Climatic trend and the retreat and disintegration of ice shelves on the Antarctic Peninsula: an overview

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Observations of the retreat and disintegration of ice shelves around the Antarctic Peninsula during the last three decades and associated changes in air temperature, measured at various meteorological stations on the Antarctic Peninsula, are reviewed. The climatically induced retreat of the northern Larsen Ice Shelf on the east coast and of the Wordie, George VI, and Wilkins ice shelves on the west coast amounted to about 10 000 km^2 since the mid-1960s. A summary is presented on the recession history of the Larsen Ice Shelf and on the collapse of those sections north of Robertson Island in early 1995. The area changes were derived from images of various satellites, dating back to a late 1963 image from the recently declassified US Argon space missions. This photograph reveals a previously unknown, minor advance of the northern Larsen Ice Shelf before 1975. During the period of retreat a consistent and pronounced warming trend was observed at the stations on both east and west coasts of the Antarctic Peninsula, but a major cause of the fast retreat and final collapse of the northernmost sections of the Larsen Ice Shelf were several unusually warm summers. Temperature records from the nearby station Marambio show that a positive mean summer temperature was reached for the first time in 1992–93. Recent observations indicate that the process of ice shelf disintegration is proceeding further south on both sides of the Antarctic Peninsula.

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Introduction

Few events in polar glaciology have attracted so much attention as the retreat of ice shelves on the Antarctic Peninsula, especially the disintegration and calving events which occurred in early 1995 on the Larsen Ice Shelf. These events provide an excellent basis for studying the mechanisms of ice shelf disintegration but their environmental impact has still to be assessed.

The analyses of temperature and sea ice data since the mid-1940s indicate a slight warming trend for Antarctica and the surrounding oceans associated with the reduction in the sea ice extent (Jacka & Budd 1998). The increase of surface air temperatures is particularly evident in the region of the Antarctic Peninsula. King (1994) reports a significant warming for the west coast, which is of similar magnitude as the trend on the east coast (Skvarca et al. 1998). Furthermore, the longest instrumental temperature record available from Antarctica (Orcadas, South Orkney Islands) shows that the last two decades were the warmest in this century (Hoffmann et al. 1997) and the record derived from an ice core from the Dyer Plateau reveals that these two decades were among the warmest since 1510 AD (Thompson et al. 1994).

Twenty years ago Mercer (1978) predicted the disintegration of ice shelves along the Antarctic Peninsula in response to a warming trend which may result from an enhanced greenhouse effect. Since Mercer's statement several ice shelves in this region have retreated to some extent, some quite significantly. Wordie Ice Shelf, located on the west coast, was the first to suffer major retreat (Doake & Vaughan 1991), while the northern Larsen Ice Shelf on the east coast retreated steadily after 1975 (Skvarca 1993; Rott, Skvarca et al.

1995) until two sections collapsed in early 1995 (Rott, Skvarca et al. 1996; Vaughan & Doake 1996; Rott, Rack et al. 1998). The disintegration of ice shelves seems to be proceeding further south along the west coast. More recently, the Wilkins Ice Shelf, reported previously to be in rather stable condition (Vaughan et al. 1993), has started to retreat at its northern margin (Lucchitta & Rosanova 1998).

In this paper we present an overview of ice shelf retreat and disintegration coinciding with a period of atmospheric warming. Emphasis is on the Larsen Ice Shelf due to the magnitude and rapidity of changes and the possibility that this disintegration will continue further south, as concluded by Doake et al. (1998) from model calculations on the stability of the ice shelf.

Atmospheric warming

In order to describe the recent climatic conditions on the Antarctic Peninsula, five stations located in different climatic regimes have been selected (Fig. 1): a) Orcadas (60.73° S, 44.73° W) in the South Orkney Islands, influenced by low pressure systems of the Drake Passage; b) Esperanza (63.40° S, 57.00° W) at the northern tip of the Antarctic Peninsula; c) Vernadsky (formerly Faraday; 65.25° S, 64.27° W) on the west coast and within the maritime climate affected by the sea ice extent in Bellingshausen Sea; d) Marambio (64.23° S, 56.62° W; 198 m asl); and e) Matienzo (64.98° S, 60.07° W). Marambio and Matienzo, representative of conditions on the Larsen Ice Shelf, are located within a pseudo-continental climate which is controlled by the persistent pack ice conditions in the Weddell Sea.

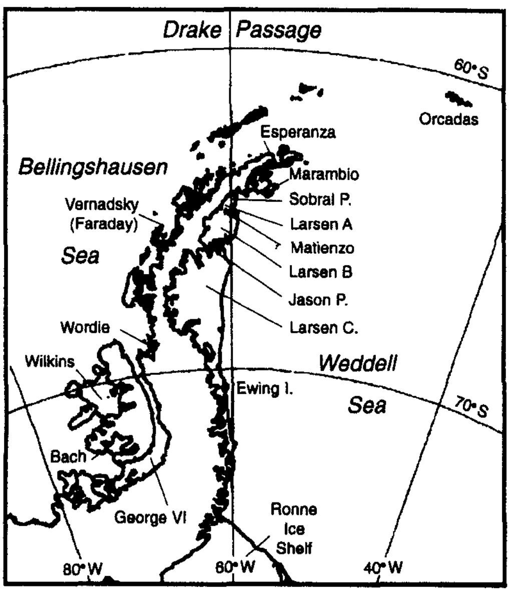

Fig. 1. Antarctic Peninsula with locations of the stations and ice shelves discussed in the text.

Instrumental meteorological observations in Antarctica started in 1903 at the station Orcadas, located on Laurie Island, South Orkney Islands. This is the longest temperature record in Antarctica and it shows a mean cooling trend of 0.4°C/decade for the period 1904–1930, which was followed by a warming trend. Hoffmann et al. (1997) noted that the difference in decadal averages of air temperature between the decades 1921–1930 and 1981–1990, which was the warmest decade, amounted to 2.1°C. They also reported an increase of 1.0°C from 1971–1980 to 1981–1990 at Orcadas, Esperanza and Marambio. A strong correlation between South Orkney Islands and the stations of the Antarctic Peninsula was indicated by Limbert (1974). Recent analyses show higher correlations with Esperanza and Marambio on the east side than with Vernadsky on the west coast (Skvarca et al. 1998). The main reason for this is that the warmest period recorded at Vernadsky, 1970–75, did not correspond to the warmest period recorded at the other stations (Fig. 2). Major climatic signals which affected the Antarctic Peninsula since 1960 are evident in all temperature series, such as the low temperature in 1980, the maximum in 1989 and the trend of above average temperatures after 1980 (Fig. 2). The year 1989, which had the highest mean temperature on the west coast (Morrison 1990), coincided with a minimum sea ice extent in the Bellingshausen Sea (Jacobs & Comiso 1993). The coupling between temperatures and sea ice extent in this region was discussed by King (1994).

For the station Orcadas the linear fit shows a temperature increase of 0.026°C/year for the period 1930–1997, based on up-dated mean annual temperatures. This is a smaller trend than at Vernadsky, which may be considered representative for the west coast, with 0.056°C/year (2.5°C total increase) during the period 1945–1990 (King 1994). However, considering the period 1971–1997 the trend at Marambio of 0.050°C/year (1.4°C total increase) is comparable to that at

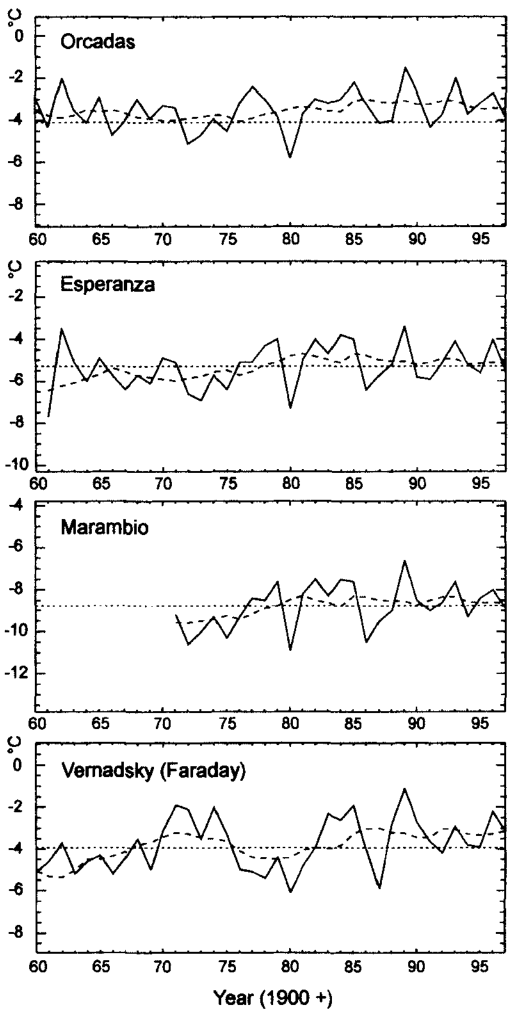

Fig. 2. Mean annual temperatures at the stations Orcadas, Esperanza and Vernadsky (Faraday) from 1960 to 1997, and at Marambio from 1970 to 1997, with 9-year moving means (after Skvarca et al. 1998).

Vernadsky. The increase at Esperanza on the northernmost tip of the peninsula was somewhat smaller (0.035°C/year) than at Marambio (1971–1997), despite a strong correlation of the mean annual temperatures of both stations. Skvarca et al. (1998) found that, according to the Kendall–Mann test, the trends are significant at 95% for the 1930–1997 Orcadas series and for the summer temperature series of Esperanza and Marambio. It can be concluded that the recent atmospheric warming has also affected the north-eastern region of the Antarctic Peninsula.

Retreat and disintegration of ice shelves on the Antarctic Peninsula

Only the decay of parts of the four largest ice shelves on the Antarctic Peninsula (Fig. 1) is discussed below. Müller and Jones ice shelves, the two northernmost ice shelves on the west coast, are also in retreat; however they are quite small, and the Bach Ice Shelf did not show changes in extent (Vaughan & Doake 1996). Wordie Ice Shelf, affected by enhanced fracturing probably induced by atmospheric warming, was the first on which disintegration was observed at the end of the 1980s. It decreased by 1300 km^2 in area between 1966 and 1989 (Doake & Vaughan 1991). The analysis of radar images showed that the retreat of this ice shelf has continued (Vaughan 1993).

For the northern margin of the George VI Ice Shelf, Lucchitta & Rosanova (1998) derived an area loss of 993 km^2 from 1974 to 1995. For the Wilkins Ice Shelf (also at its northern part) they measured a decrease of 1360 km^2 between 1990 and 1995.

However, the most remarkable changes and area loss during the last two decades were observed on the Larsen Ice Shelf, the largest ice shelf on the Antarctic Peninsula. Its northernmost limit is currently located at about 65° S. Fig. 1 indicates different sections referred to by Vaughan & Doake (1996): Larsen A (Sobral Peninsula to Robertson Island); Larsen B (Robertson Island to Jason Peninsula); and Larsen C (Jason Peninsula to Ewing Island). While no significant changes occurred between 1957 and 1986 in its northernmost section, which was confined within the Prince Gustav Channel (Fig. 3) (Skvarca 1993), this section disappeared almost completely during 1986–1997, with a decrease in area of 837 km^2 during this period (Rott, Rack et al. 1998). From 1975 to 1986 the ice shelf sections between Cape Longing and Seal Nunataks (Fig. 4) retreated by about 540 km^2 (Skvarca 1993), and from 1986 to 1997 by another 2624 km^2 as Rott, Rack et al. (1998) measured from time series of ERS-1/2 SAR images. During the same period Larsen B lost 2163 km^2 in area, mainly due to the calving event in 1995 which gave rise to the iceberg A32 (Fig. 3), 1720 km^2 in area (Rott, Skvarca et al. 1996). A further decrease of about 110 km^2, measured from a Radarsat image of 25 April 1998, occurred as a result of calving in this section between February and March 1998, as revealed by NOAA-AVHRR images. To sum up, the Larsen Ice Shelf has diminished by about 6300 km^2 since late 1975. For the four ice shelves (Wordie, George VI, Wilkins and Larsen) the total area lost by climatically induced retreat and disintegration during the observation periods (1966–1989, 1974–1995, 1990–95 and 1975–1998, respectively) amounted to around 10 000 km^2.

Due to the rapidity of the event the disintegration of northernmost sections of the Larsen Ice Shelf was remarkable. To illustrate the Larsen disintegration and calving of 1995, two NOAA-AVHRR images are shown (Figs. 3a, b). These images provide an overview of the ice shelf before and after the event. The disintegration process north of Seal Nunataks and the calving between Robertson Island and Jason Peninsula were analysed in detail by means of ERS-1 SAR images (Rott, Skvarca et al. 1996), and were observed directly by personnel at the station Matienzo, located on the Larsen Nunatak. They reported intense ice-quakes from 23 to 30 January, the main period of fracturing and disintegration. During this period intense westerly winds and unusually warm air temperatures were also observed. The satellite images show the presence of meltwater features on the ice shelf, which is typical for warm summers; 1994–95 was the warmest summer of the 28 year record of the station Marambio (Rott, Skvarca et al. 1996; Skvarca et al. 1998).

Fig. 4 presents the time series of retreat for Larsen Inlet and Larsen A. With the exception of one date (23 October 1994), the frontal positions shown were derived from satellite imagery extending back to 1963. The general retreat of the ice front from 1975 onwards and the recent collapse have already have been described in detail by Skvarca (1993), Rott, Skvarca et al. (1995, 1996), Vaughan & Doake (1996) and Rott, Rack et al. (1998). This information is presented here in order to show the complete sequence of the temporal and spatial changes of this ice shelf section. After an advance between 1963 and 1975, observed by means of recently declassified US military satellite data (Argon), this section re-

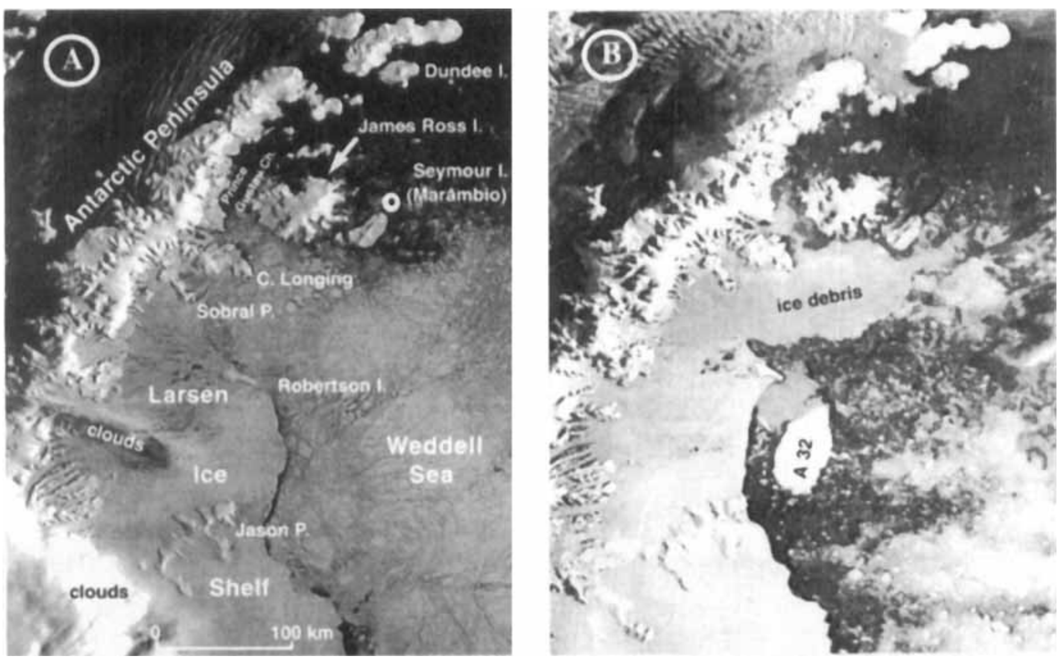

Fig. 3. NOAA-12 AVHRR (Advanced Very High Resolution Radiometer) images of the northern Antarctic Peninsula showing all sections of the Larsen Ice Shelf which were affected by the 1995 events. A: 9 January 1995, prior to the events. B: 23 February 1995, after the events. This image shows the ice shelf between Sobral Peninsula and Robertson Island fragmented into thousands of small icebergs which, together with ice debris, formed a large plume extending 200 km towards Seymour Island. The iceberg A32 had separated parallel to the ice edge due to the strong north-westerly winds (Rott, Skvarca et al. 1996). The abundance of meltwater on the ice shelf surface (dark patches) resulting from the exceptionally warm summer 1994–95 (Fig. 5) can be observed on both images to extend well south of Robertson Island.

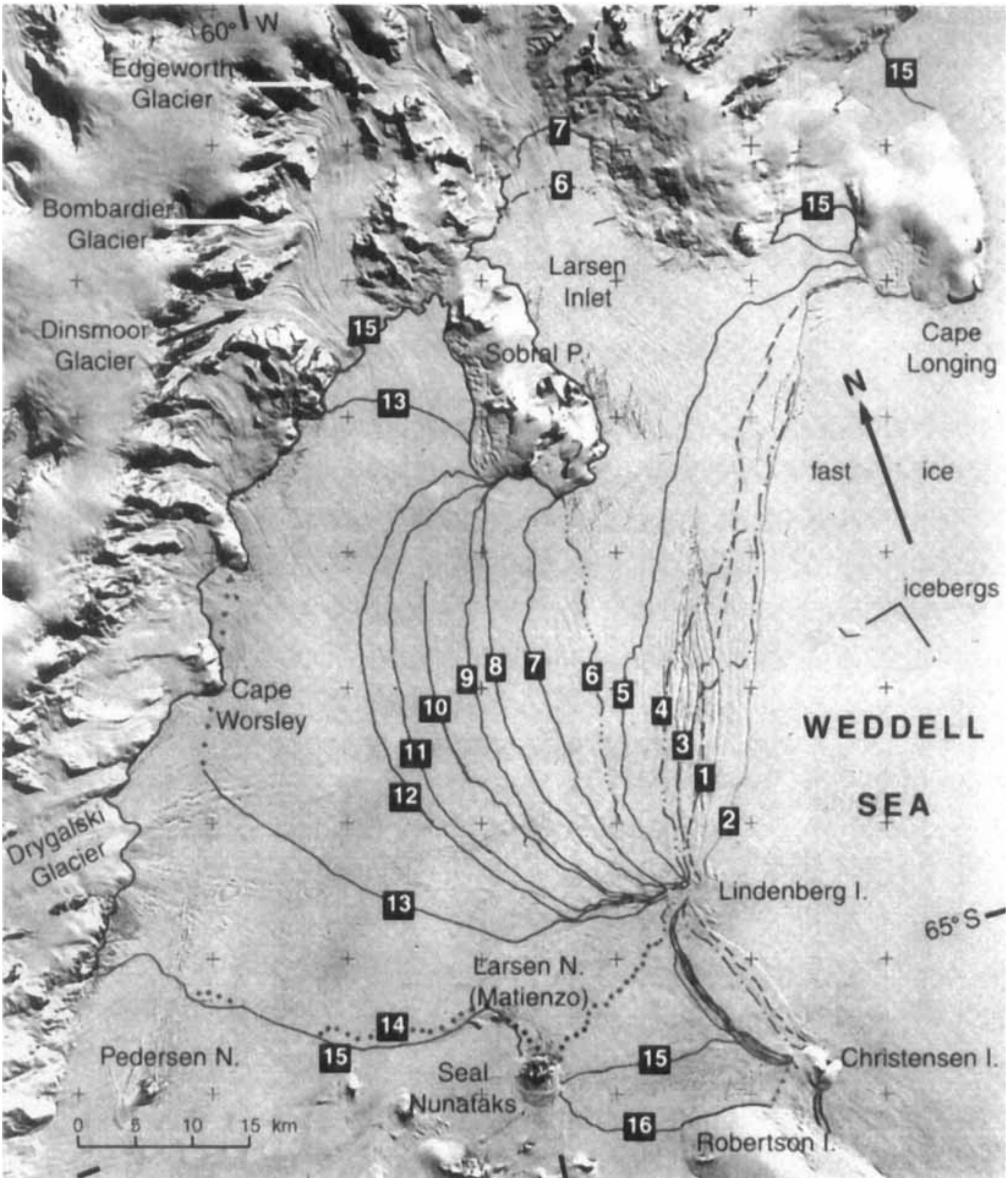

Fig. 4. Section of the Kosmos KATE-200 photograph taken on 3 October 1975 (Skvarca 1993), showing superimposed the ice front positions (numbers in black boxes) in different years. 1: The ice front position indicated by dashed line is new information and corresponds to 30 August 1963 Argon photograph (Frame 115, Mission 9058A), recently declassified by US: 2: 3 October 1975; 3: 4 November 1978; 4: 20 February 1979; 5: 1 March 1986; 6: 5 November 1989 (after Skvarca 1993); 7: 8 December 1992; 8: 12 January 1993; 9: 16 February 1993; 10: 23 October 1994; 11: 25 January 1995; 12: 28 January 1995; 13: 30 January 1995 (after Rott, Skvarca et al. 1996); 14: 8 March 1995; 15: 2 March 1997; 16: July, 1997 (after Rott, Rack et al. 1998). The front positions after 1992 were derived from ERS-SAR, except for position 10, surveyed with GPS. The positions prior to 1992 correspond to Landsat TM (positions 5 and 6), Landsat MSS (positions 3 and 4), ARGON (1) and Kosmos KATE-200 (2). (After Skvarca 1993; published by courtesy of Sojuzkarta.)

treated since 1975. The advance followed a cold period which affected all of the Antarctic Peninsula between 1956 and 1959 (Limbert 1974).

Discussion

Mercer (1978) assumed the 0°C January air temperature isotherm as the climatic limit for the existence of ice shelves, whereas according to Reynolds (1981) the critical limit is close to the 5°C mean annual isotherm at sea level. Vaughan & Doake (1996) discussed the migration of the northern limit of ice shelf viability in response to atmospheric warming, based on the mean annual temperature map of the Antarctic Peninsula of Reynolds (1981) and taking into account the 2.5°C air temperature increase since 1945 (King 1994). They suggested that a further increase of 1°C might trigger the decay of the George VI and Wilkins ice shelves. According to Lucchitta & Rosanova (1998), the northern margins of both ice shelves are already retreating significantly.

In the case of the Larsen Ice Shelf the southward shift of the climatic limit towards Robertson Island has been mentioned by Skvarca (1994), based on the accelerated rate of retreat north of the Seal Nunataks. It has been shown (Skvarca et al. 1998) that a warming trend similar to that occurring on the west coast is also affecting the region of the northern Larsen Ice Shelf, which is responsible for the disintegration of this ice shelf. The observed southward shift of the northern boundary of the Larsen Ice Shelf to its present position at Seal Nunataks (Fig. 4) could not be expected from the isotherms shown by Reynolds, even if the warming trend of Marambio is taken into account. Possibly the temperature map, compiled more than 20 years ago, is inaccurate due to lack of data from this region of strong gradients of surface air temperature. To understand the ongoing changes on the Antarctic Peninsula, it will, however, be important to know in detail the present climatic conditions, as well as the pattern of temporal changes during the last decades.

Continuous meteorological observations are not available for the Larsen Ice Shelf. For the station Matienzo on Larsen Nunatak temperature observations throughout the year are available only from 1961 to 1972. After that the observations continued only in summer and with some interruptions until 1985. Recent work (Skvarca et al. 1998) has shown a good correlation (correlation coefficient R = 0.90) between the summer temperatures of Matienzo and Marambio, which indicates that Marambio is representative of summer conditions on the northern Larsen Ice Shelf.

The amount of surface meltwater on ice shelves plays an important role in the fracturing process and disintegration (Doake & Vaughan 1991). Ridley (1993) concluded from the analysis of spaceborne passive microwave data of the period 1978 to 1991 that the duration of the summer melt season on the ice shelves of the Antarctic Peninsula has increased slightly during this period, at a rate of about 1 day/year. These observations are in agreement with the observations of increased surface melt in SAR images which are available from ERS-1 and ERS-2 since 1992. The pronounced increase of mean summer temperatures at Marambio is also an indicator of more intense surface melt during recent years. The linear regression of time series of mean summer temperatures at Esperanza and Marambio (Fig. 5) show a pronounced trend at both stations. However, as mentioned above, of particular importance for the Larsen Ice Shelf is the trend of 0.074°C/year observed at Marambio between the summers 1970/71 and 1997/98. The observed decrease in net surface accumulation on the northern Larsen Ice Shelf was probably caused by the increasing melt rates due to this warming trend: at the station Marambio the mean summer temperatures in the 1990s were positive twice and at Esperanza very close to or above 0°C from summer 1973–74 to the present (Fig. 5).

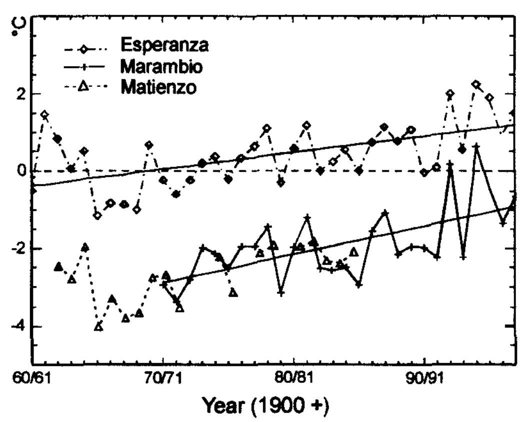

Fig. 5. Mean summer temperatures at Marambio, Esperanza and Matienzo with least-square fits for Marambio and Esperanza (reprinted from the *Annals of Glaciology* with permission of the International Glaciological Society; Skvarca et al. 1998).

During the recession phase of the northern Larsen Ice Shelf (Fig. 4) the major events of retreat and the final collapse coincided with periods of temperatures which were clearly above the average. For instance, the disintegration of the Larsen Inlet took place during the period 1987–89, which shows two peaks in mean summer temperatures (Fig. 5). The next major change in this region was the decrease of 209 km^2 in area of Larsen A (Rott, Skvarca et al. 1995) indicated by ice front positions 7 and 9 (Fig. 4), which took place in the warm summer 1992–93 when the mean summer temperature at Marambio was positive for the first time. Finally, the collapse of Larsen A, with a decrease of 1640 km^2 between November 1994 and March 1995, was associated with the highest summer temperature (+0.6 °C) of the record at Marambio. The main disintegration took place within just two days (January 28–30), when 856 km^2 of the ice shelf broke off in the form of comparatively small icebergs and drifted away (Rott, Skvarca et al. 1996).

Conclusions

The observed retreat and disintegration of the ice shelves around the Antarctic Peninsula can be taken as a clear indicator of regional climatic change. If the warming trend of the last two decades continues, the disintegration will very likely proceed further south on both sides of the Peninsula. This is also suggested by the recent observations of retreat on the Wilkins and Larsen ice shelves. The estimated total decrease in the area of the ice shelves since 1966/1975 amounts to about 10 000 km^2, 63% of which refer to the Larsen Ice Shelf. The impact of these changes on the regional oceanic and atmospheric environment has still to be assessed. As a new coastline has been exposed due to the ice shelf decay, the inland grounded ice should be monitored in detail to detect any further retreat as a potential contributor to a rise in sea level.

Acknowledgements. – Thanks are due to P. Alagia and J. L. Fornaro for assistance in producing the figures. Temperatures of Argentine stations were provided by Servicio Meteorológico Nacional, Fuerza Aérea Argentina. The Vernadsky (Faraday) data are from the British Antarctic Survey data set. This work is a contribution to the Larsen Ice Shelf Project of Instituto Antártico Argentino, Dirección Nacional del Antártico, and to Austrian Science Fund (FWF) Project No. 12923 GEO.

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