

Retreat of northern margins of George VI and Wilkins Ice Shelves, Antarctic Peninsula

B. K. LUCCHITTA, C. E. ROSANOVA

U.S. Geological Survey, 2255 North Gemini Drive, Flagstaff, AZ 86001, U.S.A.

ABSTRACT. The George VI and Wilkins Ice Shelves are considered at risk of disintegration due to a regional atmospheric warming trend on the Antarctic Peninsula. Retreat of the northern margin of the George VI Ice Shelf has been observed previously, but the Wilkins Ice Shelf was thought to be stable. We investigated the positions of the northern fronts of these shelves from the literature and looked for changes on 1974 Landsat and 1992 and 1995 European remote-sensing satellite (ERS) synthetic aperture radar images. Our investigation shows that the northern George VI Ice Shelf lost a total of 906 km² between 1974 and 1992, and an additional 87 km² by 1995. The northern margin of the Wilkins Ice Shelf lost 796 km² between 1990 and 1992, and another 564 km² between 1992 and 1995. Armadas of tabular icebergs were visible in front of this shelf in the ERS images. These two ice shelves mark the southernmost documented conspicuous retreat of ice-shelf margins.

INTRODUCTION

Mercer (1978) predicted that global greenhouse warming would lead to disintegration of ice shelves on the Antarctic Peninsula. Whether related to global or local processes, climatic warming on the Antarctic Peninsula has recently become evident (Raper and others, 1984; Morrison, 1990; Ridley, 1993; King, 1994; Thompson and others, 1994; Vaughan and Doake, 1996) and local ice-sheet disintegration has been documented (Doake and Vaughan, 1991; Skvarca, 1993, 1994; Ward 1995; Rott and others, 1996). For instance, the Wordie Ice Shelf on the west side of the Antarctic

Peninsula has completely disappeared (Doake and Vaughan, 1991). Until now this shelf has marked the southern limit of ice-shelf disintegration. Farther south, retreat of the northern margin of the George VI Ice Shelf was observed by Mercer (1978), Lennon and others (1982) and Potter and others (1988). By contrast, the Wilkins Ice Shelf has been considered stable, though near its limit of viability (Vaughan and others, 1993). Here we report that the retreat of the northern margin of the George VI Ice Shelf is continuing and that recession of the northern margin of the Wilkins Ice Shelf has begun (Fig. 1). We determined past frontal positions of these shelves from the literature and measured recent changes on older Landsat and more recent European remote-sensing satellite synthetic aperture radar (ERS SAR) images.

METHOD

We used two band 7 (near-infrared) 1974 Landsat multi-spectral scanner (MSS; 80 m/pixel resolution) images in the form of computer-compatible tapes, archived at the

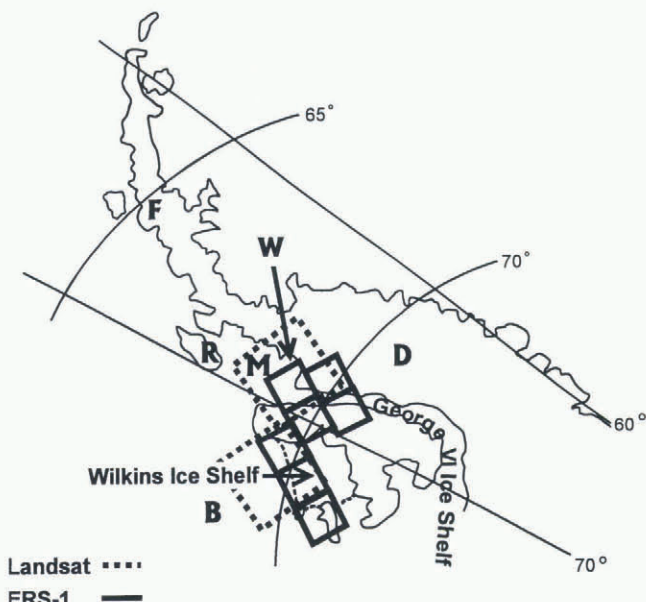


Fig. 1. Antarctic Peninsula. Location map of ice shelves, Landsat and ERS-1 images. B, Bellinghousen Sea; D, Dyer Plateau; F, Faraday Station; M, Marguerite Bay; R, Rothera Station; W, Wordie Ice Shelf.

Table 1. Satellite images used in study

George VI Ice Shelf			Wilkins Ice Shelf		
Scene ID	Date		Scene ID	Date	
Landsat	1532/2325	6 Jan 1974	Landsat	1535/2500	9 Jan 1974
ERS-1	5350/5049	24 Jul 1992	ERS-1	5436/5049	30 Jul 1992
ERS-1	5350/5067	24 Jul 1992	ERS-1	5436/5067	30 Jul 1992
ERS-1	7268/5067	5 Dec 1992	ERS-1	5436/5085	30 Jul 1992
ERS-1	7268/5085	5 Dec 1992	ERS-1	22313/5049	21 Oct 1995
ERS-1	22227/5049	15 Oct 1995	ERS-1	22313/5067	21 Oct 1995
ERS-1	22227/5067	15 Oct 1995	ERS-1	22313/5085	21 Oct 1995
ERS-1	22642/5067	13 Nov 1995			
ERS-1	22642/5085	13 Nov 1995			

U.S. Geological Survey, Flagstaff, AZ (Fig. 1; Table 1). Additionally, we used 1992 and 1995 ERS-1 image mosaics (25 m resolution at 12.5 m/pixel), in the form of CD-ROMs in Universal Transverse Mercator map projection using the World Geodetic System 1984 ellipsoid, and furnished by the European Space Agency through the German DLR (Deutsche Forschungsanstalt für Luft und Raumfahrt) (Fig. 1; Table 1). The DLR also provided all images geometrically adjusted to reference levels of sea level (0 m elevation). This procedure ensured that the coastline, where at sea level, has no range displacement or layover errors. Thus, the coastlines are correct on map projections and match on the mosaics. However, within the SAR images, all elevations above this level are subject to terrain distortion. Because the early Landsat images have unstable internal geometry, we registered the Landsat images to the ERS images. To co-register ERS images, we used the furnished latitude and longitude coordinates based on orbital parameters. Previous investigations (Lucchitta and others, 1995) showed that images coregistered by furnished coordinates may have relative maximum ground location errors of 50 m (Roth and others, 1993). Compressing the images to 25 m/pixel by averaging squares of four pixels reduced speckle on the radar images. Noisy data were also removed by applying adaptive box filters described in Eliason and McEwen (1990). We enhanced the Landsat images to bring out details in the ice-shelf fronts by applying contrast-enhancing stretches.

After the above processing, we recorded the location of ice-shelf fronts and crevasses. For multi-temporal composites, we overlaid the mosaics taken at three different times represented by the early Landsat and two later ERS images. The colors on the composites are due to spectral reflectivity of the Landsat band and backscatter intensity on the ERS images. On Landsat images, the differences between shelf ice and sea ice are small, making it difficult to distinguish between them. On ERS images these ice types are readily distinguished. After converting the multi-temporal composites to Lambert azimuthal equal-area projections, we digitized the locations of the ice-shelf margins at different times and calculated the areas of ice lost during retreat.

GEORGE VI ICE SHELF

The George VI Ice Shelf measures about 25 000 km² (Potter and others, 1988). It receives most of its ice from the Antarctic Peninsula, whose ice streams extend into the shelf and almost reach its western margin. Ice from Alexander Island extends only a few kilometers into the shelf (Bishop and Walton, 1981; Potter and others, 1984). The ice shelf varies in thickness from about 100 m near its northern ice front to a maximum of about 500 m (Bishop and Walton, 1981; Lennon and others, 1982; Talbot, 1988). Warm-water intrusion from the Circumpolar Deep Water current from the southeast Pacific basin emerges onto the continental shelf and extends underneath the northern George VI Ice Shelf (Lennon and others, 1982; Potter and others, 1984; Potter and Paren, 1985; Talbot, 1988). The warm water contributes significantly to basal melting of the shelf (Potter and others, 1988), with a resulting average equilibrium basal melt rate of about 2 m a⁻¹ (Lennon and others, 1982; Potter and others, 1984; Potter and Paren, 1985). The basal melt rate at the ice front

was estimated to be as high as 10 m a⁻¹ (Lennon and others, 1982).

The British Graham Land Expedition visited Cape Jeremy in 1936 and reported that shelf ice filled George VI Sound (Fig. 2) and was broken by rifts which were floored by sea ice (Fleming and others, 1938). This statement has been interpreted to indicate that the sound was filled with shelf ice to Cape Jeremy (Doake, 1982). A 1979 sketch map (U.S. Geological Survey, 1979) shows the ice-shelf front extending from Niznik Island southwestward across the sound. The shelf south of the front is occupied by broken shelf segments. This portrayal was based on the early but unenhanced Landsat images, which showed the position of the ice front poorly. Doake (1982) commented that it was difficult to locate the true ice-shelf front because of the fragmented shelf. The frontal position as shown on this sketch map is reproduced in most subsequent articles discussing the George VI Ice Shelf (Bishop and Walton, 1981; Lennon and others, 1982). Our contrast-stretched Landsat image of 1974 depicts the ice-shelf front clearly and shows that the previously published front positions were incorrect; the front extended from just north of Niznik Island westward straight across the sound to Alexander Island (Fig. 2). By 1974, the area north of this front had cleared of the rifted icebergs and shelf segments reported by the 1936 Fleming expedition. If the shelf in 1936 indeed extended all the way to Cape Jeremy, this clearing of rifted ice would mean a 40 km retreat of the shelf between 1936 and 1974.

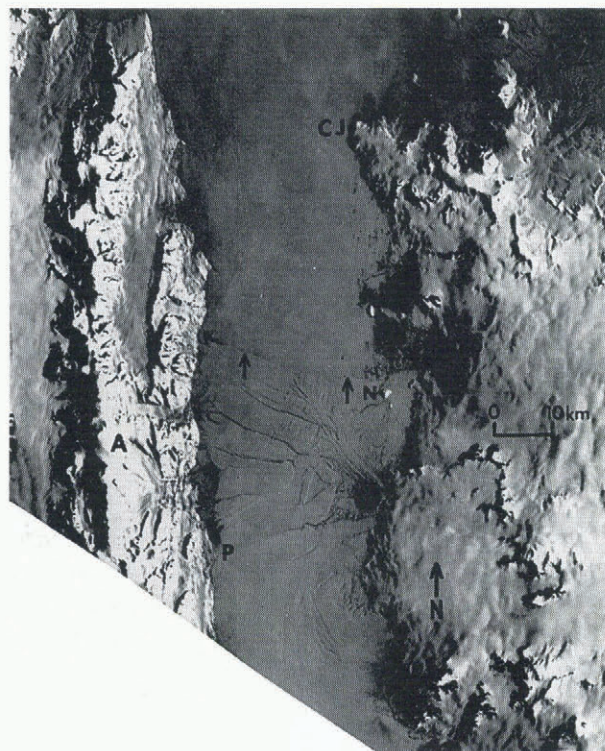


Fig. 2. Excerpt of Landsat image, 6 January 1974, showing George VI Sound and covering northern margin of George VI Ice Shelf. Arrows denote location of ice-shelf front. A, Alexander Island; CJ, Cape Jeremy; N, Niznik Island; P, polynya.

By 1974, as shown on maps and observed by Doake (1982), the region behind the front was again occupied by complexly divided large shelf segments separated by rifts, including the fractured tongue of an unnamed glacier. Lennon and others (1982) report on ice-front retreats

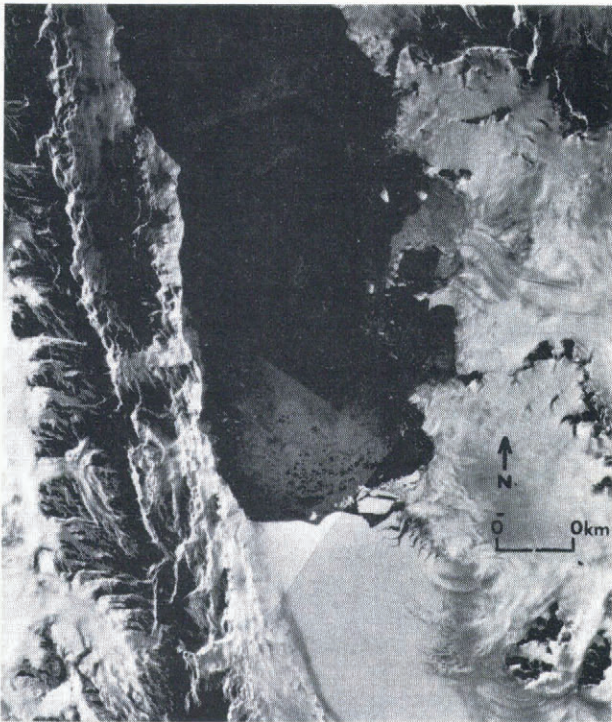


Fig. 3. Excerpt of 15 October and 13 November 1995 ERS-1 image mosaic covering northern margin of George VI Ice Shelf. Ice-shelf margin has retreated to south of the polynya shown in Figure 2.

observed in 1977, 1979 and 1981. Potter and others (1988) show the location of the 1983 front as a few km north of that shown on our ERS images. By July 1992, as seen on the earlier ERS image, the front had retreated 20–30 km from the 1974 position, and all the rifted ice-shelf segments and the fractured ice-stream tongue had broken out; the region was completely cleared of the 1974 shelf ice (Fig. 3). The front had retreated beyond the southern margin of a conspicuous polynya at the west side of the sound that was already open in 1974 (Fig. 2) and that has been mentioned in several reports as the only ice-free area near the northern ice front

(Lennon and others, 1982; Potter and Paren, 1985; Potter and others, 1988). This polynya is now gone due to shelf retreat, and our ERS radar images show no trace of it in the sea ice. Our investigation shows that a total of 906 km² of ice was lost between 1974 and 1992, amounting to an average of about 50 km² a⁻¹ (Fig. 4; Table 2).

Table 2. Areas and average ice loss for George VI and Wilkins Ice Shelves

Location	Dates	Area loss	Average retreat
		km ²	km ² a ⁻¹
George VI Ice Shelf	6 Jan 1974–24 Jul 1992	906	49
George VI Ice Shelf	24 Jul 1992–15 Oct 1995	87	27
Wilkins Ice Shelf	27 Jan 1990*–30 Jul 1992	796	318
Wilkins Ice Shelf	30 Jul 1992–21 Oct 1995	564	175

* Assumes ice front on Landsat image of 27 January 1990 of Vaughan and others (1993) is in same position as that seen on Landsat image of 9 January 1974.

By October 1995 (ERS image), an additional 6 km had calved on the east side of the shelf. The area lost is 87 km², or an average of about 30 km² a⁻¹ (Fig. 4; Table 2). Overall, the shelf behind the 1995 front is less rifted than that behind earlier frontal positions, except for a region along the east side of the shelf, where large crevasses already existed in 1974.

Potter and Paren (1985) estimate that the ice-shelf front between 1974 and 1979 lost about 25 km³ by calving, or an average of 5 km³ a⁻¹, whereas annual equilibrium loss would be only about 0.3 km³. Assuming a frontal ice thickness of about 100 m, the area lost between 1974 and 1979 would average 50 km² a⁻¹. Our retreat rates of about 50 km² a⁻¹ (1974–92) and about 30 km² a⁻¹ (1992–95) agree reasonably well with their estimate. Our data confirm that the average retreat rate significantly outpaces the hypothetical advance rate of a stable front and show that rapid retreat continued through 1995.

Vaughan and Doake (1996) define an ice shelf that is no longer viable as one that will suffer progressive retreat, via a series of small calving events occurring each year over a period of many years, without substantial readvance. Normal calving, by contrast, follows significant readvance of the ice shelf. Our observations show that the George VI Ice Shelf has undergone a persistent retreat over at least the last 20 years and perhaps since 1936, without any significant observable readvance. Thus, it fits Vaughan and Doake's definition, and we may indeed be witnessing the first stages of disintegration.

WILKINS ICE SHELF

The Wilkins Ice Shelf has an area of about 16 000 km² (Vaughan and others, 1993). It is fed mostly by in situ accumulation, like the Larsen Ice Shelf on the northeast side of the peninsula (Vaughan and others, 1993), but unlike the George VI and Wordie Ice Shelves (Doake and Vaughan, 1991), which are fed by glaciers. The middle of the shelf is very low, but Vaughan and others (1993) mapped a topographic bulge along the shelf's western margin, where most of the accumulation appears to occur.

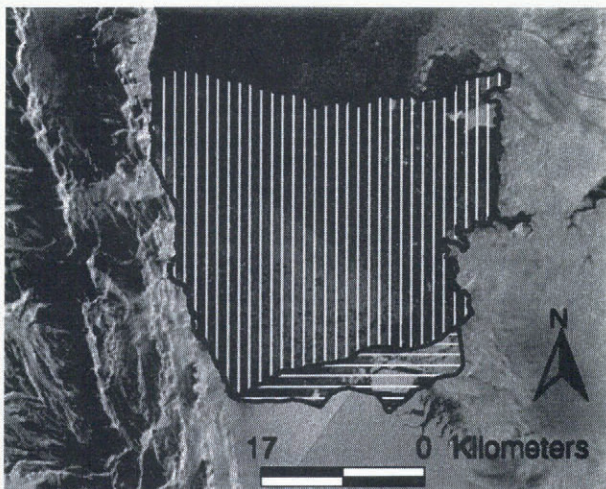


Fig. 4. Areas of retreat. Vertical hachures (906 km²) show retreat from Landsat 1974 ice-shelf front (upper boundary) to ERS-1 1992 front (middle boundary). Horizontal hachures (87 km²) show retreat from ERS-1 1992 front to 1995 front (lower boundary). Diagram is superimposed on ERS-1 image mosaic of 15 October and 13 November 1995.

The Wilkins Ice Shelf has been studied relatively little. Radio-echo sounding of the late 1960s and early 1970s (Smith, 1972; Crabtree, 1983) was largely unsuccessful. Velocity measurements (about 60 m a^{-1}) were made near the center of the shelf in 1972–73 (Vaughan and others, 1993), and a hole was drilled in that area (Swithinbank, 1988). The most comprehensive report is by Vaughan and others (1993), who looked at the shelf using a variety of remote-sensing techniques and reviewed previously acquired data within the context of their investigation. They discussed the morphology of the shelf based on Landsat images and Geosat altimeter data. They also investigated the ice-front positions on Landsat images of 1973, 1986 and 1990 and found them stable for the two preceding decades; the ice front on all Landsat images up to that time showed no significant advance or retreat. However, our ERS images show that by 1992 a significant change had occurred.

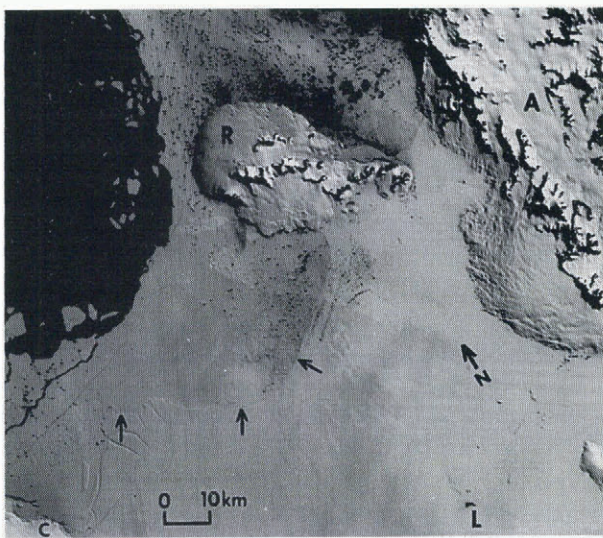


Fig. 5. Landsat image, 9 January 1974, covering northern margin of Wilkins Ice Shelf. Arrows denote location of ice-shelf front. Note extensive sea-ice cover, even though image was acquired in summer. A, Alexander Island; C, Charcot Island; R, Rothschild Island; L, lake/hole in ice shelf of Vaughan and others (1993).

Our Landsat image of January 1974 shows that the northern margin of the Wilkins Ice Shelf extended from Rothschild Island near the Alexander Peninsula to Charcot Island farther west (Fig. 5). The ice-shelf front had a conspicuous promontory projecting north near Charcot Island, and a bay extending south near Rothschild Island. By 1992 the front had retreated by about 10 km, the promontory had disappeared and the bay was enlarged (Fig. 6). Armadas of sharp-edged tabular icebergs were visible in front of the shelf, suggesting recent break-up. Several of the icebergs are larger than 1 km by 10 km, similar in size to tabular icebergs that were observed in the early stages of break-up of the western part of the Wordie Ice Shelf (Doake and Vaughan, 1991). The icebergs are close to the shelf front, not far removed from their pre-calving position. By 1995 (ERS image), the front retreated another 8–10 km, further enlarging the bay near Rothschild Island and shedding a new set of icebergs (Fig. 7). Most of these newer icebergs are not as sharply delineated by straight edges as those from the earlier iceberg discharge; they show more irregular boundaries



Fig. 6. Excerpt of ERS-1 image mosaic, 30 July 1992, covering Wilkins Ice Shelf. Note tabular icebergs calving off northern margin at top of image. L, lake/hole in ice shelf.

and a greater range in size. Large rifts developed behind the new front, lining up with rifts that already existed in the 1974 Landsat image. Our investigation showed that between 1990 and 1992 the shelf lost 796 km^2 , at an average rate of about $320 \text{ km}^2 \text{ a}^{-1}$, assuming that the position of 1990 (Vaughan and others, 1993) matches that of 1974 (Fig. 8; Table 2). Between 1992 and 1995 the shelf lost 564 km^2 of ice, at an average rate of about $180 \text{ km}^2 \text{ a}^{-1}$.



Fig. 7. Excerpt of ERS-1 image mosaic, 21 October 1995, covering Wilkins Ice Shelf. Note tabular icebergs north of new set of more irregular icebergs. Next to ice-shelf margin is sea ice with narrow iceberg slivers. Also note new rifts. L, lake/hole in ice shelf.

Near the northern shelf center a lake, or a hole in the shelf, persisted for the last two decades (Fig. 5). The lake/hole coincides with a local depression almost at sea level (Vaughan and others, 1993). The lake/hole appears to have a similar size on our 1992 ERS image to that on previous Landsat images, but is surrounded by ice with lower backscatter characteristics, perhaps seasonally wet ice. Similar-looking dark splotches are seen farther east on both ERS images. Ice-surface melt pools noted by Vaughan and others (1993) near Rothschild Island also persist on our images. The Wilkins Ice Shelf had the longest melt season among four shelves on the peninsula investigated by Ridley (1993, fig. 4). Swithinbank (1988) comments that the ice shelf may be unusually thin and that the failure to acquire radio-echo sounding returns could indicate that parts of the ice shelf are brine-soaked to sea level. A hole drilled with a hand auger in January 1972 penetrated soaked snow and found a water table at a depth of 5.5 m. All of these observations suggest that the shelf may be subject to rapid break-up.

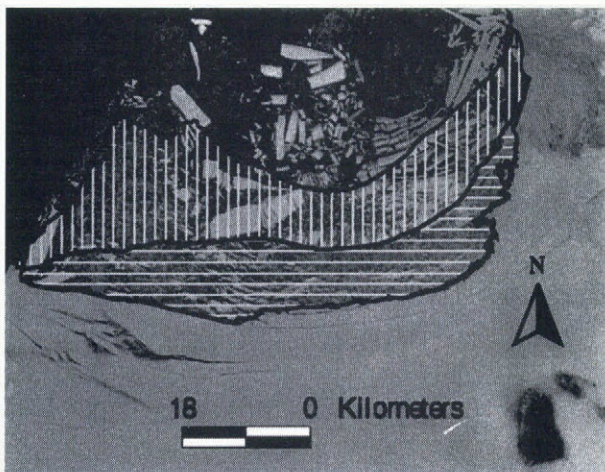


Fig. 8. Areas of retreat. Vertical hachures (796 km^2) show retreat from Landsat 1974 ice-shelf front (upper boundary) to ERS-1 1992 front (middle boundary). Horizontal hachures (564 km^2) show retreat from ERS-1 1992 to 1995 front (lower boundary). Diagram is superimposed on ERS-1 image of 21 October 1995.

Vaughan and others (1993) speculate that the Wilkins ice front is likely to decay by normal calving processes and is unlikely to undergo the sudden disintegration seen on the Wordie Ice Shelf, at least until the calving front decouples from the fringing islands. However, they caution that changes in accumulation and basal melting rates may dominate any dynamic effect. The basal melt rate of the shelf is assumed to be $1\text{--}2 \text{ m a}^{-1}$, similar to that of the George VI Ice Shelf, because it receives the same warm-water influx of the Circumpolar Deep Water current (Potter and others, 1988). Talbot (1988) suggests that this warm water may contribute to the recent disintegration of ice shelves. Also striking is a major decrease in sea-ice extent in the Bellingshausen Sea from late 1988 through early 1991 (Jacobs and Comiso, 1993), coincident with the warmest years on record at the Antarctic Peninsula (Morrison, 1990). These authors observed a record retreat of sea ice in March 1989, and their figure 2 shows that in February of 1989–91 most of the sea ice off the northern margin of the Wilkins Ice Shelf was missing. Whether and how this sea-ice loss has affected the ice-shelf margin remains to be explored.

WARMING TREND

The disintegration of Antarctic ice shelves has been attributed to a recent atmospheric warming trend (Vaughan and Doake, 1996). Morrison (1990) showed that 1989 was the warmest year on record at Rothera Station near Marguerite Bay. She states that the warming is caused by a lack of cold periods, particularly in the winter months. Ridley (1993) counted the number of days showing melt features over ice shelves on the peninsula and elsewhere using passive microwave sensors. He concluded that between 1978 and 1991 the number of melt days on ice shelves of the Antarctic Peninsula has increased by about 1 day per year. Satellite passive microwave data show a record decrease in sea-ice extent in the Bellingshausen Sea from mid-1988 through early 1991 (Jacobs and Comiso, 1993). Thompson and others (1994), from oxygen-isotope analysis of ice-core records on the Dyer Plateau, established a prominent warming trend since 1950, with the last two decades being the warmest in 500 years. At Faraday Station, a warming trend of about 2.5°C has been measured since 1945 (King, 1994).

The west side of the Antarctic Peninsula is about $6\text{--}7^\circ\text{C}$ warmer than the east side (Martin and Peel, 1978; Reynolds, 1981), suggesting that ice shelves on the west side are more likely to disintegrate. Mercer (1978) placed the limit of ice-shelf viability near the January 0°C air-temperature isotherm, whereas Vaughan and Doake (1996) placed the limit at the 5°C mean annual air-temperature isotherm, after observing that this isotherm coincided reasonably well with non-viable shelves. Reynolds (1981) plotted a contour map of mean annual air temperatures over the Antarctic Peninsula between 1965 and 1980, based on temperatures in ice cores taken 10 m below the surface. Assuming a warming trend of about 2.5°C as reported by King (1994), Reynolds' -7.5°C isotherm would be near the present-day -5°C isotherm (Vaughan and Doake, 1996), and therefore his -7.5°C isotherm designates the location of the possible present limit of ice-shelf viability.

The northern margin of the George VI Ice Shelf falls exactly on Reynolds' -7.5°C isotherm and thus may be at its limit of viability. The northern margin of the Wilkins Ice Shelf lies at Reynolds' (1981) -8°C isotherm, south of, but close to, the -7.5°C isotherm. The coincidence of these isotherms with our observed ice-shelf retreats strongly suggests that the retreats are linked to this atmospheric warming trend. Our observations thus bear out Mercer's (1978) prediction of potential ice-shelf loss on the Antarctic Peninsula.

CONCLUSION

The effects of the warming trend in the Antarctic Peninsula appear to be spreading south. We are now witnessing significant retreat of the northern margins of the George VI Ice Shelf, and a dramatic and fast disintegration of the northern margin of the Wilkins Ice Shelf. These two shelves mark the southernmost occurrence of ice-shelf retreat documented. Our observations support previous predictions (Mercer, 1978; Vaughan and others, 1993; Vaughan and Doake, 1996) that these shelves are the most likely to break up if the warming trend continues.

ACKNOWLEDGEMENTS

We are grateful for helpful reviews by B. Raup, J. Kargel

and H. Rott. The research was funded by the Global Change and Climate History Program of the U.S. Geological Survey. The European Space Agency provided the ERS images free of charge.

REFERENCES

- Bishop, J. F. and J. L. W. Walton. 1981. Bottom melting under George VI Ice Shelf, Antarctica. *J. Glaciol.*, **27**(97), 429–447.
- Crabtree, R. D. 1983. *Alexander Island*. British Antarctic Survey, Cambridge. (British Antarctic Territory ice thickness map, Series BAS 500 R Sheet 1, Scale 1:500 000.)
- Doake, C. S. M. 1982. State of balance of the ice sheet in the Antarctic Peninsula. *Ann. Glaciol.*, **3**, 77–82.
- Doake, C. S. M. and D. G. Vaughan. 1991. Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming. *Nature*, **350**(6316), 328–330.
- Eliason, E. M. and A. S. McEwen. 1990. Adaptive box filters for removal of random noise from digital images. *Photogramm. Eng. Remote Sensing*, **56**(4), 453–458.
- Fleming, W. L. S., A. Stephenson, B. B. Roberts and G. C. L. Bertram. 1938. Notes on the scientific work of the British Graham Land Expedition, 1934–37. *Geogr. J.*, **91**(6), 508–532.
- Jacobs, S. S. and J. C. Comiso. 1993. A recent sea-ice retreat west of the Antarctic Peninsula. *Geophys. Res. Lett.*, **20**(12), 1171–1174.
- King, J. C. 1994. Recent climate variability in the vicinity of the Antarctic Peninsula. *Int. J. Climatol.*, **14**(4), 357–369.
- Lennon, P. W., J. Loynes, J. G. Paren and J. R. Potter. 1982. Oceanographic observations from George VI Ice Shelf, Antarctic Peninsula. *Ann. Glaciol.*, **3**, 178–183.
- Lucchitta, B. K., C. E. Rosanova and K. F. Mullins. 1995. Velocities of Pine Island Glacier, West Antarctica, from ERS-1 SAR images. *Ann. Glaciol.*, **21**, 277–283.
- Martin, P. J. and D. A. Peel. 1978. The spatial distribution of 10 m temperatures in the Antarctic Peninsula. *J. Glaciol.*, **20**(83), 311–317.
- Mercer, J. H. 1978. West Antarctic ice sheet and CO₂ greenhouse effect: a threat of disaster. *Nature*, **271**(5643), 321–325.
- Morrison, S. J. 1990. Warmest year on record on the Antarctic Peninsula? *Weather*, **45**(6), 231–232.
- Potter, J. R. and J. G. Paren. 1985. Interaction between ice shelf and ocean in George VI Sound, Antarctica. In Jacobs, S. S., ed. *Oceanology of the Antarctic continental shelf*. Washington, DC, American Geophysical Union, 35–58. (Antarctic Research Series 43.)
- Potter, J. R., J. G. Paren and J. Loynes. 1984. Glaciological and oceanographic calculations of the mass balance and oxygen isotope ratio of a melting ice shelf. *J. Glaciol.*, **30**(105), 161–170.
- Potter, J. R., M. H. Talbot and J. G. Paren. 1988. Oceanic regimes at the ice fronts of George VI Sound, Antarctic Peninsula. *Continental Shelf Res.*, **8**(4), 347–362.
- Raper, S. C. B., T. M. L. Wigley, P. R. Mayes, P. D. Jones and M. J. Salinger. 1984. Variations in surface air temperatures. Part 3: The Antarctic, 1957–82. *Mon. Weather Rev.*, **112**(7), 1341–1353.
- Reynolds, J. M. 1981. The distribution of mean annual temperatures in the Antarctic Peninsula. *Br. Antarct. Surv. Bull.* 54, 123–133.
- Ridley, J. 1993. Surface melting on Antarctic Peninsula ice shelves detected by passive microwave sensors. *Geophys. Res. Lett.*, **20**(23), 2639–2642.
- Roth, A., T. Hugel, D. Kosman, M. Matschke and G. Schreier. 1993. Experiences with ERS-1 SAR compositional accuracy. *Proc. IEEE*, **81**, Vol. 3, 1450–1452.
- Rott, H., P. Skvarca and T. Nagler. 1996. Rapid collapse of northern Larsen Ice Shelf, Antarctica. *Science*, **271**(5250), 788–792.
- Skvarca, P. 1993. Fast recession of the northern Larsen Ice Shelf monitored by space images. *Ann. Glaciol.*, **17**, 317–321.
- Skvarca, P. 1994. Changes and surface features of the Larsen Ice Shelf, Antarctica, derived from Landsat and Kosmos mosaics. *Ann. Glaciol.*, **20**, 6–12.
- Smith, B. M. E. 1972. Airborne radio echo sounding of glaciers in the Antarctic Peninsula. *Br. Antarct. Surv. Sci. Rep.* 72.
- Swithinbank, C. 1988. Antarctica. *U.S. Geol. Surv. Prof. Pap.* 1386-B, B1–B138.
- Talbot, M. H. 1988. Oceanic environment of George VI Ice Shelf, Antarctic Peninsula. *Ann. Glaciol.*, **11**, 161–164.
- Thompson, L. G. and 7 others. 1994. Climate since AD 1510 on Dyer Plateau, Antarctic Peninsula: evidence for recent climate change. *Ann. Glaciol.*, **20**, 420–426.
- United States Geological Survey (USGS). 1979. *Palmer Land, north part*. Reston, VA, U.S. Geological Survey. (Antarctica sketch map, Scale 1:500 000.)
- Vaughan, D. G. and C. S. M. Doake. 1996. Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature*, **379**(6563), 328–331.
- Vaughan, D. G., D. R. Mantripp, J. Sievers and C. S. M. Doake. 1993. A synthesis of remote sensing data on Wilkins Ice Shelf, Antarctica. *Ann. Glaciol.*, **17**, 211–218.
- Ward, C. G. 1995. Mapping ice front changes of Müller Ice Shelf, Antarctic Peninsula. *Antarct. Sci.*, **7**(2), 197–198.