LETTERS

# Fortnightly variations in the flow velocity of Rutford Ice Stream, West Antarctica

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**Most of the ice lost from the Antarctic ice sheet passes through a few fast-flowing and highly dynamic ice streams[1]. Quantifying temporal variations in flow in these ice streams, and understanding their causes, is a prerequisite for estimating the potential contribution of the Antarctic ice sheet to global sea-level change[2,3]. Here I show that surface velocities on a major West Antarctic Ice Stream, Rutford Ice Stream, vary periodically by about 20 per cent every two weeks as a result of tidal forcing. Tidally induced motion on ice streams has previously been thought to be limited to diurnal or even shorter-term variations[4–9]. The existence of strong fortnightly variations in flow demonstrates the potential pitfalls of using repeated velocity measurements over intervals of days to infer long-term change.**

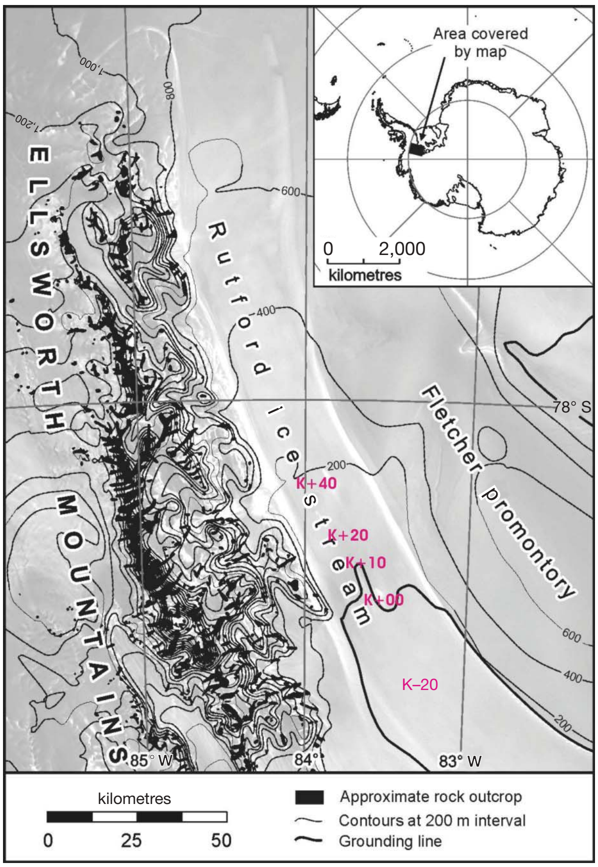


**Figure 1 | Map of Rutford Ice Stream, West Antartica.** Locations of the GPS stations discussed in the text are indicated using the labels K − 20 to K + 40. The position of the grounding line is shown as a heavy black line.

Field measurements on Rutford Ice Stream (78° S, 83° W), West Antarctica (Fig. 1), have revealed fortnightly variations in flow speeds with about 20% peak-to-peak amplitude (Fig. 2). Global Positioning System (GPS) observations were collected continuously at five sites over a seven-week period from late December 2003 until mid-February 2004. One site was on a floating ice shelf some 20 km downstream of the grounding line. The other four locations were along the central flow line extending 40 km upstream of the grounding line (Fig. 1). Kinematic position solutions were calculated every 5 min using the Bernese GPS software[10,11].

The bottom panel of Fig. 2 shows hourly averaged velocities at four sites labelled R − 20, R + 00, R + 20, and R + 40, where numbers refer to the distance in kilometres upstream from the grounding line. (R − 20 was 20 km downstream of the grounding line.) For clarity, data from R + 10 are not shown in Fig. 2 (but are shown in Fig. 3). At all locations, fortnightly variations in flow speed are observed, but the peak-to-peak amplitudes of the velocity variations change with distance from the grounding line. At the grounding line, velocities change over one week from about 0.9 to 1.2 m day$^{-1}$, 27% of the total velocity. At R + 40 the range is 0.95 to 1.07 m day$^{-1}$, or about 12% variation. No significant temporal variations in vertical or transverse velocities were observed upstream of the grounding line.

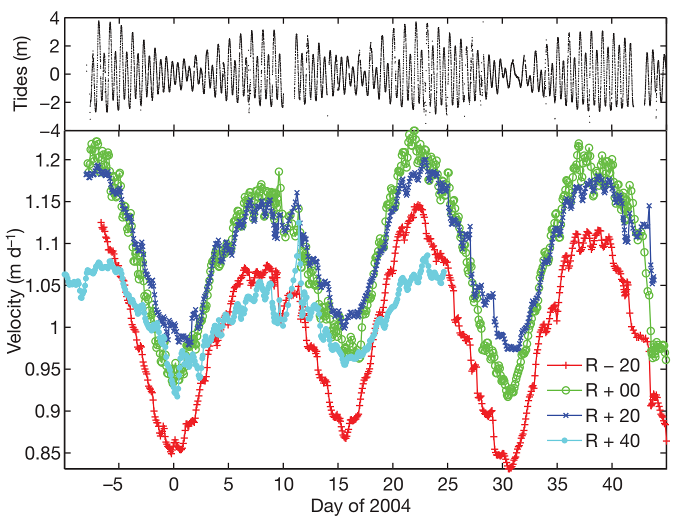


**Figure 2 | Surface speed and tidal amplitudes as a function of time.** The top panel shows vertical tidal amplitudes some 20 km downstream of the grounding line of the Rutford Ice Stream, as measured on the surface of the floating ice shelf. The bottom panel shows surface speeds 20 km downstream (red crosses), at the grounding line (green circles), and 20 km (dark blue exes) and 40 km (light blue circles) upstream from the grounding line. (The grounding line marks the division between the floating and the grounded parts of the ice.)

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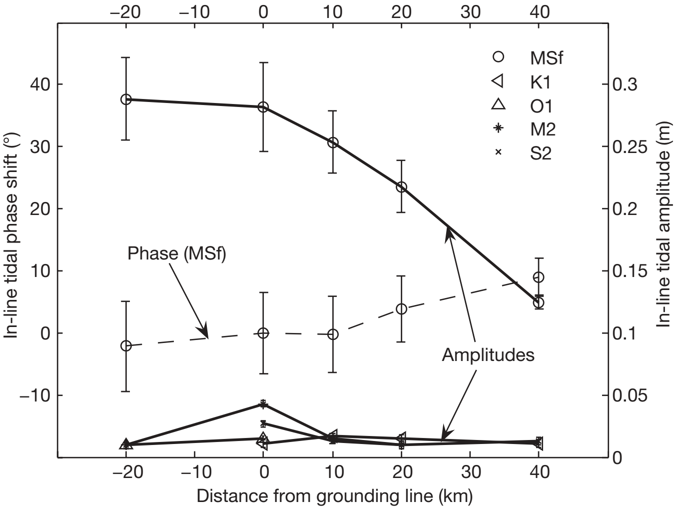


**Figure 3 | Tidal components.** Tidal amplitudes (thick solid lines) of horizontal in-line positions as functions of distance from grounding line, with distance measured positively in upstream direction. In addition, the phase shift (thin dashed lines) of the MSf tide with respect to the grounding line is shown. The MSf is a fortnightly tide with a period of 13.66 days. The O1 and K1 are diurnal tides with periods of 25.82 and 23.93 hours, respectively, and M2 and S2 are semidiurnal tides with periods of 12.42 and 12.00 hours. The error bars are 95% confidence intervals calculated using the bootstrap method.

The upper panel of Fig. 2 shows measured vertical displacement at the Ronne Ice Shelf at site R − 20 measured with the same techniques. The dominant tides are semi-diurnal with clear spring-to-neap tidal cycles. A comparison of the upper and the lower panels of Fig. 2 suggests a simple correlation between temporal variations in velocities and the spring-to-neap tidal cycle, with velocities generally increasing in the period leading up to a spring tide, and decreasing thereafter until the next neap tide. Superimposed on the fortnightly flow variations are rather smaller-amplitude diurnal and semi-diurnal variations in flow speeds.

Figure 3 shows results of a tidal analysis of detrended in-line positions, in-line positions being defined as horizontal positions measured along the mean flow direction. The tidal analysis was done using the *t_tide* software package[12]. At all locations the lunisolar synodic fortnightly tidal constituent (MSf) with a period of 13.66 days has the largest amplitude. The MSf tidal amplitude is equally large at R − 20 and R + 00, but decays roughly linearly with distance upstream. The dashed thin line in Fig. 3 shows the phase shift of the fortnightly MSf tide with respect to the grounding line. The phase changes by about 9° from R + 00 to R + 40 which, when taking into account the estimates of the phase error, corresponds to a velocity of 1 to 2 $\mathrm{m\,s^{-1}}$.

The neap-to-spring increase in velocity and the subsequent spring-to-neap velocity decrease (Fig. 2), suggests that the velocity perturbation is related to peak-to-peak changes in the semi-diurnal tide, implying a nonlinear system response. A possible explanation for the observed fortnightly flow variations goes as follows: elastic stresses set up by the tides perturb the basal shear stress distribution of the ice stream. Because the relationship between basal motion and shear basal stress is nonlinear, the increase in basal motion by a positive perturbation in shear stress is larger than the corresponding decrease from an equally large but negative shear stress perturbation. Over one tidal cycle, this imbalance results in a net additional forward displacement. The magnitude of this imbalance varies with changes in peak-to-peak tidal amplitude from the spring tide to the neap tide, resulting in fortnightly variation in flow speeds.

Interferometric synthetic aperture radar (InSAR) data has been used extensively to calculate surface flow velocities on ice streams using one-day or three-day intervals[13–15], with longer intervals rarely used because of loss of coherence. As shown here, ice stream speeds can vary significantly in response to the spring-to-neap tidal cycle. Caution must therefore be exercised in interpreting InSAR velocities on the basis of image pairs separated by a few days.

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