Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry

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[1] RADARSAT data from the 1997 Antarctic Mapping Mission are used interferometrically to solve for the 3-dimensional surface ice motion in the interior of the West Antarctic Ice Sheet (WAIS). An area of ~125 km^2 in a tributary of the Kamb Ice Stream slumped vertically downwards by up to ~50 cm between September 26 and October 18, 1997. Areas in the Bindschadler Ice Stream also exhibited comparable upward and downward surface displacements. As the uplift and subsidence features correspond to sites at which the basal water apparently experiences a hydraulic potential well, we suggest transient movement of pockets of subglacial water as the most likely cause for the vertical surface displacements. These results, and related lidar observations, imply that imaging the change in ice surface elevation can help reveal the key role of water in the difficult-to-observe subglacial environment, and its important influence on ice dynamics.
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1. Introduction

[2] It is important to understand current and past changes in ice flow from the West Antarctic Ice Sheet (WAIS) in order to constrain estimates of the future contribution of West Antarctica to global sea level rise [*Alley and Bindschadler*, 2001]. The Siple Coast ice streams in particular have exhibited very large flow fluctuations [*Fahnestock et al.*, 2000], including stagnation of Kamb Ice Stream (KIS, previously Ice Stream C) around 150 years ago [*Retzlaff and Bentley*, 1993], and the current slowdown of Whillans Ice Stream (WIS, previously Ice Stream B) [*Joughin et al.*, 2002]. Although unproven, it is widely accepted that the KIS stagnation is associated with a decrease in availability of subglacial water [*Alley et al.*, 1994]. Consequently, understanding changes in the WAIS mass balance and predicting its future contribution to sea level rise depend to a large extent on improved knowledge of the basal water system [*Bougamont et al.*, 2004]. Here we present evidence for surface height changes suggesting that subglacial water drainage beneath some ice streams and tributaries is not always continuous, but can include a transient or episodic component. Our results are based mainly on analysis of RADARSAT interferometric (InSAR) data.

[3] Survey measurements on mountain glaciers have shown that water storage and release can cause ice surface elevation changes [*Iken et al.*, 1983]. Also, *Fatland and Lingle* [2002] observed concentric phase patterns or 'bulls eyes' with ERS 1- and 3-day InSAR pairs from the 1993–95 surge of the Bering Glacier in Alaska, and suggested that they represented surface rise/fall events associated with migrating pockets of subglacial water. Airborne lidar data flown in the WAIS during the 1997/1998 and 1999/2000 Antarctic field seasons [*Spikes et al.*, 2003] revealed elevation changes of a few meters on a spatial scale of ~10 km. For example, results from a KIS flightline (Line L1 in Figure 1) show a 2-year surface height increase of up to 3.5 m at the centre of a ~10 km long region. Lidar profiles over the more rapidly moving ice in WIS (Line L2 in Figure 1) showed that one region that was ~4 m lower in 1998 than in 2000.

2. InSAR Techniques and Results

[4] The Canadian RADARSAT satellite imaged Antarctica during the 30-day Antarctic Mapping Mission (AMM) in 1997 while the radar was oriented to the south [*Jezek*, 2002]. Satellite radar interferometry (InSAR) requires repeat coverage with the same geometry which is only possible with RADARSAT every 24 days. Most areas in the WAIS were covered by only one image pair, some areas had no repeat coverage at all, but a few areas had coverage by 2 pairs. With only one InSAR pair the ice velocity can be estimated by assuming that the flow vector is parallel to the ice surface and then combining displacements in the line-of-sight direction with less accurate estimates of along-track displacement made using the 'speckle tracking' technique [*Gray et al.*, 2001; *Joughin*, 2002]. However, for the few areas in the WAIS for which there are both ascending and descending pass pairs it is possible to solve for the 3-dimensional displacements without using the surface-parallel-flow assumption.

[5] RADARSAT imaged area A1 (Figure 1) in a KIS tributary during a descending pass on 24 September 1997, and again in an ascending pass on the 26 September. Both

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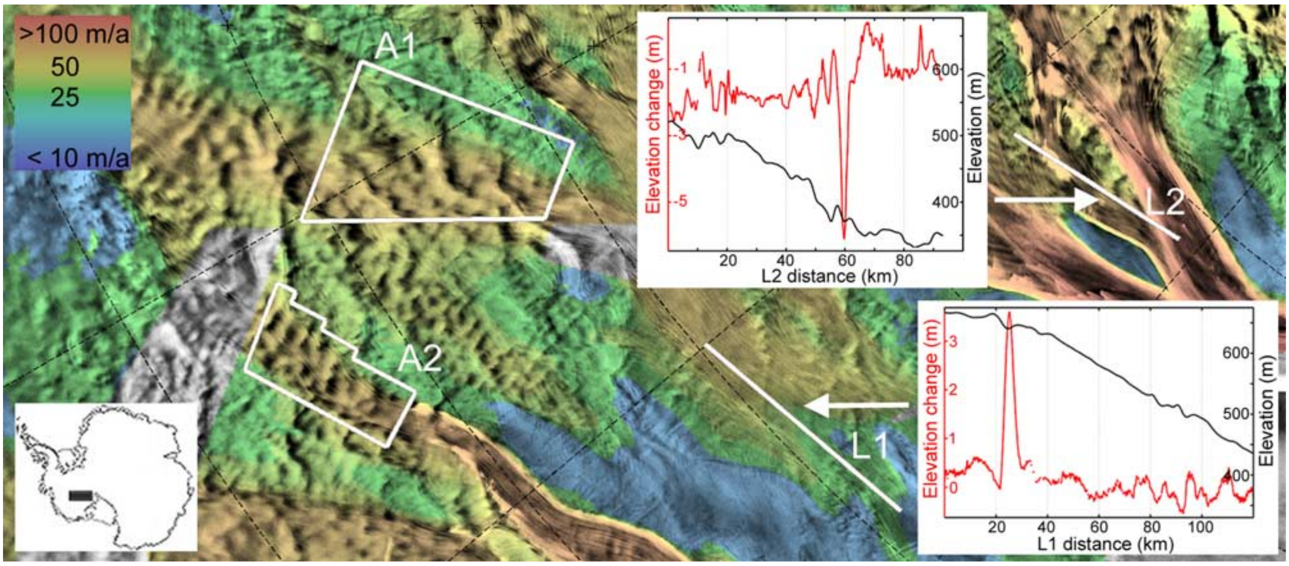

Figure 1. Study areas in the West Antarctic Ice Sheet (WAIS). The background image is from the RADARSAT Antarctic Mapping Mission mosaic, and the color overlay indicates ice speed. Boxes A1 in the tributary of Kamb Ice Stream (KIS) and A2 in the Bindschadler Ice Stream (BIS) outline the areas for which we have a solution for vertical displacement, (Figures 2b and 3b). L1 and L2 indicate the position of the lidar results discussed in the text. The inset graphs illustrate surface elevation (black) and elevation change (red) for lines L1 and L2.

acquisitions were repeated 24 days later to form two temporally overlapping interferometric pairs. A solution for vertical displacement was obtained using the ascending and descending pass InSAR range displacements (from InSAR phase), and the descending pass azimuth (along-track) displacement from speckle tracking. The north, east and vertical displacements can then be derived from the known geometry of the 3 non-orthogonal displacements. Errors in the derived horizontal and vertical displacements are dominated by the error in the smoothed azimuth shift. With a 2×2 km smoothing the standard deviation in the 24-day vertical displacement is $\sim$3–5 cm. It is hard to constrain absolute errors without more reference velocities, so there is the possibility of slowly changing bias errors of a few cm across Figure 2b.

[6] Ice surface velocity is shown as a colour overlay in Figure 2a, together with the 24-day vertical displacement (Figure 2b). The dark blue area in Figure 2b moved vertically downwards by up to 50 cm during the 24-day repeat cycle. Interferometric phase patterns (inset images in Figure 2b) from the ascending and descending InSAR pairs reflect the line-of-sight range displacement between each pair in the two different orbit geometries. Since the two passes intersect at $\sim$110°, we expect the phase patterns to be quite different except for those variations arising from displacements that subtend the same angle to the two range planes. Vertical displacements satisfy this condition and will lead to the same phase patterns. The depressed area reflected by the common concentric fringe pattern is $\sim$125 km^2 in area with a diameter of $\sim$12 km.

[7] Vertical surface displacement is also observed in area A2 (Figure 1) upstream of the Bindschadler Ice Stream (BIS, formerly Ice Stream D). In this case the horizontal velocity field (Figure 3a) was interpolated from the movement of GPS reference positions measured in the Austral summers of 1995/1996 and 1996/1997 [*Bindschadler et al.*, 2000]. These data were used to estimate the 24-day horizontal displacements and combined with the radar line-of-sight displacement from an interferometric pair (from Sept. 26 and Oct. 20, 1997) to derive the local vertical displacement (Figure 3b). The red and blue areas (Figure 3b) represent surface uplift and subsidence, respectively.

3. Vertical Surface Movement and the Link to Subglacial Water Transport

[8] The location of the InSAR vertical displacement features provides a clue as to their origin. The line through the box in Figure 2a and the arrows in Figure 2c illustrate the position of the bed and surface elevation profiles (Figure 2d, CASERTZ data) [*Blankenship et al.*, 2001]. Surface and bed elevation data at the positions marked by dots in Figure 2c show that the surface subsidence feature spans a minimum in basal water hydraulic potential of $\sim$400 kPa. The dark area in the background SAR image in Figure 2a is also indicative of the higher snow accumulation that often accompanies a surface depression. The inset graph of surface uplift and elevation in Figure 3b, together with *Price et al.* [2002, Figure 5a], show that the BIS uplift feature is also positioned over a comparable dip in hydraulic potential. Therefore, we expect that subglacial water could collect at these sites.

[9] The absence of strong divergence in the surface horizontal velocity field permits a comparison of the ice flux into and out of the feature in Figure 2. Gate G2 is downstream from G1 (Figure 2c) and both are perpendicular to the flow direction and 3 km wide. The 24-day flux into G1 (20 ± 2.10^6 m^3) is based on the surface velocity across the gate and the ice thickness at the lower end of the gate. This estimate may be conservative as the absence of CASERTZ thickness data in the upper part of G1 implies loss of the radio echo sounding bed return, and presumably

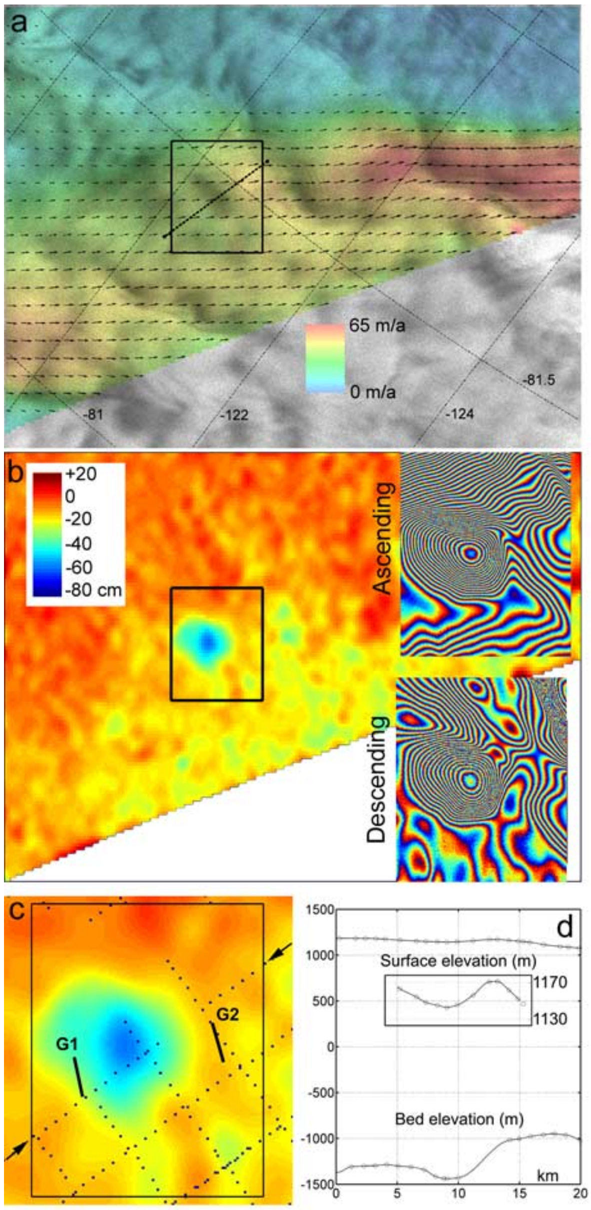

Figure 2. a: Background SAR image with overlay of ice speed (color) and direction in the overlap region of the ascending and descending passes. b: Color image of the 24-day surface elevation change; the center of the dark blue area indicates 50 cm surface depression. The phase patterns for the ascending and descending InSAR pairs, corresponding to the black rectangle in a, b and c, are quite different except for the region of predominantly vertical subsidence which corresponds to the concentric phase pattern in each phase image. c: Blow-up of the depression feature in b with dots at the positions of the CASERTZ surface and bed heights. G1 and G2 are the positions of the gates discussed in the text. d: surface and bed profiles between the arrows in c, and also for the line through the box in a.

somewhat thicker ice. The flux through downstream G2 is estimated as 22 ± 1.10^6 m^3 and the volume equivalent of the surface depression between G1 and G2 is 7 ± 1.10^6 m^3. It is clear that the output flux is too low to explain the surface subsidence on the basis of a temporary increase in ice speed across a sticky spot or ridge. However, the inconsistency in volumes disappears if the subsidence was caused by relatively rapid subglacial water drainage.

[10] Consequently, we suggest that an imbalance in water input and outflow from hydropotential wells best explains the vertical surface movements. This implies a significant 24-day movement of subglacial water; $\sim$20 10^6 m^3 on KIS and $\sim$10 10^6 m^3 for BIS. In the BIS case (Figure 3b), we observe areas of upstream subsidence and downstream uplift suggesting that water draining from the blue areas has forced the uplift in the red area. Basal melt rates of 0 to $\sim$15 mm a^{-1} have been estimated for the upstream regions of the KIS and BIS tributaries [*Joughin et al.*, 2003; *Price et al.*, 2002]. The model for basal melt for the area upstream of the KIS subsidence feature in Figure 2 [*Joughin et al.*, 2003], and the expected area for this melt, suggests that the volume of subglacial water associated with the KIS subsidence feature may be a significant fraction of the yearly upstream basal water production.

[11] Effective basal water pressure (ice overburden pressure minus basal water pressure) from borehole measurements on WAIS ice streams varies both spatially and

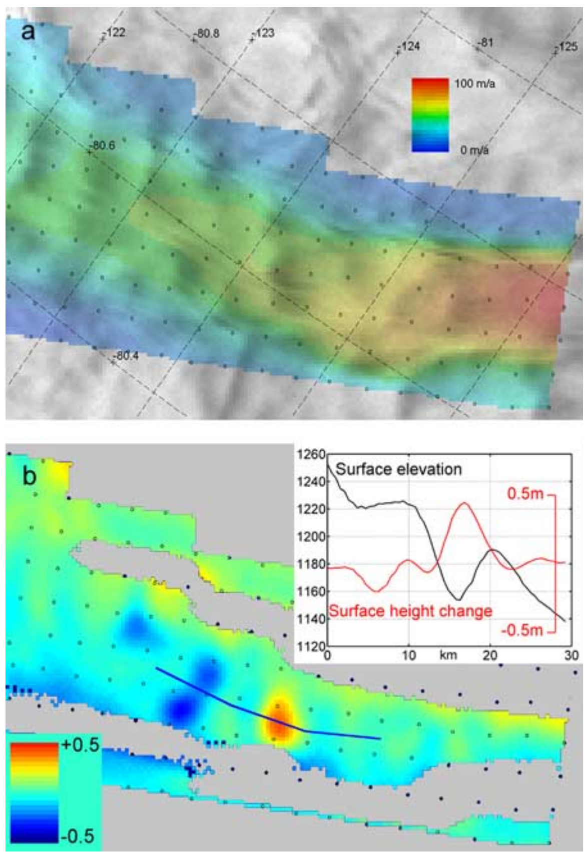

Figure 3. a: RADARSAT image of area A2 with superimposed ice speed. b: 24-day vertical displacement; red represents surface uplift, blue is surface subsidence. Data are omitted in regions (gray) of large velocity gradients where either the phase unwrapping or the velocity interpolation between GPS stake positions (small circles) became unreliable. The insert plot in b shows surface elevation (black) and 24-day elevation change (red) for the line profile through the uplift feature.

temporally [*Engelhardt and Kamb*, 1997; *Kamb*, 2001]. These data show that the effective pressure is close to zero and in some cases do not preclude the possibility that the ice is temporarily at flotation. Sometimes the temporal change in basal water pressure is gradual, e.g., in a KIS borehole a decrease in effective pressure equivalent to ~5 m of water over the first year was followed by an increase of ~3 m in the second [*Kamb*, 2001, Figure 5a]. Sometimes the changes are fast; e.g., in a WIS borehole an abrupt drop in pressure of ~5 m in two adjacent boreholes was followed by a recovery over ~100 days [*Engelhardt and Kamb*, 1997, Figure 14]. The complexity of the pressure data records and the discovery of a water cavity ~1.5 m deep at the base of a KIS borehole (B. Kamb et al. (2001), Unexpected basal conditions under Antarctic Ice Stream C discovered with a new borehole video probe, press release, 2001, available at http://skua.gps.caltech.edu/hermann/upc/pressrelease.html), are consistent with transient subglacial water transport coupled with vertical surface movement.

4. Discussion and Conclusions

[12] The interferometric radar data imply a vertical surface movement of up to ~2 cm per day. The lidar data of *Spikes et al.* [2003] also indicate vertical movement that could not be sustained over many years. The results in this paper represent a first indication that these anomalous changes in surface elevation on WAIS ice streams may be linked to subglacial water transport. Further work is required to establish the precise spatial and temporal variation in surface elevation.

[13] Continuing debate about WAIS stability [*Alley and Bindschadler*, 2001], recent interest in Antarctic subglacial lakes [*Priscu et al.*, 2003], and sediment transport by glaciers [*Alley et al.*, 2003], highlight the need for an improved understanding of the generation, distribution, and flux of subglacial water. Our results suggest that imaging all three components of surface ice displacement in the WAIS will help establish links between basal water transport in the subglacial environment, and ice dynamics and mass transport to the ocean. The RADARSAT 2 satellite to be launched in late 2005, with its flexible geometry and ability to view left or right of track, should help provide such a capability.

[14] **Acknowledgments.** RADARSAT data are copyright the Canadian Space Agency (CSA) and provided by RADARSAT International (RSI) and the Alaska SAR Facility. The AMM data were collected as a result of a NASA/CSA/OSU/JPL/ASF/VEXCEL project. The 125 m mosaic and the DEM were produced by the Byrd Polar Research Center (BPRC) of The Ohio State University. NASA's Earth Science Enterprise supported the work of RB and ST. IJ performed his contribution to this work at JPL, Caltech, under contract with NASA. LG acknowledges the support of the Canada Centre for Remote Sensing, Natural Resources Canada and help from Naomi Short.

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