An Active Subglacial Water System in West Antarctica Mapped from Space

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Satellite laser altimeter elevation profiles from 2003 to 2006 collected over the lower parts of Whillans and Mercer ice streams, West Antarctica, reveal 14 regions of temporally varying elevation, which we interpret as the surface expression of subglacial water movement. Vertical motion and spatial extent of two of the largest regions are confirmed by satellite image differencing. A major, previously unknown subglacial lake near the grounding line of Whillans Ice Stream is observed to drain 2.0 cubic kilometers of water into the ocean over ~3 years, while elsewhere a similar volume of water is being stored subglacially. These observations reveal a widespread, dynamic subglacial water system that may exert an important control on ice flow and mass balance.

At least 145 subglacial lakes have been mapped beneath the Antarctic Ice Sheet (*1*). Recent pivotal studies based on satellite data have demonstrated that Antarctic subglacial water can move in large volumes between lakes, on short time scales and over long distances (*2*, *3*). Large outbursts of subglacial water have been observed in coastal regions (*4*), but it is not known how frequently these occur, nor the total amount of water involved continent-wide. Water beneath an ice stream, acting as a lubricant either between the ice and subglacial bed or between grains of a subglacial till, affects ice flow rates (*5*). Subglacial lakes have recently been linked to the broad onset of faster flow of the Recovery Ice Stream (*6*) and are located at the heads of other Antarctic ice stream tributaries (*7*). The drastic deceleration (a "shutdown") ~150 years ago of Kamb Ice Stream has been attributed to a decrease in subglacial water supply (*8*). Thus, knowledge of subglacial water movement is fundamental to understanding Antarctic ice stream dynamics and to predicting future Antarctic ice sheet behavior and sea-level contribution.

Subglacial water systems are pressurized to near the weight of the overlying ice (*9*), so movement of water can cause an elevation change of the ice surface that can be detected by satellites. Past observations interpreted to be Antarctic sub-

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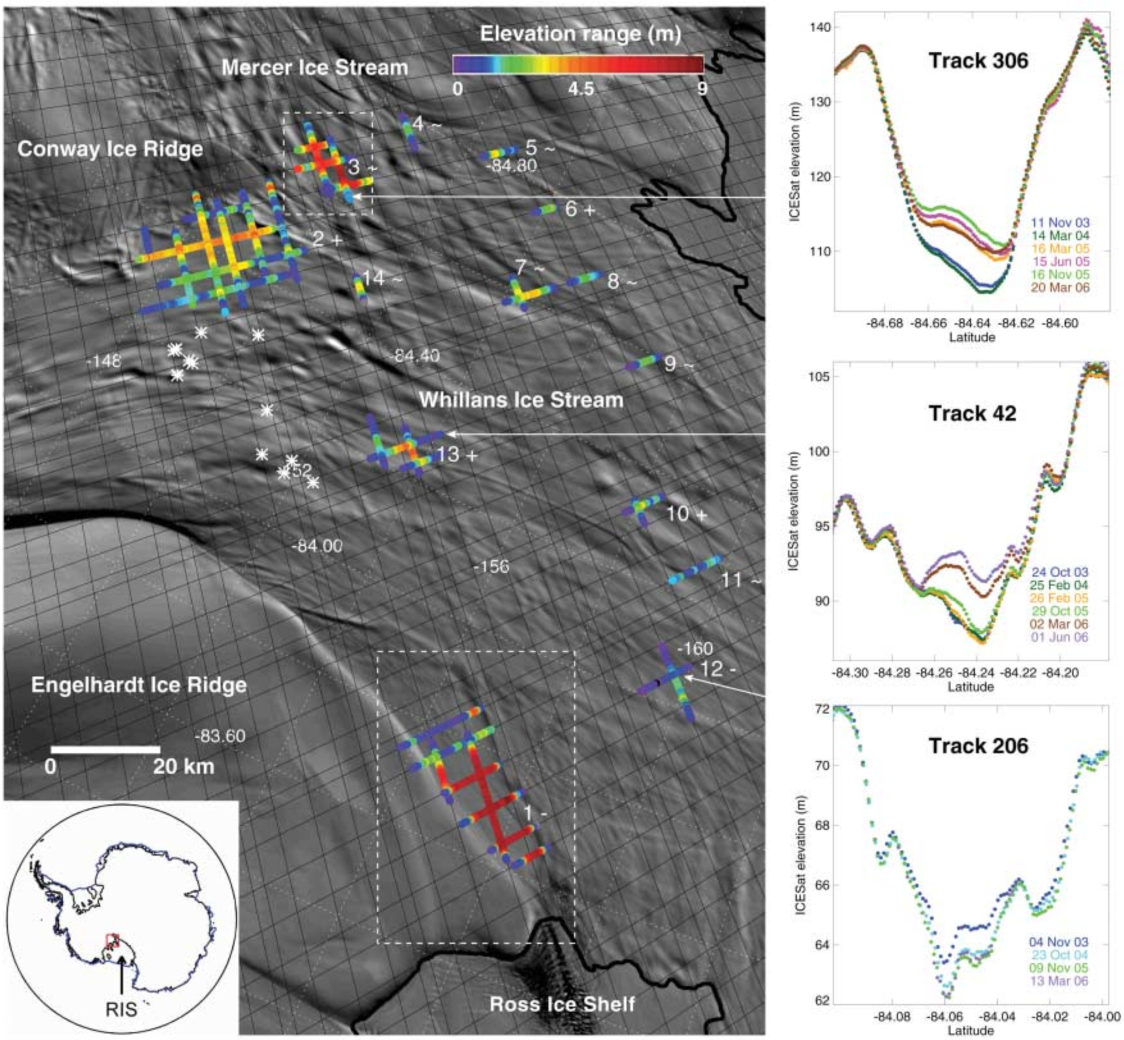

Fig. 1. (**Left**) Locations of elevation-change events identified through ICESat repeat-track analysis on lower WIS and MIS (2003 to 2006). Straight black lines show the ICESat reference ground tracks. Colored track segments represent range in elevation amplitude for each elevation-change event. Events cluster into 14 elevation-change regions, which are either rising (+), falling (–), or oscillating (~). Ice flow is from top left to lower right. Background image is MODIS Mosaic of Antarctica (MOA) (*30*), and inset map shows its location in Antarctica. Bold black line indicates the break-in-slope associated with the grounding zone of the Ross Ice Shelf (RIS). White dashed boxes show regions covered in Fig. 2. White asterisks indicate locations of small surface-collapse features observed on WIS in 1987–1988 (fig. S4). (**Right**) Repeat ICESat elevation profiles along track segments that cross each type of region (~, +, –). Arrows point to the location of each track segment on the image.

glacial water movement have been made with interferometric synthetic aperture radar (InSAR) (*2*) and satellite radar altimetry (*3*). However, InSAR data for high southern latitudes (>80°S) are presently limited to a brief period during late 1997 (*10*, *11*). Radar altimetry has a relatively long record and many repeat observations, but has limited coverage and spatial resolution (*12*).

ICESat Laser Altimetry

Our approach combines accurate, repeated elevation profiling from satellite laser altimetry with satellite image differencing to map and monitor elevation changes. NASA's Ice, Cloud, and land Elevation Satellite (ICESat), which carries the Geoscience Laser Altimeter System (GLAS), provides elevation data with a small (~65 m) spatial footprint, high vertical accuracy [±20 cm (*13*)], and high along-track resolution (~170 m). We analyzed all available ICESat data across the Whillans and Mercer ice streams (WIS and MIS) (Fig. 1) from a series of 10 data-acquisition periods spanning February 2003 through June 2006 (Table 1) for apparent elevation changes using repeat-track analysis (*14*, *15*). This indicated 101 candidate elevation-change "events." Horizontal offsets of repeated tracks (up to ~500 m) cause apparent elevation changes in the presence of nonzero cross-track slopes. To focus on temporal variability, we conservatively discarded events where the elevation trend was correlated with track offset. Most of the 46 remaining events showed a change in elevation confined to a trough or basin bounded by steeper sections of the ice stream surface (Fig. 1). Plotting these events on an image map showed that they clustered in 14 distinct elevation-change regions in the vicinity of the WIS/MIS confluence and grounding line (Fig. 1). Events within each region had consistent patterns of timing and displacement magnitude. The large (~350 km^2) region, near the grounding line of Ross Ice Shelf (RIS) next to Engelhardt Ice Ridge (near the bottom of Fig. 1), has the largest-amplitude signal and is a special case that will be discussed later. The other two large regions are located on either side of Conway Ridge; one on WIS (~500 km^2) and the other on MIS (~120 km^2). The remaining elevation-change regions in the lower glacier trunk are smaller, being sampled by just one to four tracks, and sum to an estimated area of 250 km^2. None are identified over the central trunk of WIS between 148°W and 140°W, but there are five additional smaller-amplitude regions farther upstream (fig. S1). Some events may be undetectable with our technique and conservative criteria, especially in the central ice stream where topography is rougher. Overall, ~10% of the lower WIS/MIS area shown in Fig. 1 is occupied by elevation-change regions. The smallest along-track extent of the 46 events was 3.5 km and the mean extent was 9.1 km, suggesting that ICESat track spacing in this area (3 to 5 km) (Fig. 1) is adequate to capture most changing regions.

Table 1. ICESat operations periods, orbit repeat periods, dates of data acquisition, and release numbers (*46*) for the data used in this work. ICESat has operated in two repeat orbits: 8 and 91 days, the latter with a 33-day subcycle. The last 33 days of the Laser 2a 91-day operations period (since 10/25/2003) have been repeated in all subsequent operations periods (Laser 2b onward) ~4 months apart.

Operations period	Repeat (days)	Dates	Release
Laser 1	8	02/20/03–03/29/03	118
Laser 2a	8	09/25/03–10/04/03	426
Laser 2a	91	10/04/03–11/19/03	426
Laser 2b	91	02/17/04–03/21/04	428
Laser 2c	91	05/18/04–06/21/04	117
Laser 3a	91	10/03/04–11/08/04	428
Laser 3b	91	02/17/05–03/24/05	428
Laser 3c	91	05/20/05–06/23/05	122
Laser 3d	91	10/21/05–11/24/05	428
Laser 3e	91	02/22/06–03/28/06	428
Laser 3f	91	05/24/06–06/26/06	126

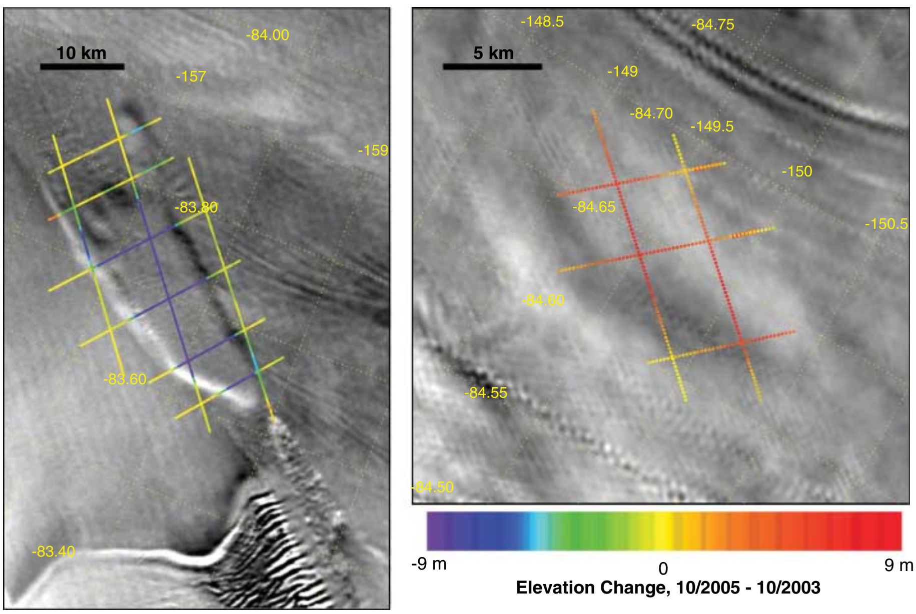

Fig. 2. MODIS difference images (December 2005 minus December 2003) over regions 1 (left) and 3 (right). ICESat tracks across both regions are color-coded by the elevation change from October/November 2003 to October/November 2005, close in time to when the images that were differenced were acquired. Illumination of all images used to make the difference images was from the upper right. Images for region 1 are shown as an animated sequence in movie S2.

Satellite Image Differencing

To map the spatial extent of the elevation-change regions and to confirm the ICESat-detected changes, we used a technique involving subtraction of similarly illuminated groups of satellite images. High-precision radiometric images of a uniform snow/ice surface are sensitive to surface slope (*16*, *17*). We used images from the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor, flying on NASA's Terra and Aqua satellites. We constructed a multiyear series of calibrated surface reflectance images from multiple cloud-masked, destriped, visible-band scenes acquired over brief intervals (a few weeks) each year (fig. S2). This "image stacking" process yields scenes with improved radiometric and spatial detail (*18*). By subtracting these images, the resultant image emphasizes areas where surface slope changed [see "Satellite Image Differencing" in (*19*)]. Figure 2 illustrates how image differencing complements the ICESat analysis by defining the spatial extent of the two regions with the largest elevation changes. For these regions, image differencing confirmed the sign of surface elevation change and the relative magnitude of the surface slope changes. No additional regions of change were identified.