

Spatial patterns in mass balance of the Siple Coast and Amundsen Sea sectors, West Antarctica

Gordon S. HAMILTON, V. Blue SPIKES,* Leigh A. STEARNS

*Climate Change Institute, University of Maine, 303 Bryand Global Sciences Center, Orono, ME 04469-5790, USA
E-mail: gordon.hamilton@maine.edu*

ABSTRACT. Local rates of change in ice-sheet thickness were calculated at 15 sites in West Antarctica using the submergence velocity technique. This method entails a comparison of the vertical velocity of the ice sheet, measured using repeat global positioning system surveys of markers, and local long-term rates of snow accumulation obtained using firn-core stratigraphy. Any significant difference between these two quantities represents a thickness change with time. Measurements were conducted at sites located ~100–200 km apart along US ITASE traverse routes, and at several isolated locations. All but one of the sites are distributed in the Siple Coast and the Amundsen Sea basin along contours of constant elevation, along flowlines, across ice divides and close to regions of enhanced flow. Calculated rates of thickness change are different from site to site. Most of the large rates of change in ice thickness (~10 cm a⁻¹ or larger) are observed in or close to regions of rapid flow, and are probably related to ice-dynamics effects. Near-steady-state conditions are calculated mostly at sites in the slow-moving ice-sheet interior and near the main West Antarctic ice divide. These results are consistent with regional estimates of ice-sheet change derived from remote-sensing measurements at similar locations in West Antarctica.

1. INTRODUCTION

Earth's polar ice sheets play an important role in modulating global sea level, but at present there is no accurate assessment of how much of the observed sea-level rise is due to changes in ice-sheet mass balance (Rignot and Thomas, 2002). The West Antarctic ice sheet is a potential contributor, because observed changes in ice dynamics appear to be causing net mass loss. Recent remote-sensing studies indicate contrasting spatial patterns of ice-sheet behavior, characterized by a positive mass balance in the Siple Coast catchment (Joughin and Tulaczyk, 2002) and rapid thinning in parts of the Amundsen Sea basin (Wingham and others, 1998), which appear to be related to changes in ice dynamics. These studies describe the behavior of the ice sheet on short (~decadal) timescales but may not adequately describe longer-term change of the ice sheet. Independent measurements of ice-mass change, representative of longer timescales, are therefore useful for assessing current ice-sheet behavior and predicting future changes.

Estimates for the mass balance of the West Antarctic ice sheet are available from several different methods. Remote-sensing techniques, based on measurements of ice flow and surface elevation, provide the most spatially extensive estimates. One such study, by Joughin and Tulaczyk (2002), compared the outgoing flux of ice, derived from widespread measurements of surface velocity obtained by satellite interferometry, with the distribution of basin-wide snowfall to show that the Siple Coast ice streams have an overall positive mass balance. Most of this positive budget was attributed to the rapid thickening of one currently inactive ice stream (Kamb Ice Stream). Other ice streams were shown to be thinning, albeit at slower rates (Joughin and Tulaczyk, 2002). Another study, by Wingham and others

(1998), used repeat satellite altimeter measurements of surface elevations to show that while most of the interior West Antarctic ice sheet was changing at very slow rates, rapid thinning was occurring in parts of the Pine Island and Thwaites glacier basins in the Amundsen Sea sector. Because of the short timescale of observation (1992–96), it is difficult to assess whether the altimetry results are indicative of changes in ice dynamics or whether the elevation changes are dominated by interannual fluctuations in snowfall.

Here we describe local estimates of ice-sheet mass balance obtained at 15 sites in West Antarctica using the submergence velocity method (Hulbe and Whillans, 1994; Hamilton and Whillans, 2000). This technique provides long-term mass-balance estimates applicable to the time-scales governing changes in ice flow and decadal–centennial accumulation rate. As such, the results provide a means of interpreting and validating altimetry studies, and of assessing changes at smaller length scales than can be investigated by remote-sensing techniques. Most of the field measurements were conducted at sites along traverse routes of the United States component of the International Trans-Antarctic Scientific Expedition (US ITASE). A few other sites were installed separately using aircraft support.

2. SUBMERGENCE VELOCITY METHOD

The technique entails comparison of ice vertical velocity \dot{z} , derived from repeat global positioning system (GPS) surveys of markers, with the local accumulation rate \dot{b} , obtained from core stratigraphy. Any significant difference between measured values of \dot{z} and \dot{b} at a point location indicates a rate of ice-sheet thickness change \dot{H} . Because both measured quantities are representative of long time-scales (10²–10³ years), calculated values of \dot{H} indicate long-term behavior of measurement locations on the ice sheet. The technique is described in detail by Hamilton and Whillans (2000).

*Present address: Earth Science Agency, LLC, Stateline, NV 89449, USA.

Table 1. Location of measurement sites and dates of survey occupation. Elevations are meters above the World Geodetic System 1984 (WGS84) ellipsoid

Site	Observation dates	Latitude	Longitude	Elevation m
Dragon	2 Dec 1992	-83.57889	-138.09750	349
	27 Nov 1993			
	3 Dec 1996			
UpB	17 Nov 1997	-83.45583	-137.81833	338
	9 Dec 1995			
	2 Dec 1996			
Snake	17 Nov 1997	-83.26556	-137.61889	354
	3 Dec 1996			
	16 Nov 1997			
Inland-WIS	14 Jan 2000	-83.50083	-119.97333	1069
	2 Dec 1996			
	18 Nov 1997			
UpC	4 Dec 1996	-82.43917	-135.97111	526
	16 Nov 1997			
	12 Dec 1999			
99-2	22 Dec 2001	-81.18833	-125.90667	963
	12 Dec 2001			
	1 Dec 2000			
00-1A	21 Dec 2001	-79.38375	-111.23982	1792
	18 Dec 2002			
	4 Dec 2000			
00-1B	21 Dec 2000	-79.29864	-110.23722	1804
	18 Dec 2002			
	2 Dec 2000			
00-1C	21 Dec 2001	-79.48622	-112.35302	1758
	18 Dec 2002			
	16 Dec 2000			
00-5	22 Dec 2001	-78.08335	-120.08042	1701
	19 Dec 2002			
	24 Nov 2001			
01-1	19 Dec 2002	-79.33028	-104.89611	1854
	5 Dec 2001			
	19 Dec 2002			
01-3	20 Dec 2002	-78.12389	-95.60972	1618
	10 Dec 2001			
	20 Dec 2002			
01-4	21 Dec 2002	-77.62250	-92.26194	1494
	14 Dec 2001			
	21 Dec 2002			
01-5	22 Dec 2002	-77.06167	-89.17278	1259
	24 Dec 2001			
	22 Dec 2002			
01-6		-76.09667	-89.01806	1229

In this study, vertical velocities were obtained from repeat GPS surveys of markers installed ~5–20 m beneath the ice surface. Dual-frequency GPS data were acquired over a 12–24 hour period during each survey. These data were post-processed using precise satellite orbit and clock solutions (Zumberge and others, 1997) to yield precise point positions for each marker. Marker velocities were computed using repeat positions obtained from surveys conducted 1–5 years apart.

Calculated vertical velocities include the effects of firm compaction beneath the markers and the horizontal flow of markers along a slope. Firm compaction was taken into account by installing several markers (four to eight) at different depths, and hence different densities, at each site. Depth–density profiles obtained from measurements of firn-core samples (obtained for the dual purpose of determining accumulation rates) were used to test for the steadiness of firm densification (Paterson, 1994; Hamilton and Whillans, 2000). The adjustment for along-slope flow was made using calculated values of horizontal velocity \vec{u} obtained from the

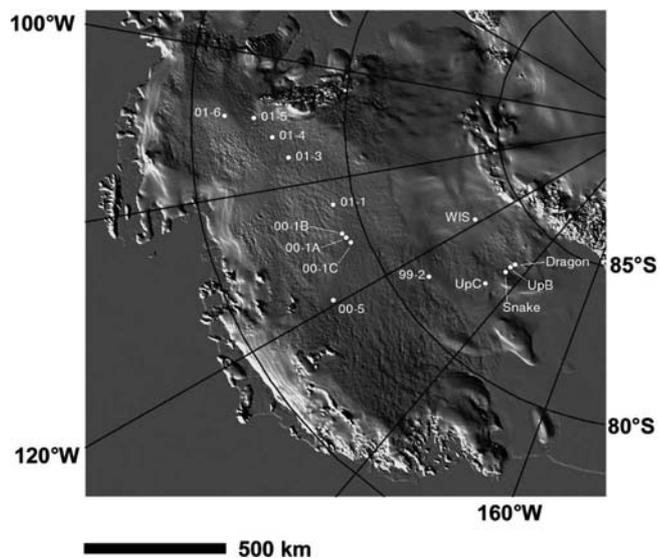


Fig. 1. Shaded relief image of the OSU DEM (digital elevation model; Liu and others, 1999) showing the location of submergence velocity stations in West Antarctica. Illumination is from 90° W.

repeat GPS surveys of markers, and surface slopes in the direction of flow $\vec{\alpha}$ obtained from kinematic GPS surveys around each marker site. These adjustments usually result in only a small change in vertical velocity, except for locations where marker sites have relatively large horizontal velocities.

Long-term snow accumulation rates were derived from ice-core stratigraphy. Accumulation records of several centuries duration were obtained at most sites, based on multi-parameter annual-layer dating of 50–120 m deep cores (Kaspari and others, 2004). For the remaining sites, ~40 year average accumulation rates were determined by detecting elevated levels of gross beta radioactivity (cf. Whillans and Bindshadler, 1988) in shallow (<20 m deep) firn cores.

The field measurements were used to solve

$$\dot{H} = \frac{\dot{b}}{\rho} + \dot{z} + \vec{u} \cdot \vec{\alpha} \quad (1)$$

for each marker, where ρ is density. Uncertainties in \dot{H} were obtained from the propagation of variances in each measured term (Hamilton and Whillans, 2000) which were usually small and well constrained. Uncertainties in \dot{z} and \dot{b} usually dominated the error budget, with nearly equal contributions from each term.

For accumulation rates, the uncertainty incorporates measurement errors and spatial–temporal variability. Core diameter is the principal measurement error in determining accumulation rate because it enters into the calculation of sample volume and density (cf. Hulbe and Whillans, 1994). The influence of temporal variability was minimized by averaging long-term (centennial) accumulation rate estimates. There is no apparent long-term trend in accumulation rates at most of the measurement sites (Kaspari and others, 2004). Spatial variability in snowfall is a source of uncertainty in point determinations of accumulation rate, like those used here. We estimated this variability from ground-penetrating radar surveys of firn stratigraphy around several of the measurement sites (Spikes and others, 2004). Accumulation rates vary by about 10% over a distance of 2 km from ice-core sites. Because this variability increases significantly beyond 50 km (Spikes and others, 2004), we

Table 2. Measured and derived quantities at each of the sites discussed in the text, and accompanying $1-\sigma$ uncertainties. Horizontal velocities \bar{u} were derived from repeat GPS surveys. Accumulation rates \dot{b} were derived from ice-core stratigraphy (Kaspari and others, 2004) and represent long-term averages (100–400 years). Asterisks denote ~ 40 year average accumulation rates derived from detection of bomb horizons. Rates of thickness change \dot{H} were obtained by solving Equation (1). Our results are compared, where possible, with other mass-balance estimates

Site	\bar{u} m a^{-1}	\dot{b} m a^{-1}	\dot{H} m a^{-1}	Comparison \dot{H} m a^{-1}
Dragon	1.98 at 296°	0.061 ± 0.021*	−0.098 ± 0.021	
Snake	12.7 at 221°	0.079 ± 0.02*	−0.189 ± 0.019	
UpB	416.1 at 242°	0.088 ± 0.018*	−1.316 ± 0.085	+0.032 ± 0.02 ^a − 0.57 ± 0.08 ^b
Inland-WIS	11.32 at 261°	0.165 ± 0.018*	−0.019 ± 0.021	−0.64 ± 0.08 ^b
UpC	13.54 at 241°	0.095 ± 0.019*	+0.559 ± 0.019	+0.145 ± 0.022 ^a + 0.35 ± 0.07 ^b
99-2	22.4 at 204°	0.120 ± 0.021	−0.167 ± 0.015	
00-1A	0.98 at 243°	0.223 ± 0.02	+0.014 ± 0.015	
00-1B	0.97 at 185°	0.240 ± 0.019*	+0.017 ± 0.018	
00-1C	5.71 at 254°	0.210 ± 0.022*	+0.016 ± 0.018	
00-5	0.93 at 045°	0.146 ± 0.021	−0.038 ± 0.020	} −0.09 ± 0.03 ^c
01-1	10.93 at 325°	0.300 ± 0.028	−0.220 ± 0.016	
01-3	34.21 at 016°	0.327 ± 0.027	−0.156 ± 0.018	} −0.21 ± 0.03 ^c
01-4	43.64 at 009°	0.350 ± 0.022	−0.249 ± 0.020	
01-5	32.31 at 050°	0.365 ± 0.028	−0.147 ± 0.028	
01-6	2.65 at 269°	0.397 ± 0.03*	+0.031 ± 0.027	

^aSpatial averages over 143 000 km² (for the UpC comparison) and 153 400 km² (for the UpB comparison), from Joughin and Tulaczyk (2002).

^b5000 km² spatial average over the region closest to UpB and a crossover measurement at UpC, from Spikes and others (2003).

^cSpatial averages for slow-moving ice (<20 m a^{−1}) ($\sim 20\,000\text{ km}^2$) and intermediate ice ($\sim 50\text{--}200\text{ m a}^{-1}$) ($50\,000\text{ km}^2$) in the Amundsen Sea basin, from Shepherd and others (2001).

emphasize that the rates of thickness change calculated in our study are local estimates. Errors in ice velocity were the result of positioning uncertainties, and were usually smaller for modern surveys (due to improved GPS receiver performance) and for sites with multiple occupations (due to the longer interval between surveys). Combined $1-\sigma$ uncertainties in \dot{H} are typically $\sim 0.02\text{ m a}^{-1}$ or less, except in cases where a rapid \bar{u} propagates a large uncertainty in the adjustment for along-slope flow of a marker.

We neglect the effect on \dot{z} of isostatic adjustment of the crust due to glacial loading and unloading. Bedrock elevation changes due to short-term elastic and longer-term viscoelastic effects are poorly constrained in West Antarctica. The best estimate (James and Ivins, 1998) of present-day glacial rebound in the study region indicates only a small ($\sim 0.008\text{ m a}^{-1}$) potential isostatic contribution to \dot{z} .

Field measurements were made at 15 sites in West Antarctica (Fig. 1; Table 1). These sites were located in and close to zones of rapid flow in the Siple Coast and the Amundsen Sea basin, on slow-moving flanks in the ice-sheet interior and across the main ice divide in West Antarctica. One site was located in the upper catchment of Rutford Ice Stream.

3. RESULTS

3.1. Siple Coast ice streams

Six sites were installed on or close to the main trunks of several ice streams draining the Siple Coast. There are reasons to expect mass-balance changes in this part of West Antarctica because of observations of recent large-scale changes in ice dynamics (e.g. Joughin and others, 2002).

UpB is located on the fast-flowing central part of Whillans Ice Stream. Results of calculations using the submergence velocity technique show that rapid thinning

of $\sim 1.32\text{ m a}^{-1}$ ($1-\sigma$ uncertainty 0.09 m a^{-1}) is occurring at this site (Table 2). We note the fast horizontal motion of this site introduces a large along-slope component in vertical velocity which is difficult to remove with confidence, as indicated by the large uncertainty. The thinning rate, however, is more than an order of magnitude larger than the local 40 year average accumulation rate ($\sim 0.09\text{ m a}^{-1}$), implying either an ice-dynamics forcing or a substantial change in accumulation rate. An observed reduction of flow speeds in this part of Whillans Ice Stream (Hulbe and Whillans, 1997; Joughin and others, 2002; Stearns and others, 2005; this study) might account for some of the calculated thinning by decreasing the incoming mass flux. The horizontal velocity at UpB, adjusted for down-glacier advection of the survey site, decelerated from $\sim 430\text{ m a}^{-1}$, as measured in 1991–92 (Hulbe and Whillans, 1997), to $\sim 416\text{ m a}^{-1}$, as measured in 1996–97 in the current study. Because of this non-steady flow, however, we caution that the thinning results be interpreted carefully.

A marker site was installed in the high-elevation catchment of Whillans Ice Stream to test for longitudinal variations in mass balance. The Inland-WIS station is $\sim 100\text{ km}$ up-glacier of the region of rapid flow. Here, results of the calculations indicate steady-state conditions (Table 2). These conditions have persisted for at least the length of the accumulation rate record (~ 40 years) and may indicate that sustained drawdown of the catchment due to the rapid flow of Whillans Ice Stream is nearing an end.

The Snake site is located <500 m outboard of the northern shear margin (the ‘snake’) to Whillans Ice Stream. Horizontal velocities at this location ($\sim 12.7\text{ m a}^{-1}$; Table 2) show that slow-flowing interstream ridge ice is accelerating as it approaches the shear margin. A thinning rate of $0.20 \pm 0.02\text{ m a}^{-1}$ was calculated for this site, which is slightly faster than similar calculations indicated for the Dragon site on the

opposite shear margin (Hamilton and others, 1998). This thinning rate is within the range of thinning calculated farther down-glacier on the 'snake' shear margin using a different dataset (Stearns and others, 2005).

UpC is the only submergence velocity station on the stagnant Kamb Ice Stream. The horizontal velocity over the period 1995–97 was 13.5 m a^{-1} . Submergence velocity calculations show that this site is currently thickening at $\sim 0.56 \pm 0.02 \text{ m a}^{-1}$. This thickening rate is several times larger than the measured local accumulation rate of 0.1 m a^{-1} (Table 2). It is unlikely the thickening rate is due to a recent change in accumulation rate, because it implies a several-fold increase in snowfall which is inconsistent with other accumulation rate evidence in this region (e.g. Hamilton, 2002). An ice-dynamics cause is more likely. Flow speeds farther up-glacier are $\sim 100 \text{ m a}^{-1}$ or larger (Joughin and others, 2002), indicating a steady incoming flux of ice to the UpC site. The outgoing flux, however, is very small because Kamb Ice Stream is stagnant down-glacier of UpC (Anandakrishnan and others, 2001). This flux imbalance is inferred as the cause of the calculated ice-sheet thickening (cf. Price and others, 2001).

One site (99-2; Fig. 1) was installed close to the onset of rapid motion of a tributary to Bindschadler Ice Stream, in a region of intermediate-speed ice (Table 2). The results of calculations indicate slow thinning at $\sim 0.1 \pm 0.01 \text{ m a}^{-1}$. This thinning might be a result of continued drawdown of tributary ice by Bindschadler Ice Stream.

3.2. Amundsen Sea basin

The largest outlet glaciers in this basin are Pine Island and Thwaites Glaciers. Mass-flux calculations (Rignot, 1998) and satellite altimeter measurements (Wingham and others, 1998; Shepherd and others, 2001) suggest that rapid thinning is occurring in parts of each catchment, although Vaughan and others (2001) suggest that, input–output as a whole, Pine Island Glacier is close to balance. Independent ground-based estimates of change are, however, lacking for this part of Antarctica.

One submergence velocity station was installed in the upper reaches of Thwaites Glacier. Site 01-1 is approximately 100 km from the ice divide, in a region of inland flow (Fig. 1). Thinning of $\sim 0.22 \pm 0.016 \text{ m a}^{-1}$ was calculated for this location (Table 2).

Three sites were located in the upper part of Pine Island Glacier (Fig. 1). Sites 01-3 and 01-4 are located in a 'neck' between the northern and southern lobes of the glacier basin identified by Vaughan and others (2001). Thinning was calculated for both sites, in the range $\sim 0.15\text{--}0.25 \pm 0.02 \text{ m a}^{-1}$ (Table 2). The third site, 01-6, was installed within $\sim 25 \text{ km}$ of the ice divide separating Pine Island Glacier from Rutford Ice Stream, as indicated by the very slow flow speeds (Table 2). Results of the submergence velocity technique show this site is close to steady state (Table 2), although we note that the accumulation rate record for this location is relatively short (~ 18 years).

One site, 01-5, was installed in the upper catchment of Rutford Ice Stream (Fig. 1), about 75 km from the ice divide with Pine Island Glacier. The rate of thickness change at this site indicates a negative mass balance ($\sim 0.15 \pm 0.016 \text{ m a}^{-1}$).

These large rates of change in ice thickness are likely due to ice dynamics, because an analysis of accumulation rates from ice cores collected at these sites indicates no significant trend or variations in snowfall over the last ~ 200 years

(Kaspari and others, 2004). Unfortunately, with just two sites in the 'neck', we are unable to test the hypothesis that the presence of two catchment lobes is an indication of unsteady flow conditions in the basin (cf. Vaughan and others, 2001). However, both sites (01-3 and 01-4) are thinning at $\sim 0.2 \text{ m a}^{-1}$, and it is tempting to speculate that this represents evidence of increased drawdown of ice from the southern lobe and the 'neck' region.

3.3. Main West Antarctic ice divide

This divide separates the Siple Coast from the Amundsen Sea basin. It is a broad, flat feature (Liu and others, 1999) at approximately 1750 m elevation.

Three submergence velocity stations were installed in the vicinity of a proposed deep ice-core drilling site (Morse and others, 2002). The sites, 00-1A, 00-1B and 00-1C, are arranged along a $\sim 50 \text{ km}$ transect approximately orthogonal to the divide ridge (Fig. 1). All three sites appear to be located slightly off the flow divide in the catchment of Bindschadler Ice Stream, based on flow azimuths (Table 2). Results indicate near-steady-state conditions at each location, with very small residual rates of thickening in excess of the calculated uncertainties. There does not appear to be any difference in mass-balance conditions between the sites, although there is a detectable gradient in accumulation rate (Table 2). We are unable to test for divide migration, for example by detecting differential rates of thickness change (Hamilton, 2002), because these sites do not span both flanks of the ridge.

Flow vectors indicate that site 00-5 (Fig. 1) lies slightly within the Amundsen Sea sector. Steady-state conditions were calculated for this location (Table 2). Although the four sites (00-1A, 00-1B, 00-1C and 00-5) do not fall on a straight line orientated orthogonal to the divide axis, the absence of differential rates of thickness change might be indirect evidence that the divide is not currently migrating.

4. DISCUSSION

The results from our distributed set of submergence velocity stations reveal the largest rates of change in ice thickness are occurring in and very close to regions of enhanced flow identified by Bamber and others (2000). Conversely, we find that interior regions of the ice sheet characterized by slow sheet flow appear to be close to steady-state conditions. This broad spatial pattern is consistent with earlier results of calculations using the submergence velocity technique at a smaller number of sites (Hamilton and others, 1998; Hamilton, 2002).

Our results are also consistent with larger-scale remote-sensing estimates of mass balance for West Antarctica (Table 2). Mass-flux calculations based on space-borne measurements of ice velocity (Joughin and Tulaczyk, 2002) indicate rates of thickness change for Whillans, Kamb and Bindschadler Ice Streams that are in line with our results. Spikes and others (2003) conducted repeat airborne laser altimeter surveys over selected regions of Whillans and Kamb Ice Streams, and, for sites where measurements overlap (Table 2), their results agree with our local rates of thickness change from the submergence velocity technique. Ordinarily, short-term repeat altimeter surveys (<5 years apart) might not be expected to agree with long-term rates of change from other methods, such as the submergence velocity technique, because of interannual variability in

snowfall and the effects of firn compaction. The close agreement between our results and those of Spikes and others (2003) is probably due to the large size of the ice-dynamics-forced changes ($\sim 0.1 \text{ m a}^{-1}$) relative to short-term accumulation rate variability in this part of West Antarctica.

Similarly good agreement is found between our results and satellite radar altimeter-derived estimates of elevation change (Wingham and others, 1998; Shepherd and others, 2001) on the main West Antarctic ice divide and in the Amundsen Sea basin (Table 2). The sites with the fastest rates of thickness change calculated using the submergence velocity technique (01-1, 01-2 and 01-4) fall in regions noted by Shepherd and others (2001) as having large changes in elevation during the period 1992–99. Sites with conditions calculated to be close to steady state (00-1A, 00-5, 01-6 (Table 1) and Byrd Station (Hamilton and others, 1998)) showed little change in elevation during the radar altimeter surveys. The agreement between the two sets of results suggests that the conclusion reached by Wingham and others (1998), that of steady-state conditions for most of Antarctica and rapid changes in a few isolated catchments, i.e. the Amundsen Sea basin and the Siple Coast, is largely correct.

An independent analysis (Kaspari and others, 2004) of ice-core accumulation rate records from the Amundsen Sea basin provides a useful context for interpreting the present results and those of Shepherd and others (2001). No significant trends or changes in snowfall over the past ~ 200 years were present in these records (Kaspari and others, 2004), suggesting that the thinning rates calculated from the submergence velocity technique are an ice-dynamics effect. In addition, Kaspari and others (2004) report there was no anomalous variability in snowfall during the 1990s which might account for the surface elevation lowering observed in satellite altimeter results (Shepherd and others, 2001), further supporting an ice-dynamics forcing of current mass balance in the Amundsen Sea basin.

One potential concern of interpreting our results as indicators of long-term ice-sheet behavior is recent evidence of short-period changes in ice flow (e.g. Bindschadler and others, 2003). The submergence velocity technique assumes that ice-sheet vertical velocities are steady on timescales similar to those used to determine accumulation rates (10^2 – 10^3 years). This assumption might not be valid for sites on or near active ice streams, where decadal trends in velocity (e.g. Joughin and others, 2002) and tidal-forced daily velocity fluctuations (Bindschadler and others, 2003) have been observed. We argue, however, that sub-annual-scale velocity variations are unimportant, on the basis of results from several ice-stream sites that have more than one measurement epoch (Table 1). In those cases, rates of thickness change are similar when calculated using individual epochs or all available data. The effect of decadal-scale trends in velocity is more difficult to assess, but perhaps implies that rates of change calculated at sites of rapid flow might only apply to the periods of measurement (a few years) rather than longer accumulation rate timescales.

5. CONCLUSIONS

Local rates of ice-thickness change were obtained using measurements of ice vertical velocity and accumulation rate at 15 sites in West Antarctica. Calculated rates of change are very different at each site. In general, the largest changes are

occurring in or near regions of rapid flow in the Siple Coast and Amundsen Sea sectors. Near-steady-state conditions were calculated for sites in the slow-moving ice-sheet interior and close to the main ice divide.

The results are consistent with larger-scale elevation change and mass-balance estimates from remote-sensing methods (e.g. Wingham and others, 1998; Joughin and Tulaczyk, 2002; Spikes and others, 2003). This level of agreement suggests that the remote-sensing results, appropriately adjusted for short-term fluctuations in surface mass balance, are valid indicators of long-term ice-sheet behavior.

In general, most parts of the ice sheet currently do not appear to be undergoing significant changes in mass. However, large rates of change are calculated for several sites in or close to regions of rapid flow. Because of the importance of ice streams and outlet glaciers in controlling ice-sheet mass balance, and in light of a complex series of changes observed on Whillans Ice Stream, we believe there is merit in continuing to monitor ice-sheet mass balance at local scales.

ACKNOWLEDGEMENTS

The fieldwork was made possible by the hard work of S. Price, E. Venteris, I. Whillans, the air crews of Kenn Borek Air, and members of US ITASE. S. Kaspari and D. Dixon supplied most of the accumulation rate data. Comments from R. Arthern, A. Shepherd and D. Vaughan improved the final manuscript. This research was supported by the US National Science Foundation (OPP-9419396 and OPP-0196441).

REFERENCES

- Anandakrishnan, S., R.B. Alley, R.W. Jacobel and H. Conway. 2001. The flow regime of Ice Stream C and hypotheses concerning its recent stagnation. *In* Alley, R.B. and R.A. Bindschadler, eds. *The West Antarctic ice sheet: behavior and environment*. Washington, DC, American Geophysical Union, 283–294. (Antarctic Research Series 77.)
- Bamber, J.L., D.G. Vaughan and I. Joughin. 2000. Widespread complex flow in the interior of the Antarctic ice sheet. *Science*, **287**(5456), 1248–1250.
- Bindschadler, R.A., M.A. King, R.B. Alley, S. Anandakrishnan and L. Padman. 2003. Tidally controlled stick-slip discharge of a West Antarctic ice stream. *Science*, **301**(5636), 1087–1089.
- Hamilton, G.S. 2002. Mass balance and accumulation rate across Siple Dome, West Antarctica. *Ann. Glaciol.*, **35**, 102–106.
- Hamilton, G.S. and I.M. Whillans. 2000. Point measurements of mass balance of the Greenland ice sheet using precision vertical global positioning system (GPS) surveys. *J. Geophys. Res.*, **105**(B7), 16,295–16,301.
- Hamilton, G.S., I.M. Whillans and P.J. Morgan. 1998. First point measurements of ice-sheet thickness change in Antarctica. *Ann. Glaciol.*, **27**, 125–129.
- Hulbe, C.L. and I.M. Whillans. 1994. A method for determining ice-thickness change at remote locations using GPS. *Ann. Glaciol.*, **20**, 263–268.
- Hulbe, C.L. and I.M. Whillans. 1997. Weak bands within Ice Stream B, West Antarctica. *J. Glaciol.*, **43**(145), 377–386.
- James, T.S. and E.R. Ivins. 1998. Predictions of Antarctic crustal motions driven by present-day ice sheet evolution and by isostatic memory of the Last Glacial Maximum. *J. Geophys. Res.*, **103**(B3), 4993–5017.
- Joughin, I. and S. Tulaczyk. 2002. Positive mass balance of the Ross ice streams, West Antarctica. *Science*, **295**(5554), 476–480.

- Joughin, I., S. Tulaczyk, R.A. Bindschadler and S. Price. 2002. Changes in West Antarctic ice stream velocities: observation and analysis. *J. Geophys. Res.*, **107**(B11), 2289. (10.1029/2001JB001029.)
- Kaspari, S. and 6 others. 2004. Climate variability in West Antarctica derived from annual accumulation rate records from ITASE firn/ice cores. *Ann. Glaciol.*, **39**, 585–594.
- Liu, H., K.C. Jezek and B. Li. 1999. Development of an Antarctic digital elevation model by integrating cartographic and remotely sensed data: a geographic information system based approach. *J. Geophys. Res.*, **104**(B10), 23,199–23,213.
- Morse, D.L., D.D. Blankenship, E.D. Waddington and T.A. Neumann. 2002. A site for deep ice coring in West Antarctica: results from aerogeophysical surveys and thermo-kinematic modeling. *Ann. Glaciol.*, **35**, 36–44.
- Paterson, W.S.B. 1994. *The physics of glaciers. Third edition.* Oxford, etc., Elsevier.
- Price, S.F., R.A. Bindschadler, C.L. Hulbe and I.R. Joughin. 2001. Post-stagnation behavior in the upstream regions of Ice Stream C, West Antarctica. *J. Glaciol.*, **47**(157), 283–294.
- Rignot, E.J. 1998. Fast recession of a West Antarctic glacier. *Science*, **281**(5376), 549–551.
- Rignot, E. and R.H. Thomas. 2002. Mass balance of polar ice sheets. *Science*, **297**(5586), 1502–1506.
- Shepherd, A., D.J. Wingham, J.A.D. Mansley and H.F.J. Corr. 2001. Inland thinning of Pine Island Glacier, West Antarctica. *Science*, **291**(5505), 862–864.
- Spikes, V.B., B.M. Csathó, G.S. Hamilton and I.M. Whillans. 2003. Thickness changes on Whillans Ice Stream and Ice Stream C, West Antarctica, derived from laser altimeter measurements. *J. Glaciol.*, **49**(165), 223–230.
- Spikes, V.B., G.S. Hamilton, S.A. Arcone, S. Kaspari and P. Mayewski. 2004. Variability in accumulation rates from GPR profiling on the West Antarctic plateau. *Ann. Glaciol.*, **39**, 238–244.
- Stearns, L.A., K.C. Jezek and C.J. van der Veen. 2005. Decadal-scale variations in ice flow along Whillans Ice Stream and its tributaries, West Antarctica. *J. Glaciol.*, **51**(172), 147–157.
- Vaughan, D.G. and 9 others. 2001. A review of Pine Island Glacier basin, West Antarctica: hypotheses of instability vs. observations of change. In Alley, R.B. and R.A. Bindschadler, eds. *The West Antarctic ice sheet: behavior and environment.* Washington, DC, American Geophysical Union, 237–256. (Antarctic Research Series 77.)
- Whillans, I.M. and R.A. Bindschadler. 1988. Mass balance of Ice Stream B, West Antarctica. *Ann. Glaciol.*, **11**, 187–193.
- Wingham, D.J., A.L. Ridout, R. Scharroo, R.J. Arthern and C.K. Shum. 1998. Antarctic elevation change 1992 to 1996. *Science*, **282**(5388), 456–458.
- Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins and F.H. Webb. 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. *J. Geophys. Res.*, **102**(B3), 5005–5017.