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

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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 sometime between September 26 and October 18, 1997. Areas in the Bindschadler Ice Stream also exhibited comparable upward and downward surface displacements. As the inflation and deflation 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.

INDEX TERMS: 1827 Hydrology: Glaciology (1863); 6924 Radio Science: Interferometry; 0933 Exploration Geophysics: Remote sensing; 6969 Radio Science: Remote sensing.

1. Introduction

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 in flow 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].

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Although unproven, it is widely accepted that the KIS stagnation is associated with a decrease in water availability underneath the ice stream [*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 InSAR data.

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 interferometric 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 during the 1997/1998 and 1999/2000 Antarctic field seasons [*Spikes et al.,* 2003] have also revealed elevation changes on a spatial scale comparable to that mapped by the InSAR data. Results from a KIS flightline (Line L1 in Fig.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 Fig. 1) show that the centre of a ~6 km section is ~4 m lower in 1998 than in 2000.

2. InSAR techniques and results

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 resort to the surface-parallel-flow assumption.

RADARSAT imaged area A1 (Fig. 1) in a KIS tributary during a descending pass on 24 September 1997, and again in an ascending pass on the 26 September. Both 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 x 2 km smoothing the standard deviation in the 24-day vertical displacement is ~ 3 – 5 cm. It is hard to constrain absolute errors without more reference velocities, so there is the possibility of slowly changing bias errors across Fig. 2b.

Ice surface velocity is shown as a colour overlay in Fig. 2a, together with the 24-day vertical displacement (Fig. 2b). The dark blue area in Fig. 2b moved vertically downwards by up to 50 cm during the 24-day repeat cycle. Interferometric phase patterns 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 ~ 110^0, we expect the phase patterns to be quite different except for those variations arising from displacements that subtend the same angle to the 2 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 ~ 125 km^2 in area with a diameter of ~ 12 km.

Vertical surface displacement is also observed in area A2 (Fig. 1) upstream of the Bindschadler Ice Stream (BIS, formerly ice stream D). In this case the horizontal velocity field (Fig. 3a) was interpolated from the movement of GPS reference positions measured in the Austral summers of 1995/1996 and 1996/1997 [*Chen et al.,* 1998]. 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 (Fig. 3b). The red and blue areas (Fig. 3b) represent uplift and subsidence, respectively.

3. Vertical surface motion and the link to subglacial water transport

The location of the InSAR vertical displacement features provide a clue as to their origin. The line through the box in Fig. 2a and the arrows in Fig. 2c illustrate the position of the profiles (Fig. 2d) of bed and surface elevation (CASERTZ data, *Blankenship et al.*, [2001]. The dots in Fig. 2c show the position of both bed and surface data showing that the feature spans a minimum in both the surface and bed elevation, which implies a dip in the hydraulic potential of ~ 400 kPa. The dark area in the background SAR image in Fig. 2a is also indicative of the higher snow accumulation that often accompanies a surface depression. The inset graph of surface uplift and elevation in Fig. 3b, together with Fig. 5a in *Price et al.,* [2002], show that the BIS inflation feature is positioned over a dip in the hydrologic potential of ~ 300 kPa. Therefore, we expect that subglacial water could collect at these sites.

The absence of strong divergence in the surface horizontal velocity field permits an estimation of the ice flux into and out of the feature in Fig. 2. Gate G2 is downstream from G1 (Fig. 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 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 much too low to explain the surface deflation on the basis of a temporary increase in ice speed across a sticky spot or ridge. However, the inconsistency in volumes disappears if the deflation was caused by relatively rapid subglacial water drainage.

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; ~ 20 10^6 m^3 on KIS and ~ 10 10^6 m^3 for BIS. In the BIS case (Fig 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 5–20 mm a^{-1} have been estimated for these regions in the KIS and BIS tributaries [*Joughin et al.* 2003, *Price et al.,* 2002] which suggests that the KIS deflation volume may be a significant fraction of the yearly upstream basal water production.

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

Kamb, 1997, *Kamb,* 2001]. These data show that the effective pressure is close to zero and in some cases does 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 (fig. 5a, *Kamb,* [2001]). 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, (fig. 14 in *Engelhardt and Kamb*, 1997). 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 [*Kamb et al.,* 2001], are consistent with transient subglacial water transport coupled with vertical surface movement.

4 Discussion and conclusions

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 cannot be sustained on the long term. While further work is required to establish how the precise surface elevation varies with time, these results represent a first indication that anomalous changes in surface elevation on WAIS ice streams may be linked to subglacial water transport.

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], further highlight the need for an improved understanding of the generation, distribution, and flux of subglacial water. Although point and profile surface positional measurements are necessary, our results suggest that longer term imaging of all three components of surface ice displacement will help establish stronger links between the subglacial environment on the one hand, and ice dynamics and mass transport to the ocean on the other. The RADARSAT 2 satellite to be launched in 2005, with its flexible geometry and left-right viewing capabilities, should help provide such a capability.

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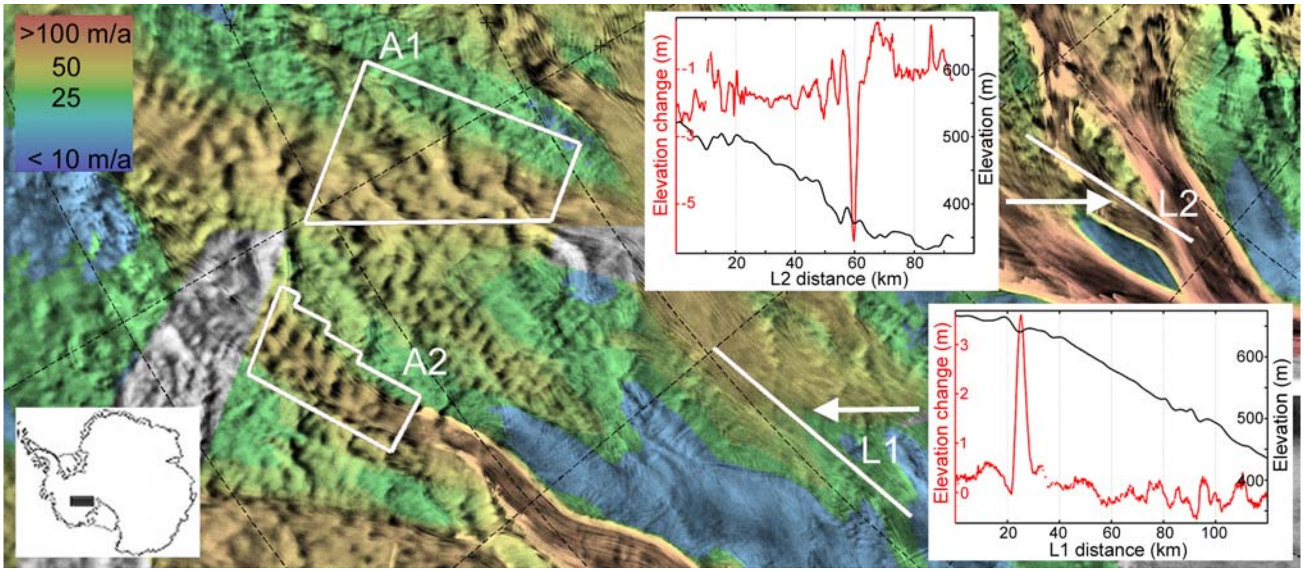

Figure 1 Study areas in the West Antarctic Ice Sheet (WAIS). The background image is from the RADARSAT Antarctic Mapping Mission mosaic, and the color overlay indicates ice speed. Boxes A1 in the tributary of Kamb Ice Stream (KIS) and A2 in the Bindschadler Ice Stream (BIS) outline the areas for which we have a solution for vertical displacement, (Figs. 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 L1 and L2.

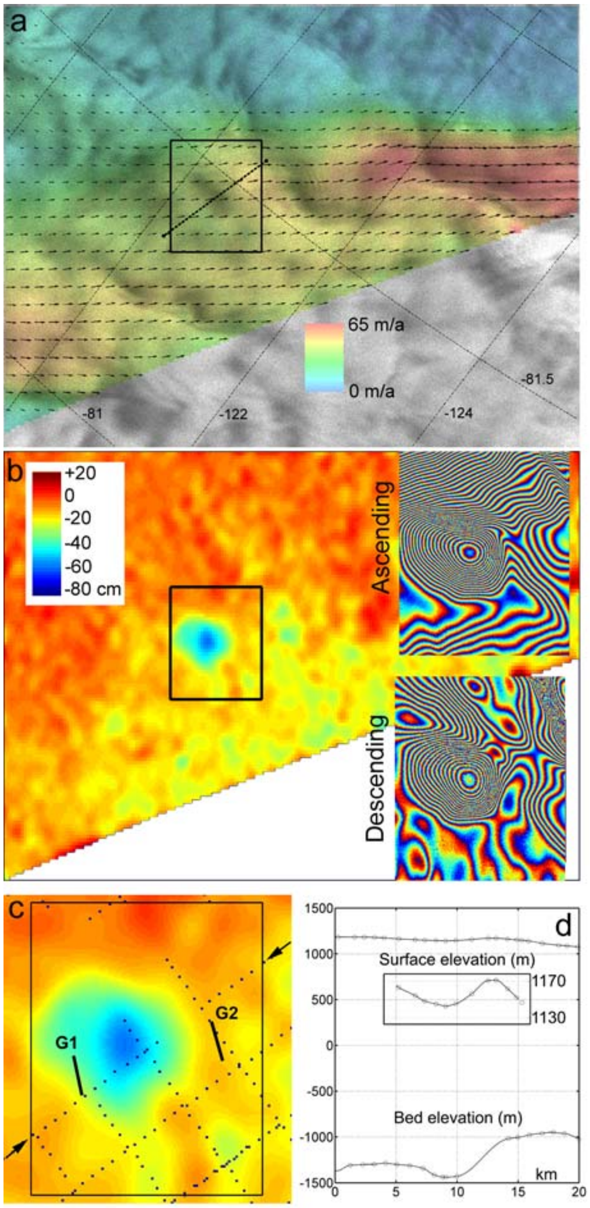

Figure 2 **a:** Background SAR image with overlay of ice speed (color) and direction in the overlap region of the ascending and descending passes. **b:** The center of the dark blue area in the image of 24-day vertical displacement indicates 50 cm surface depression. The phase patterns for the ascending 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 bewteen the arrows in **c**, and also for the line through the box in **a**.

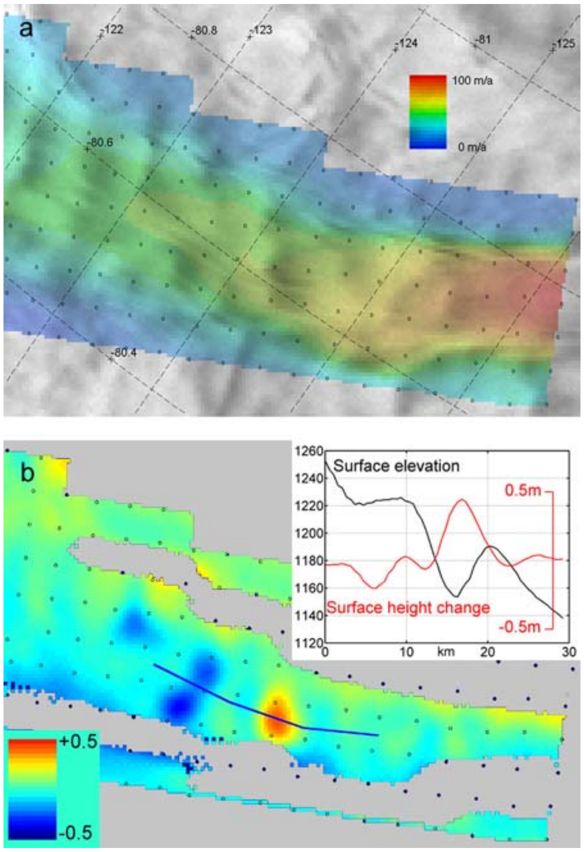

Figure 3 a: RADARSAT image of area A2 with superimposed ice speed. **b:** 24-day vertical displacement; red represents surface uplift, blue is surface subsidence. Data are omitted in regions (gray) of large velocity gradients where either the phase unwrapping or the velocity interpolation between GPS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