PHILOSOPHICAL TRANSACTIONS A

rsta.royalsocietypublishing.org

Review

Cite this article: Fricker HA, Siegfried MR, Carter SP, Scambos TA. 2016 A decade of progress in observing and modelling Antarctic subglacial water systems. *Phil. Trans. R. Soc. A* **374**: 20140294.
http://dx.doi.org/10.1098/rsta.2014.0294

Accepted: 5 October 2015

One contribution of 17 to a Theo Murphy meeting issue 'Antarctic subglacial lake exploration: first results and future plans'.

Subject Areas:
glaciology, geophysics, hydrology

Keywords:
subglacial lakes, Antarctic ice sheet, satellite altimetry

Author for correspondence:
Helen A. Fricker
e-mail: hafricker@ucsd.edu

THE ROYAL SOCIETY PUBLISHING

A decade of progress in observing and modelling Antarctic subglacial water systems

Helen A. Fricker[1], Matthew R. Siegfried[1], Sasha P. Carter[1] and Ted A. Scambos[2]

[1]Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0225, USA
[2]National Snow and Ice Data Center, CIRES, University of Colorado, Boulder, 1540 30th Street, Bldg. RL-2, Boulder, CO 80303, USA

In the decade since the discovery of active Antarctic subglacial water systems by detection of subtle surface displacements, much progress has been made in our understanding of these dynamic systems. Here, we present some of the key results of observations derived from ICESat laser altimetry, CryoSat-2 radar altimetry, Operation IceBridge airborne laser altimetry, satellite image differencing and ground-based continuous Global Positioning System (GPS) experiments deployed in hydrologically active regions. These observations provide us with an increased understanding of various lake systems in Antarctica: Whillans/Mercer Ice Streams, Crane Glacier, Recovery Ice Stream, Byrd Glacier and eastern Wilkes Land. In several cases, subglacial water systems are shown to control ice flux through the glacier system. For some lake systems, we have been able to construct more than a decade of continuous lake activity, revealing internal variability on time scales ranging from days to years. This variability indicates that continuous, accurate time series of altimetry data are critical to understanding these systems. On Whillans Ice Stream, our results from a 5-year continuous GPS record demonstrate that subglacial lake flood events significantly change the regional ice dynamics. We also show how models for subglacial water flow have evolved since the availability of observations of lake volume change, from regional-scale models of water routeing to process models of channels carved into the subglacial sediment instead of the overlying ice. We show that progress in understanding the processes governing lake drainage now allows us to create simulated lake volume time series that reproduce time series from satellite observations. This transformational decade in Antarctic subglacial water research has moved us significantly closer to understanding the processes of water transfer sufficiently for inclusion in continental-scale ice-sheet models.

1. Introduction

The Antarctic ice sheet is on average 2.2 km thick [1] and rests on top of bedrock; the insulation, high pressures and geothermal heat flux at the ice–bed interface leads to melting of the basal ice layers of the order of millimetres per year [2]. When averaged over the entire ice sheet, this produces high volumes of subglacial water (an amount of 65 Gt yr^{-1} was estimated by [3], much of which is stored in subglacial lakes [4] and subglacial aquifers [5]). Located beneath kilometres of ice, Antarctica's basal environment is challenging to access, and most information about it has been inferred from remote sensing techniques above the ice-sheet surface. As recently as a decade ago, an inventory of Antarctic subglacial lakes [4] documented lakes that had been surveyed with traditional geophysical techniques (airborne radio-echo sounding and active seismic surveys); these techniques rely on imaging water bodies by exploiting the strong contrast in physical properties between ice and water (acoustic properties in seismic methods; dielectric properties in radar methods). The most recently discovered lake of this type was identified in a 2013–2014 survey of the Ellsworth Mountains [6]. The 2005 inventory lakes, and lakes detected by radar following that compilation, are mainly located on the ice-sheet plateau (figure 1). These have never been observed to change significantly, and are thus thought to be stable over long (multi-decadal to millennial) time periods (e.g. [15]).

A second type of lake is detected by virtue of the fact that its volume *is* changing on sub-decadal scales. A series of papers in 2005–2007 showed clusters of large (1–10 m) signals of height change over time on the grounded ice sheet, which were interpreted as the surface expressions of subglacial water transferring from one area of impoundment to another. When water transfers occur, the surface of the ice responds: it rises as excess water enters the lake, or falls as it leaves it. This surface-height change signal can be detected by repeated satellite measurements, e.g. interferometric synthetic aperture radar (InSAR), [16] satellite radar altimetry [17] or satellite laser altimetry [18]. The lakes discovered through surface-height changes exhibited volume changes on sub-annual to decadal time scales and thus were considered 'active' hydrological features. Observing changes to these active subglacial lakes over time through analysis of surface-height anomalies has, therefore, provided a transformational new dataset to help understand how the Antarctic subglacial water system evolves on a variety of time scales and how those changes affect ice dynamics.

The most effective instrument to date for continental-scale mapping of subglacial water movement inferred from ice surface-height anomalies has been the laser altimeter onboard the Ice, Cloud and Land Elevation Satellite (ICESat). InSAR provides detailed height-change maps (e.g. [16,19]), but has had limited temporal sampling over large swaths of the ice sheet. Satellite radar altimetry detected only a limited number of active lakes (e.g. [17]), which in general were large relative to the ICESat-detected group. Satellite radar altimetry was not capable of detecting signals over ice streams with steep undulating topography (e.g. tens of metres of relief over 3–10 km), due to its large footprint size [10]. The ICESat altimeter had a smaller footprint (approx. 60 m), dense along-track spacing (approx. 170 m), high vertical accuracy (approx. 10 cm) and the satellite repeated the same ground tracks to within a few hundred metres two to three times a year between 2003 and 2009. Following initial ICESat investigations into a single active subglacial lake system on the Whillans Ice Stream [9,18], Smith *et al.* [8] presented a continent-wide survey of repeat-track ICESat altimetry data that produced an inventory containing 124 spatially coherent height anomalies (i.e. a coherent change identified on at least two different ICESat tracks) that were interpreted as active lakes [8] (figure 1). This inventory of lake volume changes was based

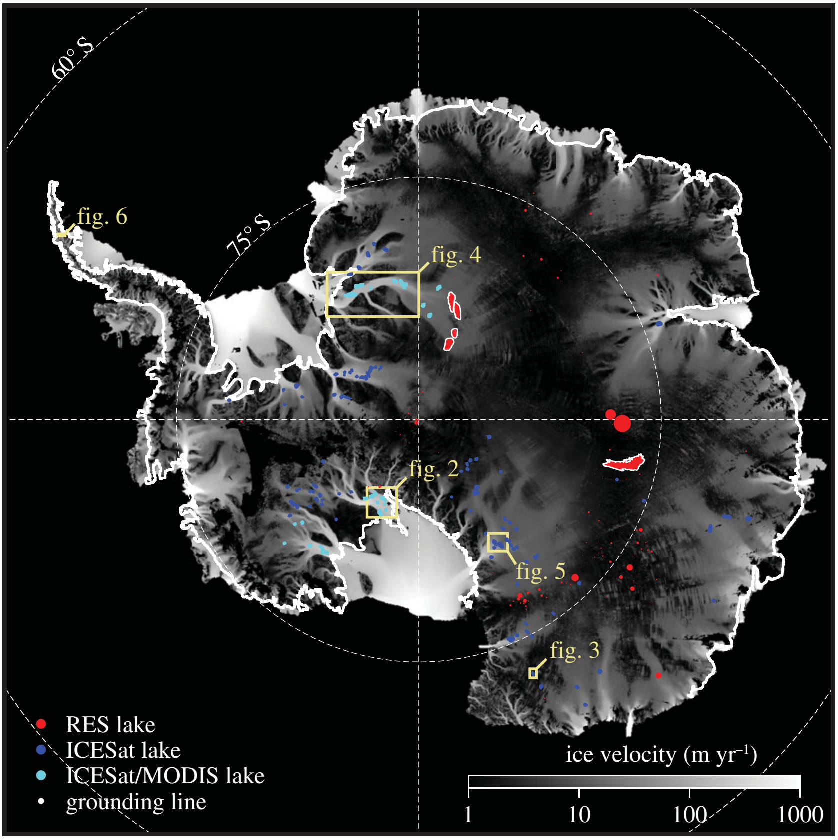

Figure 1. Known subglacial lakes in Antarctica. Locations of Antarctic subglacial lakes, showing lakes studied via RES (red [7]), ICESat (blue [8]), and ICESat and MODIS (cyan [9–11]). Outlines of upper Recovery Glacier lakes from Bell *et al*. [12] and subglacial Lake Vostok from Studinger *et al*. [13]; all other RES lakes are represented by circles, with size scaled to lake length [7]. Yellow boxes indicate locations of figures 2–6. Background is InSAR-derived ice velocity [14]. Adapted from Smith *et al*. [8].

on 4.5 years (October 2003 to March 2008). Only lakes north of 86° S could be mapped because of the geometry of the satellite's orbit.

Smith *et al*.'s [8] active subglacial lake inventory showed that active lakes are prevalent in coastal Antarctica and predominantly located under fast-flowing outlet glaciers and ice streams (figure 1), which drain as much as 90% of the ice in Antarctica from the continent towards the ocean [20]. Despite success mapping subglacial water with ICESat, there were some limitations: (i) the track spacing of ICESat altimetry precluded complete coverage of the ice sheet and, in particular, detailed analysis of some coastal fast-flow areas; (ii) ICESat operated only two to three times per year, limiting its ability to resolve important details of the fill–drain cycle; (iii) ICESat only operated between 2003 and 2009 and so could not capture recurrence intervals greater than 6 years; and (iv) ICESat could only detect lakes that had height-change anomalies greater than approximately 0.1 m. As a result of these limitations, the 124 lakes discovered probably represent only a small subset of the full distribution of active subglacial lakes.

Extending the active subglacial lake records with other satellite and airborne instruments has, therefore, become a critical requirement to understand the important spatio-temporal time scales of active subglacial hydrology. In this paper, we review the progress that has been made in understanding active subglacial lakes through repeated height observations (satellite, airborne and ground-based) and developments in modelling based on those data, concentrating mainly on the period since the ICESat mission ended in 2009.

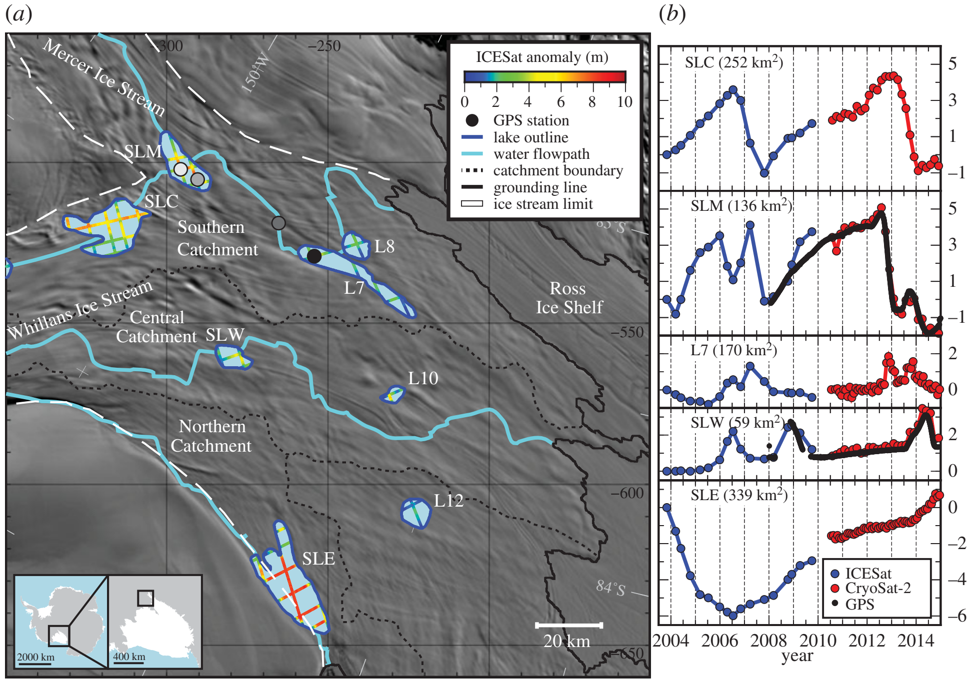

Figure 2. Subglacial water system of the Whillans/Mercer Ice Streams, West Antarctica. (*a*) Map of the subglacial lakes in the system (blue outlines) annotated with ICESat track segments used to detect them (colour-coded by surface-height change). The lakes are contained within three separate hydrologic systems, and the hydrologic flowpaths and catchment boundaries are shown. (*b*) Time series of average height change over the four largest lakes from ICESat, CryoSat-2 and GPS. Adapted from Siegfried [23].

2. Lake activity after ICESat: continuing the time series past 2009

Since the end of the ICESat operations in 2009, additional information on lake activity has been limited to lakes that were covered by the CryoSat-2 synthetic aperture radar-interferometric (SARIn) mode [19,21], the Airborne Topographic Mapper (ATM) flown by NASA's Operation IceBridge (OIB) [11] or instrumented with Global Positioning System (GPS) [21], or, in a few cases, examined by satellite image differencing [11,22]. In this section, we summarize the progress that has been made in observing lake activity since 2009.

(a) Whillans Ice Stream lakes (ICESat, GPS and CryoSat-2)

The subglacial water system of the lower Whillans Ice Stream on the Siple Coast, West Antarctica, contains numerous connected subglacial lakes in three hydrological catchments (northern, central and southern; figure 2*a*), which were all discovered through analysis of repeat tracks of ICESat laser altimetry data [9,18]. Subglacial Lake Whillans (SLW) is in the central hydrologic catchment and underwent two complete fill–drain cycles during the ICESat mission (figure 2*b*). It is unknown how long the lake had been quiescent prior to the start of the ICESat time series. Shortly after the initial discovery of the lakes in this region, a GPS campaign was designed to collect data to understand how lake activity affects ice dynamics. Several continuous GPS stations were established on and around SLW during the 2007–2008 field season, and in 2010 the GPS array was expanded to 23 sites as part of the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project [24]. The GPS stations collected data until 2015, providing an 8-year time series of data on lake activity and ice dynamics, at much higher temporal sampling than ICESat's campaign-style sampling. This is the only ground-based GPS array that has been installed in Antarctica for the purpose of measuring the response of ice dynamics to subglacial activity.

To continue broad satellite coverage of these lakes, Siegfried *et al*. [21] used radar-altimeter data from the ESA's CryoSat-2 mission, which began acquiring data in July 2010. Only part of the Antarctic ice sheet falls within the mask used for SARIn-mode data acquisition of CryoSat-2; the remainder is covered by low-resolution mode, a conventional pulse-limited altimeter operation mode that is less useful for continuing time series over subglacial lakes beneath ice streams due to the large footprint size [10]. CryoSat-2 operated in SARIn mode over the Mercer and Whillans Ice Streams, and acquired surface-height changes due to subglacial lake activity at up to monthly resolution for the period 2010–2013. Using the GPS data that spanned the gap between the ICESat and CryoSat-2 missions, Siegfried *et al*. [21] were able to construct a self-consistent record of lake activity for a full decade (figure 2*b*). These CryoSat-2 height measurements, trends and spatial patterns of change were then validated using satellite image differencing and GPS.

The combined ICESat/CryoSat-2 record [21] identified two large subglacial drainage events occurring at lakes discovered by ICESat. These were similar in magnitude and duration to previous drainage events, allowing inferences of subglacial lake cyclicality past the end of the ICESat mission. CryoSat-2 SARIn-mode data also provided more spatial information about subglacial lake filling and drainage than ICESat data owing to CryoSat-2's non-repeating ground tracks. The increased spatio-temporal information about subglacial lake evolution provided by a combined CryoSat-2/ICESat activity record is critical to understanding basic parameters (e.g. recurrence time scales, durations of inactivity, changes in lake boundaries, etc.) of these subglacial lakes.

(b) Cook E2 lake, East Antarctica (ICESat, CryoSat-2 and SAR feature tracking)

One of the lakes reported in Smith *et al*.'s inventory [8], Cook E2 in East Antarctica, drained over 20 months between 2007 and 2008 and experienced an anomalously large height change (approx. 65 m). CryoSat-2 SARIn-mode and ICESat data were combined to map and monitor this lake [19] (figure 3). They used CryoSat-2 to map the perimeter and depth of a 260 km^2 surface depression left behind after it drained, and then used this in combination with ICESat and SAR feature tracking to estimate the changes in lake volume. With a refined lake outline from CryoSat-2, they found that, during the flood of 2007–2008, between 4.9 and 6.4 km^3 of water had drained from the lake, and peak discharge exceeded 160 $m^3\,s^{-1}$. This subglacial flood was twice as large as any previously recorded and equivalent to approximately 10% of the estimated amount of meltwater generated annually beneath the ice sheet. The ice surface uplifted at a rate of $5.6 \pm 2.8\,m\,yr^{-1}$ since the ICESat mission, as detected by CryoSat-2. This study demonstrated the ability of CryoSat-2 to provide a detailed map of ice surface topography (in this case, a crater left behind after a large subglacial drainage event), as well as its potential to accurately measure subglacial lake drainage events, and the contribution it can make to understanding water flow beneath Antarctica.

(c) Recovery Ice Stream (ICESat, OIB and satellite image differencing)

Using ICESat data from 2003 to 2008, Smith *et al*.'s inventory [8] revealed a connected system of active subglacial lakes beneath the Recovery Ice Stream, East Antarctica (figure 4*a*). Fricker *et al*. [11] used the final year of ICESat data (2009) to update the ICESat repeat-track analysis, correcting all the ICESat data for the Gaussian-centroid offset [25]. This analysis confirmed that there are direct hydrologic connections between the lakes in the Recovery system and that the lakes respond rapidly to changes in lakes upstream. During the ICESat period the dominant signal was surface lowering over two mid-glacier lakes (Rec6 and Rec9 upstream, not shown) and surface inflation over the lower two lakes (Rec1 and Rec2) (figure 4*c*).

The three lower Recovery lakes were resurveyed by OIB in 2011 and 2012 following sections of ICESat tracks (figure 4*a*); Fricker *et al*. [11] used surface-height data from OIB's Airborne

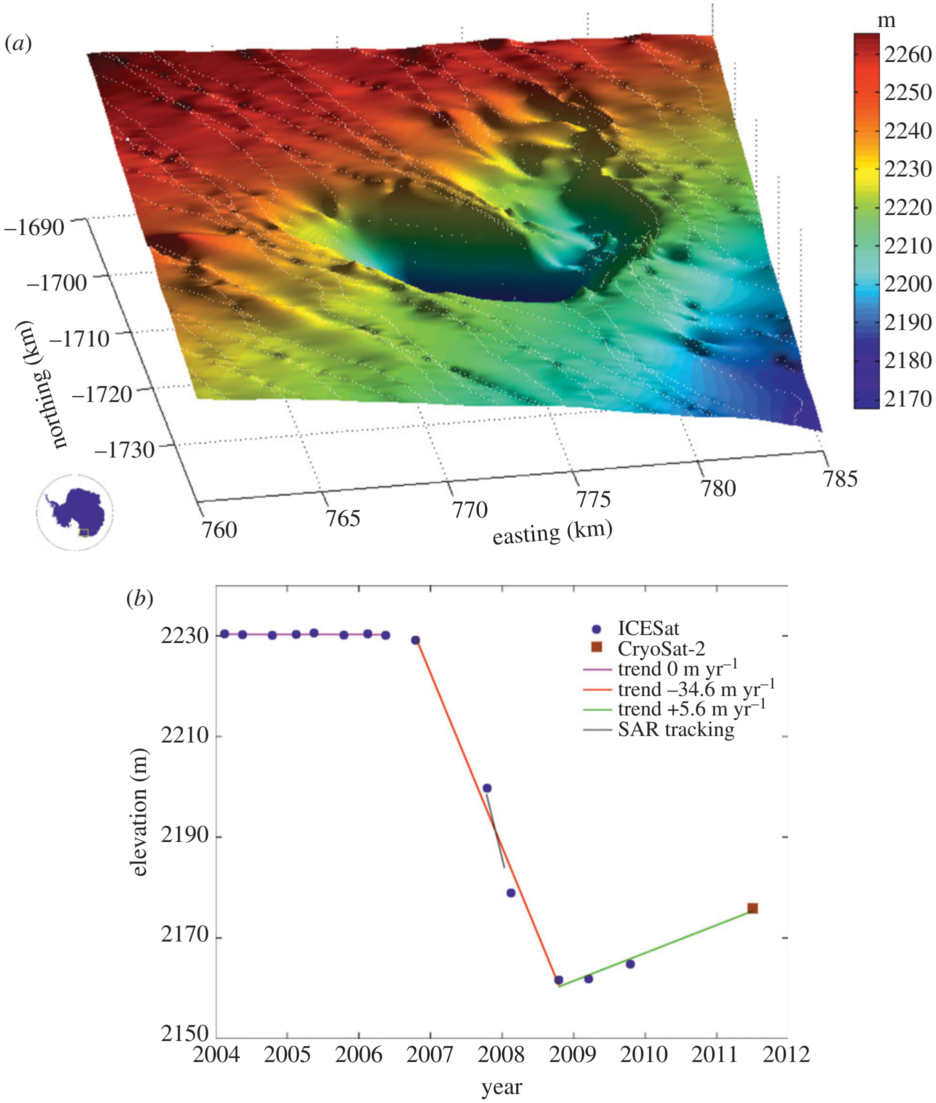

Figure 3. ICESat/CryoSat data over Cook E2 lake in East Antarctica. (*a*) Surface expression of the drained Cook E2 subglacial lake, mapped by CryoSat-2 SARIn mode data (white dots) from January to November 2011. The shaded surface is a minimum curvature interpolation of the CryoSat-2 data, and illuminated from the east. (*b*) Evolution of ice surface height above the Cook E2 subglacial lake, from ICESat (2003–2009) and CryoSat-2 (2011) observations. An independent estimate of height change derived from SAR feature tracking is also shown. Adapted from McMillan *et al*. [19].

Thematic Mapper (ATM) to extend the record of activity of these three lakes: Rec1 had undergone a monotonic increase in elevation between 2003 and 2009, interpreted as continuous filling, and showed a decrease between the 2011 and 2012 OIB surveys, interpreted as drainage; Rec2 showed a 1 m uplift between 2008 and 2011, followed by an elevation drop of 3 m relative between 2011 and 2012, interpreted as a drainage event; and Rec3, which had undergone changes only of the order of approximately 10 cm yr^{-1} between 2003 and 2009, experienced a surface subsidence of approximately 10 m some time between 2009 and 2011 (figure 5*a*).

MODIS image differencing (2008–2011; see [22]) revealed another large subsidence event downstream of Rec3 (figure 5*b*), and OIB ATM data acquired along an ICESat track segment detected a height-change anomaly of the order of 10 m between 2009 ICESat data and the 2012 flight. There had been no anomaly detected during 2003–2009. It is believed that this is the surface

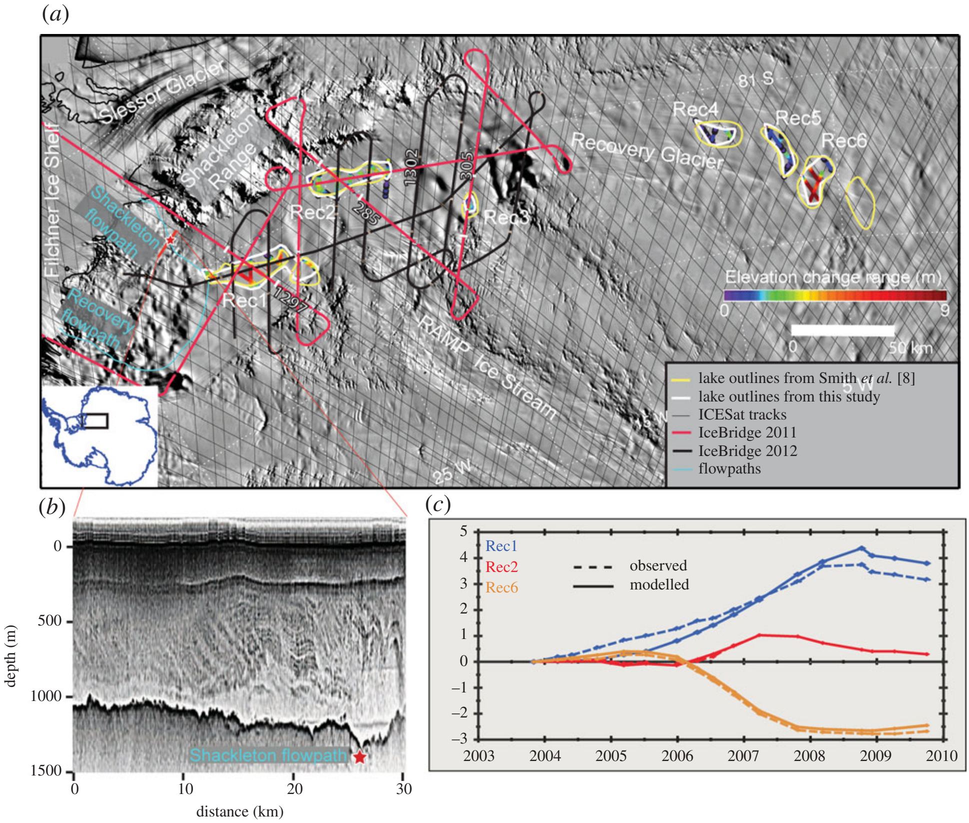

Figure 4. Active lakes of the Recovery Ice Stream, East Antarctica, from ICESat and IceBridge. (*a*) Map of the six subglacial lakes of lower Recovery Ice Stream (white outlines) annotated with ICESat track segments used to detect them (colour-coded by surface-height change). (*b*) IceBridge radargram for a track segment across the Shackleton flowpath downstream of Rec1 (see *a* for location, solid red line) showing features that are not parallel to the bed that may indicate accretion of basal water formed as water travels up and over the saddle in Shackleton Range. (*c*) ICESat-derived and modelled volume change time series for the three largest Recovery lakes. Adapted from Fricker *et al*. [11].

expression of an unusual dynamic response to the drainage of Rec3 upstream. In addition to the deflation, a change in orientation of some of the surface flowstripe features in the region suggests that the drainage of Rec3 significantly reduced the basal friction of a section of the glacier, causing a local acceleration and slight change in flow direction.

ICESat/OIB height and OIB RES data were used to map the surface and bed topography to provide constraints on the topographic setting of the lakes and about how water flows through the system. The OIB RES data showed that most of the Recovery lakes are located in an approximately 1000 km long bedrock trough under the main trunk of the ice stream, whose base is approximately 1500–2000 m below present-day sea level. The hydrologic system beneath Recovery Ice Stream is controlled primarily by this unusually pronounced and deep bedrock topography, in contrast to most Antarctic systems studied to date, which are controlled mostly by the ice surface topography (e.g. [26]).

Lower on the glacier, predicted hydrologic flowpaths showed a bifurcation just downstream of Rec1, forming two possible pathways for the water to cross the grounding line and into the sub-ice-shelf cavity: one that follows the ice flow and one that diverts to the north to cross Shackleton Ridge, along the steepest hydrologic gradient ('Recovery flowpath' and 'Shackleton flowpath' are marked on figure 4*a*). OIB RES data acquired across the proposed Shackleton Ridge flowpath showed basal features that were consistent with water being frozen onto the bed (figure 4*b*), perhaps due to a large decrease in pressure by following the flowpath over the ridge.

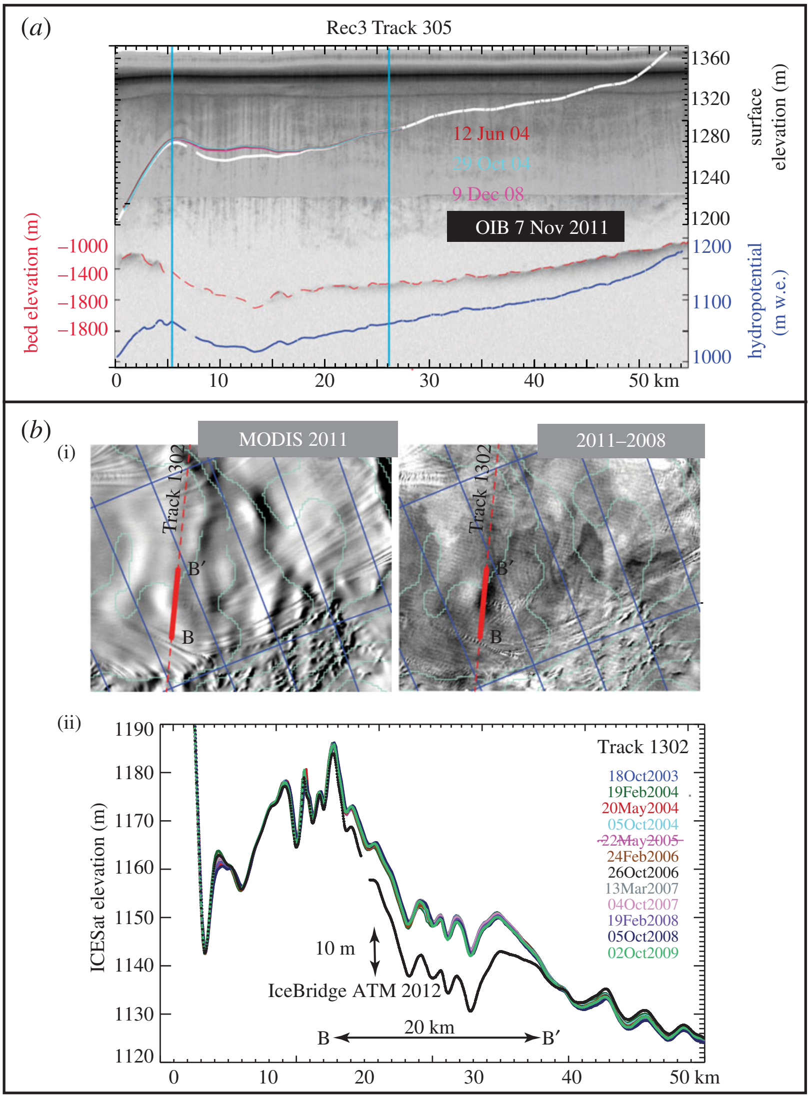

Figure 5. (*a*) IceBridge radargram acquired along ICESat track 305 on Rec3. The coloured lines towards the top are the surface-height profiles from the ICESat repeats (repeat dates in corresponding colours); white line is the IceBridge ATM surface height. The central line (dashed red) is the bed height picked from the radargram, and the bottom line (solid blue) is the hydropotential. Adapted from Fricker *et al*. [11]. (*b*) (i) MODIS image from 2011 and difference image (2011–2008) showing surface deformation along ICESat track 1302, downstream of Rec3. (ii) Repeat ICESat height profiles along track 1302 (colours) and heights derived from the OIB ATM in 2012 showing approximately 10 m surface deformation along a 20 km track segment.

3. Influence of active lakes on ice dynamics

There are now a number of theoretical studies to explain the drainage of temperate glacially dammed and subglacial lakes and the evolution of water systems in response to the abrupt addition of surface meltwater in Greenland [27]. In Antarctica, however, such work is more rare, in part due to the lack of coincident observations of ice velocity and subglacial hydrologic changes, and insufficient temporal sampling. There have been only three reports of temporary ice acceleration following the drainage of one or more lakes: on Byrd Glacier, East Antarctica [28], on Crane Glacier, Antarctic Peninsula [29] and on Whillans Ice Stream [23].

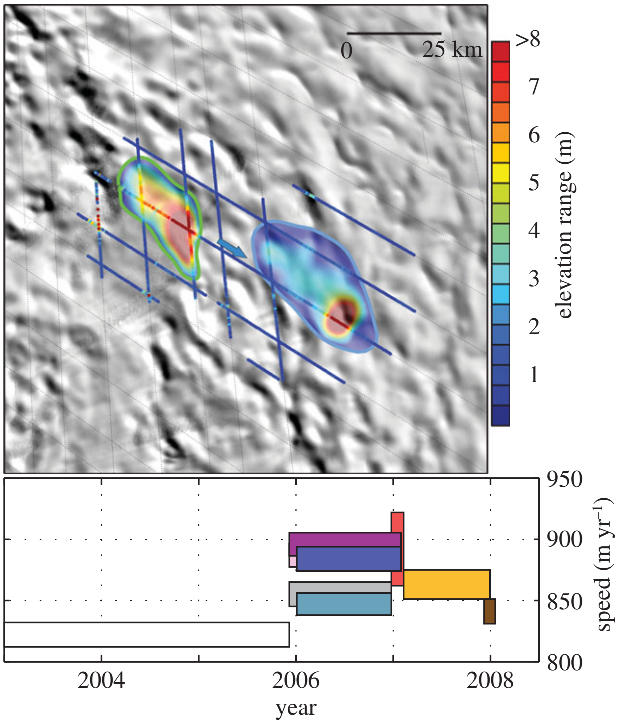

Figure 6. Impact of lake drainage on ice dynamics at Byrd Glacier. Top plot: Map of height ranges for 500 m sections of ICESat tracks, interpreted lake boundaries (green, blue outlines) and height ranges for gridded surface displacements, overlaid on a MODIS mosaic of Antarctica [31]. Surface heights track 0263 decreased over the upper lake and increased over the lower lake between November 2003 and November 2007, which was interpreted as the upper lake draining. Bottom plot: Ice speed at the grounding line from 2003 to 2008. The horizontal bars indicate start and end dates for each pair of observations and the height of each bar represents its associated error. Adapted from Stearns *et al*. [28].

(a) Byrd Glacier

Smith *et al*.'s inventory [8] identified a linked pair of large subglacial lakes located about 200 km upstream of the grounding line of Byrd Glacier, East Antarctica, which both experienced large height changes in 2003–2007. Subsequent analysis showed that the lakes released a large flood between November 2005 and April 2007, which led to changes in ice dynamics of Byrd Glacier [28] (figure 6). The activity of the downstream lake lagged that of the upstream lake by about seven months: the upstream lake inflated (with a corresponding estimated volume gain of 1.4 km^3) between November 2003 and November 2005, and then deflated (corresponding to a similar volume loss between November 2005 and April 2007). The downstream lake gained 1.7 km^3 between March 2004 and June 2006, then lost 1 km^3 between June 2006 and March 2007, and then gained again between March 2007 and November 2007. The net volume change for the two lakes was a gain of 2.1 km^3 between March 2004 and November 2005, and a loss of 1.7 km^3 between June 2006 and April 2007.

The net 1.7 km^3 discharge of the Byrd lakes was released at an estimated peak rate of approximately 70 $m^3\,s^{-1}$, which occurred between March 2006 and February 2007. Coincident with this flood, there was an increase in ice velocity of about 10% along the entire 75 km glacier trunk between December 2005 and February 2007. Deceleration coincided with the termination of the discharge. This was the first direct evidence that an active lake drainage system can cause large and rapid changes in glacier dynamics in Antarctica.

(b) Crane Glacier

On the Antarctic Peninsula, a rapid, localized surface-height change was detected by ICESat and OIB altimeter data between 2002 and 2009 in the lower central portion of Crane Glacier (approx. 10 km from the terminus; figure 7). This anomaly was inferred as the drainage of a small, deep lake [29], which was not documented by Smith *et al*. [8] as it was detected only on one ICESat track. The rate of height change was approximately 91 m yr^{-1} between September 2004 and September 2005, which was spanned by periods of more moderate rates (23 m yr^{-1} until September 2004; 12 m yr^{-1} after September 2005) that were largely a result of ongoing glacier thinning due to the extended response of Crane Glacier to the loss of the Larsen B Ice Shelf [32]. Satellite (ASTER and SPOT-5) stereo-image digital height model (DEM) differencing spanning the event showed that the area that underwent this height change was approximately 4.5 × 2.2 km.

The precise connection between subglacial lake discharge and velocity cannot be estimated at Crane Glacier, as the impact of this process could not be separated from the processes triggered by the collapse of the Larsen B Ice Shelf. The drainage event itself was apparently triggered by surface slope changes along the glacier centre line during glacier retreat, and the interpretation was that this was induced by hydraulic forcing of subglacial water past a downstream obstruction. Specifically, the retreat of the ice front from a subglacial ridge in late 2004 apparently caused a final further change in surface slope, which initiated rapid water discharge from the subglacial reservoir [29]. Only a fraction of Crane Glacier's increase in flow speed that occurred near the time of lake drainage (derived from image feature tracking) appears to be directly attributable to the event. Instead, retreat of the ice front from a subglacial ridge 6 km downstream of the lake is probably the dominant cause of renewed fast flow and more negative mass balance in the subsequent four years. Bathymetry in the newly opened Crane Glacier fjord revealed a series of flat-lying, formerly subglacial depressions interpreted as lake sediment basins, suggesting that the new lake is one of a series of past subglacial water bodies lying along the centre of the glacial fjord valley.

(c) Whillans Ice Plain

In both the documented cases of ice acceleration following subglacial drainage (Byrd and Crane Glaciers), temporal resolution of both the subglacial lake activity and ice velocity changes was limited by satellite orbits and acquisitions, preventing a detailed understanding of how subglacial water systems coevolve with the ice sheet. On Whillans Ice Stream, a GPS array was installed to provide a long-term dataset on lake activity and ice velocity at high temporal resolution in order to understand the impact of subglacial hydrology on ice dynamics.

Siegfried [23] used 5 years (2010–2015) of continuous GPS data on the Whillans and Mercer Ice Streams, West Antarctica. They observed 2 years of enhanced flow associated with a cascading subglacial lake flood event in the southern catchment (figure 2*b* and figure 8). During this 2-year period of elevated ice flow, there were three distinct, episodic velocity fluctuations of nearly 4% correlated to lake drainage evolution (figure 8). The observed velocity changes were of a large enough magnitude to reverse the regional deceleration of the Whillans Ice Stream [33–35], indicating that the long-observed deceleration varies significantly over short durations. Surface-height changes of the subglacial lakes were correlated with, but lagged, the sub-annual velocity fluctuations, indicating that the evolution of the subglacial drainage system (with time scales of days to weeks) plays a significant role in controlling the impact of subglacial lake floods on ice velocity. How these very short-time-scale, episodic changes due to subglacial lake activity impact significantly longer-time-scale processes, such as multi-year-scale subglacial water piracy [26] and millennial-scale ice stream oscillations [36], remains unknown.

4. Modelling of Antarctic subglacial systems

The recent improvement in observations of lake activity have allowed for a new generation of models to provide context for the satellite-based observations and reveal how these observations

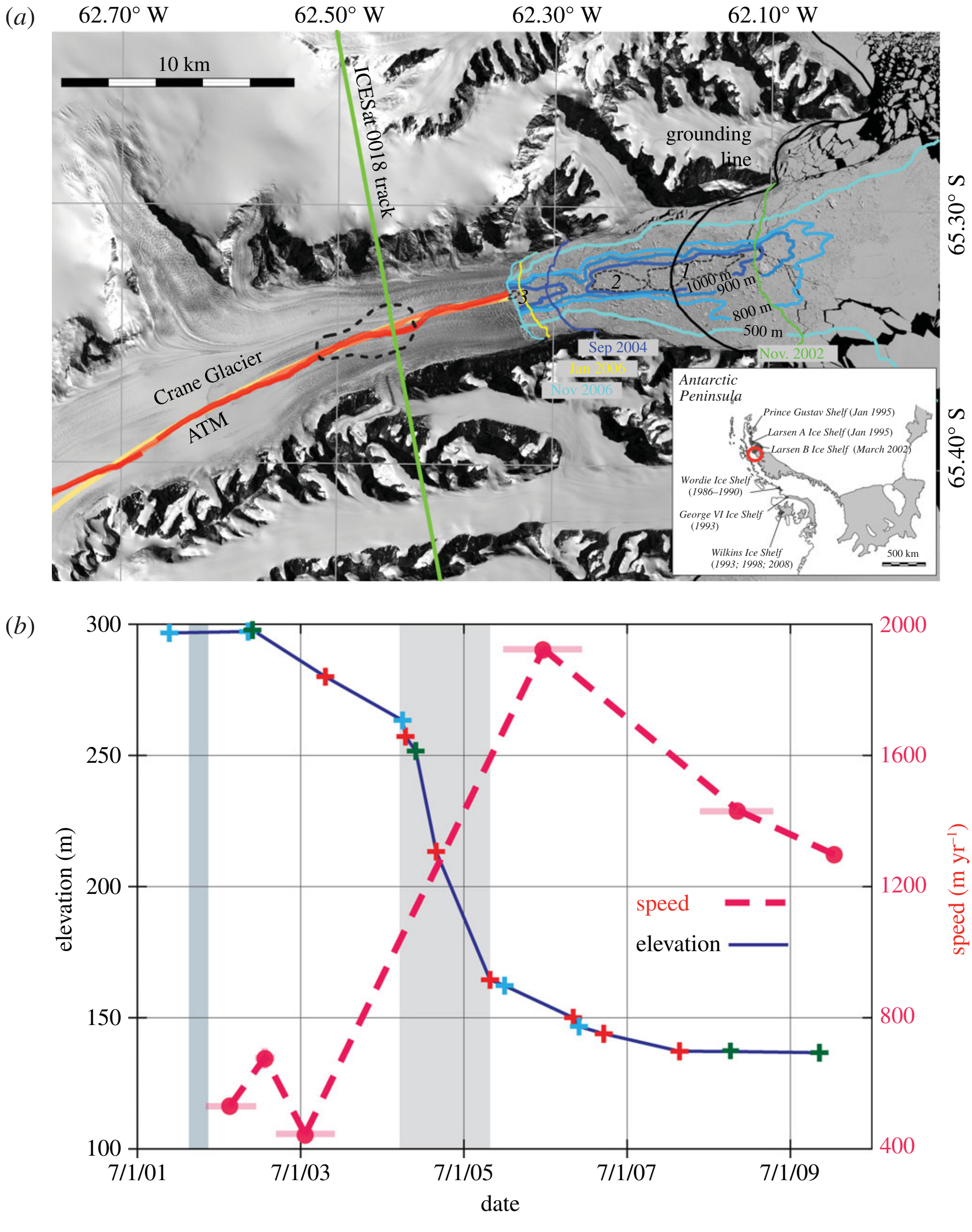

Figure 7. Drainage of Crane Glacier lake on the eastern Antarctic Peninsula. (*a*) Satellite image map of lower Crane Glacier and fjord. Image is from SPOT-5 high-resolution stereo (HRS) sensor, acquired 25 November 2006. Recent airborne laser altimetry tracks (ATM: 2002, 2004 and 2008 in yellow, orange and red, respectively) and satellite laser altimetry tracks (ICESat: 2003–09, straight green line) showed anomalously large height changes on the glacier. Numbers in the fjord (1, 2 and 3) and dashed outlines represent flat sediment-filled basins interpreted as past subglacial lake deposits, and bathymetry contours are also shown. Grounding line of 1998–2002 is from SAR interferometry [30]. Ice-front locations for floating (November 2002) and grounded ice fronts are shown; since November 2006 the ice-front position has been essentially unchanged. Inset: Locator map of Crane Glacier, within the Larsen B embayment, Antarctic Peninsula. (*b*) ICESat-derived height for track 0018 across Crane Lake (left-hand scale), and flow speed (right-hand scale). Adapted from Scambos *et al*. [29].

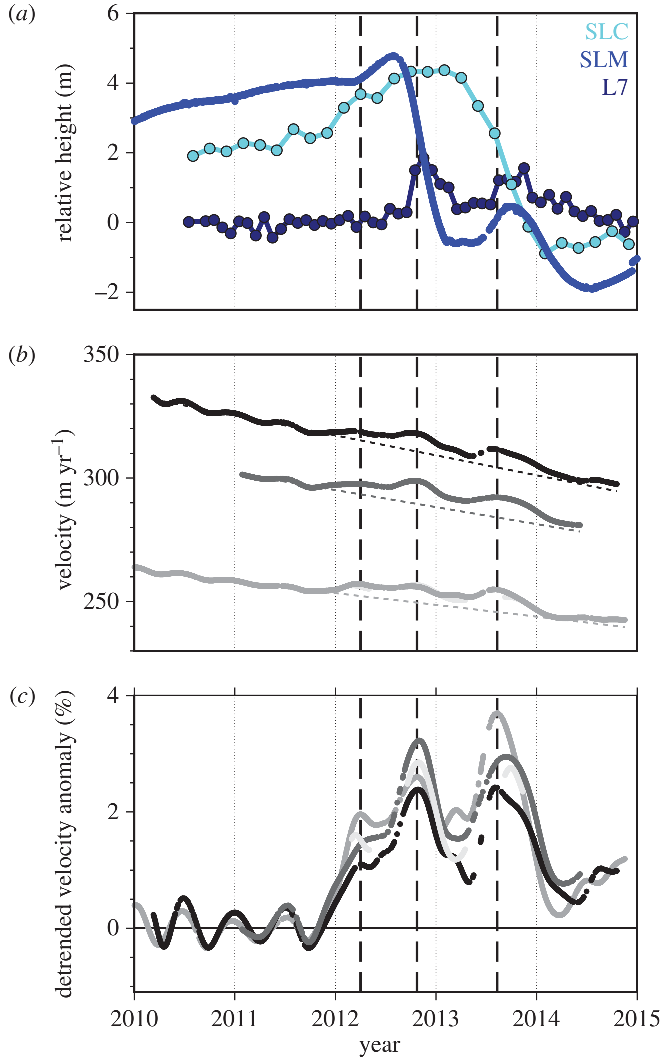

Figure 8. Effect of subglacial flood event on ice velocities. (*a*) Subglacial lake activity of SLC, SLM and Lake 7 from CryoSat-2 (SLC, L7) and GPS (SLM). (*b*) Raw velocities from four GPS stations on lower Mercer ice stream during a subglacial lake drainage event (locations of GPS and lake activity time series shown in figure 2). Dashed line indicates continued ice deceleration at pre-event rates. (*c*) Evolution of the ice velocity anomaly (relative to dashed baseline in (*b*)) caused by subglacial lake drainage, showing a broad 2-year period of enhanced ice velocities, with three rapid acceleration/deceleration episodes. Three velocity peaks are marked by vertical dashed lines. Light to dark colour variation indicates upstream to downstream. Adapted from Siegfried [23].

may provide clues to the deeper working of the subglacial hydrologic system, even in places where such lakes are not present. What is being learned from these simulations of subglacial water flow may fundamentally change how ice-sheet models treat the basal boundary condition [27] and how we understand life within this environment [37].

In this section, we summarize the progress that has been made in modelling these systems. We start with water budget modelling to quantify the hydrologic variability associated with subglacial lakes, we then explore models for their formation and impact on steady-state ice flow, and finally we discuss how their drainage takes place and how the drainage process influences basal lubrication.

(a) Water routeing and budgeting

Prior to the discovery of active lakes and the degree to which they were widespread in Antarctica, ice-sheet water models (e.g. [38]) typically approximated the ice–bed interface as a water layer of variable thickness with higher water pressures (and thus more sliding and higher water flux rates) correlating with areas of thicker water. Although this relationship appeared to be viable at coarse scales (20 × 20 km grid cells), at smaller scales models tended to concentrate water in pathways just a few grid cells across, starving adjacent cells. Models did, however, route water along the locations of many major subglacial lakes (e.g. [5,39]).

One of the initial questions addressed by modellers examined how much of the total water produced at the ice-sheet base is captured through observations of volume changes in active subglacial lakes (e.g. [8]). The first work, however, to evaluate this in a thorough manner was by Carter *et al.* [40], who used observations of lake volume change from Fricker *et al.* [10], a high-resolution DEM of the ice surface [41], and RES-based ice thickness to infer subglacial water flow routeing through multiple lakes in MacAyeal Ice Stream. Then using estimates for basal melt rate distribution from Joughin *et al.* [42] and a water transport model, they calculated that nearly all water produced in this ice stream catchment passed through at least one of the five largest lakes on the ice stream. This methodology was then expanded to the entire Siple Coast, where it was used to produce the first estimates for temporal variations in subglacial outflow to the ice shelf cavity driven by active subglacial lakes [43]. This effort also added more evidence in support of the idea that, as an active lake fills, it cuts off the flow of subglacial water downstream [40] (figure 10*a*).

Wright *et al.* [39] attempted a more expansive effort modelling the lakes in the Totten Glacier catchment in East Antarctica, combining an ice-sheet model with a water routeing scheme. In this case, however, there were substantial discrepancies in the quantities of meltwater generated upstream of the largest active lake in the system. These discrepancies are probably attributed to how the ice-sheet model calculates basal melt and internal temperatures. This study, which included radar sounding data, was among the first to note that many satellite-detected lakes did not exhibit the strong basal reflection characteristics of radar-detected lakes.

Further work with water budgeting has started to show how water flowpaths evolve on time scales ranging from months to centuries. A modelling study of the subglacial water system of the lower Whillans Ice Stream (WIS) [26] demonstrated that, to obtain model output filling rates of lakes that were consistent with the ICESat-derived rates of Fricker & Scambos [9], it was necessary to invoke two distinct episodes of water piracy in different locations: (i) water piracy from the adjacent Kamb Ice Stream associated with its slowdown 150 years ago, as predicted by Anandakrishnan & Alley [44], which increased the total water flux through the lower WIS by approximately 50% [26]; and (ii) a change in the course of a major flowpath within the upper WIS in 2005, which led to a tenfold filling rate increase for SLW for the period 2003–2008 (figure 9). Further analysis of the surface-height changes in the vicinity of the piracy event (ii) found that the likely cause was a localized bulging of the ice surface in response to slowing and thickening of the lower WIS (e.g. [34,46]). This changed the hydropotential sufficiently to divert water that originated from the upper Whillans and Kamb Ice Streams, which previously supplied the southern catchment, towards SLW. It is now believed that water piracy may be common in the Siple Coast region, where the gentle basal relief makes the basal hydropotential particularly sensitive to small changes in ice thickness.

For Recovery Ice Stream in East Antarctica, until recently there were no published estimates for meltwater production; water budgeting and the associated flow routeing revealed several surprises about this water system. Fricker *et al.* [11] showed that a mean melt rate of 0.7 mm yr^{-1} over the large Recovery catchment was sufficient to reproduce all observed filling and draining in the hydrologic system (figure 4*c*). This work also demonstrated that the filling of the active lakes did not require any water outflow from the four large static lakes further up in the catchment (discussed in [12]). Together with the study of Carter *et al.* [26], this work showed that, in the absence of more accurate information on the spatial distribution of melt rates, and without

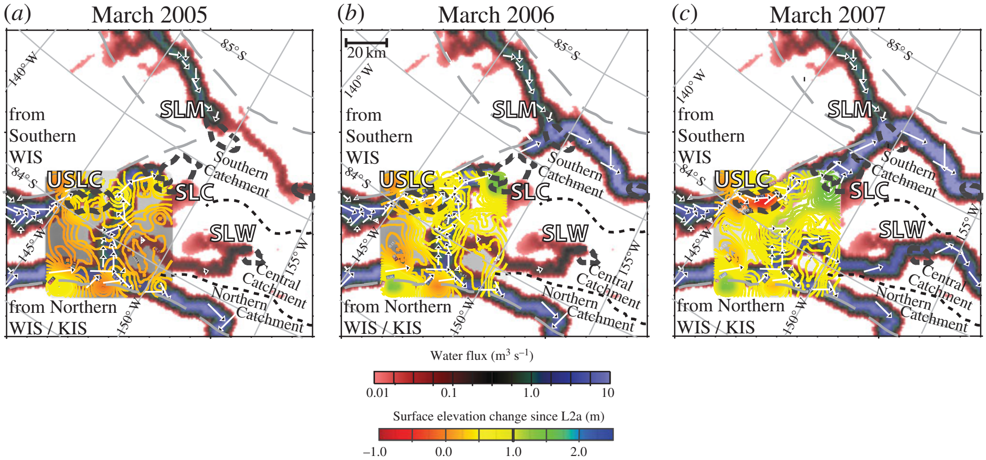

Figure 9. Flow switching on Whillans Ice Stream. Evolution of subglacial water flow routeing from (*a*) March 2005 through (*b*) March 2006 to (*c*) March 2007 resulting from a localized thickening of approximately 2 m near lake USLC. Adapted from Carter *et al*. [45].

detailed ice thickness data, observations of the lakes themselves could still be used to infer many aspects of a subglacial hydrologic system.

(b) Formation of lakes

While water budget modelling addressed the role of subglacial lakes in the subglacial water system, complementary efforts have dealt with the formation of subglacial lakes (e.g. [47]). In these models, lakes are usually placed where there is sufficient source of meltwater and an enclosed basin in the hydropotential. This approach has generally been more successful in predicting lakes in the ice-sheet interior where the hydropotential basins are typically coincident with a depression in the bedrock topography [48]. For active lakes in fast-flowing regions, however, the hydropotential basin often results from depressions in the ice surface, resulting from spatial heterogeneities in basal traction, with lakes appearing in the lee of 'sticky spots' [10,49]. In this dynamic environment, basal traction distribution and the availability of subglacial water can change quite rapidly as water flowpaths are continually rerouted in response to small changes in ice thickness [26,44,50].

(c) A new model for lake drainage

Whereas classic models for ice-dammed lakes in more temperate environments invoked the 'R-channels' incised into the base of the ice through hydrodynamic melting (e.g. [51–53]), such a mechanism is less plausible as a mechanism for draining Antarctic subglacial lakes. In addition to difficulties in generating sufficient turbulent heat along the low hydraulic gradients typical of most Antarctic subglacial drainage channels, further complications result from the loss of heat via conduction to colder ice above [54] and the supercooling of water as it moves up an adverse bed slope [55]. Given these conditions, it has been long suspected that water flow was accommodated not by R-channels, but by 'canals' incised into the sediment [56]. Although initially believed to behave similarly to non-erosive distributed systems, formulation by Ng [57] showed how they might behave more as conduits and experience run-away enlargement. Subsequent work by Kyrke-Smith & Fowler [58] further explored the viability of such a mechanism, confirming that conduits incised into the sediment could exist in Antarctic-like conditions. These modelling efforts combined with observations from harmonic tremors [59] and the response of the ice sheet to tidal forcing [60] all provide further support for the existence of higher capacity

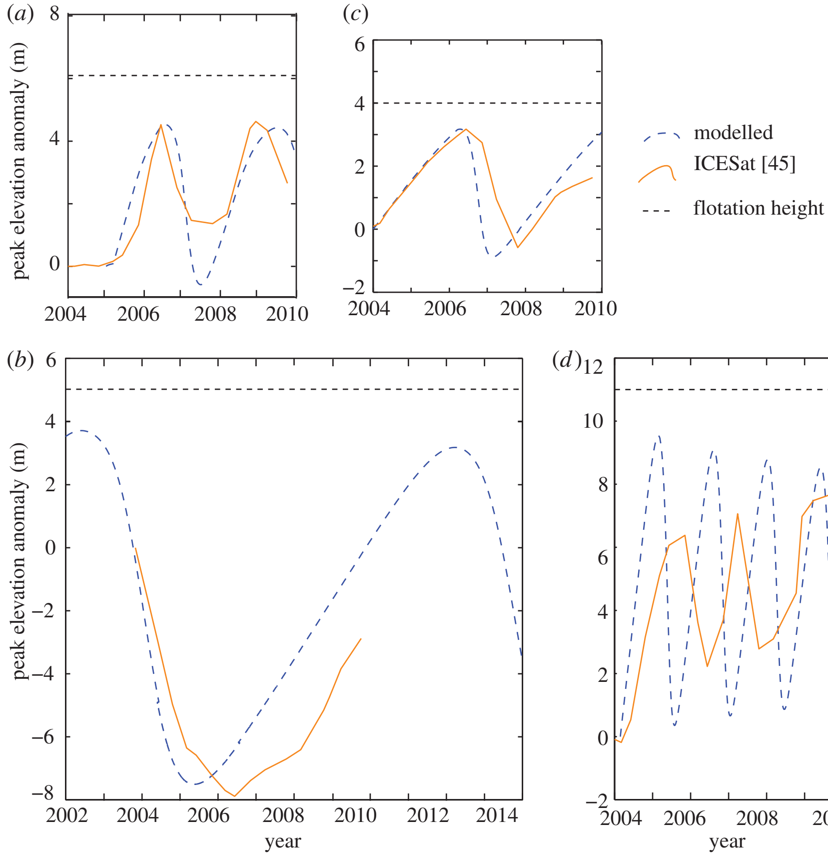

Figure 10. Modelling subglacial lake drainage. Comparison of observed [26] height anomalies with lake levels predicted by a lake drainage model developed by Carter *et al*. [45], for four lakes in the Whillans/Mercer system: (*a*) SLW; (*b*) SLE; (*c*) SLC; (*d*) SLM. Adapted from Carter *et al*. [45].

channels under the ice sheet. Modelling work by Carter *et al*. [45] finally tested the possibility that canal channels or ‘C-channels’ might serve as an effective means for draining lakes. Although there is ambiguity in the results owing to the required assumptions (which are largely unconstrained by existing data sources) regarding viscous till rheology and channel geometry [61], the Carter *et al*. [45] model successfully reproduced both the key characteristics of estimated lake volume changes when applied to the lakes of the Whillans/Mercer system for the period 2003–2009 (figure 10).

(d) Feedbacks between lakes and ice dynamics/ice-sheet mass balance

Seasonal meltwater on the surface of mountain glaciers and Greenland can access the bed through the supraglacial and englacial water system, where it has been observed to modulate ice flow speeds (e.g. [51,62,63]). In Antarctica, however, there is almost no surface melt, and the only input into the subglacial hydrologic system is water produced at the bed through basal melting, a process that is isolated from the effects of recent climate change. The relationship between subglacial lake drainage events and large-scale mass balance trends remains unclear, and has not yet been included in any model. The Crane Glacier example (§3.2) [29] implies that there could be a large number of similar small pockets of water that remain dormant until other external factors (such as, in the case of Crane Glacier, a large ice dynamical change which causes an increase in surface slope) change the boundary conditions. This example demonstrates a potentially large positive feedback between ice dynamics and subglacial lake drainage.

Interestingly, where longer-term velocity change data are available (e.g. [64]), approximately two-thirds of the known active lake systems coincide with regions of ice flow speed decrease (figure 1) [11]. Recent modelling efforts have suggested that withholding of water from points downstream during the filling phase results in a net slowdown of the ice even after water flow is allowed to return to steady state [65]. The lake drainage model of Carter *et al*. [45] suggests that the maximum sliding will occur not during peak discharge but shortly before the lake reaches high stand when water flow is higher, but before channelization has reduced water pressures. These results, along with parallel work on mountain glacier lake drainage by Kingslake & Ng [66], suggest that the formation, filling and drainage of subglacial lakes may slow the ice down over the longer term, as any sliding enhancement resulting from a lake drainage event would be less than that provided by a steady-state distributed water system. Challenges remain with regards to quantifying this effect in the context of greater ice-sheet flow.

(e) Discrepancy between locations of active and radar-detected lakes

The idea that lakes are drained via canals incised into soft deformable sediment [45] may help explain the paradox that RES surveying typically does not show flat, bright reflectors beneath areas interpreted as active lakes based on surface-height anomalies [7,67–69]. If the observed fill–drain cycles of subglacial lakes require that sediments are present between the lakes, then it is likely that such sediments are also present under the lakes themselves. The presence of saturated sediments and/or small-scale basal roughness could inhibit positive identification of these lakes using the standard criteria for subglacial lake detection (i.e. specularity and brightness relative to surroundings) [70]. The angle of repose for these sediments would imply low basal slopes and shallow lakes; thin water columns impair radar brightness in both low- [71] and high- [72] conductivity water columns. Synthetic modelling of the interaction of a radar signal and basal water layers suggests that a water column must be greater than 6 m thick to distinguish between a water layer and wet till [73]. Similarly, basal roughness on the scale of a radar wavelength can significantly reduce basal reflectivity [74]. Finally, analysis of regional hydropotential in the vicinity of active lakes of Smith *et al*.'s inventory [8] suggests that, in some cases, the surface-height anomalies used to identify lakes may be unrelated to basal hydrology (e.g. [68]).

5. Summary

The past decade has been one of remarkable progress in the study of Antarctic subglacial water. We have gone from an old view, where most subglacial water is stored for long periods in isolated lakes mainly near to the ice divides, to a new view, where water moves between lakes distances of hundreds of kilometres in broad but well-defined channels on time scales of months to several years. Lakes exist under most of Antarctica's fast-flowing ice streams and subglacial water flow continues to the grounding line, where it enters the Southern Ocean [18,43,75].

Understanding subglacial water systems is crucial for modelling the future evolution of the Antarctic ice sheet. The presence of water beneath an ice stream affects ice flow rates and continental ice flux, as it acts as a lubricant either between the ice and the subglacial bed or between grains of a subglacial till [76]. Basal water systems may also be a way to transport significant amounts of heat at the ice-sheet base [77,78]. This transformational decade in Antarctic subglacial water research has moved us significantly closer to understanding the process sufficiently for it to be included in ice-sheet models.

In addition to understanding the influence of subglacial lakes on ice flow, it is also important to understand what observations of subglacial lakes can reveal about the underlying environment. Observing the volume change undergone by a lake can reveal the rate of meltwater production in a catchment and how patterns of water routeing upstream of the lake are changing [26]. As the rates and magnitudes of filling and draining are sensitive to the properties of the subglacial till [45], it might be possible to infer how this environment is changing over repeated fill–drain cycles. Active lakes may also drive observable (and possibly predictable) variation in subglacial water flux, enabling experiments on the response of ice to varying water flow (e.g. [23]). The surface activity related to subglacial lake activity can serve as an observable window into the complex changing environment beneath that would otherwise be difficult to explore through more direct means.

Although we have made significant progress in mapping active subglacial lakes, it is highly likely that we have not yet mapped all lakes of this type using existing techniques. Several studies post-ICESat have found lakes that were not detected during that mission (e.g. [6,29]). In one location on the Antarctic Peninsula, a new lake was found that was a result of ice velocity changes [29]. Glacier changes that strongly affect ice surface slope can 'activate' subglacial water bodies and cause drainage events in lakes that had previously been dormant, implying a dynamic coevolution of the ice and subglacial hydrology. Continued monitoring of known lakes and searching for new lakes will occur as more satellite-altimeter data become available (CryoSat-2 and ICESat-2).

Authors' contributions. H.A.F., M.R.S. and T.A.S. performed the data analysis presented in this paper, which is mostly all published in peer-reviewed papers. S.P.C. performed all the modelling work, also in peer-reviewed papers. All authors contributed to the writing of the paper, as follows: all authors agreed on structure and content; H.A.F. provided the initial draft, and then all the co-authors provided iterative edits; once the text was finalized, all authors gave final approval for publication.

Competing interests. The authors declare that they have no competing interests.

Funding. We thank NSF and NASA for funding (NASA grant NNX11AQ78H (M.R.S. and H.A.F.) and NNX10AG21G (T.A.S.), and NSF grant ANT-0838885 (H.A.F.)).

Acknowledgements. The authors also thank Robin Bell, Leigh Stearns and Malcolm MacMillan.

References

1. Fretwell P *et al*. 2013 Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *Cryosphere* **7**, 375–393. (doi:10.5194/tc-7-375-2013)
2. Joughin IR, Tulaczyk S, Engelhardt HF. 2003 Basal melt beneath Whillans Ice Stream and Ice Streams A and C, West Antarctica. *Ann. Glaciol.* **36**, 257–262. (doi:10.3189/172756403781816130)
3. Pattyn F. 2010 Antarctic subglacial conditions inferred from a hybrid ice sheet/ice stream model. *Earth Planet. Sci. Lett.* **295**, 451–461. (doi:10.1016/j.epsl.2010.04.025)
4. Siegert MJ, Carter S, Tabacco I, Popov S, Blankenship DD. 2005 A revised inventory of Antarctic subglacial lakes. *Antarct. Sci.* **17**, 453–460. (doi:10.1017/S0954102005002889)
5. Christoffersen P, Bougamont M, Carter SP, Fricker HA, Tulaczyk S. 2014 Significant groundwater contribution to Antarctic ice streams hydrologic budget. *Geophys. Res. Lett.* **41**, 2003–2010. (doi:10.1002/2014GL059250)
6. Rivera A, Uribe J, Zamora R, Oberreuter J. 2015 Subglacial lake CECs: discovery and in situ survey of a privileged research site in West Antarctica. *Geophys. Res. Lett.* **42**, 3944–3953. (doi:10.1002/2015GL063390)
7. Wright A, Siegert M. 2012 A fourth inventory of Antarctic subglacial lakes. *Antarct. Sci.* **24**, 659–664. (doi:10.1017/S095410201200048X)
8. Smith BE, Fricker HA, Joughin IR, Tulaczyk S. 2009 An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). *J. Glaciol.* **55**, 573–595. (doi:10.3189/002214309789470879)
9. Fricker HA, Scambos T. 2009 Connected subglacial lake activity on lower Mercer and Whillans Ice Streams, West Antarctica, 2003–2008. *J. Glaciol.* **55**, 303–315. (doi:10.3189/002214309788608813)
10. Fricker HA, Scambos TA, Carter SP, Davis C, Haran T, Joughin IR. 2010 Synthesising multiple remote sensing techniques for subglacial hydrologic mapping: application to a lake system beneath MacAyeal Ice Stream, West Antarctica. *J. Glaciol.* **56**, 187–199. (doi:10.3189/002214310791968557)
11. Fricker HA, Carter SP, Bell RE, Scambos T. 2014 Active lakes of Recovery Ice Stream, East Antarctica: a bedrock-controlled subglacial hydrological system. *J. Glaciol.* **60**, 1015–1030. (doi:10.3189/2014JoG14J063)

12. Bell RE, Studinger M, Shuman CA, Fahnestock MA, Joughin I. 2007 Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. *Nature* **445**, 904–907. (doi:10.1038/nature05554)
13. Studinger M *et al.* 2003 Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica. *Earth Planet. Sci. Lett.* **205**, 195–210. (doi:10.1016/s0012-821x(02)01041-5)
14. Rignot E, Mouginot J, Scheuchl B. 2011 Ice flow of the Antarctic ice sheet. *Science* **333**, 1427–1430. (doi:10.1126/science.1208336)
15. Bell RE, Studinger M, Tikku AA, Clarke GKC, Gutner MM, Meertens C. 2002 Origin and fate of Lake Vostok water frozen to the base of the East Antarctic ice sheet. *Nature* **416**, 307–310. (doi:10.1038/416307a)
16. Gray L, Joughin I, Tulaczyk S, Spikes VB, Bindschadler R, Jezek K. 2005 Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. *Geophys. Res. Lett.* **32**, L03501. (doi:10.1029/2004GL021387)
17. Wingham DJ, Siegert MJ, Shepherd A, Muir AS. 2006 Rapid discharge connects Antarctic subglacial lakes. *Nature* **440**, 1033–1036. (doi:10.1038/nature04660)
18. Fricker HA, Scambos T, Bindschadler R, Padman L. 2007 An active subglacial water system in West Antarctica mapped from space. *Science* **315**, 1544–1548. (doi:10.1126/science.1136897)
19. McMillan M, Corr H, Shepherd A, Ridout A, Laxon S, Cullen R. 2013 Three-dimensional mapping by CryoSat-2 of subglacial lake volume changes. *Geophys. Res. Lett.* **40**, 4321–4327. (doi:10.1002/grl.50689)
20. Bamber JL, Vaughan DG, Joughin I. 2000 Widespread complex flow in the interior of the Antarctic ice sheet. *Science* **287**, 1248–1250. (doi:10.1126/science.287.5456.1248)
21. Siegfried MR, Fricker HA, Roberts M, Scambos TA, Tulaczyk S. 2014 A decade of West Antarctic subglacial lake interactions from combined ICESat and CryoSat-2 altimetry. *Geophys. Res. Lett.* **41**, 891–898. (doi:10.1002/2013GL058616)
22. Bindschadler RA, Scambos TA, Choi H, Haran TM. 2010 Ice sheet change detection by satellite image differencing. *Remote Sens. Environ.* **114**, 1353–1362. (doi:10.1016/j.rse.2010.01.014)
23. Siegfried MR. 2015 Investigating Antarctic ice sheet subglacial processes beneath the Whillans Ice Plain, West Antarctica, using satellite altimetry and GPS. PhD Thesis, University of California.
24. Fricker HA *et al.* 2011 Siple coast subglacial aquatic environments: the Whillans Ice Stream Subglacial Access Research Drilling project. In *Antarctic Subglacial Aquatic Environments* (eds MJ Siegert, MC Kennicutt), Geophysical Monographs Series, vol. 192, ch. 12, pp. 199–219. Washington, DC: American Geophysical Union. (doi:10.1029/2010gm000932)
25. Borsa AA, Moholdt G, Fricker HA, Brunt KM. 2014 A range correction for ICESat and its potential impact on ice sheet mass balance studies. *Cryosphere* **8**, 345–357. (doi:10.5194/tc-8-345-2014)
26. Carter SP, Fricker HA, Siegfried MR. 2013 Evidence of rapid subglacial water piracy under Whillans Ice Stream, West Antarctica. *J. Glaciol.* **59**, 1147–1162. (doi:10.3189/2013JoG13J085)
27. Flowers GE. 2015 Modelling water flow under glaciers and ice sheets. *Proc. R. Soc. A* **471**, 20140907. (doi:10.1098/rspa.2014.0907)
28. Stearns LA, Smith BE, Hamilton GS. 2008 Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nat. Geosci.* **1**, 827–831. (doi:10.1038/ngeo356)
29. Scambos TA, Berthier E, Shuman CA. 2011 The triggering of subglacial lake drainage during rapid glacier drawdown: Crane Glacier, Antarctic Peninsula. *Ann. Glaciol.* **52**, 74–82. (doi:10.3189/172756411799096204)
30. Rack W, Rott H. 2004 Pattern of retreat and disintegration of Larsen B ice shelf, Antarctic Peninsula. *Ann. Glaciol.* **39**, 505–510. (doi:10.3189/172756404781814005)
31. Haran T, Bohlander J, Scambos T, Painter T, Fahnestock M. 2005. *MODIS mosaic of Antarctica 2003–2004* (*MOA2004*) *Image Map* (updated 2013). Boulder, CO: National Snow and Ice Data Center.
32. Shuman CA, Berthier E, Scambos TA. 2011 2001–2009 elevation and mass losses in the Larsen A and B embayments, Antarctic Peninsula. *J. Glaciol.* **57**, 737–754. (doi:10.3189/002214311797409811)
33. Bindschadler R, Vornberger P, Gray L. 2005 Changes in the ice plain of Whillans Ice Stream, West Antarctica. *J. Glaciol.* **51**, 620–636. (doi:10.3189/172756505781829070)

34. Joughin I *et al.* 2005 Continued deceleration of Whillans Ice Stream, West Antarctica. *Geophys. Res. Lett.* **32**, L22501. (doi:10.1029/2005GL024319)
35. Beem LH, Tulaczyk SM, King MA, Bougamont M, Fricker HA, Christoffersen P. 2014 Variable deceleration of Whillans Ice Stream, West Antarctica. *J. Geophys. Res.* **119**, 212–224. (doi:10.1002/2013jf002958)
36. Catania G, Hulbe C, Conway H, Scambos TA, Raymond CF. 2012 Variability in the mass flux of the Ross ice streams, West Antarctica, over the last millennium. *J. Glaciol.* **58**, 741–752. (doi:10.3189/2012JoG11J219)
37. Christner BC *et al.* 2014 A microbial ecosystem beneath the West Antarctic Ice Sheet. *Nature* **512**, 310–313. (doi:10.1038/nature13667)
38. LeBrocq AM, Payne AJ, Siegert MJ, Alley RB. 2009 A subglacial water-flow model for West Antarctica. *J. Glaciol.* **55**, 879–888. (doi:10.3189/002214309790152564)
39. Wright AP *et al.* 2012 Evidence of a hydrological connection between the ice divide and ice sheet margin in the Aurora Subglacial Basin, East Antarctica. *J. Geophys. Res.* **117**, F01033. (doi:10.1029/2011JF002066)
40. Carter SP, Fricker HA, Blankenship DD, Price SF, Lipscomb WL, Johnson JV, Lipscomb WH, Price SF, Young DA. 2011 Modeling 5 years of subglacial lake activity in the MacAyeal Ice Stream (Antarctica) catchment through assimilation of ICESat laser altimetry. *J. Glaciol.* **57**, 1098–1112. (doi:10.3189/002214311798843421)
41. Haran TM, Scambos TA. 2007 Enhancing a RADARSAT/ICESat digital elevation model of West Antarctica using MODIS imagery. [Abstr. C51B-0386.] *Eos*, **88**(52), Fall Meet. Suppl. See http://adsabs.harvard.edu/abs/2007AGUFM.C51B0386H.
42. Joughin I, Tulaczyk S, MacAyeal DR, Engelhardt H. 2004 Melting and freezing beneath the Ross ice streams, Antarctica. *J. Glaciol.* **50**, 96–108. (doi:10.3189/172756504781830295)
43. Carter SP, Fricker HA. 2012 The supply of subglacial meltwater to the grounding line of the Siple Coast, West Antarctica. *Ann. Glaciol.* **53**, 267–280. (doi:10.3189/2012AoG60A119)
44. Anandakrishnan S, Alley RB. 1997 Stagnation of ice stream C, West Antarctica by water piracy. *Geophys. Res. Lett.* **24**, 265–268. (doi:10.1029/96GL04016)
45. Carter SP, Fricker HA, Siegfried MR. 2015 Active lakes in Antarctica survive on a sedimentary substrate—Part I: theory. *Cryosphere Discuss.* **9**, 2053–2099. (doi:10.5194/tcd-9-2053-2015)
46. Winberry JP, Anandakrishnan S, Alley RB, Wiens DA, Pratt MJ. 2014 Tidal pacing, skipped slips and the slowdown of Whillans Ice Stream, Antarctica. *J. Glaciol.* **60**, 795–807. (doi:10.3189/2014JoG14J038)
47. Livingstone SJ, Clark CD, Woodward J, Kingslake J. 2013 Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets. *Cryosphere* **7**, 1721–1740. (doi:10.5194/tc-7-1721-2013)
48. Tabacco IE, Cianfarra P, Forieri A, Salvini F, Zirizotti A. 2006 Physiography and tectonic setting of the subglacial lake district between Vostok and Belgica subglacial highlands (Antarctica). *Geophys. J. Int.* **165**, 1029–1040. (doi:10.1111/j.1365-246X.2006.02954.x)
49. Sergienko OV, Hulbe CL. 2011 'Sticky spots' and subglacial lakes under ice streams of the Siple Coast, Antarctica. *Ann. Glaciol.* **52**, 18–22. (doi:10.3189/172756411797252176)
50. Wright AP, Siegert MJ, Le Brocq AM, Gore DB. 2008 High sensitivity of subglacial hydrological pathways in Antarctica to small ice-sheet changes. *Geophys. Res. Lett.* **35**, L17504. (doi:10.1029/2008GL034937)
51. Röthlisberger H. 1972 Water pressure in intra- and subglacial channels. *J. Glaciol.* **11**, 177–203.
52. Nye JF. 1976 Water flow in glaciers: jokulhlaups, tunnels and veins. *J. Glaciol.* **17**, 181–207.
53. Evatt GW, Fowler AC, Clark CD, Hulton NRJ. 2006 Subglacial floods beneath ice sheets. *Phil. Trans. R. Soc. A* **364**, 1769–1794. (doi:10.1098/rsta.2006.1798)
54. Hooke RL, Fastook J. 2007 Thermal conditions at the bed of the Laurentide ice sheet in Maine during deglaciation: implications for esker formation. *J. Glaciol.* **53**, 646–658. (doi:10.3189/002214307784409243)
55. Lawson DE, Strasser JC, Evenson EB, Alley RB, Larson GJ, Arcone SA. 1998 Glaciohydraulic supercooling: a freeze-on mechanism to create stratified, debris-rich basal ice: I. Field evidence. *J. Glaciol.* **44**, 547–562.
56. Walder JS, Fowler A. 1994 Channelized subglacial drainage over a deformable bed. *J. Glaciol.* **40**, 3–15.
57. Ng FSL. 2000 Canals under sediment-based ice sheets. *Ann. Glaciol.* **30**, 146–152. (doi:10.3189/172756400781820633)

58. Kyrke-Smith TM, Fowler AC. 2014 Subglacial swamps. *Proc. R. Soc. A* **470**, 20140340. (doi:10.1098/rspa.2014.0340)
59. Winberry JP, Anandakrishnan S, Alley RB, Bindschadler RA, King MA. 2009 Basal mechanics of ice streams: insights from the stick–slip motion of Whillans Ice Stream, West Antarctica. *J. Geophys. Res.* **114**, F01016. (doi:10.1029/2008JF001035)
60. Rosier SHR, Gudmundsson GH, Green JAM. 2015 Temporal variations in the flow of a large Antarctic ice stream controlled by tidally induced changes in the subglacial water system. *Cryosphere* **9**, 1649–1661. (doi:10.5194/tc-9-1649-2015)
61. Kingslake J. 2015 Chaotic dynamics of a glaciohydraulic model. *J. Glaciol.* **61**, 493–502. (doi:10.3189/2015JoG14J208)
62. Zwally HJ, Abdalati W, Herring T, Larson K, Saba J, Steffen K. 2002 Surface melt-induced acceleration of Greenland ice-sheet flow. *Science* **297**, 218–222. (doi:10.1126/science.1072708)
63. Das SB, Joughin I, Behn MD, Howat IM, King MA, Lizarralde D, Bhatia MP. 2008 Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage. *Science* **320**, 778–781. (doi:10.1126/science.1153360)
64. Scheuchl B, Mouginot J, Rignot E. 2012 Ice velocity changes in the Ross and Ronne sectors observed using satellite radar data from 1997 and 2009. *Cryosphere* **6**, 1019–1030. (doi:10.5194/tc-6-1019-2012)
65. Goeller S, Thoma M, Grosfeld K, Miller H. 2013 A balanced water layer concept for subglacial hydrology in large scale ice sheet models. *Cryosphere* **7**, 1095–1106. (doi:10.5194/tc-7-1095-2013)
66. Kingslake J, Ng F. 2013 Modelling the coupling of flood discharge with glacier flow during jökulhlaups. *Ann. Glaciol.* **54**, 25–31. (doi:10.3189/2013AoG3163A3331)
67. Siegert MJ, Ross N, Corr H, Smith B, Jordan T, Bingham RG, Ferraccioli F, Rippin DM, Le Brocq A. 2014 Boundary conditions of an active West Antarctic subglacial lake: implications for storage of water beneath the ice sheet. *Cryosphere* **8**, 15–24. (doi:10.5194/tc-8-15-2014)
68. Wright AP, Young DA, Bamber JL, Dowdeswell JA, Payne AJ, Blankenship DD, Siegert MJ. 2014 Subglacial hydrological connectivity within the Byrd Glacier catchment, East Antarctica. *J. Glaciol.* **60**, 345–352. (doi:10.3189/2014JoG13J014)
69. Siegert MJ, Ross N, Le Brocq AM. 2016 Recent advances in understanding Antarctic subglacial lakes and hydrology. *Phil. Trans. R. Soc. A* **374**, 20140306. (doi:10.1098/rsta.2014.0306)
70. Carter SP, Blankenship DD, Peters ME, Young DA, Holt JW, Morse DL. 2007 Radar-based subglacial lake classification in Antarctica. *Geochem. Geophys. Geosyst.* **8**, Q03016. (doi:10.1029/2006GC001408)
71. Gorman MR, Siegert MJ. 1999 Penetration of Antarctic subglacial lakes by VHF electromagnetic pulses: information on the depth and electrical conductivity of basal water bodies. *J. Geophys. Res.* **104**, 29 311–29 320. (doi:10.1029/1999JB900271)
72. MacGregor JA, Anandakrishnan S, Catania GA, Winebrenner DP. 2011 The grounding zone of the Ross Ice Shelf, West Antarctica, from ice-penetrating radar. *J. Glaciol.* **57**, 917–928. (doi:10.3189/002214311798043780)
73. Christianson K, Jacobel RW, Horgan HJ, Anandakrishnan S, Alley RB. 2012 Subglacial Lake Whillans—ice-penetrating radar and GPS observations of a shallow active reservoir beneath a West Antarctic ice stream. *Earth Planet. Sci. Lett.* **331–332**, 237–245. (doi:10.1016/j.epsl.2012.03.013)
74. MacGregor JA, Matsuoka K, Waddington ED, Winebrenner DP, Pattyn F. 2012 Spatial variation of englacial radar attenuation: modeling approach and application to the Vostok flowline. *J. Geophys. Res.* **117**, F03022. (doi:10.1029/2011jf002327)
75. Le Brocq AM *et al.* 2013 Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet. *Nat. Geosci.* **6**, 945–948. (doi:10.1038/ngeo1977)
76. Kamb B. 1987 Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *J. Geophys. Res.* **92**, 9083–9100. (doi:10.1029/JB092iB09p09083)
77. Parizek BR, Alley RB, Hulbe CL. 2003 Subglacial thermal balance permits ongoing grounding-line retreat along the Siple Coast of West Antarctica. *Ann. Glaciol.* **36**, 251–256. (doi:10.3189/172756403781816167)
78. Wolovick MJ, Bell RE, Creyts TT, Frearson N. 2013 Identification and control of subglacial water networks under Dome A, Antarctica. *J. Geophys. Res.* **118**, 140–154. (doi:10.1029/2012JF002555)