Ice-flow velocities on Rutford Ice Stream, West Antarctica, are stable over decadal timescales

G.H. GUDMUNDSSON, A. JENKINS

British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge CB3 0ET, UK
E-mail: h.gudmundsson@bas.ac.uk

ABSTRACT. Surface ice-flow velocities measured at stakes on Rutford Ice Stream, West Antarctica, covering a period of ~25 years are analysed for evidence of temporal variations in flow. No indications of significant long-term changes in flow are found. Earlier observations have shown significant tidally related variations in flow speed. We conclude that temporal variability on Rutford Ice Stream, West Antarctica, appears limited to tidal periods of days and weeks, and weaker interannual variation, possibly related to long-period tides or seasonal effects, while long-term (decadal) changes in flow speed are either absent or smaller than ~0.1% a^{-1}.

INTRODUCTION

The current contribution of the Antarctic ice sheet to global sea-level change is the subject of intense scientific debate. Of particular importance is the suggestion that large sections of the West Antarctic ice sheet (WAIS) may be inherently unstable and potentially subject to a large-scale collapse (Weertman, 1974; Schoof, 2007). Presently, large regions of the WAIS are undergoing drastic changes. Surface velocities on Pine Island Glacier, for example, increased by ~7% a^{-1} in 2007 (Scott and others, 2009) after having already increased by ~40% between 1996 and 2007 (Rignot, 2008). Whillans Ice Stream decelerated by ~23% between 1973 and 1997 (Joughin and others, 2002) and continues to decelerate at a similar rate (Joughin and others, 2005). The ice plain of Whillans Ice Stream has decelerated at 1–2% a^{-1} since the start of measurements in 1975 (Bindschadler and others, 2005). Rignot and others (2008) find that ice loss from the Antarctic ice sheet has increased by 75% over the past 10 years, and that almost all of this change is due to temporal changes in the flow speed of the WAIS ice streams.

Most of our information about changes in flow of the WAIS ice streams comes from analysis of synthetic aperture radar (SAR) satellite data, which only became available in the early 1990s. Any information on changes in velocity before that time comes from ground-based observations of ice flow, but these are scarce on the active WAIS ice streams and, when available, they are usually of limited spatial coverage (e.g. Bindschadler and others, 2005). Here we present an analysis of a ground-based dataset covering most of Rutford Ice Stream, West Antarctica, (Fig. 1) that allows estimates of changes in velocity over the past 25 years. The first measurements date from the late 1970s and early 1980s, well before the period covered by SAR data.

Rutford Ice Stream is a major ice stream flowing into the Ronne Ice Shelf. It has been the subject of ongoing glaciological research since the late 1970s (Doake and others, 1987). Previously, a comparison of SAR-derived velocities from two sets of image pairs dating from 1992 and 1994 with ground-based measurements from 1984–86 suggested fluctuations of tens of metres per annum over decadal timescales in part of the marginal zone (Frolich and Doake, 1998). However, the recent discovery of strong (>10%) fortnightly variations in flow velocities on Rutford Ice Stream (Gudmundsson, 2006), and evidence for some further interannual variation in velocity (Murray and others, 2007), suggest an alternative explanation for the observed differences. Here we use all available ground-based stake measurements of velocity to estimate temporal changes in mean annual velocities over periods from 10 to 25 years.

DATA

Available velocity data come from in situ measurements of stake movement on Rutford Ice Stream conducted over almost three decades. Figure 2 shows the locations of all the repeated stake-velocity measurements used here. Most of the earlier data have been published previously and analysed for a variety of purposes (Doake and others, 1987, 2001; Gudmundsson, 2006). In addition to these, two new datasets are analysed here for the first time. These new data include a subset of measurements from a network of 98 stakes covering an area ~20–50 km upstream of the grounding line obtained in 2002/03–2003/04, and stake measurements along the medial line, ~110–230 km upstream of the grounding line, made in 2003/04–2005/06.

The first stake survey, covering a 40 km long section of the ice stream in the vicinity of the grounding line, took place in 1978/79 using a theodolite and an electronic distance-measuring instrument, controlled by stations fixed with the TRANSIT satellite positioning system (Stephenson and Doake, 1982; Doake and others, 2001). Scale errors were controlled by additional direct over-snow distance measurements. The stakes were resurveyed in 1979/80. The network of stakes was extended further upstream in 1984/85 and resurveyed in 1985/86. During the 1984/85 survey a few of the stakes from the 1979/80 survey were found at predicted positions and the two stake networks connected (Doake and others, 1987). Stake velocities were obtained using the method of Wager and others (1980) for survey reduction of moving stakes (Frolich and others, 1987). The analysis of these stake measurements resulted in two sets of annual mean velocities over different sections of the ice stream with almost no overlap, so temporal changes in velocity could not be estimated.

GPS (global positioning system)-based velocity measurements were conducted between 1993/94 and early 1996 over a stake network covering the medial line upstream from the 1984–86 survey, and along a line crossing the divide

https://doi.org/10.3189/002214309788608697 Published online by Cambridge University Press

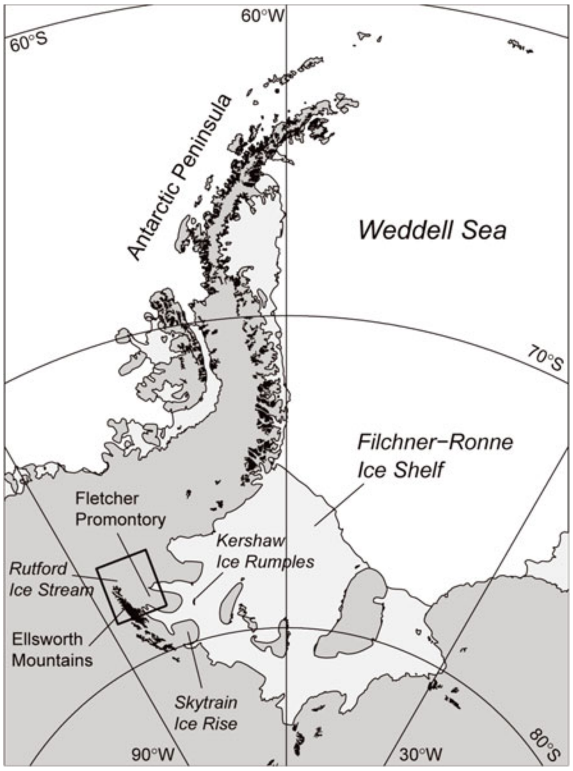

Fig. 1. Location map. The thick square marks the area shown in Figure 2.

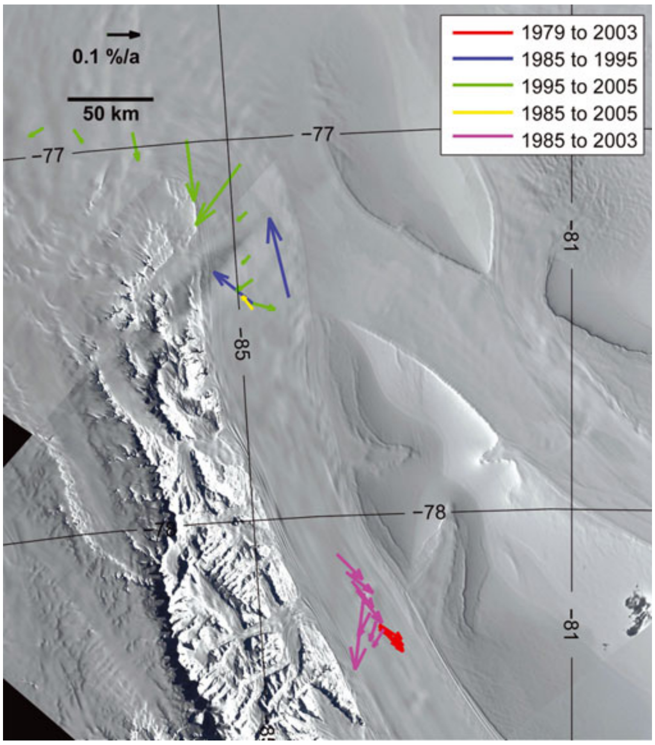

Fig. 2. Percentage difference velocity vectors. Shown are velocity vectors representing percentage differences between repeated velocity measurements at each site. The arrows are colour coded, reflecting different mean dates of the respective repeated velocity measurements. The red arrows, for example, represent change in mean velocity from the initial velocity estimate done for the austral summers 1978/79 and 1979/80, until velocities at those locations were estimated again through repeated surveying in the austral summers 2002/03 and 2003/04. In the upper left a black arrow indicating 0.1% a^{-1} change is shown for scale.

between Rutford Ice Stream and Carlson Inlet (Frolich and Doake, 1998). A reference station was located at a rock outcrop. The position of the reference station was calculated using long observations and post-processed using corrected orbits and clock corrections. The estimated accuracies in the coordinates of the reference station are 2 m. The re-survey used the exact same location for a reference station, and the same coordinates were used in the processing of the data from the second survey. For the purpose of this study, only two repeat velocity pairs resulted (blue arrows in Fig. 2), giving estimates of changes in mean velocity from 1984–86 until 1993–96, i.e. over a period of ~10 years.

In 2002/03 a network of 98 stakes was set up in an area referred to as the 'upper knoll', covering the central part of the ice stream, ~40 km upstream from the grounding line. Unexpectedly, an analysis of data collected in 2002/03 at a local GPS reference station situated on the ice stream revealed the presence of a strong (>10%) temporal variation in flow velocity with a fortnightly period (Gudmundsson, 2005).

In the 2003/04 season, five GPS stations were installed and operated continuously for about 5 weeks along the medial line. In the same season the 98 stakes from the 2002/03 season were resurveyed. Some of the sites of the resulting velocity estimates overlapped with those from the 1978/79–1979/80 (red arrows in Fig. 2) and 1984/85–1985/86 surveys (magenta arrows in Fig. 2).

The first surveys conducted with the specific aim of putting constraints on multi-annual variations in flow velocity were undertaken during the 2003/04 and 2005/06 seasons. A number of sites along the medial line of the first GPS-based surveys of 1994 and 1996 were reoccupied. Estimates of mean velocity over the approximately 2 year period from January 2004 to January 2006 were compared with velocities at the same sites measured over the period from December 1993/January 1994 to January 1996 (green arrows in Fig. 2). In addition, one site coincided with a previously occupied site from the 1984/85–1985/86 survey (yellow arrow in Fig. 2).

The five GPS stations left running continuously in the 2003/04 season showed that surface velocities vary in time, in response to ocean tides, up to at least 40 km upstream from the grounding line (Gudmundsson, 2006). At all stations, the strongest tidal amplitude in the detrended horizontal in-line displacement had a fortnightly period. A simple conceptual model showed that a non-linear till rheology could, through a strongly non-linear interaction between the two main oceanic semi-diurnal tidal components, give rise to the type of tidal response observed (Gudmundsson, 2007).

Velocity calculation and error estimates

Errors in velocity estimates are due to (1) surveying errors, (2) errors related to bending and tilting of stakes and (3) spatial gradients in velocity over the distance each stake travels between surveys, and over the mean distance between pairs of stakes used for estimating temporal changes in velocity.

The original theodolite and distance data from the first two surveys (1978/79–1979/80 and 1984/85–1985/86) are

https://doi.org/10.3189/002214309788608697 Published online by Cambridge University Press

no longer readily available and here the velocity estimates and uncertainties given by the original researchers are used (Frolich and Doake, 1998). Based on these estimates, the error in annual velocities is ~0.03%. Global network adjustment was used in deriving these velocities, and some spatial correlation of errors is likely.

Different GPS datasets have been processed in different ways, reflecting the state of processing at a given time. The 1993/94 and early 1996 GPS surveys were processed using double-differencing and a local reference station. All later data were processed using the Bernese GPS software in kinematic precise-point positioning (PPP) mode (Hugentobler and others, 2006). Examples and discussion of PPP in a glaciological context are given by King (2004) and Dach and others (2009). Stake velocities were calculated from estimated GPS stake locations using the INVERSE routine made available by the US National Geodetic Survey (http://www.ngs.noaa.gov/PC_PROD/Inv_Fwd) (Vincenty, 1975).

Spatial errors, Δx, in GPS coordinates are likely to be of the order of a few centimetres. Time intervals, Δt, between initial and final surveys of the same stake were always >1 year, in most cases 2 years. Mean velocity, v, is $\sim 400\,\mathrm{m\,a^{-1}}$, so the velocity error due to error in surveyed coordinates is $\sim\sqrt{2}\Delta x/\Delta t$ or 0.0035% of the mean velocity. The time interval, ΔT, between velocity estimates is always >8 years, and the relative error in the change in velocity is therefore $2\Delta x/(v\,\Delta T\Delta t)$ or $0.0006\%\,\mathrm{a^{-1}}$ or less.

Action of wind and snow on stakes can easily cause errors of ~0.1 m. Using the same numbers as above, the resulting error in velocity is $\sim 0.004\%\,\mathrm{a^{-1}}$.

Spatial gradients in flow affect estimates of velocities calculated from the total stake displacement, $\Delta\mathbf{s}$, over the time interval, Δt, between initial and final surveys of the corresponding stake. The distance travelled by the stake is the integral of velocity over time along the path travelled by the stake. If the velocity does not change with time and the stake travels along a straight line, the velocity, $\mathbf{v}$, can be calculated as $\mathbf{v} = \Delta\mathbf{s}/\Delta t$. However, in the time interval between surveys, each stake travels downstream with the ice, and as it does so its velocity changes with time, due to spatial gradients in the flow. The material derivative of the velocity, $\mathrm{D}v_i/\mathrm{d}t$, is the sum of the local and the convective derivatives, i.e. $\mathrm{D}v_i/\mathrm{d}t = \partial_t v_i + u_k \partial_{x_k} v_i$. Horizontal strain rates on Rutford Ice Stream are $\sim 0.001\,\mathrm{a^{-1}}$. Hence, stake velocities will change in 1 year by ~0.1% due to spatial gradients in flow alone. Spatial gradients in the flow field are not known in sufficient detail for us to correct for this effect and we must therefore expect an error of at least 0.1% in each velocity estimate. Note that this error is much larger than the 0.0035% surveying error caused by inaccuracies in GPS stake positions. Note also that when calculating the difference in velocity estimates this error approximately cancels out, provided the comparison is done between stakes that were initially at the exact same location and then both resurveyed after exactly the same period of time. However, in our dataset we use velocity estimates from stakes that were placed up to 5000 m apart. The difference in velocity estimates, Δu, from two stakes can be written as

$$\Delta u = \partial_x u\,\Delta x + \partial_t u\,\Delta T, \tag{1}$$

where u is the velocity of one of the stakes, $u + \Delta u$ is the velocity at the other stake, Δx is the distance between the stakes and ΔT is the time interval between velocity estimates. Only if

$$\partial_t u \gg \partial_x u \frac{\Delta x}{\Delta T}, \tag{2}$$

can the velocity difference, Δu, be taken as clear evidence of a temporal, as opposed to a spatial, variation in velocity. Inserting the values $\partial_x u = 0.001\,\mathrm{a^{-1}}$, $\Delta x = 5000\,\mathrm{m}$, $\Delta T = 10$ years, and using $u = 400\,\mathrm{m\,a^{-1}}$ to calculate the percentage change in u, we find that the velocity must change by at least $0.1\%\,\mathrm{a^{-1}}$ if two stake-velocity measurements, separated in time and space by 10 years and 5 km, respectively, are to reveal evidence of temporal variations in flow.

On a number of WAIS ice streams for which measurements exist, temporal variations in flow are far larger than $0.1\%\,\mathrm{a^{-1}}$. For example, on the ice plain of Whillans Ice Stream velocities change by $1\text{–}2\%\,\mathrm{a^{-1}}$ (Bindschadler and others, 2005), and on Pine Island Glacier velocities increased by ~7% in 2007 (Scott and others, 2009). Hence, despite the errors introduced by the gradients in the velocity field being much larger than the surveying errors, these errors are small compared to changes in flow speeds seen in many areas of the WAIS.

In a similar study, focusing on data from Bindschadler Ice Stream, West Antarctica, Winberry and others (2007) compared velocities measured over a grid with 2.5 km spacing to an older set of velocity data from the same area. As we find for our dataset, Winberry and others (2007) found surveying errors to be insignificant in comparison to interpolation errors. However, King and others (2007) in a careful analysis of velocity data from the centre of the Amery Ice Shelf, East Antarctica, found that a separation of a few kilometres between stakes in their dataset had negligible effect on estimates of velocity variations with time.

RESULTS

Repeated stake measurements have resulted in a number of locations where velocity changes over several decades can be estimated with considerable confidence. All such velocity pairs are shown in Figure 2. The arrows represent percentage change per annum in measured velocities at their respective sites. The velocity difference shown is the velocity vector at the earlier date subtracted from that at the later date, divided by the mean velocity for both dates and by the number of years between measurements. For an increase in speed over a time interval with no concomitant change in azimuth, the arrows in Figure 2 point in the downstream direction.

As can be seen from Figure 2, the mean velocity difference is in most cases $<0.1\%\,\mathrm{a^{-1}}$. The orientation of the arrows is not completely random. In particular, differences between GPS-based measurements and the earlier theodolite-based stake surveys appear non-random (red, blue and magenta arrows in Fig. 2). As mentioned before, these early stake surveys were subjected to network adjustment, which may have introduced some spatial correlation in the estimated velocities. We see therefore, despite this spatial correlation in some of the difference vectors, no compelling evidence for any significant change in velocities.

The velocity-difference vectors based on GPS measurements only are those between the 1993/94 to early 1996 and the 2003/04 to 2005/06 surveys (green arrows in Fig. 2). These are in some cases larger than the estimated velocity errors. Furthermore, the orientation indicates that

https://doi.org/10.3189/002214309788608697 Published online by Cambridge University Press

the velocities may have been systematically larger in the later measurement period. However, over the 2 year time period of the first observations, the stakes travelled 200–600 m downstream, while the stakes installed in 2003/04 were erroneously located at the mean location of the earlier survey. As a consequence, the mean position of the stakes of the second survey is some distance downstream of the corresponding stakes from the first survey. This introduces systematic bias in the velocity-difference vectors. Evaluating the terms of Equation (1) for each stake showed that differences of the order of those seen in Figure 2 (green arrows) are to be expected based on strain rates in the area, $\partial_x u$, difference in stake positions, Δx, and the interval, ΔT, between repeated measurements.

DISCUSSION AND CONCLUSIONS

Comparison of all available in situ stake-velocity measurements from Rutford Ice Stream has revealed no significant changes in multi-annual surface speeds for the 25 year period 1979–2004. If any such changes have taken place, they must, on average, be less than $\sim$0.1% a^{-1}. These findings are in agreement with a previous study by Frolich and Doake (1998), who found no significant change in ice movement in the central part of Rutford Ice Stream in the period 1978–80 to 1992. The data used here cover not just a longer time period than that available to Frolich and Doake (1998), but also extend over the whole of the ice stream. Frolich and Doake (1998) found some systematic deviations between SAR-derived velocities over periods of 4–6 days and mean annual in situ stake-velocity measurements (fig. 7 in Frolich and Doake, 1998). We suggest that these differences may have been caused by fortnightly velocity variations on Rutford Ice Stream (Gudmundsson, 2006), unknown at that time.

A 2 year GPS record, with some data gaps in the austral winter, was collected over the period December 2004 to January 2007 at a site toward the right-hand-side ice-stream margin, $\sim$40 km upstream of the grounding line (Murray and others, 2007). The velocity record showed the largest tidal response at the lunisolar synodic fortnightly tidal constituent (MSf) period of 14.76 days. A small but significant difference in mean annual velocities was found for the two years. Some of the annual and interannual variability could be modelled as long-period tides, leading Murray and others (2007) to suggest that ice flow is modulated by tides at up to annual periods. However, there is, as yet, no quantitative understanding of how long-period tides could affect ice-stream motion, and it is equally possible that Murray and others (2007) could have detected small velocity fluctuations related to seasonal variability in some aspect of the ice-stream forcing.

Basal conditions on Rutford Ice Stream are known to be not just spatially heterogeneous (Smith, 1997; King and others, 2004); they also vary in time. Through repeated seismic surveys along a $\sim$3 km line situated $\sim$40 km upstream from the grounding line and oriented transverse to the main flow direction, Smith and others (2007) found evidence of both rapid erosion and build-up of a drumlin-like feature in the time-span of a few years. The eroded area and the drumlin-like feature were $\sim$500 and 100 m wide, respectively. Ice thickness in the area was $\sim$2500 m. Theoretically we do not expect such small-scale features to significantly affect surface flow. Estimates of the surface response using transfer functions given by Gudmundsson (2003, 2008) suggest a surface topographic response to the newly formed drumlin having an amplitude of a few centimetres and a related small change in surface velocity. Our observations of steady velocities over decadal timescales therefore do not conflict with measurements of temporal changes in basal properties over such short (of the order of or less than one ice thickness) spatial scales.

The picture of temporal variability in flow speeds on Rutford Ice Stream that emerges from this and other recent studies (Gudmundsson, 2006; Murray and others, 2007; Aðalgeirsdóttir and others, 2008) is that of a strong tidally induced perturbation in flow with a fortnightly period, and a weaker interannual variation, possibly related to long-period tides or seasonal effects. Long-term (decadal) changes in flow speed are either absent or smaller than $\sim$0.1% a^{-1}.

The absence of any significant long-term changes in Rutford Ice Stream contrasts sharply with the situation found on ice streams in other sectors of the WAIS. In the Amundsen Sea catchment area and the Siple Coast region, significant changes (>0.5% a^{-1}) in annual flow velocities are not unusual. The question arises as to why flow velocities on Rutford Ice Stream are so stable by comparison. A partial answer to this question comes from considering the potential for temporal changes in the various forces acting on the ice stream.

Forces acting on an ice stream can be broadly divided into side drag, basal drag and longitudinal forces. Rutford Ice Stream is flanked on one side by the Ellsworth Mountains and on the other by Fletcher Promontory. Marginal positions and side drag are therefore primarily determined by topography and, thus, are not expected to change significantly on a decadal timescale. Basal drag is determined by basal topography (form drag) and basal lubrication (skin drag). Inverse modelling of a flowline on Rutford Ice Stream showed that short-scale (of the order of a few ice thicknesses) variations in surface topography and surface speed are primarily related to basal topography and not to spatial variations in basal lubrication (Raymond, 2007). Hence, the spatial variations in basal drag, which give rise to short-scale surface topography variations on Rutford Ice Stream, are also unlikely to change significantly over decadal timescales.

Temporal changes in longitudinal forces acting on an ice stream can be caused by changes in ice-shelf configuration. Over a distance of $\sim$150 km downstream from the grounding line of Rutford Ice Stream, the ice shelf is laterally confined by Fletcher Promontory and Skytrain Ice Rise (Fig. 1). Further downstream, flow of the ice shelf is additionally constrained by Kershaw Ice Rumples. Evidence for the resulting constraints on the flow of Rutford Ice Stream comes from the fact that flow velocities downstream of the grounding line decrease monotonically with distance as far as Kershaw Ice Rumples instead of increasing monotonically, as would be expected for an unconfined ice shelf (Jenkins and Doake, 1991). Thus, flow downstream of the grounding line of Rutford Ice Stream is also strongly determined by marginal and sea-bed geometry.

Changes in the basal melt rate near the grounding line would alter the ice thickness there, which, in turn, could affect the longitudinal forces within the ice stream and potentially drive migration of the grounding line. The ocean heat that drives basal melting in this region is supplied by an inflow of dense salty water, produced every winter by brine rejection during sea-ice growth to the north of the Filchner–Ronne Ice Shelf. The temperature of the water is

https://doi.org/10.3189/002214309788608697 Published online by Cambridge University Press

fixed at the surface freezing point, but the strength of the inflow shows seasonal and interannual variability. However, both observation and modelling of the sub-ice-shelf ocean circulation suggest that the southwestern corner of the ice shelf is relatively isolated from interannual changes in the inflow (Nicholls and others, in press). Although the same results show that seasonal variability penetrates further to the south and west, the observations of Jenkins and others (2006) showed no seasonal variations in melting near the Rutford Ice Stream grounding line. Seismic soundings (Smith and Doake, 1984) reveal a deep sea-bed trough downstream of the grounding line, and Jenkins and others (2006) suggest that this deep sea-bed trough may contain a large reservoir of dense water that is little affected by the seasonal inflow.

Ice production to the north of the ice shelf is driven by near-surface winds, which in this region are heavily influenced by the drainage of cold air from East Antarctica and the north–south-oriented topographic barrier formed by the Antarctic Peninsula (Van Lipzig and others, 2004). Since the topographic forcing of the winds will be invariant we would expect a relatively stable atmospheric and, as a result, oceanic regime over the continental shelf. Furthermore, the temperature of the major oceanic inflows to the sub-ice-shelf cavity is fixed absolutely at the surface freezing point. Hence, we expect ocean conditions near the Rutford Ice Stream grounding line to be stable.

We suggest that the observed stability of velocities on Rutford Ice Stream over decadal timescales is related to the presence of strong geometrical constraints on the flow of the ice stream, and the limited potential for oceanic changes in the vicinity of the grounding line.

ACKNOWLEDGEMENTS

We thank D. Routledge, D. Cameron and R. Marchant for their help in collecting the data. D. Vaughan, M. King and three anonymous reviewers made valuable comments that significantly improved an earlier version of the manuscript. This study was supported by the UK Natural Environment Research Council (NERC) Global Environment Facility (GEF) grant Nos. 711 and 785.

REFERENCES

Aðalgeirsdóttir, G. *and 6 others*. 2008. Tidal influence on Rutford Ice Stream, West Antarctica: observations of surface flow and basal processes from closely spaced GPS and passive seismic stations. *J. Glaciol.*, **54**(187), 715–724.

Bindschadler, R., P. Vornberger and L. Gray. 2005. Changes in the ice plain of Whillans Ice Stream, West Antarctica. *J. Glaciol.*, **51**(175), 620–636.

Dach, R., G. Beutler and G.H. Gudmundsson. 2009. Analysis of GPS data from an Antarctic ice stream. *In* Sideris, M.G., *ed. Observing our Changing Earth: Proceedings of the 2007 IAG General Assembly, Perugia, Italy, July 2–13, 2007.* Berlin, etc., Springer-Verlag, 569–579. (International Association of Geodesy Symposia 133.)

Doake, C.S.M., R.M. Frolich, D.R. Mantripp, A.M. Smith and D.G. Vaughan. 1987. Glaciological studies on Rutford Ice Stream, Antarctica. *J. Geophys. Res.*, **92**(B9), 8951–8960.

Doake, C.S.M. *and 7 others*. 2001. Rutford Ice Stream, Antarctica. *In* Alley, R.B. and R.A. Bindschadler, *eds. The West Antarctic ice sheet: behavior and environment.* Washington, DC, American Geophysical Union, 221–235. (Antarctic Research Series 77.)

Frolich, R.M. and C.S.M. Doake. 1998. Synthetic aperture radar interferometry over Rutford Ice Stream and Carlson Inlet, Antarctica. *J. Glaciol.*, **44**(146), 77–92.

Frolich, R.M., D.R. Mantripp, D.G. Vaughan and C.S.M. Doake. 1987. Force balance of Rutford Ice Stream, Antarctica. *IAHS Publ.* 170 (Symposium at Vancouver 1987 – *The Physical Basis of Ice Sheet Modelling*), 323–331.

Gudmundsson, G.H. 2003. Transmission of basal variability to a glacier surface. *J. Geophys. Res.*, **108**(B5), 2253. (10.1029/2002JB0022107.)

Gudmundsson, G.H. 2005. Long-range tidal effects on Rutford Ice Stream, Antarctica. *Geophys. Res. Abstr.*, 7, 01624. (1607-7962/gra/EGLI05-A-01624.)

Gudmundsson, G.H. 2006. Fortnightly variations in the flow velocity of Rutford Ice Stream, West Antarctica. *Nature*, **444**(7122), 1063–1064.

Gudmundsson, G.H. 2007. Tides and the flow of Rutford Ice Stream, West Antarctica. *J. Geophys. Res.*, **112**(F4), F04007. (10.1029/2006JF000731.)

Gudmundsson, G.H. 2008. Analytical solutions for the surface response to small amplitude perturbations in boundary data in the shallow-ice-stream approximation. *Cryosphere*, **2**(2), 77–93.

Hugentobler, U., R. Dach, P. Fridez and M. Meindle. 2006. *Bernese GPS software. Version 5.0.* Bern, University of Bern. Astronomical Institute.

Jenkins, A. and C.S.M. Doake. 1991. Ice–ocean interaction on Ronne Ice Shelf, Antarctica. *J. Geophys. Res.*, **96**(C1), 791–813.

Jenkins, A., H.F.J. Corr, K.W. Nicholls, C.L. Stewart and C.S.M. Doake. 2006. Interactions between ice and ocean observed with phase-sensitive radar near an Antarctic ice-shelf grounding line. *J. Glaciol.*, **52**(178), 325–346.

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.)

Joughin, I. *and 10 others*. 2005. Continued deceleration of Whillans Ice Stream, West Antarctica. *Geophys. Res. Lett.*, **32**(22), L22501. (10.1029/2005GL024319.)

King, M. 2004. Rigorous GPS data-processing strategies for glaciological applications. *J. Glaciol.*, **50**(171), 601–607.

King, E.C., J.M. Woodward and A.M. Smith. 2004. Seismic evidence for a water-filled canal in deforming till beneath Rutford Ice Stream, West Antarctica. *Geophys. Res. Lett.*, **31**(2), L20401. (10.1029/2004GL020379.)

King, M.A., R. Coleman, P.J. Morgan and R.S. Hurd. 2007. Velocity change of the Amery Ice Shelf, East Antarctica, during the period 1968–1999. *J. Geophys. Res.*, **112**(F1), F01013. (10.1029/2006JF000609.)

Murray, T., A.M. Smith, M.A. King and G.P. Weedon. 2007. Ice flow modulated by tides at up to annual periods at Rutford Ice Stream, West Antarctica. *Geophys. Res. Lett.*, **34**(18), L18503. (10.1029/2007GL031207.)

Nicholls, K.W., S. Østerhus, K. Makinson, T. Gammelsrød and E. Fahrbach. In press. Ice–ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: a review. *Rev. Geophys.*

Raymond, M. 2007. Estimating basal properties of glaciers and ice streams from surface measurements. *ETH-Zürich VAWE Mitt.* 202.

Rignot, E. 2008. Changes in West Antarctic ice stream dynamics observed with ALOS PALSAR data. *Geophys. Res. Lett.*, **35**(12), L12505. (10.1029/2008GL033365.)

Rignot, E. *and 6 others*. 2008. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geosci.*, **1**(2), 106–110.

Schoof, C. 2007. Ice sheet grounding line dynamics: steady states, stability, and hysteresis. *J. Geophys. Res.*, **112**(F3), F03S28. (10.1029/2006JF000664.)

https://doi.org/10.3189/002214309788608697 Published online by Cambridge University Press

Scott, J.B.T., G.H. Gudmundsson, A.M. Smith, R.G. Bingham, H.D. Pritchard and D.G. Vaughan. 2009. Increased rate of acceleration on Pine Island Glacier strongly coupled to changes in gravitational driving stress. *Cryosphere Discuss.* 3, 223–242.

Smith, A.M. 1997. Variations in basal conditions on Rutford Ice Stream, West Antarctica. *J. Glaciol.*, **43**(144), 251–261.

Smith, A.M. and C.S.M. Doake. 1994. Sea-bed depths at the mouth of Rutford Ice Stream, Antarctica. *Ann. Glaciol.*, **20**, 353–356.

Smith, A.M. *and 6 others*. 2007. Rapid erosion, drumlin formation and changing hydrology beneath an Antarctic ice stream. *Geology*, **35**(2), 127–130.

Stephenson, S.N. and C.S.M. Doake. 1982. Dynamic behaviour of Rutford Ice Stream. *Ann. Glaciol.*, **3**, 295–299.

Van Lipzig, N.P.M., J. Turner, S.R. Colwell and M.R. van den Broeke. 2004. The near-surface wind field over the Antarctic continent. *Int. J. Climatol.*, **24**(15), 1973–1982.

Vincenty, T. 1975. Direct and inverse solutions of geodesics on the ellipsoid with application of nested equations. *Surv. Rev. (Great Br.)*, **XXII**(176), 88–93.

Wager, A.C., C.S.M. Doake, J.G. Paren and J.L.W. Walton. 1980. Survey reduction for glacier movement studies. *Surv. Rev. (Great Br.)*, **25**(196), 251–263.

Weertman, J. 1974. Stability of the junction of an ice sheet and an ice shelf. *J. Glaciol.*, **13**(67), 3–11.

Winberry, J.P., S. Anandakrishnan and A.M. Smith. 2007. Changes in speed near the onset of Bindschadler Ice Stream, West Antarctica. *Ann. Glaciol.*, **46**, 83–86.

MS received 9 October 2008 and accepted in revised form 23 December 2008

https://doi.org/10.3189/002214309788608697 Published online by Cambridge University Press