Recent ice loss from the Fleming and other glaciers, Wordie Bay, West Antarctic Peninsula

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[1] Satellite radar interferometry data from 1995 to 2004, and airborne ice thickness data from 2002, reveal that the glaciers flowing into former Wordie Ice Shelf, West Antarctic Peninsula, discharge 6.8 ± 0.3 km^3/yr of ice, which is 84 ± 30 percent larger than a snow accumulation of 3.7 ± 0.8 km^3/yr over a 6,300 km^2 drainage basin. Airborne and ICESat laser altimetry elevation data reveal glacier thinning at rates up to 2 m/yr. Fifty km from its ice front, Fleming Glacier flows 50 percent faster than it did in 1974 prior to the main collapse of Wordie Ice Shelf. We conclude that the glaciers accelerated following ice shelf removal, and have been thinning and losing mass to the ocean over the last decade. This and other observations suggest that the mass loss from the northern part of the Peninsula is not negligible at present. **Citation:** Rignot, E., G. Casassa, S. Gogineni, P. Kanagaratnam, W. Krabill, H. Pritchard, A. Rivera, R. Thomas, J. Turner, and D. Vaughan (2005), Recent ice loss from the Fleming and other glaciers, Wordie Bay, West Antarctic Peninsula, *Geophys. Res. Lett.*, *32*, L07502, doi:10.1029/2004GL021947.

1. Introduction

[2] Wordie Ice Shelf is among nine ice shelves in the Antarctic Peninsula that collapsed in the last fifty years in response to pronounced regional warming [*Vaughan and Doake*, 1996; *Rott et al.*, 2002; *Skvarca et al.*, 1999; *Scambos et al.*, 2000]. Its area increased slightly between 1936 and 1966, but reduced threefold between 1974 and 1989 [*Doake and Vaughan*, 1991] (Figure 1).

[3] Because an ice shelf is afloat in the ocean, its removal does not change sea level, but it may affect glacier flow upstream, which in turn affects sea level. Using Landsat MSS imagery, *Vaughan* [1993] found no evidence for changes in flow direction of the glaciers, such as contorted flow lines suggestive of a surge activity in response to the collapse. He concluded that ice shelf removal did not affect glacier flow.

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[4] Here, we re-visit the influence of Wordie Ice Shelf on glacier mass balance using satellite radar observations collected in 1995–2004, historical data from 1974 [*Doake*, 1975], airborne ice thickness and laser-altimeter data collected in 2002 by Centro de Estudios Cientificos (CECS) and NASA, and laser-altimeter data from NASA's ICESat. We estimate ice discharge from the Airy, Rotz, Seller and Fleming Glaciers (Figure 1) and compare the outflow with the mass input from snow accumulation [*Turner et al.*, 2002] to deduce mass balance. Thinning rates are inferred from a comparison of laser-altimeter data. We conclude on the recent mass loss from this region.

2. Data and Methodology

[5] ERS-1/2 radar interferometry data are used in a standard fashion to map ice velocity in 1995/1996 (Table 1) by combining one-day time separation data acquired along ascending and descending tracks and assuming ice flow parallel to the ice surface. The precision of mapping varies with topographic quality and the length of the interferometric baseline. Existing topography [*Liu et al.*, 1999] is of low quality in this region. We measured topography of the upper part of the glacier basin from ERS-1/2 differential interferometry (DSI) using CECS/NASA laser-altimeter data for ground control. ERS-1/2 interferometry did not apply on the glacier lower reaches because of phase aliasing caused by high rates of ice deformation.

[6] Glacier grounding lines were derived from ERS-1/2 DSI (Figure 1). Approximate ice front locations were inferred from 1974, 1979, and 1996 imagery, and precise locations for 2000 and 2004 (Figure 1). The ice shelf was already broken up between Fleming and Prospect in 1974. The break up was more pronounced in 1979, and longitudinal rifts appeared in the ice shelf [*Doake and Vaughan*, 1991]. A major retreat took place in subsequent years, which left a bay filled with a mosaic of large icebergs partially detached from the ice shelf. Protruding, unconfined ice tongues were still present in 1996 in front of Fleming, Carlson, and Hariot, making it difficult to delineate the ice shelf front. These tongues progressively disappeared and were gone by 2000. In 2004, the ice shelf front retreated on all glaciers, especially Prospect. Fleming is now calving near its 1996 grounding line.

[7] Radarsat-1 data acquired every 24 days were used to map ice velocity using speckle tracking [*Michel and Rignot*, 1999]. This approach is 24 times less sensitive to topography errors than ERS-1/2 one-day interferometry. The data were processed with 4 looks in range, 12 looks in azimuth, yielding 30-m square pixels on the ground. Offsets were measured with a precision of 1/30th, yielding

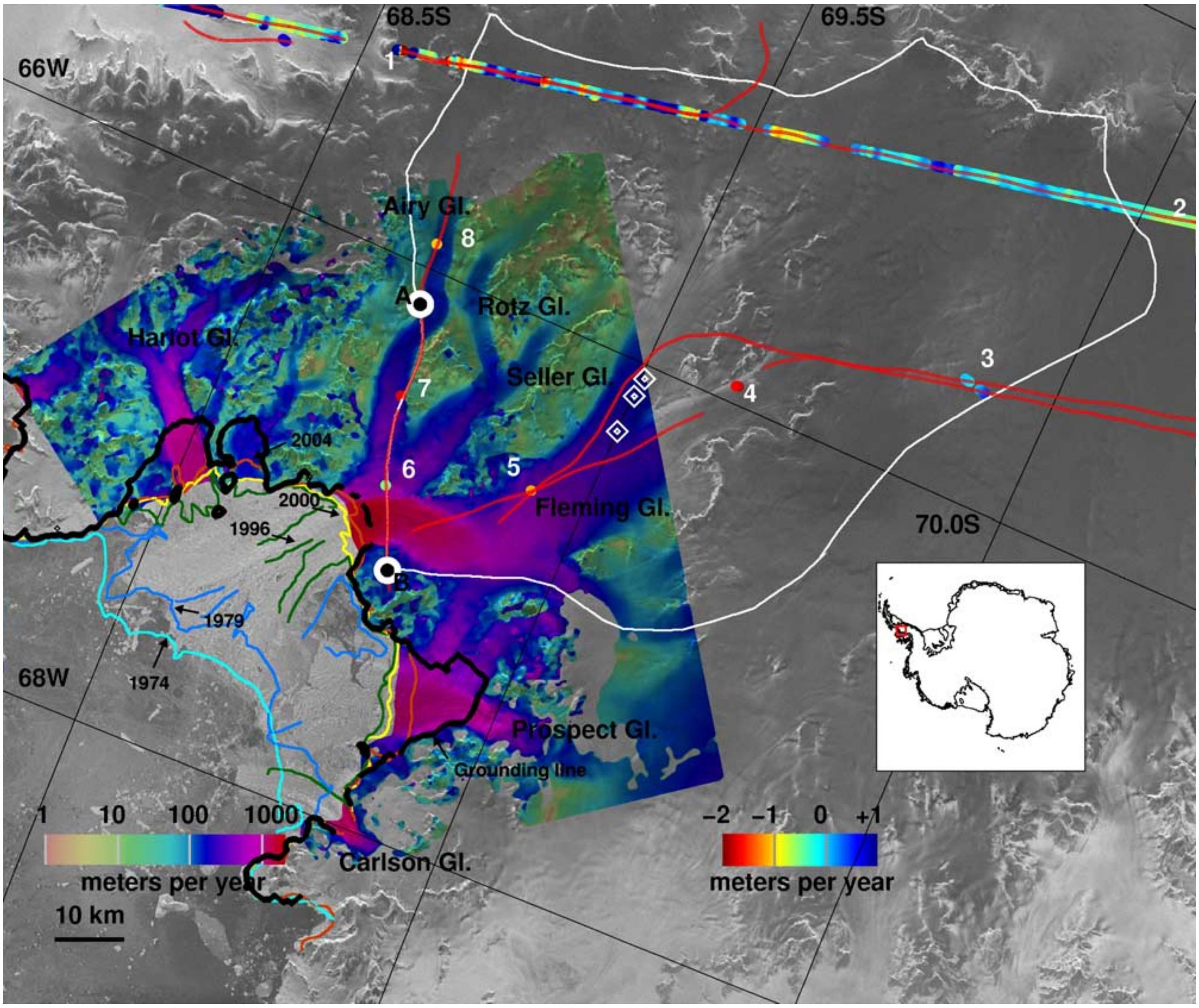

Figure 1. Ice velocity of Hariot, Airy, Rotz, Seller, Fleming, Prospect and Carlson Glaciers from ERS-1/2 1996 and Radarsat-1 2000 interferometry data combined, on a logarithmic scale, overlaid on a radar brightness image of the snow/ice surface [*Liu et al.*, 1999]. Ice velocities are set to zero beyond the 2000 ice front. Color scale for velocity is on the left, from brown (1 m/yr) to red (>1 km/yr). Grounding line location in 1996 is shown in thick black. Ice front position in 1974, 1979 (Landsat), 1996 (ERS-1), 2000 and 2004 (Radarsat-1) are shown, respectively, in light blue, blue, dark green, yellow and orange. Changes in ice sheet elevation from Nov/Dec 2002 to Sept/Nov 2003 are color coded with the scale on the right, from red (thinning) to blue (thickening). Numbers 1–8 refer to points of thinning quoted in the text. Radar sounding lines are shown in red. Drainage basin is shown in white, extending from the flux gate A-B of Figure 2. In situ velocity measurements by *Doake* [1975] are white diamonds with a center dot on Fleming.

a velocity error of 10 m/yr in areas of low noise, and 50 m/yr in areas of high noise. *Doake* [1975] measured ice velocity on the grounded part of Fleming Glacier in 1974, with a precision comparable to that of the satellite measurements (Table 2).

[8] Ice thickness was measured in Nov/Dec by the University of Kansas radar system within 10–30 m. Surface elevation was measured with a scanning laser altimeter operating at 1 km altitude within 0.3 m. NASA's ICESat laser altimeter operated in Feb/Mar and Sep/Nov 2003 and Feb/Mar 2004. Some of the aircraft surveys were along ICESat tracks, and all crossed ICESat tracks. Overlapping planar surfaces were fit to the aircraft measurements on each side of the aircraft within a 70-m along-track

Table 1. ERS-1/2 and Radarsat-1 Orbit Pairs Used in This Study[a]

Data source	Orbits	Dates
1995 ERS-1/2 SI	22413–2740	95/10/28–95/10/29
1995 ERS-1/2 SI, DSI	22394–2721	95/10/27–95/10/28
1996 ERS-1/2 DSI	24398–4725	96/03/15–96/03/16
2000 ERS-1/2 SI	44958–25285	00/02/19–00/02/20
2000 RSAT-1 ST	25621–25278	00/10/01–00/09/07
2003 RSAT-1 ST	41742–41399	03/11/03–03/10/10
2004 RSAT-1 ST	44143–43800	04/04/19–04/03/26

[a]SI = single difference interferometry; DSI = double difference; ST = speckle tracking.

distance. These platelets were compared with ICESat footprint elevations by extrapolating elevations from any platelet within 200 m distance using the platelet slope. Four adjacent ICESat/aircraft comparisons were averaged to reduce noise. ICESat error, from laser pointing errors and forward scattering in thin clouds, is less than 0.6 m over steep slopes (>2 degrees). ICESat pointing errors for Feb/Mar 2003 data are larger, so these data were not included in the analysis. Elevation change measured between NASA/CECS and ICESat data should be precise to 0.7 m.

3. Analysis

[9] ERS-1/2 data from 1995 to 2000 show no change in ice velocity, ±25 m/yr, on the grounded part of the glaciers, excluding lower reaches where pronounced surface melt decorrelated the 2000 signal. Between 2000 and 2004, we detect no change in grounded ice velocity, within ±50 m/yr. Hence, grounded ice flow has been relatively stable in the last decade.

[10] Comparison of 1996 ERS-1/2 ice velocity with Doake's velocity points indicates a 50 percent difference in flow speed, with no change in flow direction. The latter is consistent with the absence of contorted flow lines [*Vaughan*, 1993], but the former contradicts the conclusion that flow changes have not been significant. Glacier acceleration is detected more than 50 km from the glacier front. It is likely to be greater nearer to the ice front.

[11] Across the flux gate A-B (Figure 1), we calculate a total discharge of 6.8 ± 0.3 km^3/yr ice into the ocean from Airy, Rotz, Seller and Fleming glaciers (Figure 2). The flux gate drains an area of 6,300 ± 500 km^2 based on available topography (Figure 1). The digital map from *Turner et al.* [2002] indicates a long-term snow accumulation of 3.7 ± 0.8 km^3/yr ice. Ice outflow is therefore 84 ± 30 percent larger than snow input, and larger than our assumed 20 percent uncertainty in accumulation. The glaciers are collectively in a state of negative mass balance. Averaged over the entire basin, the mass loss is equivalent to a mean thinning rate of 0.5 m/yr.

[12] Comparison of ICESat and CECS/NASA altimetry data reveals thinning rates up to 2 m/yr on Airy and Fleming glaciers, and 0.2 ± 0.7 m/yr near the divide, with a high spatial variability (Figure 1). The thinning rates for locations 3–8 are, respectively, 0.0, 1.7, 1.2, 0.5, 1.7 and 1.1 m/yr. Hence, thinning is higher at lower elevation, and affects the entire basin. While the density of measurements is small and the precision is low, the results confirm the state of thinning of the glaciers deduced from the mass budget, as well as the magnitude of ice thinning.

4. Discussion

[13] The mass loss of Fleming and other glaciers may be due to a combination of factors that include a decrease in snow precipitation, an increase in surface melting, and a decrease in ice shelf buttressing. Over the last few decades, precipitation increased 10 percent at Dyer Plateau [*Raymond et al.*, 1996], which is small compared to the estimated imbalance. In 1974, air temperature averaged T = −12.6°C at Doake's point. Warming at Rothera of 9.3°C/century suggests a temperature of T = −9.8°C in 2004. Using D. G. Vaughan (Recent trends in melting conditions on the Antarctic Peninsula and their implications for ice-sheet mass balance, submitted to *Arctic and Antarctic Alpine Research*, 2004), we estimate that the number of positive degree days increased from 15 to 31 since 1974, yet melt water is not produced in sufficient quantity to allow percolation of melt water into the firn. No runoff is therefore available at the glacier bed to enhance lubrication. In addition, little runoff is generated above our flux gate, so the mass loss cannot be explained by enhanced surface melting.

Table 2. Velocity Magnitude, *V*, in Meters Per Year and Angle in Degrees From True North, α, for 1974 (in Situ) and 1995 (ERS-1/2)

Location	1974 *V*, α (m/yr, deg.)	1996 *V*, α (m/yr, deg.)
69.500S 66.267W	201, 284	306, 300
69.502S 66.123W	175, 272	271, 287
69.505S 66.049W	146, 277	224, 285

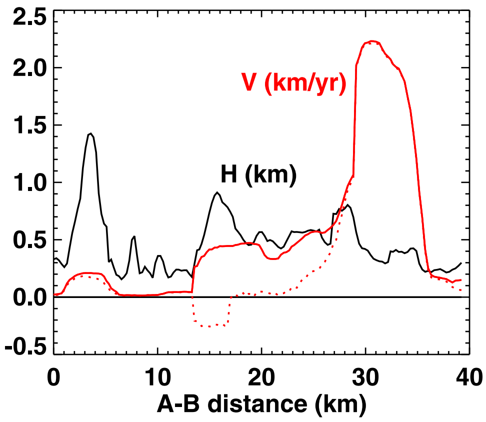

Figure 2. Ice velocity (red is magnitude, dotted red is velocity normal to flux gate) and thickness (black) from CECS/NASA of Airy, Rotz, Seller and Fleming Glaciers along flux gate A-B in Figure 1.

[14] This leaves ice shelf removal as the most likely explanation for the speed up. The acceleration of Fleming Glacier 50 km from the ice front is likely due to a diffusing thinning wave which initiated with the demise of the ice shelf as the glacier lower reaches accelerated [*Payne et al.*, 2004]. We do not have sufficient information on ice thickness and surface slope along the glacier flow to verify the time scale of propagation of the perturbation.

[15] Between 1974 and 1989, the ice shelf progressively weakened, rifted and broke up into coalescent ice tongues. The removal of ice pinning points (ice rises and rumples) and shearing along the side walls of the bay must have reduced ice shelf buttressing [*Doake and Vaughan*, 1991]. In subsequent years, the retreat left a bay stranded with large icebergs glued together, probably not exerting much backpressure on the glaciers. Between 1996 and 2000, the disappearance of the protruding tongues should not have affected glacier flow, because unconfined ice tongues exert no backpressure. Similarly, the 2000–2004 reduction in ice shelf area is small compared to that in 1974–1996, no pinning points were removed, and the area of side shearing did not change significantly. This probably explains the lack of speed up of the glaciers in the last decade.

[16] There are few remaining ice shelves north of Wordie Bay along the west flank of the Peninsula [*Vaughan and Doake*, 1996]. The west coast between Trinity Peninsula (63°) and Fleming drains an area of 30,900 km^2 with a total accumulation of 26 ± 5 km^3/yr. This region is likely to be in a state of negative mass balance: ice fronts are retreating rapidly [*Rau et al.*, 2005], and air temperatures are increasing rapidly, particularly in the north [*Morris and Vaughan*, 2003]. If we assume an imbalance similar to that recorded on Fleming glacier (i.e., 60–100 percent), this area would lose 20 ± 6 km^3/yr. Combined with a 27 ± 5 km^3/yr mass loss from some glaciers on the east coast after 2002 [*Rignot et al.*, 2004], this yields a potential mass loss of 47 ± 8 km^3/yr for the northernmost sector of the Antarctic Peninsula in recent years, sufficient to raise sea level by 0.1 mm/yr. While this number remains highly uncertain because of the extrapolation to a large area, it illustrates that the mass loss from the northern Peninsula is not negligible.

5. Conclusions

[17] In prior assessments of the contribution of polar ice sheets to sea level, Antarctic Peninsula glaciers were excluded because their climate conditions and glacier characteristics make them more similar to mountain glaciers than polar glaciers [*Church et al.*, 2001]. Antarctic Peninsula glaciers are, however, not included in mountain glacier inventories due to a lack of basic data [*Dyurgerov*, 2002]. As a result, Antarctic Peninsula glaciers have been assumed to have no impact on sea level [*Drewry and Morris*, 1992]. Our analysis of Wordie Bay glaciers, combined with other results, suggests, on the contrary, that Antarctic Peninsula glaciers are significantly out of balance at present, but we can only approximately estimate their current ice loss. Additional observations of ice thickness, velocity and accumulation are required to reduce uncertainties. As regional warming progresses further south and affects larger reservoirs of ice, the contribution to sea level is likely to increase.

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