has been rising 1.5–2 mm yr^{-1} for the past century but in the past decade this rate has increased globally to 3.0 mm yr^{-1} (ref. 3), an increase attributed primarily to the warming of the oceans[4]. A growing body of evidence suggests that the contribution of glaciers and ice sheets to global sea level will increase in the coming decades[5–7]. Changing the basal conditions of ice sheets, particularly beneath fast flowing ice streams and outlet glaciers, is one possible mechanism to increase the polar ice sheets' contribution. New evidence is emerging for a complex and dynamic subglacial hydrology that has the potential to rapidly change the basal conditions of ice sheets. Ice dynamics and the influences of subglacial hydrology were not incorporated into the Intergovernmental Panel for Climate Change Fourth Assessment Report[8], compromising their estimates of the ice sheets' contributions to global sea-level rise.

THE THREE POLAR ICE SHEETS

There are three major polar ice sheets on Earth today, each one with a unique history and future: the Greenland Ice Sheet, the West Antarctic Ice Sheet and the East Antarctic Ice Sheet. The fundamentally different boundary conditions of the three ice sheets are responsible for their distinct responses to climate change.

Containing the equivalent of 7.3 m of sea-level change[9], the Greenland Ice Sheet is strongly influenced by the North Atlantic climate patterns. Coastal mountains rim the Greenland Ice Sheet, and the majority of the ice-sheet base rests on an elevated fragment of Precambrian crust above sea level. Although ice-rafted dropstones in the Norwegian–Greenland Sea indicate glaciers in Greenland as early as 38 Myr ago[10], the present Greenland Ice Sheet first formed 3.2 Myr ago[11] and has been stable in its approximate size since the termination of the last ice age. Analysis of ice core isotopic records indicates that the ice sheet may have been much smaller during the last interglacial period (the Eemian, 120,000 years ago) when global temperatures were warmer than modern temperatures[12]. Similarly, DNA extracted from the silty ice from the base of ice cores suggests that much of Greenland may have been covered by a boreal forest at some time between 450,000 and 800,000 years ago[13]. Greenland ice is delivered to the ocean by more than 30 outlet glaciers that flow into fjords carved through the coastal mountains. The three largest outlet glaciers — the Jakobshavn Isbrae, Kangerdlugssuaq and Helheim glaciers — drain ~40% of the ice-sheet volume (Fig. 2b)[6].

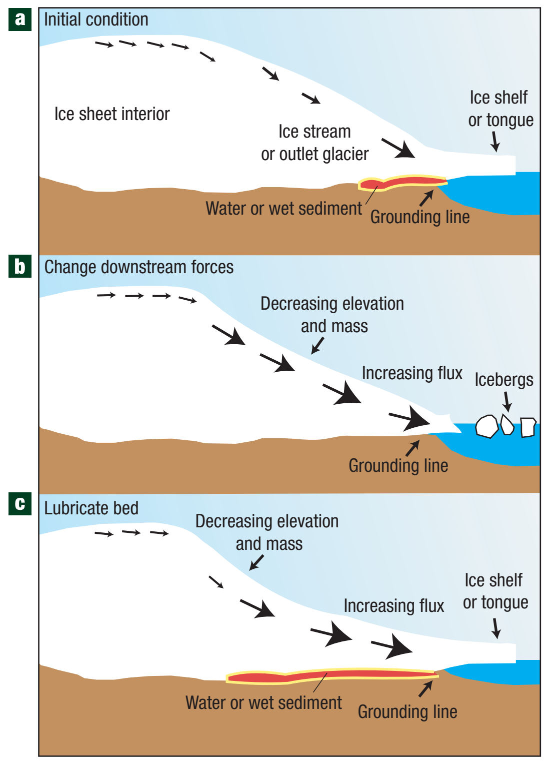
The West Antarctic Ice Sheet is similar in surface area to Greenland and contains the equivalent to 5.5 m of sea-level change[14]. In contrast to Greenland, the West Antarctic Ice Sheet rests on thinned

Box 1 Ice dynamic mechanisms for fast ice-sheet flow

The two major ice dynamic triggers capable of producing rapid change in ice sheet mass balance are (1) perturbing the force at the downstream terminus of the ice stream or outlet glacier and (2) lubricating the bed.

The force balance at the downstream terminus of an ice stream or an outlet glacier can be perturbed either by removing the buttressing ice shelf or glacier tongue, or by shifting the grounding line. The presence of an ice shelf or ice tongue as illustrated in the initial condition (**a**) provides a longitudinal compressive force, effectively slowing the flow of the ice stream[88]. Removing an ice shelf or an ice tongue will produce increased ice-sheet velocities (**b**). Four glaciers adjacent to the Larsen B ice shelf accelerated markedly in the three years after the ice shelf collapsed[89,90]. The grounding line is the point where an ice sheet that terminates in the ocean loses contact with the underlying topography and goes afloat. An inland shift of the grounding line will produce increased ice sheet velocities and subsequently thinning[91–93]. In the Amundsen Sea sector, in response to a grounding line retreat of 5 km the West Antarctic Ice Sheet is thinning and has increased ice-sheet velocities. In eastern Greenland, shifts in the forces at the downstream end may be responsible for the dramatic changes in the velocity of the Kangerdlugssuaq and Helheim Glaciers[94,95].

Lubricating the bed with either a water-saturated till or basal water will also yield increased ice-sheet velocities (**c**). Water draining from surface lakes has been suggested as a cause for both the mini-surge of Ryder Glacier in northern Greenland[66] and the increased ice-sheet velocities coincident with the summer melt season in the Jakobshavn Isbrae catchment[39]. Water generated by basal melting together with the marine sediments form the till beneath the fast flowing Ross ice streams of West Antarctica[32].



continental crust sitting below sea level. The West Antarctic Ice Sheet first formed in the late Miocene period (~9 Myr ago)[15] and may have completely disappeared as recently as 750,000 years ago[16]. Today, the ice sheet is buttressed and stabilized by large ice shelves: the Ross and the Ronne[17]. The ice sheet is drained by five large ice streams into the Ross Ice Shelf, by the Pine Island and Thwaites glaciers into the Amundsen Sea, and by several ice streams into the Ronne Ice Shelf. Because the base of the West Antarctic Ice Sheet rests below sea level and the submarine bed becomes deeper inland, it is particularly affected by changing ocean temperatures and loss of the buttressing ice shelves[17].

The East Antarctic Ice Sheet is the largest modern-day ice sheet with ice thicknesses in excess of 4,000 m. It contains the equivalent to 64.8 m of sea-level rise[14]. This ice sheet rests primarily above sea level on thick cold continental crust. The East Antarctic Ice Sheet is the oldest ice sheet, having formed initially 35 Myr ago when the final separation of the Antarctic continent from South America occurred, global carbon dioxide levels dropped[18] and the Circum- Antarctic current was established[19]. A major growth phase followed ~14.5 Myr ago. Today, the East Antarctic Ice Sheet is drained by a series of outlet glaciers in valleys cut through the Transantarctic Mountains, large ice streams draining into the Amery and Filchner ice shelves and a number of smaller glaciers around the perimeter[7].

ICE-SHEET MASS BALANCE AND FAST ICE FLOW

Mass loss from the ice sheets is localized along ice sheet margins, in regions drained by ice streams and outlet glaciers. Primary processes for accelerating mass loss from an ice sheet involve changing the conditions at the downslope terminus of an ice stream or outlet glacier, or changing the basal boundary conditions (Box 1). In the interior of an ice sheet, surface velocities are 1–5 m yr^{-1} with little horizontal velocity at the bed where the ice sheet moves by creep deformation over the underlying substrate. Downstream, the ice-sheet velocity can reach 200–1,000 m yr^{-1} in ice streams and may exceed 12,000 m yr^{-1} in the large outlet glaciers[20]. For regions of fast moving ice in both Greenland and Antarctica, a coherent signal of decreasing elevations (indicative of ice sheet thinning), reduced mass (determined from gravimetry) and increased flux is emerging.

From 1992 to 2003, the margins of the Greenland Ice Sheet lost elevation by, on average, ~2 cm yr^{-1}, whereas the ice sheet interior elevations increased by ~6.4 cm yr^{-1} (Fig. 1a)[21–24]. Over some of the fast flowing outlet glaciers, the elevation is decreasing by ~1 m yr^{-1} with extreme thinning of 10 m yr^{-1} occurring over Kangerdlugssuaq glacier[21]. Estimates of Greenland mass balance using Gravity Recovery and Climate Experiment (GRACE) observations[25] similarly show that between 2003 and 2006, the interior of the Greenland Ice Sheet (elevations >2,000 m) gained mass at a rate of 110 km^3 yr^{-1}, whereas the margins lost mass at a rate of 169 km^3 yr^{-1} (Fig. 1b). Flux studies[6] indicate that in 2005 more catchments experienced mass loss than in 1996 (Fig. 1c).

Between 1992 and 2003 in the Amundsen Sea sector, the West Antarctic Ice Sheet surface elevations decreased by ~7 cm yr^{-1}, but in the Weddell Sea sector there is no well-defined change[22,26]. A net elevation increase in the Ross Sea sector is attributed to the slowing and stopping of some of the Ross ice streams (Fig. 1d)[22,27]. The estimate of mass loss from

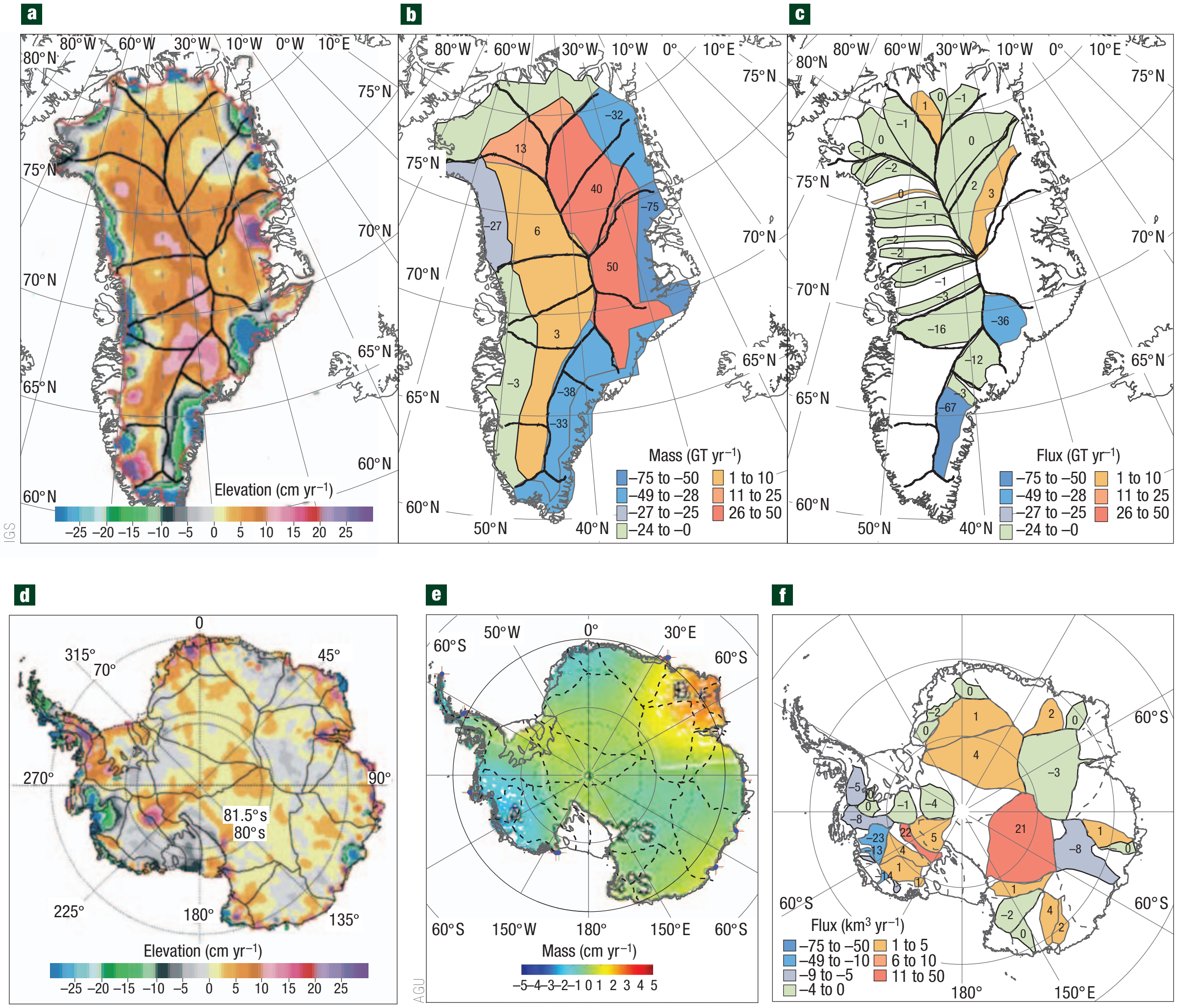


Figure 1 Recent estimates of ice sheet mass balance based on surface elevation, changing gravity fields and changing estimates for Greenland and Antarctica. Blue represents loss of elevation, mass and increasing flux, red indicates elevation gain, mass gain and decreasing flux. **a**, Greenland surface elevation changes in cm yr^{-1} (ref. 22). **b**, Greenland catchment-based estimated of mass change from GRACE gravity data in GT yr^{-1} (ref. 25). **c**, Greenland flux estimates from space velocity measurements 2005 GT yr^{-1} (ref. 6). **d**, Antarctic surface elevation changes in cm yr^{-1} (ref. 22). **e**, Antarctic mass changes from GRACE in cm yr^{-1} (ref. 29). **f**, Antarctic flux estimates from space velocity measurements km^3 yr^{-1} (ref. 99).

GRACE gravimetry during 2002–2005 is also localized over the Amundsen Sea, with loss estimates ranging from 148 km^3 yr^{-1} to 76 km^3 yr^{-1} (Fig. 1e)[28,29]. In the Amundsen Sea, the ice-sheet velocities have increased coincident with dropping surface elevations, whereas in the Ross Sea sector, they have generally slowed and in the Weddell Sea sector have been stable (Fig. 1f)[7].

Over East Antarctica the signal of change is less coherent. Surface elevations between 1992 and 2003 increased over much of the ice-sheet interior at 0.79–7.0 cm yr^{-1} (Fig. 1d)[22,26,27]. Two East Antarctic coastal regions — the Totten and Cook Basins — are decreasing in elevation. To date, the estimates of mass change from gravimetry for East Antarctica are inconsistent (Fig. 1e)[28,29]. Many of the East Antarctic outlet glaciers are in balance but several of the outlet glaciers grounded below sea level are thinning and losing mass, including the Totten and Cook glaciers (Fig. 1f)[30].

THE SOURCE AND DISTRIBUTION OF SUBGLACIAL WATER

In these fast flowing regions, the ice sheet is sliding over either a layer of deforming water saturated sediments (till) or water. As both till and water can reduce the basal stress between the ice sheet and the underlying substrate[31–34], the supply and distribution of subglacial water is a modulator of ice-sheet velocity. Early predictions of basal melting[35] were confirmed when water flowed into the base of the first drill hole to reach the base of the Antarctic ice sheet at Byrd station[36]. Subglacial water can be sourced from draining surface water, melting of the ice-sheet base or influx from underlying aquifers[37]. Little is known of the underlying aquifers so in polar studies much of the focus is on draining surface water and basal melt.

Of the three major ice sheets, only Greenland has extensive areas of surface melt that drain into the subglacial hydrologic

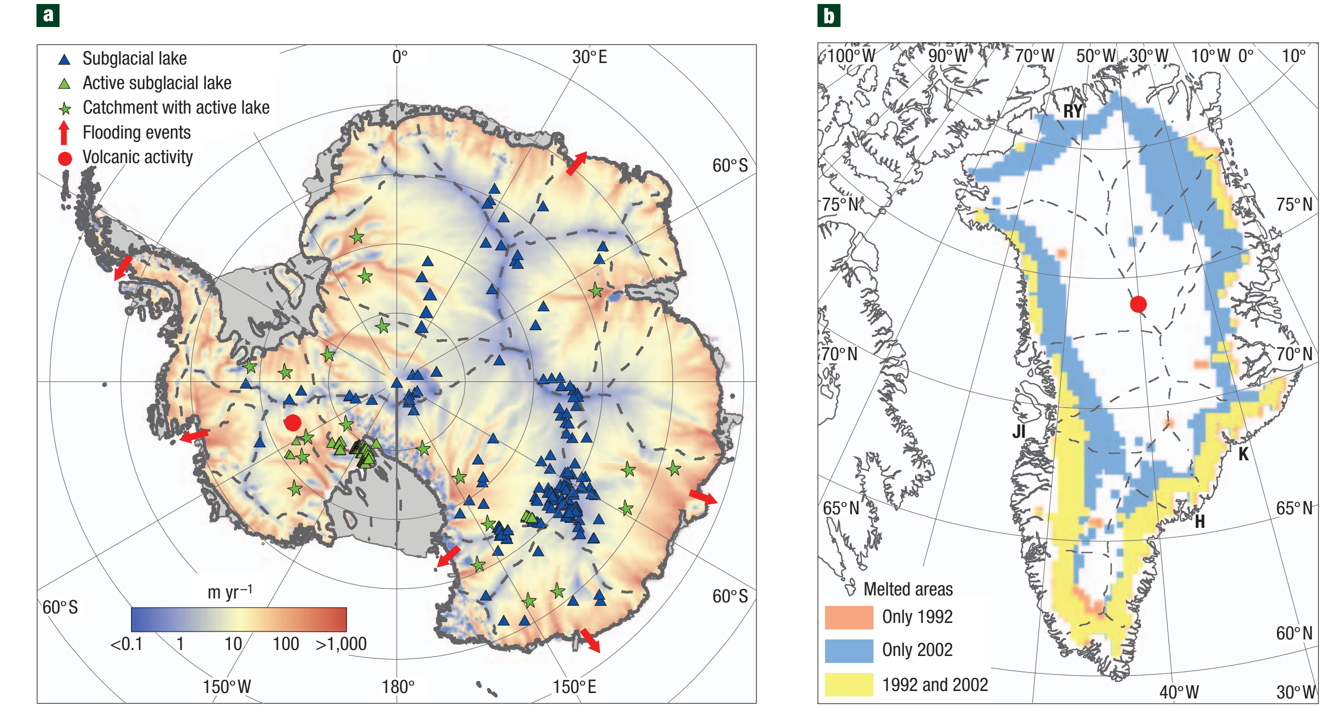


Figure 2 Distribution of water for the polar ice sheets. **a**, Antarctica with known subglacial lakes (blue triangles)[79,80] on top of balance velocities[99]. The green triangles show the locations of active lakes (refs 56, 69, 71 and B. Smith, personal communication). Red arrows represent the geomorphic and observational record of outburst floods[72–78]. The colour background represents ice-sheet balance velocities (R. Warner, private communication). **b**, Greenland surface melt extent in 1992 and 2002[38] overlain on major catchment boundaries. The four outlet glaciers, Ryder (RY), Jakobshavn Isbrae (JI), Kangerdlugssuaq (K) and Helheim (H) are identified. The locations of elevated geothermal heat flow are shown by red dots[43,97].

system. In 2002, approximately 690,000 km^2 of the surface of the Greenland Ice Sheet melted, producing ~372 km^3 of water (Fig. 2b)[38]. Surface meltwater flows both over the ice surface, disappearing into crevasses and moulins, and collects in surface lakes that, towards the end of the summer, can suddenly drain. In the heavily crevassed ablation zone, some of this surface meltwater reaches the base of the ice sheet[39]. In Greenland, both the area of surface melt and meltwater volume are increasing[38,40]. Although the spatial distribution of surface melt in Antarctica has changed,[41] there is little evidence of connectivity between the surface meltwater and the ice sheet bed.

Basal melt is an important source of subglacial water beneath all ice sheets (Box 2). Ice-sheet temperatures are controlled by the surface temperature, the surface accumulation, the ice sheet thickness, the geothermal flux and the basal stress regime[42]. Varying any of these parameters will change the basal melt rate and the subglacial hydrology, although changes at the surface propagate very slowly to the ice-sheet bed. In regions of enhanced geothermal heat flow, such as Iceland and northeastern Greenland, basal melt rates on the order of 100 mm yr^{-1} are observed[43]. In Antarctica, the changing basal stress from the interior to the fast flowing ice streams at the ice sheet margins results in basal melt rates that range from 1 to 7 mm yr^{-1} (Box 2).

Once at the bed of a glacier or an ice sheet, subglacial water can move through conduits or pipes, reside in spatially distributed cavities, rest interstitially in subglacial sediments or be captured in subglacial lakes[33,42,44]. The potential for each of these water systems to impact the velocity of the overlying ice sheet is a function of the basal effective pressure, which depends on water pressure and ice thickness. When the basal water pressure approaches the overburden pressure across extensive regions, the basal effective pressure decreases and increased ice-sheet velocities are triggered.

Conduits carrying water are evident along the base of mountain glaciers — large semicircular openings that are maintained by the viscous dissipation of heat from turbulent water counteracting the inward creep of the overlying ice[42]. These pipe-like conduits can be carved into the ice (Rothlisberger channels)[45], as well as downward into the underlying bedrock (Nye channels) or sediment[46]. Reaching diameters of metres, conduits form spatially localized arborescent systems that efficiently transport water at relatively low pressure towards ice margins. Because the water in these spatially restricted channels is at relatively low pressure, channels do not impact ice-sheet velocity. Although channels occupy a negligible fraction of the glacier bed, they can regulate the pressure of the surrounding hydraulically connected area.

Alternatively, water can reside in a network of spatially extensive subglacial hydraulic systems with varying connectivity such as a slowly draining system of linked cavities. Subglacial water flowing through a very thin distributed cavity system frequently encounters restrictions and the water tends to be at high pressure[47,48]. In surging mountain glaciers, the subglacial storage of water, particularly over a large area can produce order of magnitude increases in glacier speed[49–51]. The persistence of a high-pressure spatially distributed hydrologic system has been linked with increased ice velocities on many timescales.

Beneath ice sheets resting on sediments, water can reside interstitially between the grains of the underlying till. Water-saturated till has been recognized as contributing to fast flow in the ice streams of West Antarctica[31,32] and several mountain glaciers[49], although the precise rheology of the till has been controversial. Experimental work suggests that an increase of water pressure in a till-dominated system would produce a decoupling of the ice sheet from the bed causing an increase in ice-sheet velocity[52].

Subglacial water can also collect in hydrologic potential minima, forming subglacial lakes. Over 160 subglacial lakes have been identified in Antarctica using ice-penetrating radar data[53,54], and over 126 dynamic lakes have been defined on the basis of remote sensing of the ice surface[55–57]. The large, deep subglacial lakes are tectonically controlled[58], whereas a number of small subglacial lakes in the Dome Concordia region appear to rest in glacially scoured basins. Subglacial lakes can provide a source of water to change basal water volumes and pressure[59,60].

Changing basal hydrology can produce changing ice velocities. Basal conduits drain water rapidly and are associated with relatively slow ice velocities. In the absence of conduits, a relatively high pressure spatially distributed system can dominate, reducing the effective pressure at the ice-sheet base and triggering sliding behaviour. Shifting between these basal morphologies can abruptly change ice velocities, causing ice to surge forward or abruptly slow down[49]. If the volume of subglacial water overwhelms a conduit system, a spatially distributed system will develop, the basal effective pressure will drop and the ice will accelerate. Similarly, if conduits form and drain a linked cavity system, the basal effective pressure will increase and the ice will slow down as in the Variegated Glacier study[49–51]. As the geometry and capacity of the basal drainage system determine the water pressure as a function of water volume, ice velocities will depend on the state of the basal hydrologic system[61]. Lessons from the study of surging glaciers and jokulhlaups provide a basis for studying the role of water in ice sheet dynamics.

DYNAMIC SUBGLACIAL WATER AND FAST ICE FLOW

Until recently, the subglacial hydrodynamics beneath the large ice sheets have been considered to be steady-state systems with long residence times for water[62,63]. Increasing evidence of dynamic subglacial hydrologic systems in both Greenland and Antarctica are forcing a re-evaluation of these assumptions. The subglacial hydrologic systems have the potential to impact both the spatial and temporal evolution of the overlying ice-sheet dynamics.

Each summer as the surface melt develops in Greenland, large outlet glaciers experience a 10–15% summertime increase in velocity, and surrounding regions undergo a ~48% velocity increase[64]. An increased flux of surface meltwater into the subglacial hydrologic system has been suggested as the primary cause of these increased velocities and the observed negative mass balance[39]. Ice-sheet modelling indicates that longitudinal coupling from the well-lubricated thinning ice-sheet margins can also produce acceleration of the significant portions of the ice sheet[65]. Which portion of this summertime acceleration is a result of changing conditions at the ice-sheet margin and which portion results from surface melt lubricating the bed remains unresolved.

In Greenland, two well-documented individual draining events are associated with localized short-lived acceleration. In 1995, near the end of the summer melt season, the velocity of the Ryder Glacier increased by three-fold for a seven-week period. This period of accelerated flow was attributed to the draining of meltwater-filled supraglacial lakes to the ice-sheet base, where increased basal water pressure decoupled the ice sheet from the bed[66]. In 2006, south of Jacobshaven Isbrae, a well-instrumented surface lake drained 0.04 km^3 of water to the base of the 980 m thick ice sheet in 1.4 hours[67]. The ice surface rose immediately by 1.2 m and then subsided over the course of the next 24 hours. The associated short-lived doubling of velocity has been interpreted as evidence of a well-connected subglacial drainage system. These two examples demonstrate that water from draining surface lakes into subglacial plumbing systems can trigger transient velocity changes.

Although in Greenland surface meltwater appears important, the focus of recent Antarctic studies has been on dynamic subglacial hydrologic systems fed by basal melt. Rapid vertical motion of the ice surface has been used to detect the filling and draining of subglacial lakes. Dynamic Antarctic subglacial lakes are located beneath the Filchner–Ronne and Ross ice streams as well as the Byrd and Lambert glaciers and the interior of Wilkes Land[57].

In West Antarctica, mobile basal meltwater has now been detected along the full length of the ice streams (Fig. 2a)[56,68,69]. In the tributary region of the Ross ice streams, the decreasing elevation of a 125 km^2 area for 24 days was interpreted as the motion of ~10^7 m^3 of water. Close to the grounding line of the Mercer and Whillans ice streams, large volumes of water have cascaded between interconnected lakes[56]. A ~300 km^2 area of the ice-sheet surface dropped 10 m over three years, suggesting a major draining event. On the basis of its refilling rate, this lake should drain again in ~7 years. The amount of water (~2 km^3) moving through these grounding line lakes is approximately equal to the annual estimated volume of the melt production for the entire catchment. Similar cascading ice-stream lakes have been identified beneath the MacAyel and several other ice streams (Fig. 2a)[56,57].

Box 2 Producing water beneath ice sheets

The thick ice sheets serve as an insulating blanket from the atmosphere, maintaining the base of the ice sheet at temperatures much warmer than the ice surface.

Whereas the mean annual surface temperature over much of the East Antarctic ice sheet is −50 °C, the temperature at the base of the ice sheet, when subjected to the pressure of the overlying 3–4 km thick ice sheet, is typically −2 °C, close to the melting point of ice. The pressure of the overlying ice sheet decreases the melting temperature of the ice sheet by approximately 0.6 °C km^{-1} of ice thickness. The temperatures at the bottom of boreholes drilled thorough the interior of ice sheets are generally close to the melting point[36].

Rates of basal melt are typically 1.4–1.8 mm yr^{-1} in the interior of the ice sheet[43], where ice-sheet velocities are less than 25 m yr^{-1}. In the tributaries to the ice streams, ice-sheet velocities increase to 25–200 m yr^{-1} as both basal conditions and basal melt rates change[96]. Shear heating at the bed and internal strain heating contribute to elevated melt rates (5.5–6.7 mm yr^{-1}) in the ice stream tributaries. In the Ross ice streams, 50% of the meltwater is produced in these tributaries. As the ice-stream velocities increase, the basal stress decreases, the ice thins, and the basal melt rates generally decrease (by 3.6 mm yr^{-1} for the Bindschadler ice stream). High basal melt rates are predicted beneath Pine Island Glacier (600 mm yr^{-1}), where both the velocities and basal stress are elevated.

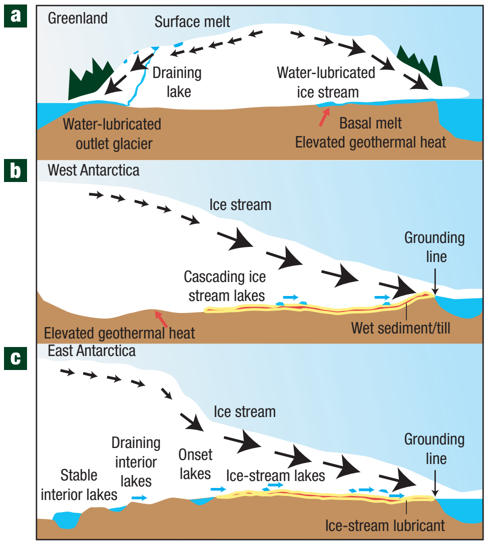
Box 3 Water and the major ice sheets

The distribution and origin of subglacial water beneath the three great ice sheets varies greatly, as does the role that water plays in ice-sheet dynamics.

In Greenland (**a**) — the warmest of the three ice sheets — subglacial water is derived both from surface meltwater that drains through the ice sheet and basal meltwater produced in regions of elevated heat flow.

In West Antarctica (**b**), subglacial water results from basal melt in the interior and in the ice-stream tributaries[56,69,96]. Beneath the ice streams, water is stored in subglacial lakes that periodically drain downstream into the surrounding ocean. Regions of elevated geothermal heat can produce increased subglacial water[97].

In East Antarctica (**c**), large deep tectonically controlled subglacial lakes such as Vostok, and Sovietskaya are found close to the ice divides[58,98]. Interconnected lakes in the interior are connected by intermittent subglacial flooding events[71]. The four lakes located at the onset of rapid flow in the Recovery ice stream[55] may lead to increased ice-sheet velocities by warming the basal ice or injecting water into the ice stream. Interconnected lakes transmit water along the axis of ice streams and outlet glaciers.



Although no changes in ice-sheet velocity have been linked with these lake cascading ice-stream events yet, draining subglacial lakes in Antarctica can modulate ice-sheet velocities. In 2005–2007, after 1.6 km^3 of water drained from a pair of subglacial lakes in the onset region of Byrd Glacier[57], the velocity of this major outlet glacier increased by 15% (100 m yr^{-1}) for 12 months[70]. The pulsed acceleration of this major East Antarctic outlet glacier is attributed to basal lubrication by lake water injected at the onset of rapid ice flow.

Dynamic lake systems are not restricted to the ice streams. In East Antarctica, over the course of 16 months, 1.8 km^3 of water travelled more than 290 km from an upstream subglacial lake to two smaller subglacial lakes downstream[71]. Over the upstream lake, the ice-sheet surface dropped by 3 m, and the surface elevation of the downstream lakes increased by 1–2 m. Although geomorphic and other evidence from the Antarctic margins indicate that outburst floods have emerged from subglacial lakes[72–78], this subglacial flood was the first evidence that a large-scale subglacial plumbing system is active today. The water was inferred to have moved through a relatively narrow conduit. A single tunnel with a radius of ~4 m would have been sufficient to carry the estimated discharge. Assuming a modest basal melt rate of 1 mm yr^{-1}, the upstream lake should drain again in 36 years. This rapid discharge suggests that beneath the East Antarctic Ice Sheet, water moves between lakes through a subglacial network of conduits and is unlikely to modulate regional ice-sheet velocities.

Subglacial water has also been linked to the onset of rapid flow. In Greenland, the region of high basal melt rates is the nucleation point for the onset of rapid ice flow of the Northeast Greenland ice stream[43]. Close to the South Pole, several small lakes are coincident with the onset of rapid ice flow although little is known about their area, depth or stability[79]. At the onset of the longest ice stream penetrating the East Antarctic Ice Sheet — the Recovery ice stream — four large lakes have been identified. Upstream of the lakes the ice-sheet velocities are 1–2 m yr^{-1} and downstream of the lakes the velocities are ~30 m yr^{-1} (ref. 55). Three mechanisms have been proposed for subglacial lakes to nucleate fast ice flow. Water in catchment lakes can provide a localized source of water for the onset of rapid flow. Warming of the base of the ice sheet by the accretion of lake water as the ice sheet traverses the lake could yield more widespread basal melt downstream of lakes. Alternatively, periodic outburst floods from the lake may carve channels that focus ice flow and thicken the ice sheet, facilitating fast flow on the downstream margin of the lake by enhanced creep in bedrock channels.

IMPLICATIONS FOR ICE-SHEET DYNAMICS AND MASS BALANCE

Subglacial hydrologic systems can directly influence the dynamics of all of the Earth's ice sheets. Although subglacial water moving through a well-connected conduit system does not affect the overlying ice-sheet dynamics, subglacial water has the potential to modulate ice-sheet velocities and nucleate the onset of rapid ice flow.

In Greenland, surface meltwater moving to the ice sheet bed has been framed as an effective mechanism for rapidly connecting changing atmospheric conditions with the ice-sheet base. Whether increased surface melt will result in increased ice-sheet velocities depends on the condition of the basal drainage system; this in turn dictates whether the influx of meltwater results in greater lubrication of the ice-sheet bed[81]. If the surface meltwater is delivered into a spatially distributed basal water system, then large regions of the ice sheet could potentially experience increased velocities as in the acceleration of the Ryder Glacier. Alternatively if the surface meltwater is transported to the ice sheet margin quickly through a system of large conduits, it will have little impact on ice sheet velocities.

In Antarctica, the Ross ice streams have undergone marked changes in velocity and configuration[82,83], as evidenced by the recent slowing down of the Whillans ice stream[84] and stoppage of the Kamb ice stream ~150 years ago[85]. The subglacial water supply and distribution has been proposed as the cause of the episodic acceleration and slow-down of ice streams, but the shutdown process remains under debate[86,87]. Under the West Antarctic ice streams, for the period 2003–2006, the cascading lakes are associated with net increase in the amount of stored subglacial water. These dynamic basal hydrodynamics are likely to contribute to the inherent variability of ice sheet flux as illustrated by the complex history of the Ross ice streams[56].

Changing volumes of subglacial water have been associated with modulating ice sheet velocities in both Greenland and Antarctica. In Antarctica, subglacial lakes are present in the catchments of many outlet glaciers. The periodic draining of subglacial lakes could produce episodic increases in ice-sheet velocities that would have been missed by most flux studies to date. The potential for episodic changes in ice sheet velocity modulated by subglacial water must be considered in assessments of mass balance.

Mounting evidence indicates that subglacial lakes and sites of elevated heat flux producing significant basal melt are closely associated with the onset of rapid ice flow. Serving as fixed sources of basal lubrication in the interior of the ice sheets, subglacial lakes and sites with elevated geothermal heat flux are potentially future nucleation sites for the initiation of fast- flowing ice streams.

The complexity of the wet subglacial environment is not captured by the current generation of ice-sheet models. These dynamic basal conditions are likely to contribute to the inherent variability of the ice-sheet flux illustrated by the complex history of the Ross ice streams. Accurate models of ice sheets are a necessary component of any assessment of climate change, so we can predict the sea-level contribution from the Earth's three ice sheets. Until basal conditions are accurately parameterized, ice-sheet models are unlikely to produce accurate results and assessments of the impact of climate change on the polar ice sheets will remain flawed.

OUTSTANDING QUESTIONS

The bases of the polar ice sheets are wet and dynamic, with the surface meltwater descending into crevasses and subglacial water moving down the hydraulic potential gradient. Subglacial conduits, cavities and lakes are part of this complex environment, linked to the dynamics of the overlying ice sheet. The very nature of the ice sheet subglacial environment makes it challenging to study. Most of the recent discoveries have been made through satellite observations: where inferences are made about the basal processes by monitoring the surface. There are many outstanding questions related to the subglacial drainage systems beneath all of the ice sheets.

In Greenland, the increasing volumes of surface meltwater may reach the bed of the ice sheet and trigger increased ice-sheet velocities. Nevertheless, the nature of the englacial water transport remains poorly understood. The distribution of water beneath the wet and fractured margins of the Greenland ice sheet is difficult to determine and the fraction of the increasing ice-sheet velocities caused by increased surface meltwater lubricating the bed remains unknown. Whether the increasing area of surface melt is resulting in a greater area of well-lubricated ice-sheet bed and increased ice velocties remains unresolved.

In Antarctica, an understanding of the role of the lakes and the subglacial water in ice sheet flow is emerging. If subglacial lakes can develop into nucleation points for increased ice-sheet velocities then the network of subglacial lakes serves as a fundamental template for ice-sheet drainage. As draining subglacial lakes can trigger transient increased ice velocities, each interior lake is also capable of modulating fluxes through ice streams and major outlet glaciers. To accurately predict ice-sheet changes for past and present climates it is imperative that we determine the location, geometry, activity and stability of these subglacial water systems so that they can be included in ice-sheet models.

The geomorphic evidence around Antarctica indicates that dynamic subglacial hydraulic systems have been persistent features of the polar ice sheets for millions of years[72]. The observational record of the dynamic nature of the polar subglacial water system is short. New active lakes are likely to be detected. A complete picture of the spatio-temporal variability of the subglacial system and the pathways of subglacial water to the ocean has not yet emerged. Understanding subglacial hydrodynamics is crucial for predicting the changing dynamics of the polar ice sheets.

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References

1. Cruikshank, J. *Do glaciers listen?: Local Knowledge, Colonial Encounters, and Social Imagination* (UBC Press, Seattle, University of Washington Press, Vancouver, 2005).
2. Small, C. & Cohen, J. E. Continual physiography, climate and the global distribution of human population. *Curr. Anthropol.* **45,** 269–277 (2004).
3. Cabanes, C., Cazenave, A. & Le Provost, C. Sea level rise during past 40 years determined from satellite and in situ observations. *Science* **294,** 840–842 (2001).
4. Cazenave, A. How fast are the ice sheets melting? *Science* **314,** 1250–1252 (2006).
5. Meier, M. F. *et al.* Glaciers dominate eustatic sea-level rise in the 21st century. *Science* **317,** 1064–1067 (2007).
6. Rignot, E. & Kanagaratnam, P. Changes in the velocity structure of the Greenland ice sheet. *Science* **311,** 986–990 (2006).
7. Rignot, E. *et al.* Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geosci.* **1,** 106–110 (2008).
8. Lemke, P. *et al.* in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomon, S. *et al.*) 337–383 (Cambridge Univ. Press, Cambridge, UK and New York, USA, 2007).
9. Bamber, J. L., Layberry, R. L. & Gogineni, S. A new ice thickness and bed data set for the Greenland ice sheet. 1. Measurement, data reduction, and errors. *J. Geophys. Res. —Atmos.* **106,** 33773–33780 (2001).
10. Eldrett, J. S. *et al.* Continental ice in Greenland during the Eocene and Oligocene. *Nature* **446,** 176–179 (2007).
11. Shackleton, N. J. *et al.* Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. *Nature* **307,** 620–623 (1984).
12. Cuffey, K. M. & Marshall, S. J. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. *Nature* **404,** 591–594 (2000).
13. Willerslev, E. *et al.* Ancient biomolecules from deep ice cores reveal a forested southern Greenland. *Science* **317,** 111–114 (2007).
14. Lythe, M. B. & Vaughan, D. G. BEDMAP: A new ice thickness and subglacial topographic model of Antarctica. *J. Geophys. Res.— Sol. Ea.* **106,** 11335–11351 (2001).
15. Flower, B. P. Middle Miocene deep-water paleoceanography in the Southwest Pacific — Relations with East Antarctic ice-sheet development. *Paleoceanography* **10,** 1095–1112 (1995).
16. Scherer, R. P. *et al.* Pleistocene collapse of the West Antarctic Ice Sheet. *Science* **281,** 82–85 (1998).
17. Alley, R. B. & Bindshadler, R. A. The West Antarctic Ice Sheet and sea level change. *Antarctic Research Series* **77,** 1–11 (2001).
18. DeConto, R. M. & Pollard, D. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO2. *Nature* **421,** 245–249 (2003).
19. Flower, B. P. & Kennett, J. P. Middle Miocene ocean-climate transition — High-resolution oxygen and carbon isotopic records from Deep-Sea Drilling Project Site 588a, southwest Pacific. *Paleoceanography* **8,** 811–843 (1993).
20. Joughin, I., Abdalati, W. & Fahnestock, M. Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier. *Nature* **432,** 608–610 (2004).
21. Krabill, W. *et al.* Greenland Ice Sheet: Increased coastal thinning. *Geophys. Res. Lett.* **31,** doi:10.1029/2004GL021533 (2004).
22. Zwally, H. J. *et al.* Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. *J. Glaciol.* **51,** 509–527 (2005).
23. Thomas, R., Frederick, E., Krabill, W., Manizade, S. & Martin C. Progressive increase in ice loss from Greenland. *Geophys. Res. Lett.* **33,** doi:10.1029/2006GL026075 (2006).
24. Johannessen, O. Recent ice-sheet growth in the interior of Greenland. *Science* **310,** 5750 (2005).
25. Luthcke, S. B. *et al.* Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science* **314,** 1286–1289 (2006).
26. Davis, C. H. *et al.* Snowfall-driven growth in East Antarctic ice sheet mitigates recent sea-level rise. *Science* 308 (5730), 1898–1901 (2005).
27. Wingham, D. J., Shepherd, A., Muir, A. & Marshall, G. J. Mass balance of the Antarctic ice sheet. Evolution of the Antarctic ice sheet; new understanding and challenges. *Phil. Trans. R. Soc.* **364,** 1627–1635 (2006).
28. Velicogna, I. & Wahr, J. Measurements of time-variable gravity show mass loss in Antarctica. *Science* **311,** 1754–1756 (2006).
29. Chen, J. L., Wilson, C. R., Blankenship, D. D. & Tapley, B. D. Antarctic mass rates from GRACE. *Geophys. Res. Lett.* **33,** doi:10.1029/2006GL026369 (2006).
30. Rignot, E. Changes in ice dynamics and mass balance of the Antarctic ice sheet. *Phil. Trans. R. Soc. A* **364,** 1637–1655 (2006).
31. Alley, R. B. Deformation of till beneath ice stream B, West Antarctica. *Nature* **322,** 57–59 (1986).
32. Blankenship, D. D. Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream. *Nature* **322,** 54–57 (1986).

33. Clarke, G. K. C. Subglacial processes. *Annu. Rev. Earth Planet. Sci.* **33,** 247–276 (2005).
34. Kamb, B. Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion in the West Antarctic Ice Sheet. *Antarctic Research Series* **77,** 157–199 (2001).
35. Robin, G. d. Q. Ice movement and temperature distribution in glaciers and ice sheets. *J. Glaciol.* **2,** 523–532 (1955).
36. Gow, A. J., Ueda, H. T. & Garfield, D. E. Antarctic Ice Sheet — Preliminary results of first core hole to bedrock. *Science* **161,** 1011–1013 (1968).
37. Flowers, G. E. & Clarke, G. K. C. A multi-component coupled model of glacier hydrology: 1. Theory and synthetic examples. *J. Geophys. Res.* **107,** doi:10.1029/2001JB001122 (2002).
38. Steffen, K., Nghiem, S. V., Huff, R. & Neumann, G. The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations. *Geophys. Res. Lett.* **31,** doi:10.1029/2004GL020444 (2004).
39. Zwally, H. J. *et al.* Surface melt-induced acceleration of Greenland ice-sheet flow. *Science* **297,** 218–222 (2002).
40. Abdalati, W. & Steffen, K., Greenland ice sheet melt extent: 1979–1999. *J. Geophys. Res. — Atmos.* **106,** 33983–33988 (2001).
41. Tedesco, M., Abdalati, W. & Zwally, H. J. Persistent surface snowmelt over Antarctica (1987–2006) from 19.35 GHz brightness temperatures. *Geophys. Res. Lett.* **34,** doi:10.1029/2007GL031199 (2007).
42. Paterson, W. S. B. *The Physics of Glaciers* 3rd edn (Pergamon, Oxford, UK, Tarrytown, New York, 1994).
43. Fahnestock, M. *et al.* High geothermal heat flow basal melt, and the origin of rapid ice flow in central Greenland. *Science* **294,** 2338–2342 (2001).
44. Fountain, A. G. & Walder, J. S. Water flow through temperate glaciers. *Rev. Geophys.* **36,** 299–328 (1998).
45. Rothlisberger, H. Water pressure in intra- and subglacial channels. *J. Glaciol.* **11,** 117–203 (1972).
46. Nye, J. F. Water flow in glaciers: jokulhlaups, tunnels and veins. *J. Glaciol.* **17,** 181–207 (1976).
47. Weertman, J. On the sliding of glaciers. *J. Glaciol.* **3,** 33–38 (1957).
48. Lliboutry, L. Contribution à la théorie du frottement des glaciers sur leur lit. *C. R. Séances Acad. Sci.* **247D,** 318–320 (1958).
49. Kamb, B. Glacial surge mechanism 1982–1983 surge of variegated glacier, Alaska. *Science* **227,** 269–279 (1985).
50. Kamb, B., Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *J. Geophys. Res.* **92,** 9083–9100 (1987).
51. Kamb, B. *et al.* Mechanical and hydrologic basis for the rapid motion of a large tidewater glacier. 2. Interpretation. *J. Geophys. Res. — Sol. Ea.* **99,** 15231–15244 (1994).
52. Iverson, N. R., Hanson, B., Hooke, R. L. & Jannson, P. Flow mechanism of glaciers on soft beds. *Science* **267,** 80–81 (1995).
53. Siegert, M. J. *et al.* A revised inventory of Antarctic subglacial lakes. *Antarctic Science* **17,** 453–460 (2005).
54. Vaughan, D. G. A. *et al.* Topographic and hydrological controls on Subglacial Lake Ellsworth, West Antarctica. *Geophys. Res. Lett.* **34,** doi:10.1029/2007GL030769 (2007).
55. Bell, R. E. *et al.* Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. *Nature.* **445,** 904–907 (2007).
56. Fricker, H. A., Scambos, T., Bindschadler, R. & Padman, L. An active subglacial water system in West Antarctica mapped from space. *Science* **315,** 1544–1548 (2007).
57. Smith, B. E., Joughin, I. R., Fricker, H. A. & Tulaczyk, S. Subglacial water transport throughout Antarctica from ICESAT laser altimetry. *Eos Trans. AGU* **88** (Fall Meet. Suppl.), abstract C53A-08 (2007).
58. Bell, R. E., Studinger, M., Fahnestock, M. A. & Shuman, C. A. Tectonically controlled subglacial lakes on the flanks of the Gamburtsev Subglacial Mountains, East Antarctica. *Geophys. Res. Lett.* **33,** doi:10.1029/2005GL025207 (2006).
59. Bjornsson, H., Hydrological characteristics of the drainage system beneath a surging glacier. *Nature* **395,** 771–774 (1998).
60. Flowers, G. E., Bjornsson, H., Palsson, F. & Clarke, G. K. C. A coupled sheet-conduit mechanism for jokulhlaup propagation. *Geophys. Res. Lett.* **31,** doi:10.1029/2003GL019088 (2004).
61. Bartholomaus, T. C., Anderson, R. S. & Anderson, S. P. Response of glacier basal motion to transient water storage. *Nature Geosci.* **1,** 33–37 (2007).
62. Jouzel, J. More than 200 meters of lake ice above subglacial Lake Vostok. *Science* **286,** 2138–2141 (1999).
63. Bell, R. E., Origin and fate of Lake Vostok water refrozen to the base of the East Antarctic ice sheet. *Nature* **416,** 307–310 (2002).
64. Joughin, I. *et al.* Seasonal speedup along the Western Flank of the Greenland Ice Sheet. *Science* (in the press).
65. Price, S. F., Payne, A. J., Catania, G. A. & Neumann, T. A. Seasonal acceleration of inland ice via longitudinal coupling to marginal ice. *J. Glaciol.* (in the press).
66. Joughin, I., Tulaczyk, S., Fahnestock, M. & Kwok, R. A mini-surge on the Ryder Glacier, Greenland, observed by satellite radar interferometry. *Science* **274,** 228–230 (1996).
67. Das, S. B. *et al.* Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage. *Science* (in the press).
68. Peters, L. E., Anandakrishnan, S., Alley, R. B. & Smith, A. M. Extensive storage of basal meltwater in the onset region of a major West Antarctic ice stream. *Geology* **35,** 251–254 (2007).
69. Gray, L. *et al.* Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. *Geophys. Res. Lett.* **32,** doi:10.1029/2004GL021387 (2005).
70. Stearns, L. A. & Hamilton, G. S. Thinning and acceleration of East Antarctic outlet glaciers. *Eos Trans. AGU* **88** (Fall Meet. Suppl.), abstract C41C-08 (2007).
71. Wingham, D. J., Siegert, M. J., Shepherd, A. & Muir, A. S. Rapid discharge connects Antarctic subglacial lakes. *Nature* **440,** 1033–1036 (2006).
72. Lewis, A. R. *et al.* The age and origin of the Labyrinth, western Dry Valleys, Antarctica: Evidence for extensive middle Miocene subglacial floods and freshwater discharge to the Southern Ocean. *Geology* **34,** 513–516 (2006).
73. Denton, G. E. & Sugden, D. E. Meltwater features that suggest Miocene ice-sheet overriding of the Transantarctic Mountains in Victoria Land, Antarctica. *Geogr. Ann. A* **87,** 67–85 (2005).
74. Lowe, A. L. & Anderson, J. B. Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica. *J. Glaciol.* **49,** 125–138 (2003).
75. Goodwin, I. D. The nature and origin of a Jokulhlaup near Casey-Station, Antarctica. *J. Glaciol.* **34,** 95–101 (1988).
76. Leventer, A. *et al.* Marine sediment record from the East Antarctic margin reveals dynamics of ice sheet recession. *GSA Today* **16** (12), 4–10 (2006).
77. Sawagaki, T. & Hirakawa, K. Erosion of bedrock by subglacial meltwater, Soya Coast, East Antarctica. *Geogr. Ann. A* **79,** 223–238 (1997).
78. Anderson, J. B. & Fretwell, L. O. Geomorphology of the onset of a paleo-ice stream, Marguerite Bay, Antarctic Peninsula. *Earth Surf. Processes* **33,** 503–512 (2008).
79. Siegert, M. J. & Bamber, J. L. Subglacial water at the heads of Antarctic ice stream tributaries. *J. Glaciol.* **46,** 702–703 (2000).
80. Kohler, J. Lubricating lakes. *Nature* **445,** 830–831 (2007).
81. Alley, R. B., Dupont, T. K., Parizek, B. R. & Anandakrishnan, S. Access of surface meltwater to beds of sub-freezing glaciers: preliminary insights. *Ann. Glaciol.* **40,** 8–14 (2005).
82. Conway, H. *et al.* Switch of flow direction in an Antarctic ice stream. *Nature* **419,** 465–467 (2002).
83. Ng, F. & Conway, H. Fast-flow signature in the stagnated Kamb Ice Stream, West Antarctica. *Geology* **32,** 481–484 (2004).
84. Joughin, I., Tulaczyk, S., Bindschadler, R. & Price, S. F. Changes in west Antarctic ice stream velocities: Observation and analysis. *J. Geophys. Res. — Sol. Ea.* **107,** doi:10.1029/2001JB001029 (2002).
85. Retzlaff, R. & Bentley, C. R. Timing of stagnation of ice stream C, West Antarctica from short-pulse-radar studies of buried surface crevasses. *J. Glaciol.* **39,** 533–561 (1993).
86. Anandakrishnan, S. & Alley, R. B. Stagnation of ice stream C, West Antarctica by water piracy. *Geophys. Res. Lett.* **24,** 265–268 (1997).
87. Price, S. F., Bindschadler, R. A., Hulbe, C. L. & Joughin, I. R. Post-stagnation behavior in the upstream regions of Ice Stream C, West Antarctica. *J. Glaciol.* **47,** 283–294 (2001).
88. MacAyeal, D. R. *et al.* An Ice-Shelf Model Test Based on the Ross Ice Shelf. *Ann. Glaciol.* **23,** 46–51 (1996).
89. Scambos, T. A., Bohlander, J. A., Shuman, C. A. & Skvarca, P. Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophys. Res. Lett.* **31,** doi:10.1029/2004GL020670 (2004).
90. Rignot, E. *et al.* Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophys. Res. Lett.* **31,** doi:10.1029/2004GL020697 (2004).
91. Anandakrishnan, S., Catania, G. A., Alley, R. B. & Horgan, H. J. Discovery of till deposition at the grounding line of Whillans Ice Stream. *Science* **315,** 1835–1838 (2007).
92. Alley, R. B. *et al.* Effect of sedimentation on ice-sheet grounding-line stability. *Science* **315,** 1838–1841 (2007).
93. Payne, A. J. *et al.* Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. *Geophys. Res. Lett.* **31,** doi:10.1029/2004GL021284 (2004).
94. Luckman, A., Murray, T., de Lange, R. & Hanna, E. Rapid and synchronous ice-dynamic changes in East Greenland. *Geophys. Res. Lett.* **33,** doi:10.1029/2005GL025428 (2006).
95. Howat, I. M., Joughin, I. & Scambos, T. A. Rapid changes in ice discharge from Greenland outlet glaciers. *Science* **315,** 1559–1561 (2007).
96. Joughin, I., Tulaczyk, S., MacAyeal, D. R. & Engelhardt, H. Melting and freezing beneath the Ross ice streams, Antarctica. *J. Glaciol.* **50,** 96–108 (2004).
97. Blankenship, D. D. Active volcanism beneath the West Antarctic Ice Sheet and implications for ice-sheet stability. *Nature* **361,** 526–529 (1993).
98. Studinger, M. *et al.* Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica. *Earth Planet. Sci. Lett.* **205,** 195–210 (2003).
99. Rignot, E. & Thomas, R. H. Mass balance of polar ice sheets. *Science* **297,** 1502–1506 (2002).

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