An Exceptional Winter Sea-Ice Retreat/Advance in the Bellingshausen Sea, Antarctica

J. Turner*, S. A. Harangozo, J. C. King, W. M. Connolley,
T. A. Lachlan-Cope and G. J. Marshall

British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 OET United Kingdom

[Orignial manuscript received 11 October 2002; in revised form 6 March 2003]

ABSTRACT *The exceptional sea-ice retreat and advance that occurred in the Bellingshausen Sea, Antarctica during August 1993 was the largest such winter event in this sector of the Antarctic during the satellite era. The reasons for this fluctuation of ice are investigated using passive microwave satellite imagery, ice motion vectors derived from the satellite data, in-situ meteorological reports and near-surface winds and temperatures from the European Centre for Medium-range Weather Forecasts (ECMWF) numerical weather prediction model. The ice edge retreat of more than 400 km took place near 80°W from approximately 1–15 August, although the southward migration of the ice edge was not continuous and short periods of advance were also recorded. Between 16 August and 2 September there was almost continuous sea-ice recovery. The rate of change of the ice edge location during both the retreat and advance phases significantly exceeded the southward and northward velocity components of ice within the pack, pointing to the importance of ice production and melting during this event. During the month, markedly different air masses affected the area, resulting in temperature changes from +2°C to –21°C at the nearby Rothera station. 'Bulk' movement of the pack, and compaction and divergence of the sea ice, made a secondary, but still significant, contribution to the observed advance and retreat. The ice extent fluctuations were so extreme because strong meridional atmospheric flow was experienced in a sector of the Southern Ocean where relatively low ice concentrations were occurring. The very rapid ice retreat/advance was associated with pronounced low-high surface pressure anomaly couplets on either side of the Antarctic Peninsula.*

RÉSUMÉ *[traduit par la rédaction] Le recul et l'avancée exceptionnels de la glace de mer qui se sont produits dans la mer de Bellingshausen, dans l'Antarctique, en août 1993, constituent l'événement le plus important à se produire l'hiver dans ce secteur de l'Antarctique depuis le début de l'ère des satellites. On a examiné les causes de cette fluctuation de la glace de mer à l'aide d'imagerie satellitaire en hyperfréquences passives, de vecteurs de déplacement des glaces dérivés des données de satellite, de rapports météorologiques obtenus sur place et de données sur les températures et les vents proches de la surface tirées du modèle numérique de prévision météorologique du Centre européen pour les prévisions météorologiques à moyen terme (CEPMMT). La lisière de glace a reculé plus de 400 km à environ 80° de latitude W à peu près entre le 1 août et le 15 août; toutefois, le déplacement vers le sud de la lisière de glace ne s'est pas fait de façon continue et a été interrompu par de courtes périodes d'avancée. Entre le 16 août et le 2 septembre, il y a eu rétablissement presque sans arrêt de la glace de mer. Le taux de changement de l'emplacement de la lisière de glace pendant les phases de recul et d'avancée a largement dépassé les composantes sud et nord de la vitesse de la glace au sein du pack, ce qui atteste de l'importance de la formation et de la fonte de la glace de mer pendant cet événement. Pendant le mois, des masses d'air très différents ont recouvert la région, produisant des variations de température de +2 °C à –21 °C à la station voisine de Rothera. Le déplacement d'une grande partie du pack ainsi que le tassement et la divergence de la glace de mer ont eu un effet secondaire, mais néanmoins significatif, sur l'avancée et le recul observés. Ces fluctuations aussi extrêmes de l'étendue de la glace sont attribuées à un fort courant atmosphérique méridional dans un secteur de l'océan austral où les concentrations de glace de mer étaient relativement faibles. Le recul et l'avancée très rapides de la glace de mer étaient associés à des couples d'anomalies de haute et de basse pression de surface très marquées, localisées de part et d'autre de la péninsule Antarctique.*

1 Introduction

The belt of sea ice that rings the Antarctic continent is an important determinant of the climate of the region by virtue of its role in radiative, energy and mass exchange processes (Allison, 1972; Carleton and Carpenter, 1989; Zwally et al., 1983). The spatial extent of the sea ice varies markedly on a seasonal timescale from about 4×10^6 km^2 in March to a maximum of 19×10^6 km^2 in September-October (Gloersen et al., 1992). Under ice-free conditions, there can be large fluxes of heat and moisture between the ocean and atmosphere. However, the presence of a layer of sea ice on the

*Corresponding author's e-mail: J.Turner@BAS.AC.UK

ocean surface can reduce the heat flux by two orders of magnitude (Maykut, 1978), which has a marked effect on atmospheric stability and cloud formation. The change in albedo from around 10–15% (Lamb, 1982) over the ice-free ocean to about 90% when snow-covered sea ice is present (Grenfell, 1983) also affects the amount of short-wave radiation that can be absorbed by the surface and reach the deeper ocean.

Studies carried out since the early 1970s, when passive microwave imagery from the polar orbiting satellites became routinely available, have shown that the extent of Antarctic sea ice is also very variable on interannual and decadal timescales (Gloersen et al., 1992) and that there are complex interactions between the atmospheric circulation and the sea ice (Cavalieri and Parkinson, 1981; King, 1994). Clearly, if we are to predict how the Antarctic climate will change over the coming decades and centuries, it will be necessary to represent realistically these complex feedback mechanisms between the ocean, atmosphere and sea ice in global climate models. However, there have been very few detailed case studies of the variability of Antarctic sea ice during the austral winter, when it is known that large ice advances and retreats can take place, and none using ice motion vectors to examine the relative importance of dynamics and thermodynamics during such events. This paper therefore examines the largest winter ice retreat/advance episode observed in the Bellingshausen Sea, Antarctica (see Fig. 1 for places referred to in the text) during the period of availability of reliable satellite data (1978 to the present). The event took place during the austral winter of 1993, with the general ice retreat taking place from 1–15 August, although the southward migration of the ice edge was not continuous and short periods of northward motion were recorded. Between 16 August and 2 September there was almost continuous sea-ice recovery, at a rate (500 km over 17 days) greater than that found during the retreat and with only three or four days of slight southward motion. Stammerjohn and Smith (1996) have also noted that the speeds of sea-ice advances in this area generally exceed those of retreats.

The primary source of satellite data for this study was daily fields of sea-ice concentration derived from passive microwave imagery from the Special Sensor Microwave/Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) satellites. In addition, extensive use was made of ice motion vectors derived from the imagery by the Technical University of Denmark (TUD). Ice motion vectors derived by tracking buoys have been used in a number of studies in both polar regions (Prinsenberg and Peterson, 1992; Kottmeier et al., 1992) but unfortunately there were no buoys in the Bellingshausen Sea during August 1993. Vectors produced by tracking features in sequences of SSM/I have proved valuable in Arctic sea-ice research (Agnew and Le, 1996), but have not been used extensively in Antarctic investigations.

Sea-ice motion vectors were also computed from 1-km resolution Advanced Very High Resolution Radiometer (AVHRR) imagery collected at Rothera Station on the Antarctic Peninsula (see Section 2). Such data have proven to be of value in Arctic sea-ice studies (Dey, 1981), although the large amount of low cloud found in the Antarctic coastal region (Warren et al., 1988) limited the number of vectors that could be derived from the infra-red imagery.

During August and September 1993, at the end of the period under investigation here, the US research vessel *Nathaniel B. Palmer* was involved in a cruise in the Amundsen and Bellingshausen Sea pack ice. The cruise resulted in a number of publications on sea-ice properties, including ice thickness (Worby et al., 1996) and the structure of the sea ice (Jeffries et al., 1997). These data, along with the meteorological observations collected on the ship, were used in this study.

In Section 2 we describe the satellite data that were available for the study and the processing undertaken to derive the geophysical parameters. In Section 3 the atmospheric circulation during the sea-ice retreat and advance is described based on analyses produced by the operational numerical weather prediction systems. The broadscale evolution of the sea ice in the Bellingshausen Sea and the detailed motion of the sea ice, as determined from the passive microwave and infra-red AVHRR imagery, are presented in Section 4 and discussed in the light of the atmospheric forcing. In Section 5 we discuss the implications of such events for the climate of the Antarctic coastal region and consider the difficulties of reproducing such sea-ice changes in climate models.

2 Satellite data

SSM/I full swath data from the DMSP F11 satellite were obtained for the period July to September 1993 and processed into ice concentration data using the National Aeronautics and Space Administration (NASA) sea-ice algorithm working group procedure (Comiso et al., 1997). The tie-points that define the brightness temperature of each ice type and open water in the satellite measurements were those given by the National Snow and Ice Data Center (National Snow and Ice Data Center, 1992). In a detailed comparison of sea-ice edge detection algorithms (Heygster et al., 1996), good agreement was obtained between the ice edges in AVHRR data and the output of the NASA Team Algorithm when a concentration of 33% was taken as the limit of the ice. We have used this value here, but all the SSM/I charts of sea ice also show concentration values of 40, 50, 60, 70, 80, 90 and 100%. Other studies (Stammerjohn and Smith, 1996), have found that the passive microwave data overestimate the coverage of sea ice by 0–40% when compared to visible satellite imagery; however, our use of a higher threshold for the ice edge should reduce this bias.

The orbital characteristics of the DMSP satellite and swath width of the SSM/I instrument allowed the production of two composite images for each day derived from all morning and afternoon satellite passes. Since the Bellingshausen Sea is at a relatively high latitude, a fairly complete picture could be obtained of the sea-ice coverage on a twice daily basis and, in fact, there was often a significant overlap of passes. However, some gaps in the ice edge were apparent in the images because of missing data. The position of the ice edge, as determined from the NASA algorithm, was input to a

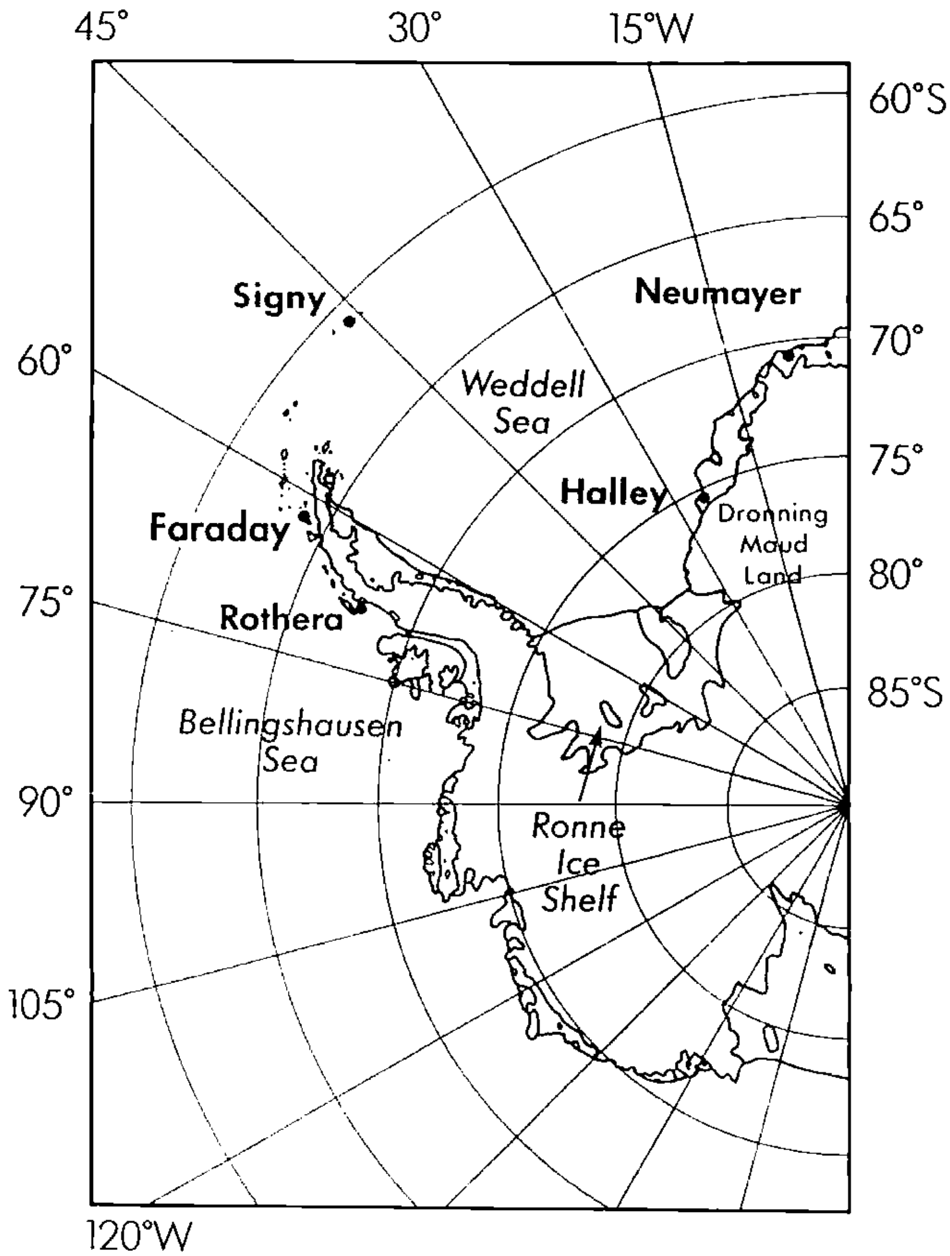

Fig. 1 A map showing places referred to in the text.

Geographic Information System (GIS) package and this enabled precise maps of the ice edge to be produced every 12 hours. Cavalieri et al. (1984) estimated that the ice concentrations for first-year ice determined using their algorithm with Scanning Multichannel Microwave Radiometer (SMMR) data had an accuracy of 2 to 5% during an 11-month period. A comparable error should be found using SSM/I data. In order to check the collocation of the ice edge derived from the SSM/I data, the AVHRR imagery for a cloud-free occasion was compared with the ice concentrations from the NASA Team algorithm. Figure 2 shows an AVHRR image for 00:00 UTC 22 July 1993 with overlaid contours of ice concentration as computed from the SSM/I data. Although, as is usual for the Antarctic, there is a great deal of low cloud in the image, it can be seen that in the relatively cloud-free area to the east of the frontal band there is good agreement between the ice edge apparent in the AVHRR imagery and that determined from the passive microwave data. In infra-red AVHRR imagery it is not easy to identify sea ice when the ice concentration is less than about 50%; however, close examination of the data suggests that taking the 33% concentration isopleth as the ice edge gives good agreement with the AVHRR imagery, considering that the passive microwave data used here had a resolution of 25 km.

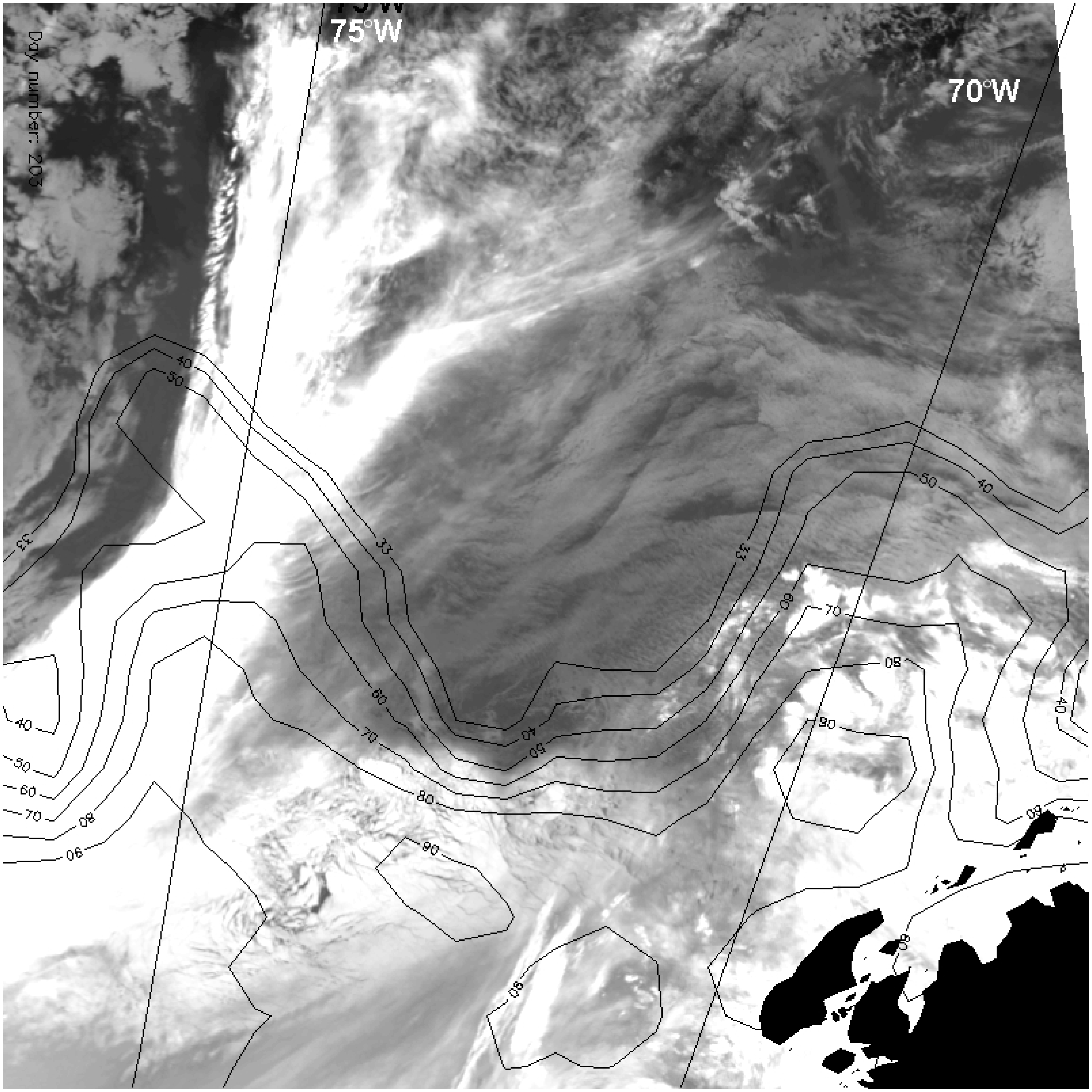

Fig. 2 A thermal infra-red AVHRR image of the eastern Bellingshausen Sea on 22 July 1993 with overlaid sea-ice concentrations derived from SSM/I data.

One of the most valuable sources of data for this study was the ice motion vectors produced from the SSM/I imagery. Medium and high resolution satellite imagery has been used to derive ice motion vectors by a number of researchers in recent years (Ninnis et al., 1986) and is used routinely at the Alaska Synthetic Aperture Radar (SAR) facility (Kwok and Tsatsoulis, 1998). Here we have used vectors produced at the TUD using the algorithm described in Lemke et al. (2001). This is based on correlating scenes in two images by moving a window chosen from scene 1 stepwise through the search area in scene 2. The correlation between the two images is computed at each step, with the largest correlation in the search being determined. If this is greater than a pre-defined threshold, then a motion vector is computed. Clearly, a complete field of motion vectors cannot be produced on any particular day and the TUD dataset consists of daily files containing randomly-located 2-day ice motion vectors. The motion vectors were converted to velocity vectors, which were then re-gridded on to a regular 1.25° × 1.25° grid and stored as daily fields.

The AVHRR High Resolution Picture Transmission (HRPT) data were collected at the British Research Station 'Rothera' (67° 34′S, 66° 08′W) in the central part of the Antarctic Peninsula. Because the station is located at a relatively high latitude, it is possible to collect about 14 passes of HRPT data each day, providing frequent coverage of the Bellingshausen Sea area. In order to generate sea-ice motion vectors, cloud-free images separated in time by about 24 hours were selected and re-mapped onto a polar stereographic projection. Ice motion vectors were determined by manually tracking floes that were clearly identifiable on both images and computing the mean speed and direction of travel during the period by extracting the location of some feature apparent on both images. The registration of the two images was checked by examining sections of the satellite swaths that crossed part of the coast. If the coastal areas co-registered correctly, then it was assumed that the regions further north over the sea ice some several hundred kilometres before or after the coastal crossing point were still earth-located correctly. This is a reasonable assumption since the main problems in earth-locating images are using poor orbital elements or drifts in the clock on the satellites. By checking the location of coastal areas on the same satellite orbits for which ice motion vectors are required both these factors will be accounted for.

Clearly the use of infra-red imagery means that ice motion vectors can only be calculated under cloud-free conditions. Many periods of rapid ice advance or retreat are assumed to be associated with the strong winds found close to deep depressions and under these conditions there will always be extensive cloud. The ice motion vectors are, therefore, generally available for anticyclonic conditions and when there was a dry, offshore flow. A small number of pairs of SAR images were also available for the period under investigation and these data were used to derive some ice motion vectors in cloudy conditions. However, the images only cover an area of approximately 100 by 100 km so that the vectors did not contribute greatly to our knowledge of the broadscale motion of the ice, which we are concerned with here.

Atmospheric data were obtained from the European Centre for Medium-range Weather Forecasts (ECMWF) re-analysis (ERA) project fields (Gibson et al., 1996). The ECMWF fields consisted of the wind at 10 m and the temperature at 1.5 m.

3 The atmospheric conditions during the study period

The area of interest here is within the Antarctic circumpolar trough, which is characterized by many depressions and generally brief anticyclonic episodes (Jones and Simmonds, 1994). The atmospheric conditions during the study period consisted of the following periods:

27 July–2 August. A weak pressure gradient to the west of the Antarctic Peninsula was soon replaced by mainly north-westerly flow between high pressure centres over the Peninsula/Weddell Sea area and low pressure centres over the western Bellingshausen Sea. This can be seen in Fig. 3, which shows the meridional component of the surface wind at 77.5°W between 64° and 72°S, along with sea-ice concentrations.

3–7 August. A series of deep lows in the Bellingshausen Sea introduced strong north to north-westerly winds across the area, and, as high pressure built in the Weddell Sea, there was an increasingly strong northerly flow at 77.5°W.

8–9 August. As a low pressure centre tracked eastwards across the Peninsula and a ridge built over the Bellingshausen Sea it introduced a short period of strong southerly flow.

10–13 August. Pressure remained high over the Weddell Sea while a succession of lows was present in the Bellingshausen Sea giving the strongest period of northerly flow during the whole study period.

14–15 August. The high pressure in the Weddell Sea declined, although low pressure systems in the Bellingshausen Sea still produced a north-westerly flow to the west of the Peninsula. The end of the sea-ice retreat occurred on 15 August.

16–21 August. At the start of this period, a low over the north Weddell Sea produced a southerly flow to the west of the Peninsula, but during the following few days the atmospheric circulation was fairly mobile and a major low moved from the Bellingshausen Sea to the Weddell Sea during 20 – 21 August. This produced the marked switch, apparent in Fig. 3, from strong northerly to southerly flow across the latitude band 64° – 67°S.

22–25 August. A low moved eastwards across the base of the Peninsula into the central Weddell Sea maintaining south-westerly winds along 77.5°W.

26-28 August. The atmospheric circulation during these three days produced the strongest southerly flow found during the entire period. This was remarkable for the fact that the strong flow extended through the whole band of 64°–73°S and was strongest at the southern end of the area we considered, which was over the Antarctic continent. Examination of the synoptic charts for this period showed that the event was associated with a low that crossed the Peninsula into the Weddell Sea at a time when a major ridge developed over the Bellingshausen Sea, giving a very strong east-west pressure gradient.

29 August – 1 September. Although the ridge remained over the Bellingshausen Sea until about 30 August, the low in the Weddell Sea moved to the east. At the very end of the study period the flow became more mobile with a weak depression passing from west to east across the area.

4 The sea-ice conditions in the Bellingshausen Sea in relation to the atmospheric flow

a *The Broad Scale Sea-Ice Conditions During August 1993*

The sea-ice concentrations on 31 July 1993, at the start of the period of interest, are shown in Fig. 4. The concentrations indicate that the sea-ice edge (taken as the 33% concentration values) ran from south-west to north-east across the Bellingshausen Sea and that it had its most northerly limit at about 62°S, close to 65°W. At 90°W the ice edge was at 67°S,

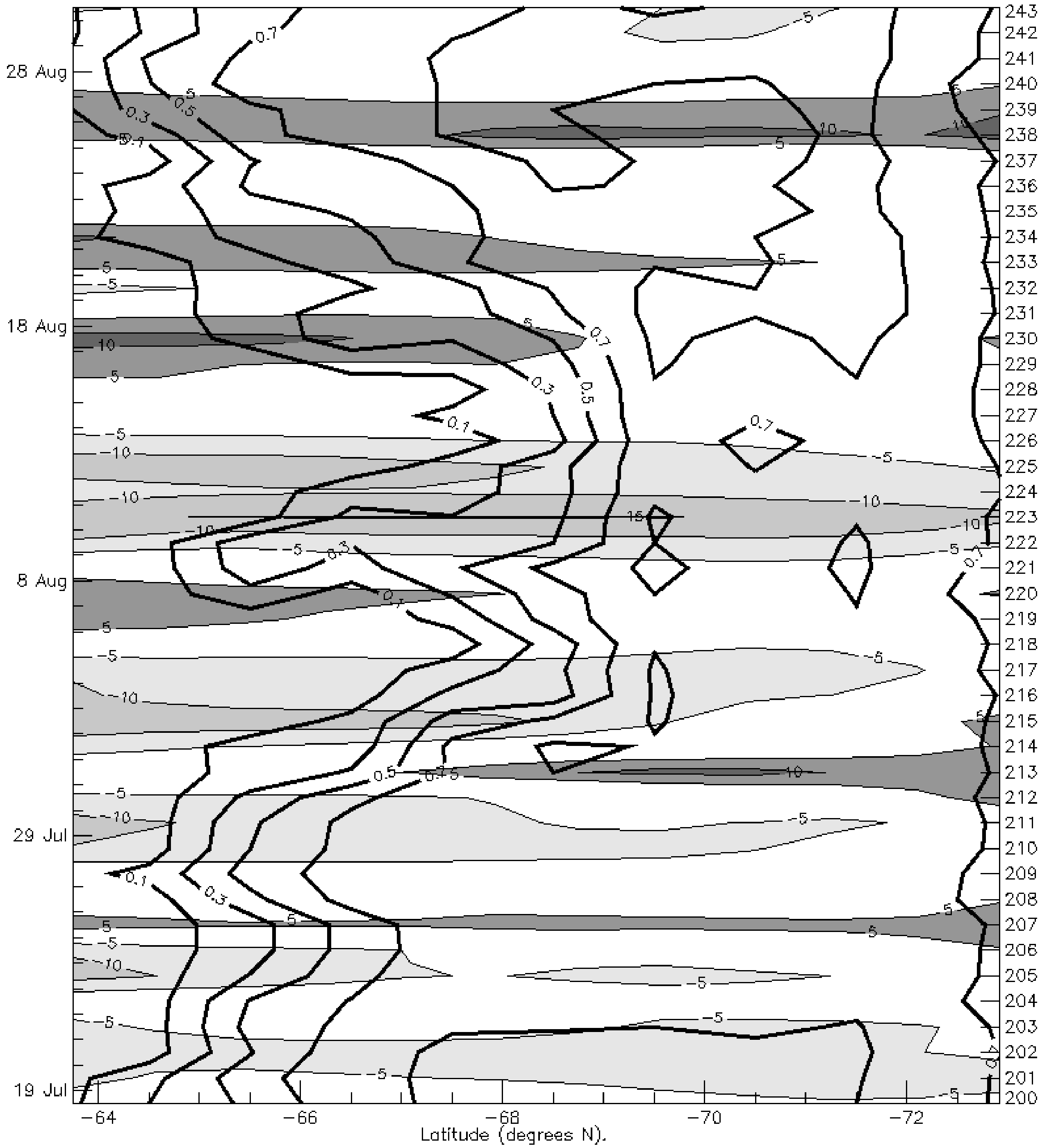

Fig. 3 The meridional component of the surface wind (shaded in m s^{-1}) at 77.5°W between 64 and 72°S. Sea-ice concentrations are shown for 0.1, 0.3, 0.5, 0.7 and 0.9. Dates (Julian days) are shown on the left (right) side.

some 600 km further south. The ice concentration isopleths ran almost parallel to the ice edge, but the concentration gradient was less near 80°W, where there was a northward extension of the ice edge. Some care must be taken when using ice concentrations derived from SSM/I data since errors can occur because of atmospheric effects and failings in the processing algorithms. However, since this southward retreat in the ice edge and other features were present on several days and the concentration isopleths changed in a smooth fashion from day-to-day, we believe that the concentration values are correct to better than 10% (Gloersen et al., 1992) and that the changes reflect real variations in the sea-ice extent and concentration.

As can be seen in Fig. 3, the largest retreat of the sea ice at 77.5°W during the entire study period took place between 31 July and 6 August. The sea-ice chart for the end of this

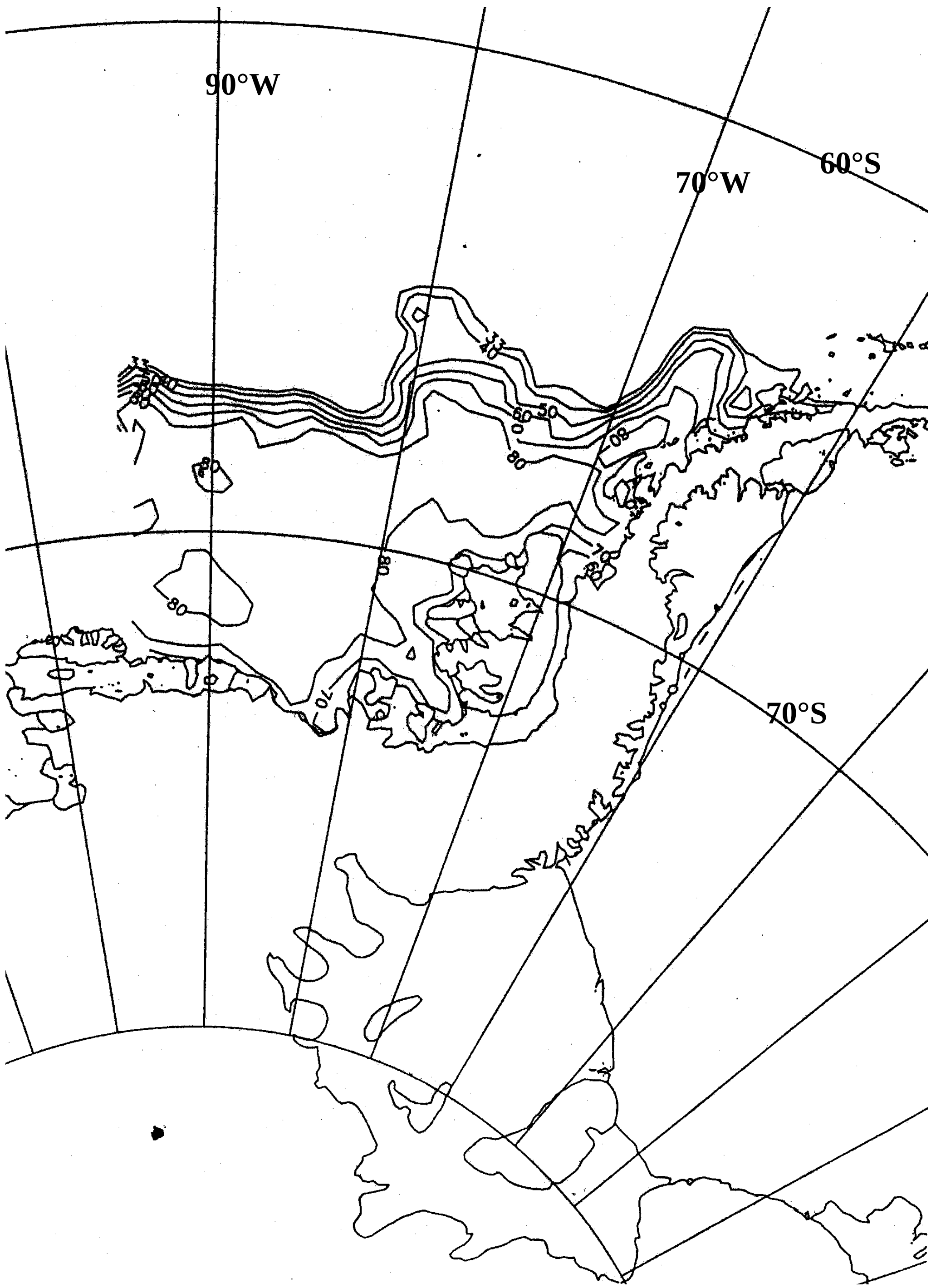

Fig. 4 The sea-ice concentration in the Bellingshausen Sea as determined from the SSM/I data for 31 July 1993.

period is shown in Fig. 5. During this time the northward extension of the ice edge at 80°W disappeared, resulting in a strong gradient of concentrations across the entire region. The retreat took place as northerly winds occurred when a deep low became established over the Bellingshausen Sea. However, as shown on Fig. 3, the northerly component of the wind in the ERA dataset was only around 10–12 m s^{-1}, which was not particularly strong for the Bellingshausen Sea. However, the Rothera wind speeds, shown in Fig. 6, indicate that during this period speeds of up to 22 m s^{-1} were recorded on several occasions. This flow regime was particularly well marked on 5 August and the daily maps of sea-ice coverage (not shown) from the SSM/I indicate that it was during this period that the greatest ice retreat took place.

During 6 – 9 August, the tongue of sea ice close to 78°W extended northwards again, with the 10% ice concentration

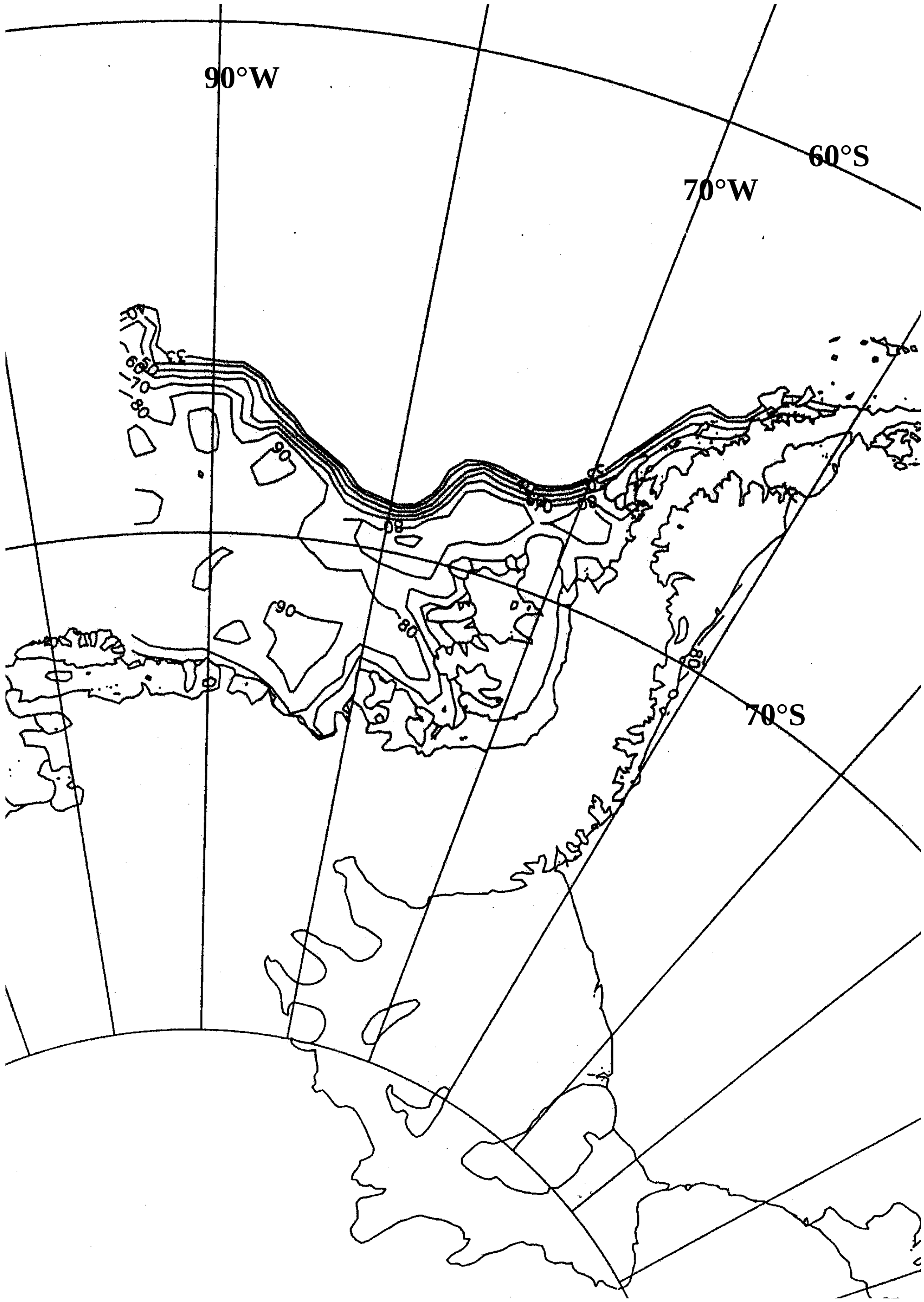

Fig. 5 The sea-ice concentration in the Bellingshausen Sea as determined from the SSM/I data for 6 August 1993.

contour advancing to the position it had at the start of the study period. However, as can be seen in Fig. 3, the 80% concentration contour hardly moved north and the ice edge (defined as the 33% concentration) only moved 140 km north. Changes in the 10% ice concentration contour have to be interpreted with care, since they occur equatorwards of what we regard as the ice edge. Nevertheless, consistent signals can be seen in the sequence of daily ice concentration charts and they appear to indicate real changes within the marginal ice zone (MIZ).

From the 9 – 15 August, the ice edge at 77.5°W retreated again by 64 km during the six days as strong northerly flow returned over the Bellingshausen Sea. As shown on Fig. 3, the tongue of low ice concentrations that had formed during the

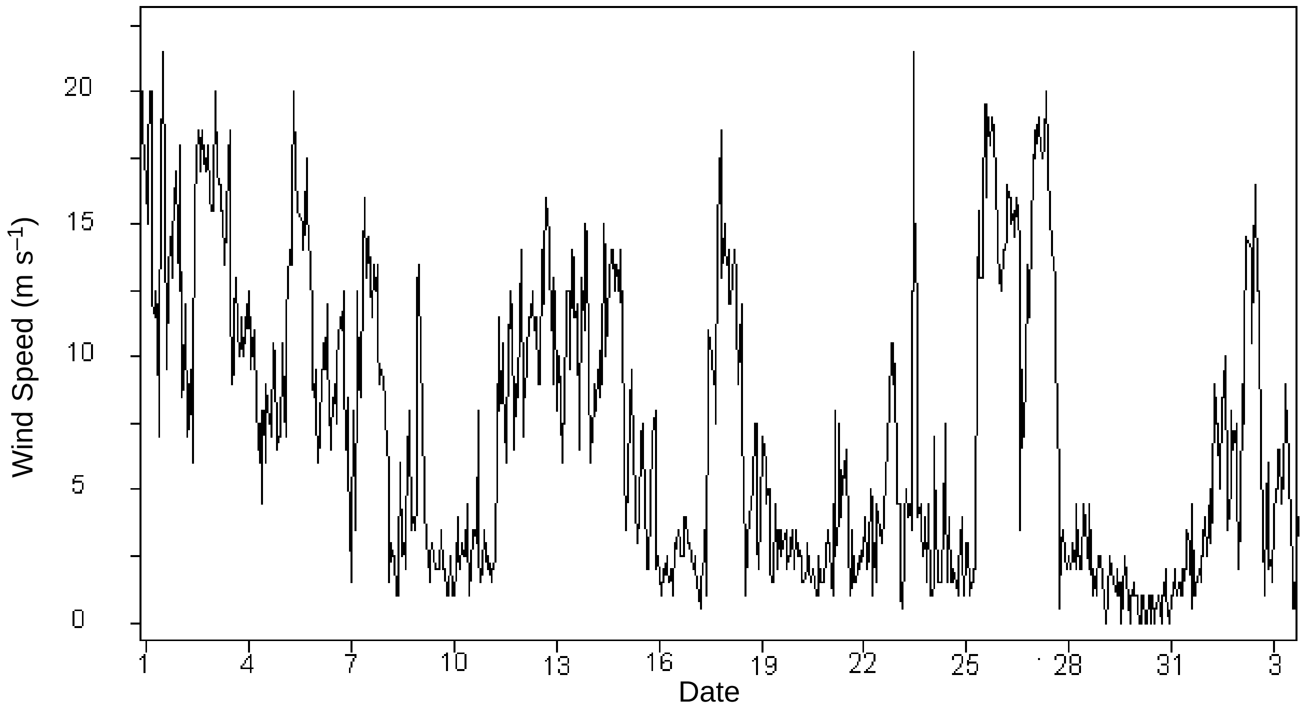

Fig. 6 The Rothera wind speeds (m s^{-1}) from 1 August to 3 September 1993.

previous few days was destroyed and the ice retreated to its most southerly location since July. The rapid fluctuations within the MIZ during this period indicate the highly dynamic nature of the sea ice at this time as it responded to the rapidly changing atmospheric circulation.

From 16 August to the end of the study period there was essentially continuous advance of the sea ice at 77.5°W, with the most rapid northward advance being between 20 and 27 August. Figure 6 indicates that 25–27 August was a period of almost continuous gale force winds at Rothera. There were two periods of strong southerly winds around 22 and 27 August (Fig. 3). During 21 – 23 August a high pressure system built over the Amundsen Sea and, coupled with a deep low close to the tip of the Peninsula, resulted in strong southerly flow over the western part of the region. The northward advance of the ice between 21 and 23 August was quite variable across the longitude band 70° – 80°W. Figures 7a and 7b show that at 80°W the ice edge was almost stationary, while it extended northwards by 87 km at 70°W. In between these two longitudes there was considerable variation in the northward movement of the ice edge. At 75°W the ice edge, as defined by the 33% concentration value, only moved north by about 20–30 km, while the two northward extensions of sea ice close to 72° and 78°W showed a much greater northward movement, with the edge at the eastern side being 162 km further north. At Rothera Station, some 160 km south–south-east of the area being considered here, the surface temperature during 20–21 August varied from –3°C to –16°C (Fig. 8). Although the surface temperatures close to the ice edge will have been slightly higher, the wind direction during this period was predominantly from the south or south-west, thus giving mainly off-ice flow. Under such conditions there would clearly have been formation of new ice when the air left the edge of the main pack. Although the ice would have been thin and possibly not have given complete coverage, the satellite measurements were clearly affected, resulting in marked changes in the ice extent and concentration maps.

b *Ice Motion*

Earlier studies (Martinson and Wamser, 1990) have suggested that the sea ice is advected at about 3% of the geostrophic wind speed. Our results are consistent with this ratio.

Figure 9a shows a time series of the ice edge latitude at 70°W during July–September 1993. As discussed earlier, the major ice retreat began on about 29 July, continuing to about 7 August, with a secondary advance and retreat during 7–15 August. The major re-advance took place more or less continuously from 15 to 30 August. By contrast, the ice edge at 90°W (Fig. 9b) shows much less variability, with a fairly steady advance taking place during the season.

The meridional component of ice motion (v) averaged over the sector bounded by 65°W, 75°W, 65°S and 68°S is shown in Fig. 9c. This is generally negative (southwards) during the period of ice retreat and positive (northwards) during the re-advance, but shows considerable short-term variability. The v component is both smaller on average and less variable in the more westerly sector, bounded by 95°W, 85°W, 69°S and 72°S (Fig. 9d).

Between 20 July and 6 August, the ice edge at 70°W retreated by 424.9 km, giving a mean retreat speed of 0.27 m s^{-1}. This is significantly greater than the mean southwards component of ice motion (0.075 m s^{-1}) in this sector during

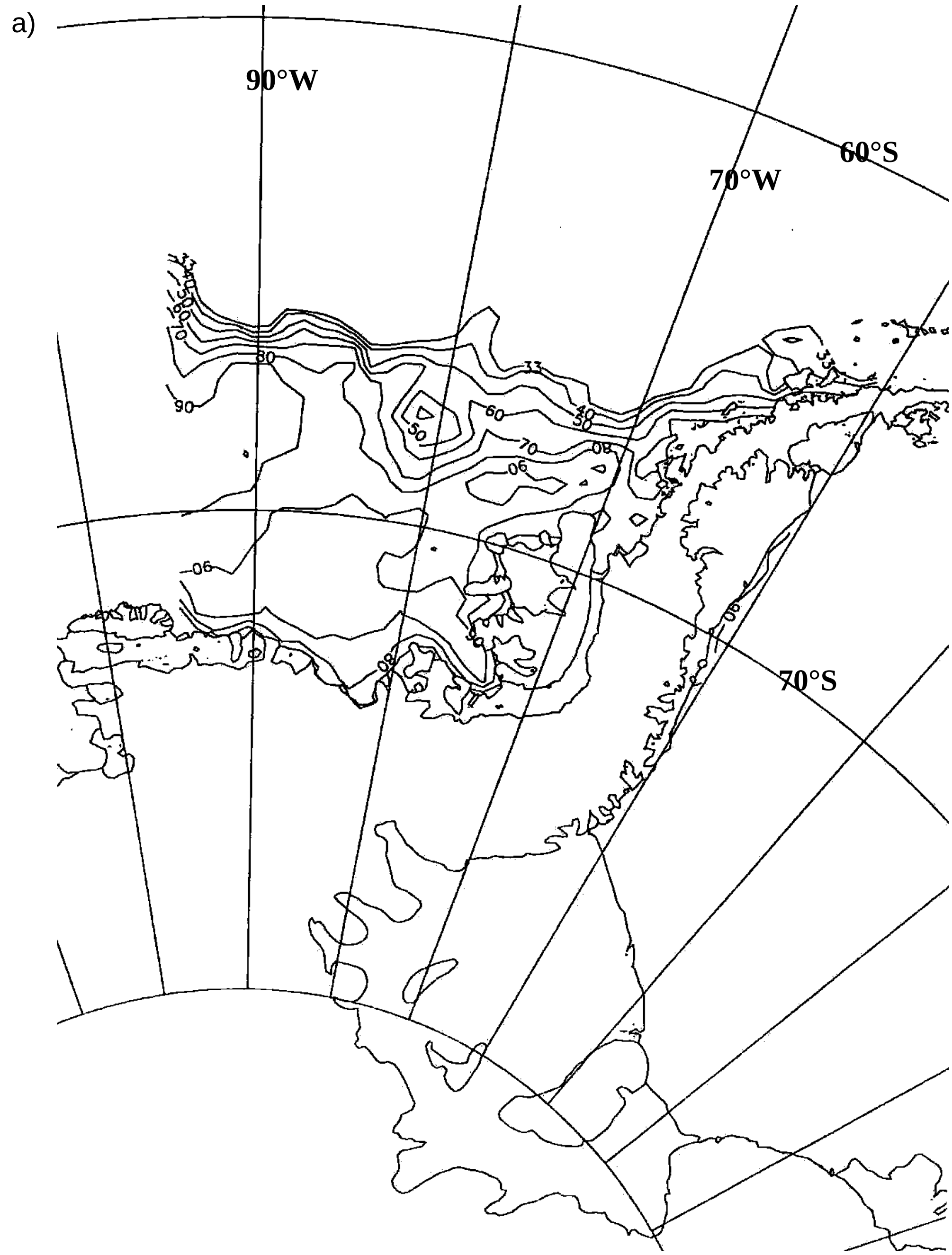

Fig. 7 The sea-ice distribution in the Bellingshausen Sea as determined from the SSM/I data on a) 21 August 1993 and b) 23 August 1993.

the same period. The re-advance at 70°W between 15 and 30 August amounted to 487.1 km, equivalent to an advance speed of 0.38 m s^{-1}. The mean northwards component of ice velocity in this sector during the same period was 0.102 m s^{-1}, again significantly less than the advance speed of the ice edge.

In summary, the ice motion data suggest that the rate of change of the ice edge position during both the advance and retreat phases significantly exceeded the southward or northward velocity components of ice within the pack, pointing to the importance of ice production and melting in the MIZ. 'Bulk' movement of the pack, with associated compaction and divergence of the sea ice, made a secondary, but still significant, contribution to the observed advance and retreat.

5 Discussion

Ice retreat during winter is not uncommon in the Bellingshausen Sea and can be as important as ice advance in determining ice extent anomalies (Harangozo, 1997). On average, ice extent in this region is greatest in August and early September. In 1993, however, ice extent at the end of

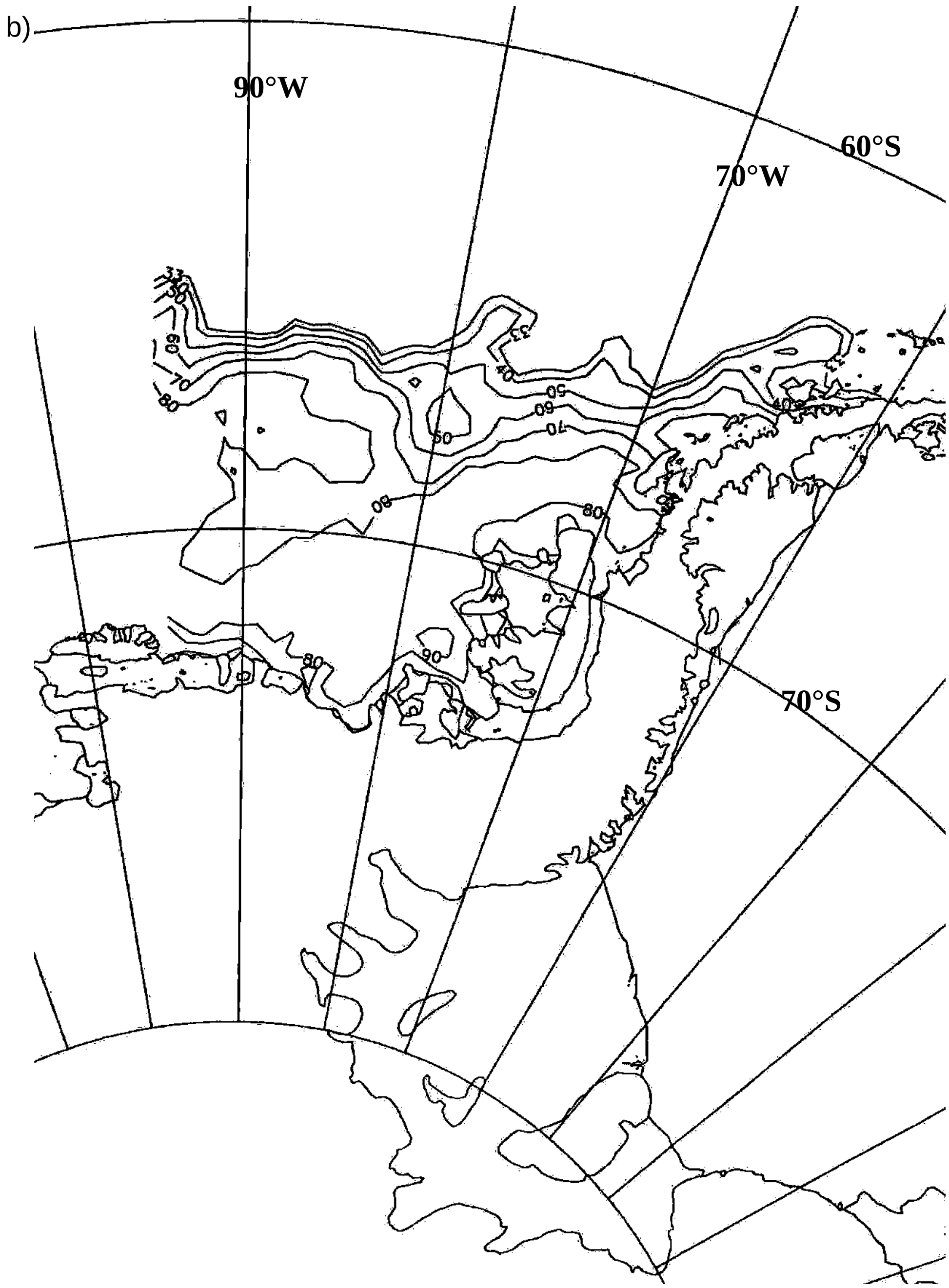

Fig. 7 *Concluded*

winter (August) was less than at the start in the eastern Bellingshausen Sea and unchanged further west. Since 1973 there have only been three other times when ice extent has decreased during the winter (as deduced from US National Ice Center charts and passive microwave data). One of these has been discussed in detail by Ackley and Keliher (1976) who found late winter ice retreat of similar magnitude to that in 1993.

Ackley and Keliher (1976) and Harangozo (1997) have found that winter ice retreat in the Bellingshausen Sea is usually associated with a combination of enhanced poleward flow and warm air advection. Ice extent increases did take place in May and June of 1993 (not shown) but the incursion of northerly flows in July and August could thus not be expected to favour retention of the ice cover. This deduction is supported by the observation that sea-ice extent in the Bellingshausen Sea in winters, when enhanced northerly flows persist throughout the season, is typically average or below-normal, i.e., not conducive to extensive sea ice. An example is discussed in detail by Harangozo (1997).

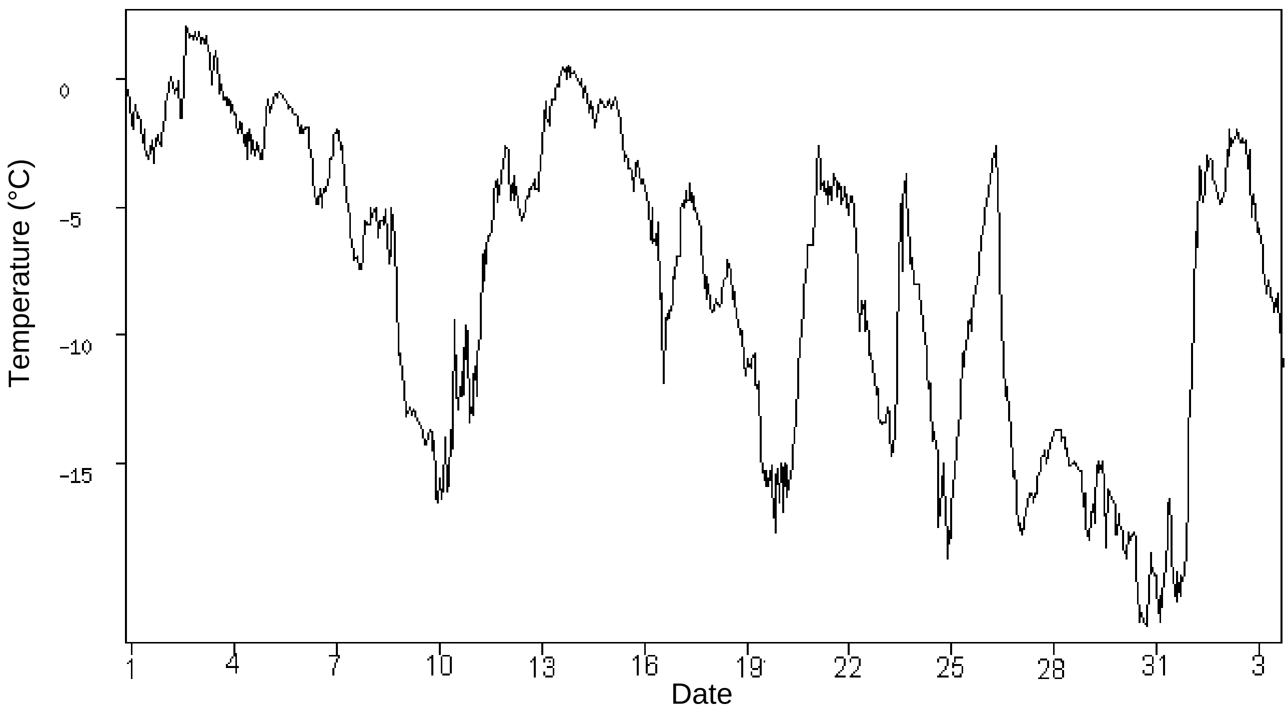

Fig. 8 The Rothera surface temperatures from 1 August to 2 September 1993.

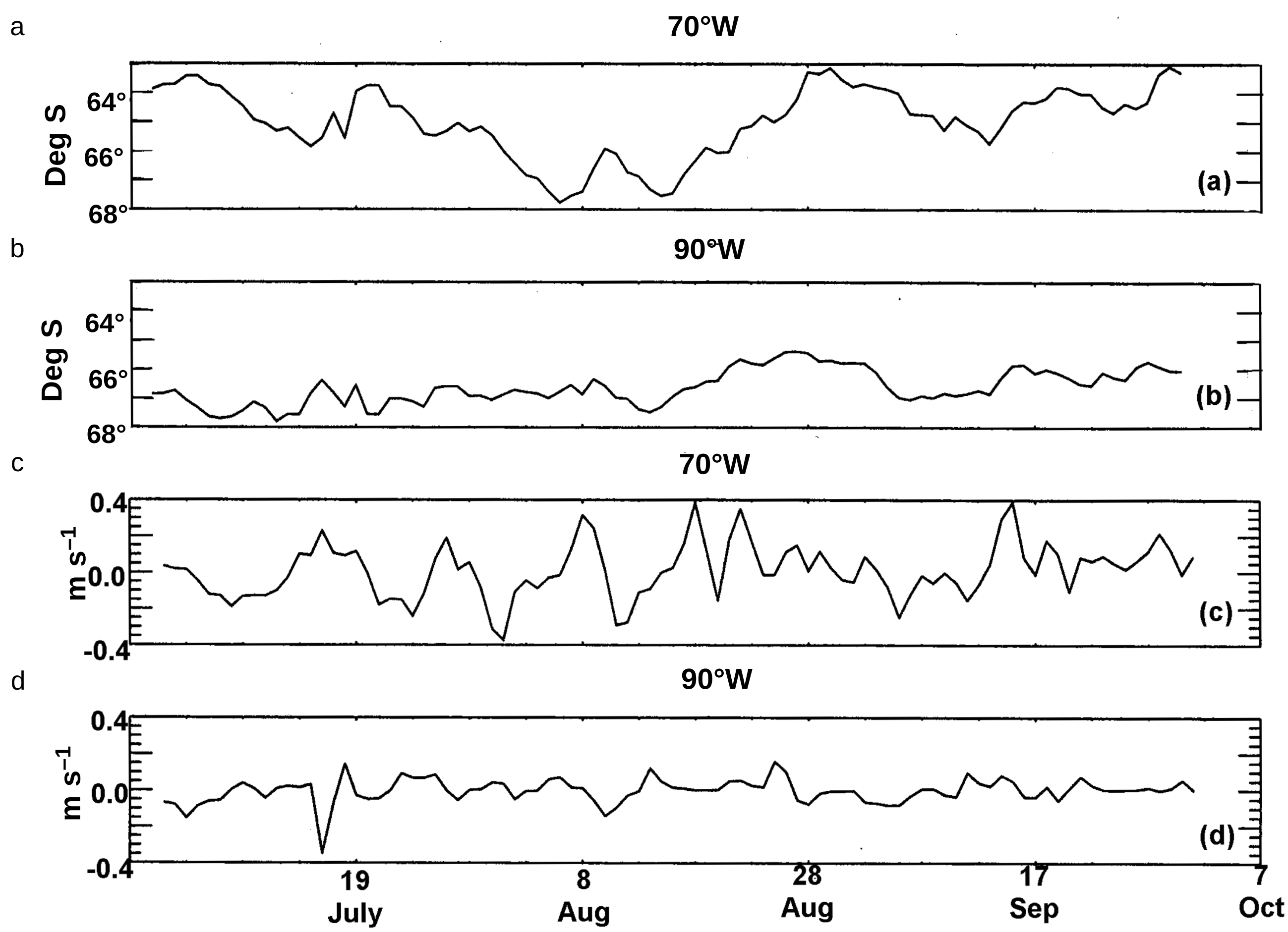

Fig. 9 Time series of the ice edge latitude during July–September 1993 at (a) 70°W and (b) 90°W. (c) The meridional component of ice motion (v) averaged over the sector bounded by 65°W, 75°W, 65°S and 68°S. (d) The meridional component of ice motion (v) averaged over the sector bounded by 95°W, 85°W, 69°S and 72°S.

The period of sea-ice retreat and advance investigated here is a good example of the sensitivity of the sea-ice extent to changes in atmospheric circulation and the frequency, depth and track of depressions in and to the north of the circumpolar trough. During periods of blocked flow when the low pressure systems are slow-moving and there is persistent meridional flow, large sea-ice anomalies may become established. Studies have shown that when they occur at crucial stages in the annual cycle of growth or dissipation of sea ice, the anomalies can persist for several seasons (Harangozo, 1997).

August 1993 over the Bellingshausen Sea was remarkable for the amplitude of the north-south excursions of the sea-ice edge. The changes in the ice edge location were so pronounced because of the strong meridional winds induced by strong high-low pressure couplets on either side of the Antarctic Peninsula and the marked changes of near-surface temperature that they brought about. What occurred during August 1993 were extreme versions of the ice extent advance/retreat atmospheric flow patterns shown in Cavalieri and Parkinson (1987). The Bellingshausen Sea is usually characterized by many deep depressions, but the strongest meridional flow is found when a marked east-west pressure gradient is present, when positive and negative surface pressure anomalies are present on either side of the Peninsula. During August 1993 the surface pressure field was remarkable for having strong high-low pressure couplets across the Peninsula, but of opposite sign during the two halves of the month. These periods of strong meridional flow, when coupled with the fact that the sea-ice concentrations in the Bellingshausen Sea were relatively low, making the ice susceptible to melting and re-freezing, were the reason that the ice edge changes were the largest in the 20-year satellite record of ice extent.

In the east Indian Ocean, Allison (1989) found that in the MIZ, ice edge advance was mainly due to ice drift, not in-situ formation. In our case the opposite appears to be true. The in-situ formation of sea ice during large, fast re-advances following retreats has been noted in the Arctic (Kimura and Wakatsuchi, 1999), but has not received attention in the Antarctic. Similarly, high temperatures and melting of sea ice during retreats in the Arctic have been well documented (Niebauer, 1980), but have received less attention in the Antarctic.

Strong northerly atmospheric flow brings relatively warm air masses into the Antarctic coastal region, and such conditions are responsible for many of the moderate and heavy precipitation events reported at the stations (Turner et al., 1995). It is therefore reasonable to assume that during August 1993 there was above average snowfall onto the sea ice during the northerly episodes, especially as there were 48 6-hourly synoptic observations at Rothera reporting precipitation based on the 6-hourly synoptic observations. This would be consistent with the observation from Jeffries et al. (1997), who found larger amounts of snow-ice than had been reported in earlier studies when they made in-situ measurements of ice properties from the *Nathaniel B. Palmer* during August and September 1993. Worby et al. (1996) also report that 82% of freeboard measurements were less than or equal to zero during this cruise, which is further evidence of the frequent snowfall during this period. This cruise also provided valuable information on the sea-ice thickness across the Bellingshausen Sea during the period of interest. Many of the rapid changes in ice extent reported here took place close to the ice edge where the thicknesses are assumed to have been less. This is consistent with ice-thickness data collected near the ice edge collected by the *Nathaniel B. Palmer* and reported by Worby et al. (1996).

The atmospheric circulation of the Antarctic is remarkable for its high degree of variability on all timescales, and this was particularly true during August 1993. Although the month was broadly characterized by sea-ice retreat followed by advance, within these periods there were higher frequency fluctuations as the synoptic-scale atmospheric flow changed. Deep depressions rarely remain stationary for extended periods, and while the Bellingshausen Sea had lower surface pressure than normal for the first half of the month, this arose because of a sequence of active lows moving over the area. This resulted in the rapid switches of wind direction apparent in Fig. 3.

It is very important that the development of sea-ice anomalies, such as those observed during August 1993, are represented correctly in the global models used to simulate the present and possible future climate scenarios, especially if retreat significantly affects the late winter extent, as it clearly does here and in the Ackley and Keliher (1976) case. Although current general circulation models only have fairly simple representations of the sea ice (such as free drift), future versions will use more sophisticated sea-ice models, which will need to be able to represent realistically the variability of ice on a day-to-day basis if the important anomalies are to be captured. The situation in the Bellingshausen Sea during August 1993 should provide a good test case for high resolution sea-ice models.

In the preceding sections we have discussed in detail the role of the atmospheric circulation in forcing the observed sea-ice anomalies. However, the ocean also plays a role through advection of the sea ice and the formation and melting of the ice. Clearly no time series of ocean conditions are available for the Bellingshausen Sea for the duration of this case, but with the rapid fluctuations in the sea-ice edge correlating so well with changes in the atmospheric circulation we feel that the ocean played a secondary role in this event.

In this study we have mainly discussed the relatively large synoptic-scale weather systems that are resolved by the operational weather analyses. However, recent studies of the atmospheric flow around the Antarctic based on high resolution satellite imagery have suggested that there are many more weather systems around the continent than are resolved by the numerical analyses (Turner et al., 1998). Many of these lows will be vigorous and will affect the sea-ice concentrations and the location of the ice edge. Clearly we would not expect many of the mesoscale lows, which have a diameter of less than 1000 km, to be represented in the numerical analyses, since many of these depressions will only extend across a very small number of grid lengths of the model. However, there are many small synoptic-scale lows just to the north of the Antarctic coastline that are very difficult for the analysis system to resolve, but which will affect the movement of the sea ice for up to two days. A major challenge facing climate modellers in the coming years will be to ensure that sea-ice changes taking place because of variability in the atmospheric flow, such as discussed in this paper, along with less rapid changes in sea-ice extent and thickness, are represented correctly in climate models.

Acknowledgements

Much of this work was carried out as part of the European Union Project for the Estimation of Long-term Ice CONcentrations (PELICON) project under contract EVSV-CT93-0268. The authors would also like to thank Dr. L. Toudal and Mr. R. Saldo of the Technical University of Denmark for providing the ice motion vectors.

References

ACKLEY, S.F. and T.E. KELIHER. 1976. Antarctic sea ice dynamics and its possible climatic effects. *AIDJEX Bull.* **33**: 53–76.

AGNEW, T.A. and LE, H.1996. A more comprehensive view of the dynamics of Arctic sea ice revealed through 85.5 GHz SSM/I imagery. NSIDC Notes no. 19, National Snow and Ice Data Center, Boulder, 11 pp.

ALLISON, I.F. 1972. A sample study of the energy fluxes preceding and accompanying the formation of Antarctic sea ice. *In*: Energy fluxes over polar surfaces. WMO Technical Note No. 129, World Meteorological Organisation, Geneva. pp. 115–132.

———. 1989. Pack-ice drift off East Antarctica and some implications. *Ann. Glaciol.* **12**: 1–8.

CARLETON, A.M. and D.A. CARPENTER. 1989. Intermediate-scale sea ice-atmosphere interactions over high southern latitudes in winter. *Geoj.* **18**: 87–101.

CAVALIERI, D.J. and C.L. PARKINSON. 1981. Large-scale variations in observed Antarctic sea ice extent and associated atmospheric circulation. *Mon. Weather Rev.* **109**: 2323–2336.

———; P. GLOERSEN and W.J. CAMPBELL. 1984. Determination of sea ice parameters with the Nimbus-7 SMMR. *J. Geophys. Res.* **89**: 5355–5369.

——— and C.L. PARKINSON. 1987. On the relationship between atmospheric circulation and the fluctuations in the sea ice extents of the Bering and Okhotsk seas. *J. Geophys. Res.* **92**: 7141–7162.

COMISO, J.C.; D.J. CAVALIERI, C.L. PARKINSON and P. GLOERSEN. 1997. Passive microwave algorithms for sea ice concentration: A comparison of two techniques. *Rem. Sens. Environ*. **60**: 357–384.

DEY, B. 1981. Monitoring winter sea ice dynamics in the Canadian Arctic with NOAA TIR images. *J. Geophys. Res.* **86**: 3223–3235.

GIBSON, J.K.; A. HERNANDEZ, P.K ÅLLBERG, A. NOMURA, E. SERRANO and S. UPPALA 1996. Current status of the ECMWF re-analysis project. *In*: Proceedings of the Seventh Conference on Global Change Studies. Am. Meteorol. Soc. Boston. pp. 112–115.

GLOERSEN, P.; W.J. CAMPBELL, D.J. CAVALIERI, J.C. COMISO, C.L. PARKINSON and H.J. ZWALLY. 1992. *Arctic and Antarctic Sea Ice, 1978–1987*, NASA, Washington, DC, 290 pp.

GRENFELL, T.C. 1983. A theoretical model of the optical properties of sea ice in the visible and near infrared. *J. Geophys. Res.* **88**: 9723–9735.

HARANGOZO, S.A. 1997. Atmospheric meridional circulation impacts on contrasting winter sea ice extent in two years in the Pacific sector of the Southern Ocean. *Tellus*, **49**: 388–400.

HEYGSTER, G.; B. BURNS, T. HUNEWINKEL, K. KÜNZI, L. MEYER-LERBS, H. SCHOTTMÜLLER, C. THOMAS, P. LEMKE, T. VIEHOFF, J. TURNER, S. HARANGOZO, T. LACHLAN-COPE and L. PEDERSEN. 1996. PELICON - Project for Estimation of Long-term variability in Ice CONcentration. Final report to the EC, University of Bremen, Bremen, 158 pp.

JEFFRIES, M.O.; A.P. WORBY, K. MORRIS and W.F. WEEKS. 1997.Seasonal variations in the properties and structural composition of sea ice and snow cover in the Bellingshausen and Amundsen Seas, Antarctica. *J. Glaciol.* **43**: 138–151.

JONES, D.A. and I. SIMMONDS. 1994. A climatology of Southern Hemisphere anticyclones. *Clim. Dyn.* **10**: 333–348.

KIMURA, N. and M. WAKATSUCHI. 1999. Processes controlling the advance and retreat of sea ice in the Sea of Okhotsk. *J. Geophys. Res. - Oceans,* **104**: 11137–11150.

KING, J.C. 1994. Recent climate variability in the vicinity of the Antarctic Peninsula. *Int. J. Climatol.* **14**: 357–369.

KOTTMEIER, C.; J. OLF, W. FRIEDEN and R. ROTH. 1992. Wind forcing and ice motion in the Weddell Sea region. *J. Geophys. Res.* **97**: 20373–20383.

KWOK, R. 1998. The RADARSAT geophysical processor system. In: *Analysis of SAR Data of the Polar Oceans: Recent Advances*, C. Tsatsoulis and R. Kwok (Eds) Berlin, Springer, pp. 235–257.

LAMB, H.H. 1982. The climate environment of the Arctic Ocean. In: *The Arctic Ocean*, L. Rey (Ed.), John Wiley and Sons, New York. pp. 135–161.

LEMKE, P.; T. MARTIN, S. KERN, G. HEYGSTER, K.-P. JOHNSEN, L. TOUDAL, R. SALDO, J. TURNER, S.A. HARANGOZO, S. LEONARD, W.M. CONNOLLEY, S. SCHUSTER, D. CRESSWELL, G.J. MARSHALL, T.A. LACHLAN-COPE, J.C. KING, H. POHLMANN, O. STENZEL and M. HARDER. 2001. SEA LION. Sea Ice in the Antarctic Linked with Ocean - Atmosphere Forcing. Final Report for EU Contract ENV - 4-CT97-0415 (DG 12 ESCY), University of Kiel, Kiel, 207 pp.

MARTINSON, D.G. and C. WAMSER. 1990. Ice drift and momentum exchange in winter Antarctic pack ice. *J. Geophys. Res.* **95**: 1741–1755.

MAYKUT, G.A. 1978. Energy exchange over young sea ice in the central Arctic. *J. Geophys. Res.* **83**: 3646–3658.

NATIONAL SNOW AND ICE DATA CENTER. 1992. DMSP SSM/I Brightness Temperature and Sea Ice Concentration Grids for the Polar Regions on CD-ROM. NSIDC Special Report - 1, Cooperative Institute for Research in Environmental Sciences, Boulder, 300 pp.

NIEBAUER, H.J. 1980. Sea ice and temperature variability in the eastern Bering Sea and the relation to atmospheric fluctuations. *J. Geophys. Res.* **85**: 7507–7515.

NINNIS, R.M.; W.J. EMERY and M.J. COLLINS. 1986. Automated extraction of pack ice motion from AVHRR imagery. *J. Geophys. Res.* **95**: 10725–10734.

PRINSENBERG, S.J. and I.K. PETERSON. 1992. Sea-ice properties off Labrador and Newfoundland during LIMEX ‘89. ATMOSPHERE-OCEAN. **30**: 207–222.

STAMMERJOHN, S.E. and R.C. SMITH 1996. Spatial and temporal variability of western Antarctic Peninsula sea ice coverage. In: *Foundations for Ecological Research West of the Antarctic Peninsula, AGU Antarctic Research Series, Volume 70,* R.M. Ross, E.E. Hofmann and L.B. Quetin (Eds). AGU, Washington, DC. pp. 81–104.

TURNER, J.; T.A. LACHLAN-COPE, J.P. THOMAS and S. COLWELL. 1995. The synoptic origins of precipitation over the Antarctic Peninsula. *Antarct. Sci.* **7**: 327–337.

———; G.J. MARSHALL and T.A. LACHLAN-COPE. 1998. Analysis of synoptic-scale low pressure systems within the Antarctic Peninsula sector of the circumpolar trough. *Int. J. Climatol.* **18**: 253–280.

WARREN, S.G.; C.J. HAHN, J. LONDON, R.M. CHERVIN and R.L. JENNE. 1988. Global distribution of total cloud and cloud type amounts over the ocean, NCAR Technical Note TN-317+STR/DOE Technical Report ER/0406 edition. NCAR, Boulder, 42 pp.

WORBY, A.P.; M.O. JEFFRIES, W.F. WEEKS, K. MORRIS and R. JAÑA. 1996. The thickness distribution of sea ice and snow cover during late winter in the Bellingshausen and Amundsen Seas, Antarctica. *J. Geophys. Res.* **101**: 28441–28455.

ZWALLY, H.J.; C.L. PARKINSON and J.C. COMISO. 1983. Variability of Antarctic sea ice and changes in carbon dioxide. *Science,* **220**: 1005–1012.