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ICESat measurements reveal complex pattern of elevation changes on Siple Coast ice streams, Antarctica

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[1] We compare ICESat data (2003–2004) to airborne laser altimetry data (1997–98 and 1999–2000) to monitor surface changes over portions of Van der Veen (VdVIS), Whillans (WIS) and Kamb ice streams (KIS) in the Ross Embayment of the West Antarctic Ice Sheet. The spatial pattern of detected surface changes is generally consistent with earlier observations. However, important changes have occurred during the past decade. For example, areas on the VdVIS and WIS, where large thinning was detected by the airborne surveys, are now closer to being in balance. The upper trunk of KIS continues to build up with thickening rates reaching 0.4 m/year. Our results provide new evidence that the overall mass balance of the region is becoming more positive, but a significant spatial variability exists. They also demonstrate the potential of ICESat data for detecting spatial patterns of surface elevation change in Antarctica. **Citation:** Csatho, B., Y. Ahn, T. Yoon, C. J. van der Veen, S. Vogel, G. Hamilton, D. Morse, B. Smith, and V. B. Spikes (2005), ICESat measurements reveal complex pattern of elevation changes on Siple Coast ice streams, Antarctica, *Geophys. Res. Lett.*, *32*, L23S04, doi:10.1029/2005GL024289.

1. Introduction

[2] Two decades of intensive research have revealed that West Antarctic ice streams are changing on centennial and even decadal time scales [e.g., *Joughin and Tulaczyk*, 2002; *Joughin et al.*, 2002; *Stearns et al.*, 2005]. For example, while the Whillans (WIS, former B2) and Van der Veen (VdVIS, former B1) ice streams were previously found to be thinning at a rate up to 1 m/yr [*Shabtaie et al.*, 1988; *Whillans and Bindschadler*, 1988; *Spikes et al.*, 2003b], they are currently slowing down, and getting closer to balance [*Joughin et al.*, 2002; *Joughin and Tulaczyk*, 2002]. On the other hand, Kamb Ice Stream (KIS, former C) that stopped its fast motion ~140 years ago [*Retzlaff and Bentley*, 1993], is currently thickening in its upstream region [*Joughin et al.*, 1999; *Price et al.*, 2001] and has the potential of restarting within decades [*Vogel et al.*, 2005]. Since this region of Antarctica lies south of the maximum coverage of existing satellite radar altimetry, previous mass balance studies were based on mass budget methods or local investigations of surface elevation changes based on ground or airborne observations. With maximum latitude of 86°S, the Ice, Cloud and land Elevation Satellite (ICESat) offers the first opportunity to routinely monitor surface elevation changes over most of the West Antarctic Ice Sheet, thus allowing detection of temporal and spatial patterns of change over substantially larger areas than previously possible. To evaluate the performance of ICESat, we conducted a comparison between elevations measured in 1997/98 and 1999/2000 austral summers by using airborne laser altimetry [*Spikes et al.*, 2003a, 2003b] and crossover paths from ICESat data acquired in 2003–2004. This paper presents the computation of the ice sheet surface elevation changes, shows examples of temporal evolution of local change patterns and summarizes the trends of regional surface change.

2. Computation of Ice Sheet Surface Elevation Changes From ICESat Data and Airborne Laser Altimetry

2.1. ICESat Data

[3] ICESat was launched in January 2003 and has collected data during several operational periods since February 2003. We use data from the Antarctic and Greenland Ice Sheet Data Product (GLA12) for Laser 1 (Release 18; February–March 2003), Laser 2a (Release 21; October–November 2003), Laser 2b (Release 16; February–March 2004), Laser 2c (Release 17; May–June 2004) and Laser 3a (Release 22; October–November 2004). To reduce the range error induced by detector saturation, we apply the correction described by *Fricker et al.* [2005]. As described in Section 2.3, outlier observations are detected and removed by comparing point estimates of elevation changes with interpolated values along transects. Since the results of the airborne laser altimetry surveys as well as elevations from other surface and submergence measurements are referenced to the WGS-84 geodetic reference system, we transform ICESat locations from their reference ellipsoid (Topex/Poseidon) to WGS-84.

2.2. Airborne Laser Altimetry

[4] The Support Office of Aerogeophysical Research (SOAR) at the University of Texas collected airborne laser altimetry data during 1997/98 and 1999/2000 austral summers (referred here as SOAR 1998 and SOAR 2000 surveys) over several sites in West Antarctica [*Spikes et*

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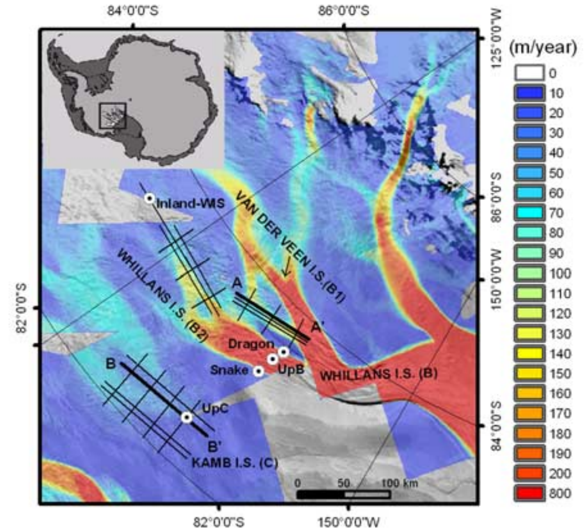

Figure 1. Location of airborne laser altimetry surveys. Background combines the RADARSAT SAR mosaic in grey scale [*Jezek and RAMP Product Team*, 2002] and ice velocities derived from RADARSAT data in color [*Joughin et al.*, 2002]. Thick lines mark transects shown in Figure 2 and circles are submergence velocity stations [*Hamilton et al.*, 2005]. Inset shows the location of Siple Coast ice streams in Antarctica.

al., 2003a, 2003b]. Figure 1 shows the three sites analyzed in this paper, namely the northern tributary of the VdVIS, the upstream region of WIS and the area located upstream of the stagnating trunk of KIS. We derive surface elevation changes from repeat track SOAR measurements by computing the average elevation difference between each laser point in the SOAR 1998 dataset and its three nearest neighbors from the SOAR 2000 dataset within a 40 meter radius. From the crossover analysis by *Spikes et al.* [2003a], we estimate the elevation accuracy of the SOAR surveys to be 0.09 m.

2.3. Computation of Surface Elevation Changes

[5] To compute the surface elevation changes from SOAR 2000 and ICESat measurements, first we identify all ICESat orbit segments intersecting SOAR transects. This is followed by the computation of crossover locations and elevation differences by intersecting 3D lines fitted through the ICESat and SOAR observations and the computation of elevation change rates. To obtain accurate elevation changes, crossovers located near data gaps are eliminated. Based on error estimates by *Luthcke et al.* [2005] and *Fricker et al.* [2005] we assume an elevation error of 0.3 meter caused by residual pointing bias over the small slopes typical for the ice streams (0.1 degree or 2 m/1000 m), a 0.15 m error caused by a residual ranging bias and an additional error of 0.1 m from waveform processing. Our analysis, in agreement with results of *Fricker et al.* [2005], indicates a larger range bias for data from Laser 2c operation period (Figure 2); consequently we have not used these data. Combining all elevation errors via error propagation, and assuming that elevation change rates were constant between the SOAR 2000 and ICESat surveys, we obtain an error of 0.09 m/yr for the surface elevation change rates.

[6] To detect outlier ICESat observations and to analyze the spatial and temporal patterns we compare elevation change rates from SOAR 1998 and SOAR 2000 observations as well as from SOAR 2000 and ICESat data along SOAR transects (Figure 2). We apply a pointwise running average filter to reduce the effect of sastrugi and errors in SOAR laser ranging. Elevation change rates between the second SOAR mission (SOAR 2000) and ICESat measurements are computed by averaging surface elevation change rates at crossover points, using all intersecting ICESat ground tracks, followed by a cubic spline interpolation. Then we compute the Root Mean Square Error (RMSE) of surface elevation change rates for each SOAR transect. Observations with residuals greater than 2 RMSE are removed and the fitted polynomials are recomputed. ICESat observations rejected by this criterion, as well as those collected during Laser 2c period and showing 0.13 m/yr

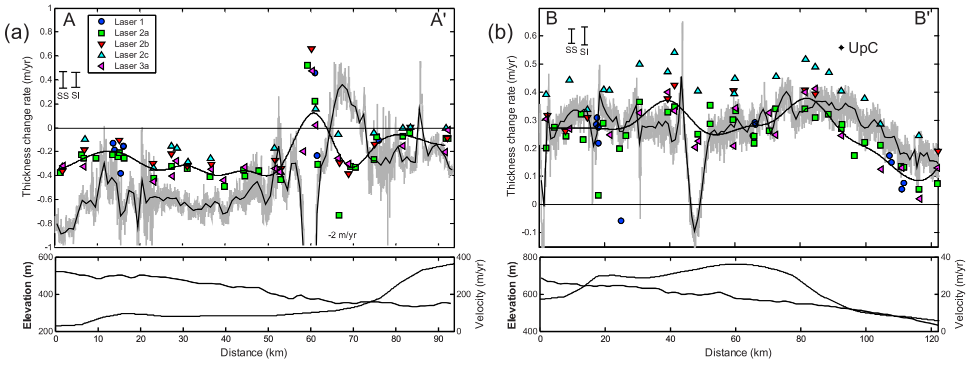

Figure 2. Elevation change rates along SOAR transects on (a) VdVIS and (b) KIS. (top) Elevation change rates between 1998 and 2000 from repeat SOAR airborne surveys (grey line) and between 2000–2004 from crossover comparison of ICESat and SOAR measurements (color symbols). Elevation change rates between 1998 and 2000 are smoothed by running mean (black line), and those between 2000 and 2004 are interpolated by cubic splines (bold black line). SS and SI mark two times RMSE of observations. UpC is local thickness change rate in 1995–96 from submergence velocity station measurement of *Hamilton et al.* [2005]. (bottom) Ice surface elevations from SOAR airborne laser altimetry (bold lines) and ice velocities from *Joughin et al.* [2002] are plotted.

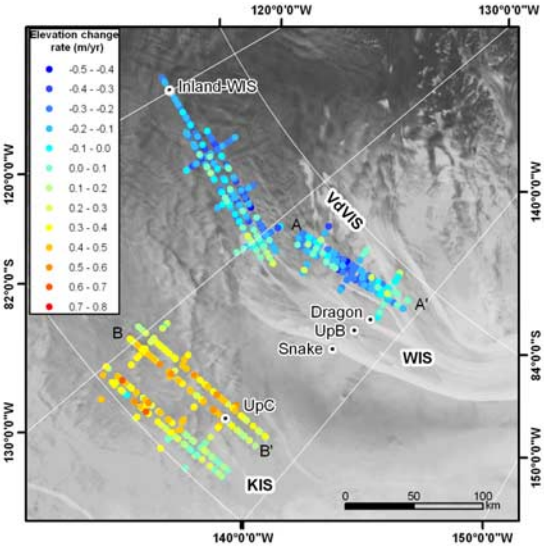

Figure 3. Elevation change rates between 2000–2004 from cross-over comparison of SOAR airborne and ICESat satellite laser altimetry data shown on top of RADARSAT SAR mosaic.

bias (blue triangles in Figure 2), are excluded from subsequent analysis. Inspection of ICESat return waveforms reveals that outliers are mostly caused by errors in ICESat ranging. For example, return waveforms of ICESat observations at 19 and 23 km on transect BB′ (Figure 2b) indicate forward scattering. These waveforms have long "tails", caused by delays of photons scattered within ground fog or blowing snow, resulting in longer ranges, and a decrease in surface elevation change rates. However, outliers can also indicate rapid local surface changes. For example, *Whillans et al.* [2001] pointed out that rapid local surface changes, such as sagging and collapsing snow bridges and drifts forming downwind of newly opened crevasses, frequently occur in heavily crevassed areas. Rapid local changes may also indicate changes in the subglacial hydrological system [e.g., *Gray et al.*, 2005].

[7] Figure 3 shows the spatial pattern of surface elevation change rates between 2000 and 2004 from the comparison of SOAR 2000 and ICESat data. Kriging interpolation is used to obtain surface elevation change grids from repeat SOAR observations (e.g., Figure 4) and from the comparison of SOAR and ICESat data. In order to compare our results with ongoing changes derived from ICESat observations we computed regional averages from the gridded data sets over rectangular regions covering the sites (e.g., red boxes in Figure 4). Surface change rates during the ICESat mission are computed by the linear regression presented by *Smith et al.* [2005] over the same regions. Table 1 summarizes temporal changes of average thickness change rates between 1998 and 2005.

3. Results and Discussion

[8] The Van der Veen Ice Stream (*VdVIS*) site covers several different flow regimes, showing a complex spatial and temporal change pattern (Figure 4). Transect AA′ (Figure 2a) starts at an almost stagnant area then crosses obliquely the northern tributary of VdVIS and ends over its fast flowing trunk. The overall surface lowering is consistent with earlier observations [*Shabtaie et al.*, 1988; *Spikes et al.*, 2003b; *Stearns et al.*, 2005], but our results indicate that surface lowering decreases over time and this area now is closer to being in balance. However, comparison of SOAR and ICESat observations confirms that high thinning rates, first detected by *Spikes et al.* [2003b], are maintained over the interstream ridges (Figure 4). Given the small area of the ridges, surface lowering at a rate of 0.2–0.3 m/yr might indicate some significant changes, such as ongoing migration of both shear margins into the interstream ridge, previously observed on the Dragon shear margin by *Hamilton et al.* [1998] and *Echelmeyer and Harrison* [1999]. The observed changes may also be associated with a reorganization of the general flow pattern in the WIS and VdVIS catchment area. For example, significant surface lowering (exceeding 0.3 m/yr), is detected over the "chromosomes" and "seagulls" crevasse formations. These areas were named by *Merry and Whillans* [1993], who concluded that the shape of these crevasses can not be explained by steady flow. The main trunk of VdVIS, characterized by streaming flow (v > 300 m/yr), has been in balance since the second SOAR survey in 2000 (Figure 2a).

[9] The overall pattern of change over Whillans Ice Stream (WIS) site is similar to that of the northern tributary of VdVIS (Figure 3). Thinning rates over the tributary flow decrease with distance along the tributary and over time. The region at the onset of streaming flow, previously thinning by 0.2–0.6 m/yr [*Spikes et al.*, 2003b], is now in balance (Figure 3). The thinning gradient over the tributary, 0.2 m/yr over a distance of 100 km, is consistent with the overall deceleration of WIS reported by *Joughin et al.* [2002]. This gradient could indicate thinning that originated downstream, possibly near the grounding line, and that has now propagated far inland.

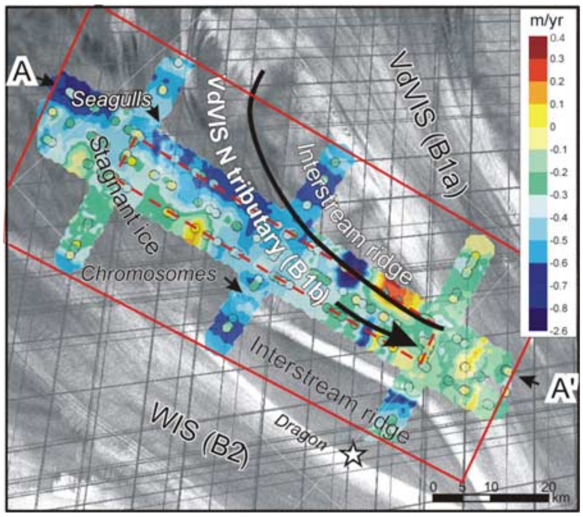

Figure 4. Comparison of elevation change rates over VdVIS between 1998–2000 and 2000–2004. Elevation change rates between 1998 and 2000, derived from the SOAR surveys, are interpolated by using ordinary kriging and shown as a color map. Large circles, colored according the elevation change rate between 2000 and 2003–04, represent the crossovers of the SOAR 2000 survey and ICESat orbits. Red boxes show areas where average rates, listed in Table 1, are computed.

Table 1. Temporal Variation of Average Elevation Changes Rates From 1998 to 2005[a]

	1997–2000 dh/dt, m/yr	1999–2004 dh/dt, m/yr	2003–2005 dh/dt, m/yr
VdVIS outer	−0.40 ± 0.09	−0.23 ± 0.08	−0.24 ± 0.03
VdVIS inner	−0.38 ± 0.09	−0.23 ± 0.08	−0.22 ± 0.07
WIS outer	−0.44 ± 0.09	−0.23 ± 0.09	−0.24 ± 0.03
WIS inner	−0.44 ± 0.08	−0.24 ± 0.09	−0.18 ± 0.1
KIS outer	0.32 ± 0.04	0.33 ± 0.05	0.41 ± 0.04
KIS inner	0.30 ± 0.05	0.35 ± 0.05	0.40 ± 0.05

[a] Inner rectangles are bounded by SOAR transects and outer ones are defined as smallest rectangles covering all SOAR observations (e.g., red boxes in Figure 4). Data sources: 1998–2000: repeat-track comparison of SOAR airborne laser altimetry, 2000–2004: crossover comparison of SOAR airborne laser altimetry and ICESat data, 2003–2005: crossover comparison of ICESat observations computed by the technique described by *Smith et al.* [2005] from ICESat data acquired during L1–L3a operational periods.

[10] The Kamb Ice Stream (*KIS*) continues to build up with an average surface elevation change rate reaching 0.4 m/year. As Figure 2b illustrates, there has been very little overall change between 1998 and 2004. Thickening has slightly decreased over the first 20 to 25 km and the last ~30 km of profile BB′ (Figure 2b) while it remained constant or even increased at the center part of the profile. These changes might be due to the diversion of flow towards the WIS catchment. The detected spatial pattern of changes is remarkably similar to previous estimates of *Price et al.* [2001], although our observed rates are slightly lower.

[11] Local elevation changes, reaching several meters on a spatial scale of 5–10 km, were detected on the VdVIS and KIS between 1998 and 2000 (e.g., at 60 km in Figure 2a and at 45 km in Figure 2b). These features, located behind reversed slopes, may represent surface rise/fall events associated with migrating pockets of subglacial water [*Gray et al.*, 2005]. ICESat surface elevations shows complex pattern of surface elevation changes since 2000. For example, the strong reversal in thickening and thinning rates at the southern margin of VdVIS (Figures 2a and 4) indicates that this region, deflated between 1998 and 2000, has returned to its original level.

4. Summary

[12] Comparison of ICESat data with results from earlier airborne altimeter surveys reveals significant changes in the dynamics of West Antarctic ice streams on timescales of a few years. For example, the tributaries of VdVIS and WIS, where thinning of almost 1 m/yr was detected between 1998 and 2000 by *Spikes et al.* [2003b], are now much closer to being in balance. The upstream trunk of KIS continues to build up mass, although thickening rates have slightly decreased. The reasons for these changes are not yet fully understood, but it is clear that ICEsat provides sufficient accuracy to monitor the pattern of local changes in West Antarctica. Obtaining this information is essential for better understanding the dynamics of this ice sheet and its possible contribution to future sea level rise.

[13] **Acknowledgments.** We thank NASA's ICESat Science Project and the NSIDC for distribution of the ICESat data (http://icesat.gsfc.nasa.gov and http://nsidc.org/data/icesat/). Suggestions from Helen Fricker and Ian Joughin have improved this manuscript. Byrd Polar Research Center Contribution Number C-1331.

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