Retreating Glacier Fronts on the Antarctic Peninsula over the Past Half-Century
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technique has a sizeable advantage: The inner and outer fluids remain totally separate, providing for efficient and robust encapsulation. In addition to polymerosomes, it should also be possible to form liposomes from phospholipids in the same manner. Alternatively, other methods to produce robust encapsulants include surface-induced polymerization of either the inner or outer interface or temperature-induced gelation of the inner or middle fluid.

Our microcapillary fluidic device is truly three dimensional, completely shielding the inner fluid from the outer one. It can generate double emulsions dispersed in either hydrophilic or hydrophobic fluids. Its production of double emulsion droplets is limited by the drop formation frequency, which varies between approximately 100 and 5000 Hz. Increasing the production rate requires the operation of parallel devices; for this, a stamping technique (*43*) would be highly desirable. However, an operational device would require control of the wetting properties of the inner channels. Alternatively, a hybrid device incorporating capillary tubes into the superstructure may offer an alternate means of making devices to produce double emulsions.

References and Notes

1. K. J. Lissant, *Emulsion and Emulsion Technology* (Marcel Dekker, New York, 1974), vol. 6.
2. C. Laugel, A. Baillet, M. P. Y. Piemi, J. P. Marty, D. Ferrier, *Int. J. Pharm.* **160**, 109 (1998).
3. C. Laugel, P. Rafidison, G. Potard, L. Aguadisch, A. Baillet, *J. Controlled Release* **63**, 7 (2000).
4. M. Gallarate, M. E. Carlotti, M. Trotta, S. Bovo, *Int. J. Pharm.* **188**, 233 (1999).
5. B. Raghuraman, N. Tirmizi, J. Wiencek, *Environ. Sci. Technol.* **28**, 1090 (1994).
6. A. Edris, B. Bergnstahl, *Nahrung/Food* **45**, 133 (2001).
7. A. Benichou, A. Aserin, N. Garti, *Polym. Adv. Technol.* **13**, 1019 (2002).
8. N. Vasishtha, H. W. Schlameus, *Microencapsulation of Food Ingredients*, P. Vilstrup, Ed. (Leatherhead Food International, Leatherhead, UK, 2001).
9. D. Lee *et al.*, *J. Dispersion Sci. Technol.* **23**, 491 (2002).
10. M. Lee, S. Oh, S. Moon, S. Bae, *J. Colloid Interface Sci.* **240**, 83 (2001).
11. V. Muguet *et al.*, *J. Controlled Release* **70**, 37 (2001).
12. S. Omi, K. Katami, T. Taguchi, K. Kaneko, M. Iso, *J. Appl. Polym. Sci.* **57**, 1013 (2003).
13. L-Y. Chu *et al.*, *J. Colloid Interface Sci.* **265**, 187 (2003).
14. R. Alex, R. Bodmeier, *J. Microencapsul.* **7**, 347 (1990).
15. S. Cohen, T. Yoshioka, M. Lucarelli, L. H. Hwang, R. Langer, *Pharm. Res.* **8**, 713 (1991).
16. N. Nihant, C. Schugens, C. Grandfils, R. Jérôme, P. Teyssié, *Pharm. Res.* **11**, 1479 (1994).
17. R. Cortesi, E. Esposito, G. Luca, C. Nastruzzi, *Biomaterials* **23**, 2283 (2002).
18. A. Lamprecht, H. Yamamoto, H. Takeuchi, Y. Kawashima, *J. Controlled Release* **98**, 1 (2004).
19. H. K. Kim, T. G. Park, *J. Controlled Release* **98**, 115 (2004).
20. M. Chiba, J. Hanes, R. Langer, *Biomaterials* **18**, 893 (1997).
21. Y. Yamaguchi *et al.*, *J. Controlled Release* **81**, 235 (2002).
22. C. Goubault *et al.*, *Langmuir* **17**, 5184 (2001).
23. S. Okushima, T. Nisisako, T. Torii, T. Higuchi, *Langmuir* **20**, 9905 (2004).
24. I. G. Loscertales *et al.*, *Science* **295**, 1695 (2002).
25. M. F. Ficheux, L. Bonakdar, F. Leal-Calderon, J. Bibette, *Langmuir* **14**, 2702 (1998).
26. R. Mezzenga, B. M. Folmer, E. Hughes, *Langmuir* **20**, 3574 (2004).
27. J. Jiao, D. G. Rhodes, D. J. Burgess, *J. Colloid Interface Sci.* **250**, 444 (2002).
28. K. Pays, J. Giermanska-Kahn, B. Pouligny, J. Bibette, F. Leal-Calderon, *Phys. Rev. Lett.* **87**, 178304 (2001).
29. L. Wen, K. D. Papadopoulos, *J. Colloid Interface Sci.* **235**, 398 (2000).
30. C. H. Villa, L. B. Lawson, Y. Li, K. D. Papadopoulos, *Langmuir* **19**, 244 (2003).
31. H. González-Ochoa, L. Ibarra-Bracamontes, J. L. Arauz-Lara, *Langmuir* **19**, 7837 (2003).
32. S. L. Anna, N. Bontoux, H. A. Stone, *Appl. Phys. Lett.* **82**, 364 (2003).
33. I. Cohen, H. Li, J. L. Hougland, M. Mrksich, S. R. Nagel, *Science* **292**, 265 (2001).
34. B. Ambravaneswaran, H. J. Subramani, S. D. Phillips, O. A. Basaran, *Phys. Rev. Lett.* **93**, 034501 (2004).
35. C. Clanet, J. C. Lasheras, *J. Fluid Mech.* **383**, 307 (1999).
36. The exact value of the flow rate at which this transition occurs will depend on the details of the tube geometry.
37. J. Plateau, *Acad. Sci. Bruxelles Mem.* **23**, 5 (1849).
38. L. Rayleigh, *Proc. R. Soc. London* **29**, 71 (1879).
39. T. R. Powers, D. Zhang, R. E. Goldstein, H. A. Stone, *Phys. Fluids* **10**, 1052 (1998).
40. S. Tomotika, *Proc. R. Soc. London Ser. A* **150**, 322 (1935).
41. B. M. Discher *et al.*, *Science* **284**, 1143 (1999).
42. PBA-PAA has a molecular weight of 5500 g/mol with the hydrophobic block (PBA) making up 70% of the total molecular weight.
43. G. M. Whitesides, A. D. Stroock, *Phys. Today* **54**, 42 (2001).

44. We thank M. P. Brenner, G. Cristobal, M. Joanicot, M. Abkarian, I. Cohen, and S. Paruchuri for helpful discussions and comments. This work was supported by NSF (grant DMR-0243715), the Harvard Materials Research Science and Engineering Center (grant DMR-0213805), Rhodia, and Unilever.

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Fig. S1
Movies S1 to S4

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Retreating Glacier Fronts on the Antarctic Peninsula over the Past Half-Century

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The continued retreat of ice shelves on the Antarctic Peninsula has been widely attributed to recent atmospheric warming, but there is little published work describing changes in glacier margin positions. We present trends in 244 marine glacier fronts on the peninsula and associated islands over the past 61 years. Of these glaciers, 87% have retreated and a clear boundary between mean advance and retreat has migrated progressively southward. The pattern is broadly compatible with retreat driven by atmospheric warming, but the rapidity of the migration suggests that this may not be the sole driver of glacier retreat in this region.

Recent changes in the Antarctic ice sheet have been caused by many different drivers, including Holocene climatic change (*1*), increasing precipitation (*2*), and changing ocean temperatures (*3*). Recent regional climate change has also begun to have a direct and immediate effect on marginal parts of the ice sheet. One notable area is the Antarctic Peninsula, where climate has warmed by ~2°C since the 1950s (*4*). Retreat of ice shelves is already well underway (*5*) with retreat of 10 ice shelves during the latter part of the 20th century (*6*–*13*). Antarctic Peninsula glaciers drain a large volume of ice, although this flux is largely balanced by snow accumulation. However, the loss of ice shelves has caused acceleration of the glaciers that fed them (*14*, *15*), creating locally high imbalances. Removal of other areas of floating ice could further increase this imbalance and thus make a substantial contribution to sea level rise.

As part of a wider project funded by the U.S. Geological Survey that will record coastal change for the whole continent (*16*, *17*), we compiled maps describing changes in the ice sheet margin around the Antarctic Peninsula. The detailed cartography, including changes in glaciers and ice shelves, will be published as maps (*18*, *19*) and as digital data (*20*). Here, we present an analysis of this comprehensive time-series data set describing the extent of the 244 marine glaciers draining the Antarctic Peninsula ice sheet and those on associated islands. All of these glaciers calve directly into the sea but comprise both tidewater glaciers and glacier ice shelves (*21*). We excluded composite ice shelves from the study because their behavior is already well documented.

The data sources (table S1) used to compile the maps included over 2000 aerial photographs dating from 1940 to 2001 and more than 100 satellite images from the 1960s onward (the example in Fig. 1 is of

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two satellite image extracts revealing glacier retreat between 1986 and 2001). The glacier fronts at different dates were mapped onto a common reference in a Geographical Information System (Arc/Info). This common reference was a mosaic of Landsat images (*22*) mainly acquired during 1986 to 1989. Absolute positional accuracy was limited by the georeferencing precision of the mosaic (±160 m root mean square) (*22*). Comparison between dates was constrained by the 30-m resolution of the common reference and the nature of the source material, but 86% of the coastal data was determined to have a better than 120-m positional accuracy. The source material available did not allow the capture of glacier changes at regular or uniform intervals across the peninsula but resulted in glaciers with coastlines from many different time periods, many of which overlapped. In addition, many glacier fronts in the north were observed on more than 10 occasions, whereas farther south, the observations were less frequent, with only five date samples available in some areas.

As a basis for the statistical analysis, sample lines perpendicular to the glacier fronts were drawn for each glacier. The intersections between sample lines and glacier fronts became the basis for the analysis, and the distance from each intersection to a common point on the sample line gave a measure of advance or retreat. Because of the variable interval between observations, the mean changes (in meters per year) were averaged into 5-year intervals, ensuring that glaciers with many more observations did not skew the results. This analysis resulted in more than 22,000 measurements of change over 5-year intervals (*23*).

The maps in Fig. 2 (and the associated statistics shown in table S2) summarize the changes in glacier fronts since the earliest records used in this study. Of the 244 glaciers, 212 (87%) have shown overall retreat since their earliest known position (which, on average, was in 1953). The other 32 glaciers have shown overall advance, but these advances are generally small in comparison with the scale of retreats observed (Table 1 shows the magnitude of changes observed). The glaciers that have advanced are not clustered in any pattern but are evenly scattered down the coast (Fig. 2).

Examination of the timing of changes along the peninsula indicates that from 1945 until 1954 there were more glaciers showing advance (62%) than those showing retreat (38%). After that time, the number in retreat has risen, with 75% in retreat in the period from 2000 to 2004. This pattern is reflected in Fig. 3, which shows that the mean rate of retreat in glaciers across the Antarctic Peninsula has been increasing since 1945. The standard deviations of retreat and advance rates over the entire domain were considerable (up to 150 m/year) but expected, due to the diverse behavior of the individual glaciers. A more useful measure of error is the likely uncertainty in the mean retreat rates, which is shown in the 95% confidence interval. The large sample size has made it possible to determine the mean behavior of glaciers on the peninsula with precision.

It has been proposed that the pattern of ice-shelf retreat on the Antarctic Peninsula is

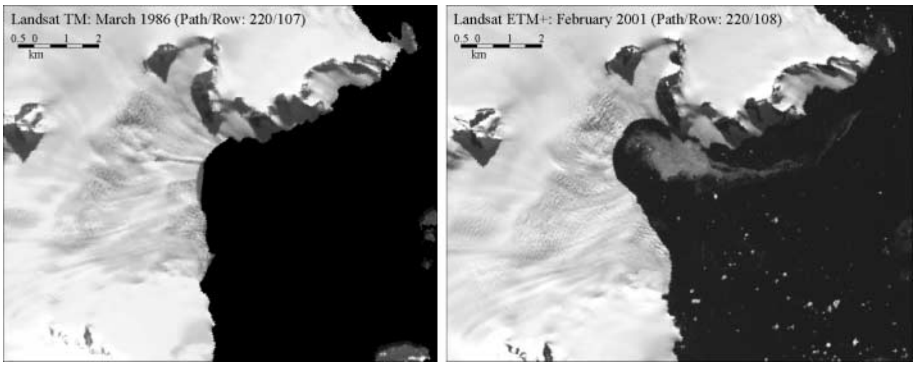

Fig. 1. Satellite image pair showing glacier retreat of Sheldon Glacier, Adelaide Island (67°32′S, 68°17′W).

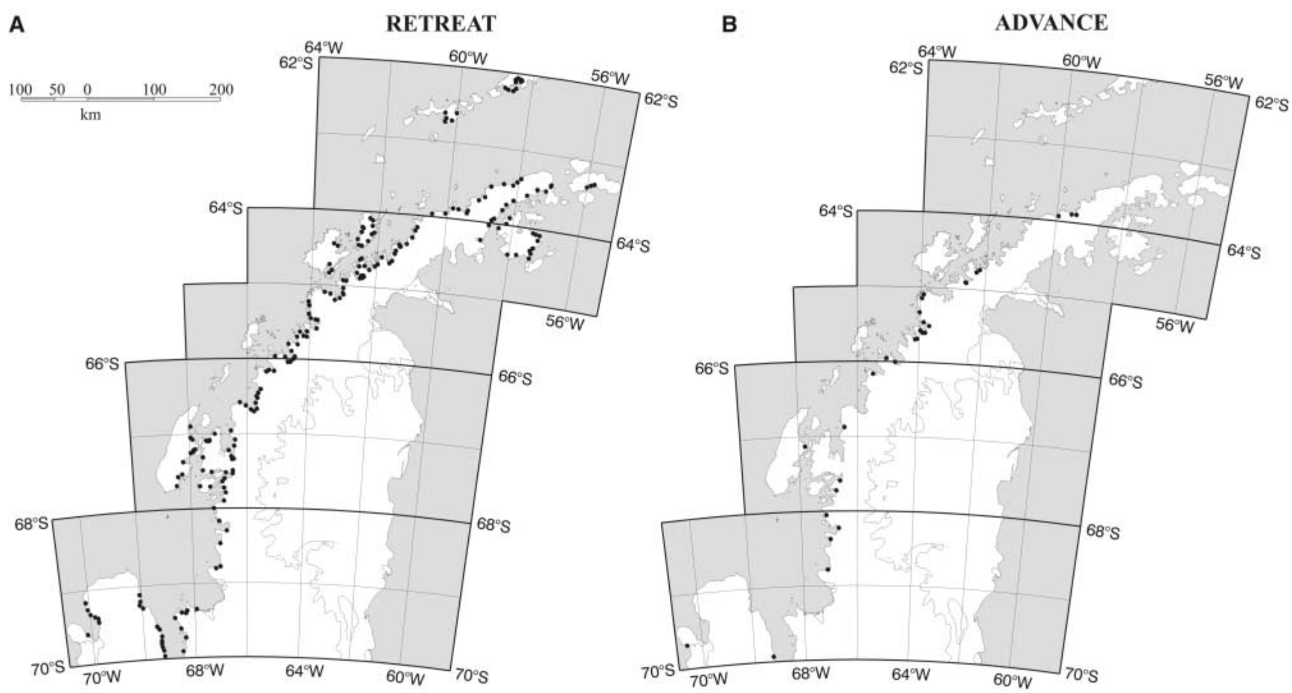

Fig. 2. Overall change observed in Antarctic Peninsula glacier fronts since earliest records.

consistent with the existence of a thermal limit on ice-shelf viability (*5*, *24*). The limit of ice shelves known to have retreated during the past 100 years is bounded by the –5° and –9°C isotherms (calculated for 2000 A.D.), suggesting that the retreat of ice shelves in this region is consistent with the observed warming trend of 3.5° ± 1.0°C per century (*24*). No ice shelves exist on the warmer side of the –9°C isotherm position, and no ice shelves on the colder side have been reported to be retreating.

Figure 4 (with accompanying statistics in table S3) reveals a similar pattern of behavior in our population of glaciers; there is a clear southerly migration of a rather abrupt transition from mean advance to mean retreat. Before 1950, glaciers north of 64°S (sector 1) were already retreating when glaciers in sectors 2, 3, and 4 were, on average, advancing. The glaciers in sector 2 transitioned from advance to retreat between 1950 and 1959, at which point only glaciers in sectors 3 and 4 were advancing. In sector 3, retreat began sometime between 1955 and at the latest, 1969 (taking into account the 95% confidence interval error bars), and in sector 4, it was between 1960 and 1969, after which glaciers in all sectors have been, on average, retreating.

In broad terms, this pattern reflects the atmospheric warming across the peninsula since the 1940s. However, a detailed examination shows that the transition from mean advance to mean retreat cannot be interpreted simply as the limit of viability for ice shelves. First, the migration of transition from mean advance to mean retreat over the period from 1955 to 1965 corresponds to a migration from the –3°C mean annual isotherm [plate 1b in (*24*)] to around –8°C in 1965. If this migration were caused by climate change, it would imply a warming much more rapid than even the maximum seasonal rate of warming: The austral winter warming at Faraday/Vernadsky Station is several times the mean annual rate (*25*). Secondly, whereas all ice shelves predicted by the limit-of-viability model appear to be retreating, the glaciers show a mixed trend with only 75% of the glaciers currently retreating.

Finally, although there is a clear reduction in the mean rate of retreat of glaciers in sectors 2, 3, and 4 in the interval from 1985 to 1994, we do not see any period of comparative cooling that could have caused this. (Figure 4 shows the mean annual temperatures for Faraday/Vernadsky binned in the same intervals; no other weather stations on the peninsula have complete air temperature records since 1945.) In addition, we have looked for correlations with summer temperature at Faraday/Vernadsky, expressed as positive degree days, and found no evidence for a causal relationship. We have analyzed satellite data from passive microwave records of sea-ice concentration for the period from 1979 to 2003 from Marguerite Bay (i.e., sector 3, Fig. 4), but these show no clear correlations with the rate of retreat of glaciers in sector 3. In particular, two periods of low sea-ice concentration (1989 to 1991 and 1998 to 2001) occurred at times when glaciers were retreating anomalously slowly and particularly rapidly, respectively. Thus, any link between retreat and sea-ice concentrations that may exist is not a simple one.

It is well known that glaciers with fully grounded marine termini exhibit unusually complex responses to changing mass balance (*26*–*28*), because in addition to the normal forcings they are subject to oceanographic forcing and subglacial topography. Indeed, several authors have suggested that the behavior of neighboring tidewater glaciers is not synchronous on decadal or century time scales (*29*). Our mixed population of tidewater and floating termini glaciers has largely shown synchronous behavior, but while we might have expected a response similar to that of ice shelves, there is no clear limit of viability to properly predict the rate of migration from mean advance to mean retreat. These glaciers must have a more complex response to climate change, perhaps to variables such as ocean temperature for which there are little data and for which we cannot test at present.

Our results indicate the existence of a clear transition between mean advance and mean retreat; a southerly migration of that transition at a time of ice-shelf retreat and progressive atmospheric warming; and a clear regime of retreat, which now exists across the Antarctic Peninsula. Future analysis of changes in all boundary conditions may reveal why the glaciers have responded in this way. Before the present retreat, the glaciers showed persistent mean advance, suggesting that the present changes could be part of longer cyclic behaviors. Such cyclic behavior, at least over decadal time scales, has been specifically ruled out for ice shelves because of their long regrowth period and evidence to suggest persistence on millennial time scales (*29*, *30*). However, it appears that in recent times this large mixed population of floating and tidewater glaciers has responded synchronously to a climatic forcing, indicating, at least statisti-

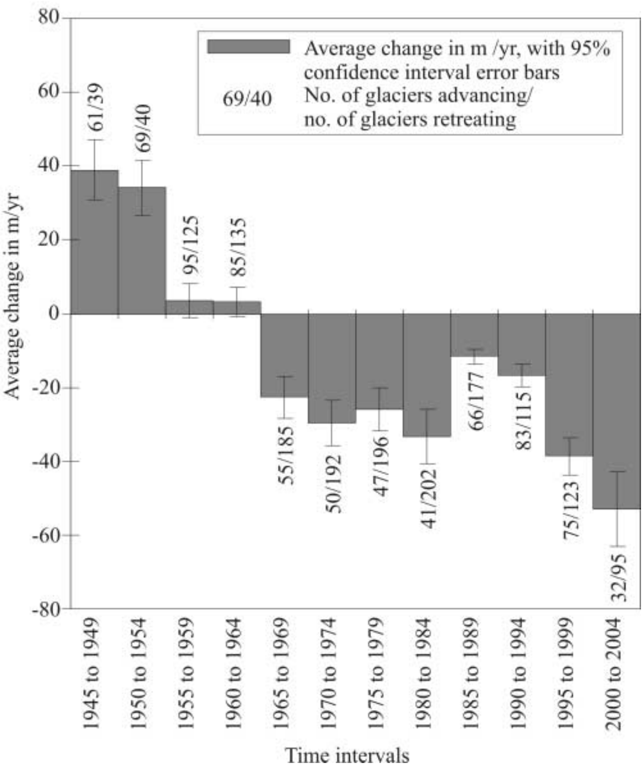

Fig. 3. Average change (with uncertainties) and average latitudes of glaciers across Antarctic Peninsula. Mean advances of 30 to 40 m/year in the 1940s and 1950s became close to stability in the 1950s and 1960s followed by an increase in rate of retreat up to the present, when retreats of 50 m/year are occurring.

Table 1. Number of glaciers showing overall advance/retreat (since earliest record) of different magnitudes. Only Sjogren Glacier at 64°14′S, 58°54′W has shown retreat of over 5 km, although this is a unique case: Until 1993, the glacier flowed into the Prince Gustav Ice Shelf, and then the ice shelf broke up and the floating glacier subsequently retreated more than 13 km.

	Advance	Retreat
Less than 500 m	27	146
500–1000 m	2	35
1000–2000 m	3	17
2000–5000 m		13
More than 5000 m		1

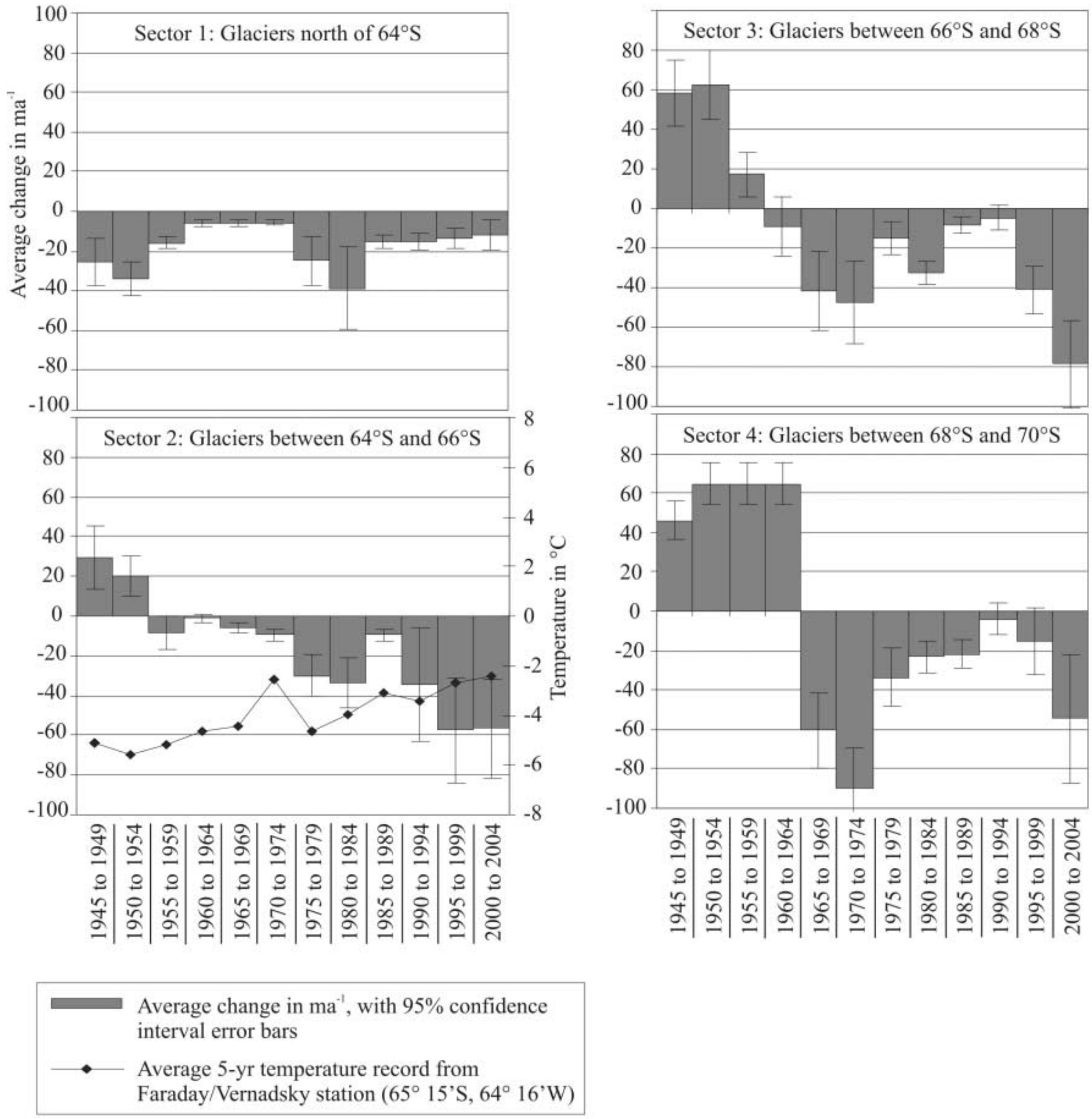

Fig. 4. Change in Antarctic Peninsula glaciers over time and by latitude. Before 1945, the limit of glacier retreat was north of 64°S; in 1955 it was in the interval between 64° and 66°S; in 1960 between 66° and 68°S; and in 1965 between 68° and 70°S. Also of note is a 10-year period in which the rate of retreat is anomalously high; it appears in all the records but is not simultaneous. In sectors 1 and 2 it appears between 1975 and 1984 and in sectors 3 and 4, between 1965 and 1974, so it appears to occur later to the north. Similarly, there is a period of noticeable reduction in the rate of retreat that occurs some time after the high retreat rates but again does not occur simultaneously between the sectors. Sector 1 shows no obvious minimum; sector 2 shows a low retreat rate between 1985 and 1989; sector 3 between 1990 and 1994; and sector 4 between 1990 and 1994, apparently occurring later to the south.

cally, that such glaciers should be predictable on decadal time scales. Because we know that the loss of floating ice shelves can cause acceleration of inland glaciers, these observations suggest that the cumulative loss of ice at the fronts of these glaciers may be leading to an increased drainage of the Antarctic Peninsula that is more widespread than previously thought.

References and Notes

1. J. O. Stone *et al.*, *Science* **299**, 99 (2003).
2. E. Mosley-Thompson, J. F. Pashkievitch, A. J. Gow, L. G. Thompson, *J. Geophys. Res.* **104**, 3877 (1999).
3. A. Shepherd, D. Wingham, T. Payne, P. Skvarca, *Science* **302**, 856 (2003).
4. D. G. Vaughan, G. J. Marshall, W. M. Connolley, J. C. King, R. Mulvaney, *Science* **293**, 1777 (2001).
5. D. G. Vaughan, C. S. M. Doake, *Nature* **379**, 328 (1996).
6. C. G. Ward, *Antarct. Sci.* **7**, 197 (1995).
7. H. Rott, P. Skvarca, T. Nagler, *Science* **271**, 788 (1996).
8. B. K. Luchitta, C. E. Rosanova, *Ann. Glaciol.* **27**, 41 (1998).
9. P. Skvarca, W. Rack, H. Rott, T. Ibarzabal y Donangelo, *Ann. Glaciol.* **27**, 628 (1998).
10. C. S. M. Doake, D. G. Vaughan, *Nature* **350**, 328 (1991).
11. A. P. R. Cooper, *Polar Rec.* **33**, 285 (1997).
12. A. J. Fox, D. G. Vaughan, in preparation.
13. T. Scambos, C. Huble, M. Fahnestock, J. Bohlander, *J. Glaciol.* **46**, 516 (2000).
14. H. Rott, W. Rack, P. Skvarca, H. de Angelis, *Ann. Glaciol.* **34**, 277 (2002).
15. H. de Angelis, P. Skvarca, *Science* **299**, 1560 (2003).
16. R. S. Williams Jr., J. G. Ferrigno, C. Swithinbank, B. K. Lucchitta, B. A. Seekins, *Ann. Glaciol.* **21**, 284 (1995).
17. R. S. Williams Jr., J. G. Ferrigno, *U.S. Geol. Surv. Fact Sheet 50–98* (1998).
18. J. G. Ferrigno, R. S. Williams Jr., J. W. Thomson, *Joint U.S. Geol. Surv.–British Antarctic Surv. Fact Sheet FS-017-02* (2002).
19. J. G. Ferrigno *et al.*, *Coastal-Change and Glaciological Maps of the Trinity Peninsula Area, Antarctica: 1843–2001* (USGS I-2600-A), in press.
20. Data are available through Antarctic Digital Database: www.add.scar.org.
21. Tidewater glaciers are defined as glaciers with grounded marine termini; glacier ice shelves are defined as the floating margins of outlet glaciers.
22. J. Sievers, A. Grindel, W. Meier, *Polarforschung* **59**(1/2), 25 (1989).
23. Although the earliest source was in 1940, only 13 glaciers (clustered in a narrow latitude band) were covered before 1945, so coastlines from these years were eliminated from the binned analysis. The latest data used for mapping coastal changes were from 2001.
24. E. M. Morris, D. G. Vaughan, *Antarct. Res. Ser.* **79**, 61 (2003).
25. D. G. Vaughan *et al.*, *Clim. Change* **60**, 243 (2003).
26. C. J. Van der Veen, *Prog. Phys. Geogr.* **26**, 96 (2002).
27. A. Vieli, J. Jania, L. Kolondra, *J. Glaciol.* **48**, 592 (2002).
28. W. T. Pfeffer, *Nature* **426**, 602 (2003).
29. E. Domack *et al.*, *Eos* **82**, 13 (2001).
30. C. J. Pudsey, J. Evans, *Geology* **29**, 787 (2001).

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Supporting Online Material
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Tables S1 to S3

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