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An intercomparison of Antarctic sea ice extent datasets from the US Joint Ice Center (JIC) and satellite passive microwave observations for 1979–88

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Abstract: US Joint Ice Center (JIC) Antarctic sea ice extent data, the longest continuous series of its kind for this part of the world, are compared with direct passive microwave-based estimates to assess their overall consistency both spatially and temporally in the period 1979–88. Using ice edge position as a proxy for ice extent, the comparison reveals close agreement in most years, in monthly averaged ice edge positions in all Antarctic regions at the time of maximum ice extent, and also in autumn and spring in the Ross and Weddell Seas. Unexpectedly, JIC relative overestimation prevails during both autumn and spring in some other areas. Previously noted differences in JIC and passive microwave total Antarctic extent in 1979–80 result mainly from problems in the Ross Sea. Reasons for the various discrepancies may lie in differences in the methods used to produce the datasets especially in spring but those in autumn seem to often arise for other reasons. It is found that the prevalent discrepancies in the Ross Sea in 1979–80 as well as those in spring in other regions from 1981 coincide with periods of ice extent change and the evolution/intensification of ice extent anomalies.

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Introduction

Studies of the climatological and time-varying characteristics of Antarctic sea ice extent as well as ice–atmospheric circulation–air temperature relationships have to date relied on two distinct data sources, namely, direct ice extent estimates from satellite passive microwave data, hereafter PM, and a historical chart series produced by the US NOAA/Navy Joint Ice Center (JIC, now the National Ice Center). Weatherly *et al.* (1991), hereafter WET, have noted some apparent discrepancies in Antarctic total ice extent estimates from these two sources. Similarly, Harangozo (1997) has also noted differences in sub-monthly ice edge positions from the JIC series and other PM-based estimates, and hence a detailed comparative study of the two is desirable.

A series of PM-based ice edge position data has been produced by the University of Bremen (UB) (Heygster *et al.* 1996) and these are used in a systematic comparison with the JIC data here. Ice edge positions, a proxy for ice extent, are obtained from the JIC and UB datasets and attention here is focused on derived monthly average ice edge positions. Close attention is paid to the times when Antarctic sea ice is climatologically extensive as well as the surrounding seasons as understanding of interannual ice extent variations depends heavily on explaining the formation of ice extent anomalies at these times.

Direct intercomparison of ice distribution from the two products has been done using extracted ice edge position information that is used to form monthly averages. Monthly average position data have been widely used to study Antarctic ice extent variability and ice-atmosphere interactions. Also, as noted later, analyses based on calculated ice extent using the same raw PM data are not always comparable, a problem avoided using ice edge positions. Because the JIC charts provide a general depiction of ice extent this study highlights differences in Antarctic/regional ice distribution akin to the analysis of WET. Throughout this paper no *a priori* assumption is made that the JIC data are more or less reliable than the UB PM data. In the next section reasons why the two products could differ are noted. A detailed intercomparison of monthly ice edge positions then follows. The discussion considers the likely source of observed discrepancies and, in view of known intrinsic limitations and differences between the datasets, also pinpoints those differences that might not in fact be anticipated.

Ice edge position data sources

This study compares two independently-produced sea ice products based on distinct data and derivation methods. First, UB have used PM data supplied by the National Snow and Ice Data Center in Boulder to derive daily sea ice concentration fields and ice edge positions (concentration >15%) for Antarctica from 1979–95. These have been worked out using the multichannel PM data from the SMMR instrument on the NASA Nimbus-7 satellite up to August 1987 and the SSM/I instrument (both 50 km resolution) on the DMSP satellite thereafter. SMMR temporal coverage amounts to about

150 days yr[-1] against 330 days from SSM/I. These data have been extensively used in Antarctic climatological sea ice studies as summarized by Zwally *et al.* (1983) and Gloersen *et al.* (1992). The UB retrieval method is essentially the same as that of Gloersen *et al.* (1992) using the NASA Team algorithm (Cavalieri *et al.* 1984) but employing recently developed fixed threshold weather filters (Cavalieri *et al.* 1995). UB have found negligible differences in total Antarctic extents derived using this retrieval method compared to those of Gloersen *et al.* (1992).The UB data have been mapped to a resolution of 50 km.

NASA Team ice extents compare closely with observations from ships, aircraft, AVHRR (Advanced High Resolution Radiometer) and SAR (Synthetic Aperture Radar) both in the Arctic and Antarctic as summarized by Gloersen *et al.* (1992). The mean difference between the algorithm-based and independently-observed ice concentration estimates is thought to be below 5% with RMS differences of 1–7%. Gloersen *et al.* (1992) note that the 15% ice concentration isopleth, used to define the UB 'ice edge', satisfactorily distinguishes areas of open water from ice 'stripes' in the marginal ice zone. In the Weddell Sea Martin *et al.* (1987) found mean differences between SIR-B (Shuttle Imaging Radar B) and SMMR October ice concentrations of 1.7% ± 7.4%. Steffen & Schweiger (1991) found mean differences between Landsat and SSM/I spring ice concentrations of -1.1% ± 3.1% in the Weddell Sea and 1.3% ± 3.6% in the Amundsen Sea. In a recent study for the Bellingshausen Sea Stammerjohn & Smith (1996) found that the AVHRR ice edge is nearest to the 20% ice concentration contour in SSM/I data in spring case studies. Parkinson (1992) states that the NASA Team algorithm is most accurate in areas of extensive flat and dry ice floes. It is limited however, by the fact that it only allows for two ice types, first and multi-year ice, and open water. Thus accuracy drops with other ice surfaces, e.g. ridges, of varying emissivity. The algorithm does not detect areas of nilas and pancake ice (Parkinson 1992). Other PM accuracy limitations are shortly noted.

The other source of long-term Antarctic sea ice extent data is the historical series of weekly charts produced by US NOAA/Navy Joint Ice Center (JIC) (now the National Ice Center) since 1973. These are produced in near real-time and distributed in digital (SIGRID) format by the National Snow and Ice Data Center. The JIC use multiple data sources (Kniskern 1991) including all available satellite PM data but also AVHRR visible and infrared imagery. Sparse surface station and ship reports are also used. These charts have been widely used in Antarctic sea ice studies (Ropelewski 1983, Carleton 1989, Enomoto & Ohmura 1990, Jacka 1991, Weatherly *et al.* 1991, Chapman & Walsh 1993, King 1994, Simmonds & Jacka 1995) and used to prepare one of the first Antarctic sea ice atlases (Naval Oceanography Command Detachment 1985).

Differences and limitations of the JIC charts and passive microwave products

Several reasons exist why differences in the position of the JIC and UB ice edges product could arise even when working with monthly averaged data. These are noted now and a distinction is made between systematic and occasional differences.

Data interpretation

Until recently the JIC has manually charted Antarctic sea ice extent mainly by using hardcopy PM brightness imagery (Ackley 1981, Zwally *et al.* 1983, Kniskern 1991). Zwally *et al.* (1983) caution that there may be accuracy limitations in gauging ice concentration using PM brightness information. For this reason studies have mainly looked at JIC ice extent or the proxy ice edge position although WET have noted good agreement in both JIC Antarctic ice extent and ice area with PM-based calculations. This is slightly surprising given that PM data tend to underestimate ice concentration, and, hence ice extent, in the spring (Gloersen *et al.* 1992) when the ice/ snow surface is perhaps frequently wet and indistinguishable from open water. This problem is avoided when using AVHRR visible and infra-red data as JIC do. The PM ice edge may thus often locate south of the JIC ice edge during spring ice melting and retreat. In practise, however, the JIC's heavy reliance on PM data due to persistent cloud cover obscuring sea ice in the AVHRR channels (Kniskern 1991, Stammerjohn & Smith 1996) suggests that differences between the JIC and PM ice edges may be the exception.

Mapping

The JIC produces charts once weekly mainly to give guidance to shipping on sea ice distribution. The charts thus represent a 'snapshot' of sea ice distribution and a record of general rather than detailed changes in ice extent. This is the main reason why this study focuses on regional and large-scale differences in monthly averaged JIC and UB ice edge positions. Lack of real-time data is a potential problem with the JIC analyses. On these occasions the JIC analysts plot estimated ice edge positions using all available data as well the previous weeks' chart for continuity. The estimated positions are also checked against climatology. In practise, estimated positions (given as dashed lines on charts) usually closely resemble those given in the previous weeks' chart. Unfortunately, the SIGRID code does not distinguish estimated and observed positions.

Unlike PM ice concentration fields, the JIC charts give variable ice concentrations at the ice edge – often varying from 10 (minimum)–80% – due to the emphasis on mapping general ice distribution. High ice concentrations are most noticeable in winter and early spring, i.e. the period of maximum ice extent. It is not known whether this practise

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could introduce a systematic bias between the JIC and UB (15% ice concentration) edges. High resolution (25 km) Arctic and Antarctic measurements from the ESMR (Electronic Scanning Microwave Radiometer) PM mission (Comiso & Zwally 1984) indicate high concentration pack >80% is reached within 130 km of open water. By comparison, ship-based winter observations in the Weddell Sea (the only ones for the Southern Hemisphere) indicate a steady ice concentration increase to 80% within 200 km (Comiso *et al.* 1984) but sometimes less than half this distance (Wadhams *et al.* 1987). Comiso *et al.* (1984) also report comparable direct and satellite-derived ice concentration gradients with best agreement in the 18 GHz channel with a gradient of 0.42% km^{-1}. Given that the JIC have heavily relied on hardcopy PM brightness imagery and, in particular, they chart the general distribution of sea ice, it is not clear, however, that the location of the JIC ice edge would systematically differ compared to PM ice concentration fields. Results to be discussed later provide no evidence for this.

Sampling constraints

The JIC's inclusion of estimated ice edge positions has a potential limitation when producing monthly averages. Harangozo (1997), hereafter SH, has noted that ice advance i.e. ice extent increase, in the South Pacific region takes place quickly with most winter ice advance falling in less than half of the winter duration. If, say, one weekly ice edge position in a given month is estimated and this coincides with ice advance or ice retreat the monthly average JIC position will either be too far north or south. Such a problem is most likely to be noticeable in autumn–early winter and spring when week-to-week changes in ice edge position can reach 1–2° latitude. Later the UB data are used to identify the major periods of change and to assess if these relate to discrepancies between the absolute JIC and UB monthly average ice edge positions.

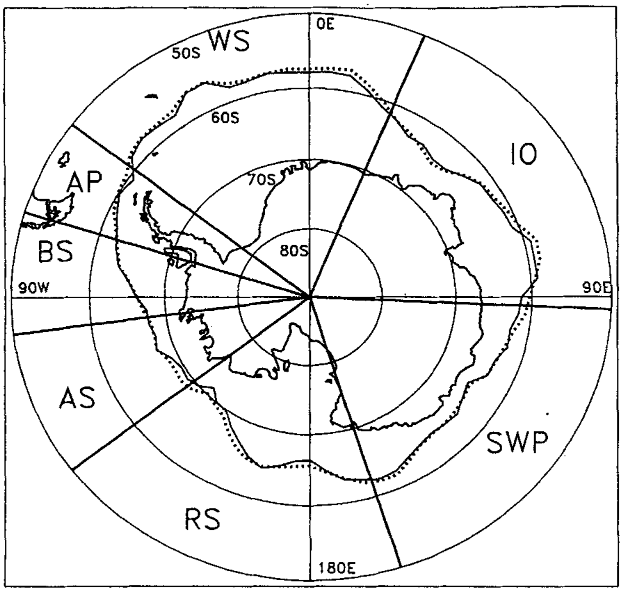

Fig. 1. Antarctic location map indicating regions referred to in the text with the monthly average position of the ice edge in the July 1980 as given by JIC charts (solid line) and University of Bremen (UB) passive microwave-based sea ice concentration data (dot) superposed. WS: Weddell Sea, IO: Indian Ocean, SWP: Southwest Pacific, RS: Ross Sea, AS: Amundsen Sea, BS: Bellingshausen Sea and AP: Antarctic Peninsula.

Data reduction

Following SH, JIC weekly ice edge locations have been extracted from the SIGRID dataset at 5° longitude intervals (72 measurement points) to provide proxy weekly ice extent measurements for all parts of Antarctica. These weekly measurements have been used to form monthly averages, i.e. 4–5 charts per month. For UB data daily averages have first been obtained by binning and averaging all available ice edge positions within 2° longitude windows centred on the same 72 JIC sampling points. Following SH, these daily positions have then been used to form weekly averages for the same weeks as in the JIC record followed by further averaging to derive monthly averages once more. This heavy averaging of the JIC and UB data helps bring out general differences in Antarctic ice extent in the two datasets on monthly timescales that is the focus of this study. Differences of ≥ 0.75° latitude between the respective monthly averaged ice edge positions are taken to represent real differences between the datasets. This is a conservative threshold given it exceeds the resolution of the raw JIC and UB data and the heavy prior averaging of both datasets.

Monthly average ice edge positions have been obtained for March to November spanning the period from just after the climatological annual sea ice minimum, the maximum in September and initial spring retreat (Gloersen *et al.* 1992, Parkinson 1992). Averages for March utilize data for the last two weeks in this month. In the intervening summer period west–east oriented 'lobes' of ice develop during ice retreat in the Weddell and Ross Seas precluding use of ice edge positions as a proxy for ice extent. Seasonal statistics have been prepared from the monthly data for autumn (March–May), winter (June–August) and spring (September–November). The intercomparison carried out here includes the Antarctic as a whole and regions (Fig. 1) closely analogous to those used by WET and Parkinson (1992). The main difference is that the Weddell Sea, 50°W–25°E excludes the western fringe adjacent to the Antarctic Peninsula that appears distinct as noted below.

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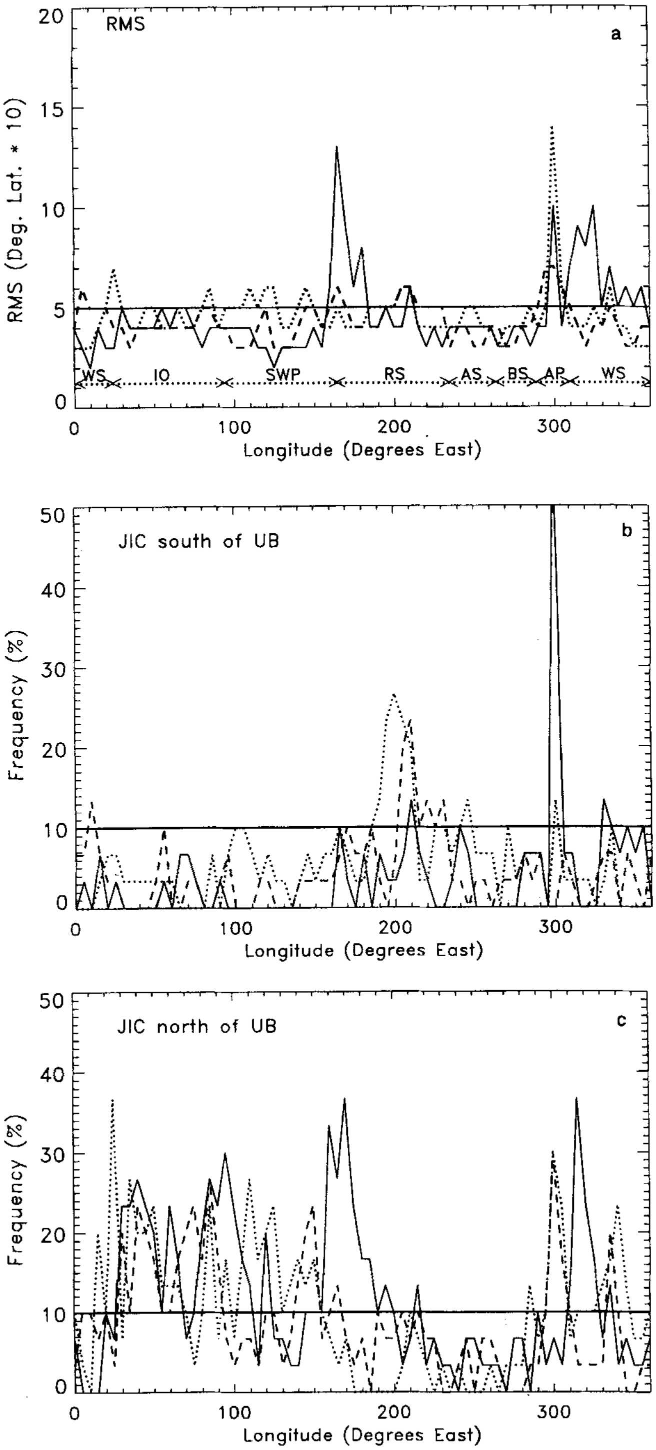

Fig. 2. The longitudinal variation of **a.** the RMS of the difference in the monthly average JIC and UB ice edge positions (°latitude*10); **b.** the frequency of cases (%) when the JIC ice edge position is ≥ 0.75° latitude south of the UB position and **c.** frequency of cases when the JIC ice edge position is ≥ 0.75° latitude north of the UB position, for 1979–88. In each case values are plotted at 5° longitude intervals and the analysis is by season for autumn (March–May) (solid line), winter (June–August) (dash) and spring (September–November) (dot). Regions marked in a. are as Fig. 1.

Monthly average ice edge position intercomparison

Results

Mean differences in monthly average JIC and UB ice edge positions (not shown) do not exceed ±0.25° latitude in any region in winter and early spring months or any season between the Indian Ocean and the Amundsen Sea. Elsewhere and at other times there is evidence of a displacement of the JIC ice edge relative to the UB position including the Weddell Sea. Here the mean differences are largest in autumn when they are often above 0.4° latitude and reach 0.7° in parts compared to generally not more than 0.4° in other seasons. The RMS of differences in monthly average positions in the 1979–88 period (Fig. 2a) generally does not exceed 0.5° latitude in autumn. This is followed by a rise in winter to a spring peak with values of up to 0.6° latitude in many places. This seasonal variation is most apparent in the Southwest Pacific. The main exception to this pattern is the western Ross Sea, with RMS differences around 0.5° latitude in winter and spring and with maximum values in autumn. An autumn peak is also evident in the west/central Weddell Sea, 55–35°W.

The frequency of offsets ≥ 0.75° latitude between the JIC and UB monthly averaged ice edge positions aggregated for the three main seasons are shown in Table I and plotted in Figs 2b & c, and also broken down by month in Table II. The main features are that cases of the JIC ice edge locating either north or south of the UB ice edge are the exception at the time of maximum ice extent in September, the rarity of either type of displacement in the Ross or Weddell Seas except in March, April and November and a marked prevalence of relative

Table I. Frequency of cases (%) when JIC monthly average ice edge positions are ≥ 0.75° latitude north (a) and south (b) of the UB position in autumn (March–May), winter (June–August) and spring (September–November) for Antarctica (ALL) and each of the main regions of the Indian Ocean (IO), Southwest Pacific (SWP), Ross Sea (RS) and Weddell Sea (WS) from 1979–88. Frequencies for the Amundsen and Bellingshausen seas do not exceed 10% in any season.

a) % of cases when the JIC monthly ice edge position is ≥ 0.75° latitude north of the UB position.

region	autumn	winter	spring
ALL	11.8	8.9	10.2
IO	18.6	16.7	16.2
SWP	13.6	9.3	15.2
RS	13.6	6.7	2.6
WS	9.6	6.4	10.7

b) % of cases when the JIC monthly ice edge position is ≥0.75° latitude south of the UB position.

region	autumn	winter	spring
ALL	3.8	4.3	5.7
IO	1.9	1.9	2.6
SWP	0	2.1	5.5
RS	4.5	10	11.9
WS	4.9	4.4	2.2

northward displacement of the JIC ice edge in transitional seasons (not shown). The latter mainly appear in the Indian Ocean and Southwest Pacific after 1980. In individual years instances of discrepancies accounting for more than 10% of spring and winter observations (Fig. 3) do arise but they are generally confined to one or two regions at one time, e.g. the Ross Sea and Southwest Pacific in the 1986 winter. Cases of the JIC ice edge locating south of the UB ice edge are rare in all seasons except in the 1980 spring when they are widespread and the Ross Sea in the 1980 winter and the 1979 spring.

Discrepancies around the time of maximum ice extent

At first glance the JIC and UB monthly ice edge position intercomparison does suggest that the two are closely comparable, and, in particular, around the time of maximum ice extent. The infrequency of discrepancies at this time for Antarctica as a whole (Fig. 3) in most years means that interannual variability as well as the absolute ice extents are well-captured in both datasets. Likewise, WET found that after 1980 their JIC- and SMMR PM-based total Antarctic total ice extents typically agree to within 0.5–0.25 million km² (see their fig. 3) in late winter–early spring. Independent estimates of SMMR multiyear total Antarctic ice extent (Gloersen & Campbell 1988) also agree with those of WET to the same level. It thus appears reasonable to treat the WET JIC-PM Antarctic ice extent differences as nominal at the time of the maximum.

WET did not extend their ice extent intercomparison to individual regions but again discrepancies are the clear exception for the two major sea ice embayments of the Ross and Weddell Sea at the time of maximum extent (when they account for about 60% of total Antarctic ice extent) both climatologically and in all but one of the 10 individual years. Thus overall Antarctic ice extent and that in the Ross and Weddell Seas are accurately gauged both in general and in most years. In contrast, according to WET their JIC estimates of total Antarctic ice extent in 1979–80 are 6–11% lower than SMMR values at the time of maximum extent (see their fig. 3). Figure 3 makes clear, however, that the distribution of JIC-UB differences varies spatially in winter and spring; JIC spring underestimation relative to SMMR data in 1980 is quite widespread but, in contrast, restricted mainly to the Ross

Table II. As Table I but by month for the main regions of the Indian Ocean (IO), Southwest Pacific (SWP), Ross Sea (RS) and Weddell Sea (WS).

Month	JIC north of UB				JIC south of UB			
	IO	SWP	RS	WS	IO	SWP	RS	WS
Mar	14	19	21	13	1	7	2	3
Apr	15	16	14	11	1	4	10	0
May	26	6	6	5	4	2	3	12
June	26	10	12	7	1	3	8	9
July	11	6	6	5	4	3	10	3
Aug	13	11	1	8	1	1	12	1
Sept	8	13	3	10	1	6	8	1
Oct	9	14	2	7	6	9	14	1
Nov	32	19	3	15	0	1	15	5

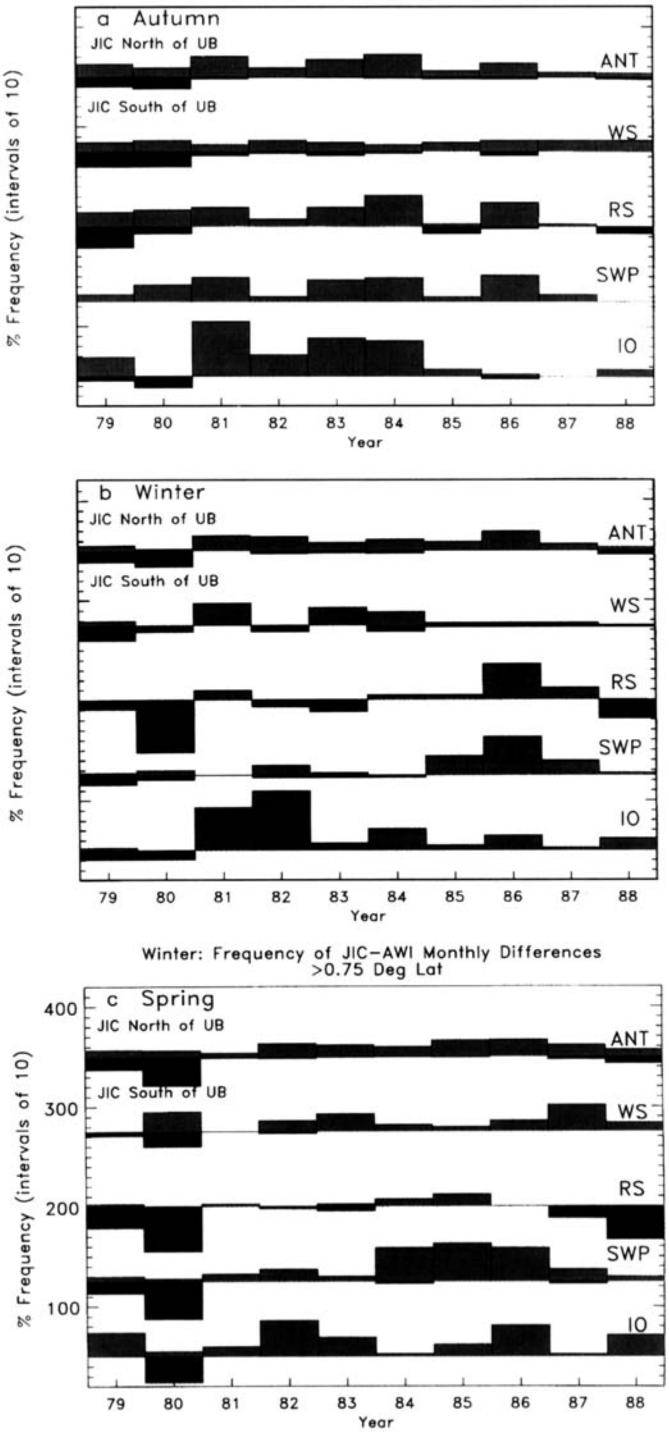

Fig. 3. Annual frequency (%) of cases when the JIC ice edge position is ≥ 0.75° latitude south of the UB position ice (dark grey shaded bars) or north (light grey) in **a.** autumn, **b.** winter and **c.** spring for Antarctica (ANT), the Weddell Sea (WS), Indian Ocean (IO), Southwest Pacific (SWP) and Ross Sea (RS).

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Sea in 1979 and also in the winter period prior to the 1980 maximum.

The reasons that discrepancies appear mainly in the Ross Sea around the time of maximum extent in 1979 and leading up to it in 1980 are unknown. The JIC charts only show occasional estimated ice edge positions over small areas. Also, limitations of PM retrievals due to surface melting could be expected to give UB ice extent underestimation compared to the JIC charts that are based on additional satellite data. Another explanation may be that the JIC made use of ESMR PM data until 1982 (Naval Oceanography Command Detachment 1982) despite sensor degradation after 1976 making these data prone to error.

It is interesting to note that the most pronounced winter negative sea ice anomaly in the Ross Sea in the SMMR PM record developed in 1980 (see fig. 4.1.24 in Gloersen *et al.* (1992)). The anomaly mainly appeared in the Ross Sea and both it and JIC-UB discrepancies continued into the following spring. The same is true of discrepancies that develop (figs 3c & 4.1.27 in Gloersen *et al.* (1992)). In view of the fact that SMMR data yield the lowest observed Ross Sea maximum ice extent in 1980 it does seem that the even lower JIC extents at this time are open to doubt. Even at this time, however, the distribution of discrepancies does vary by month, e.g. July 1980 (Fig. 1) when the expected discrepancies do appear in the Ross Sea but also extend to other regions. Thus the monthly JIC data at this time must all be treated with caution. The relationship of ice edge position discrepancies to ice extent anomalies is considered more later.

Discrepancies in transitional seasons after 1980

Present results confirm that the good overall agreement between the JIC and UB monthly ice edge positions at the time of maximum extent in the major ice embayments from 1981 onwards extends to the spring and, at least in the case of the Weddell Sea, also autumn. The autumn Ross Sea data is more problematic although only in March and April (Table II). This picture differs from that obtained in the Antarctic ice extent intercomparison by WET that indicates (their fig. 3) low JIC Antarctic ice extent estimates relative to SMMR in autumn and early winter in several years in the 1980s but agreement in late winter and, in particular, spring. Given that UB and WET have applied the same NASA-Team retrieval method to SMMR data available to mid-1987 it might be thought that both sets of analyses are correct with differences simply representing different facets of essentially similar datasets. This possibility is now explored.

Total Antarctic ice extent fluctuations mainly reflect those that take place in the Ross and Weddell Sea ice production 'factories' (Lemke *et al.* 1981). Given that ice in these two regions extends to lower latitudes than most other regions, especially in spring, any discrepancies in placement of the ice edge position here will disproportionately influence total Antarctic ice extent, i.e. ice edge excursions of a given latitudinal amount equate to greater ice extent with decreasing latitude. Given that autumn RMS differences in JIC–UB monthly ice edge positions are greatest in the Ross and Weddell Seas both in the full 1979–88 period (Fig. 2a) and 1981–88 (not shown), JIC underestimation shown in WET for autumn could be anticipated to be pronounced here. This is true for the Ross Sea in 1979–80 but not other years. Cases of the JIC ice edge locating ≥1° latitude south of the UB ice edge are rare in all autumn months for 1981–88. Instances of the JIC ice edge locating to the *north* are also rare in this period but, in contrast, in March they account for 21% of observations compared to 10% for Antarctica as a whole. The Weddell Sea also mimics Antarctica as a whole in all months. Very occasional large outliers also appear in both the Ross and Weddell Seas in the autumn transition period. Thus it is JIC ice extent overestimation relative to SMMR, mainly in March, along with the occasional outliers that accounts for the observed autumn RMS peaks in monthly average ice edge position differences in the main embayments. It should be noted that high RMS values in the Ross Sea are associated with 'outliers' when the JIC ice edge locates several degrees latitude south of the UB position at 165°E and at adjacent longitudes in the vicinity of Cape Adare. These mostly appear in March. At these times the UB ice edge is located on the open ocean side of the cape whereas the JIC charts only show ice in the Terra Nova Bay region to the south.

Scrutiny of fig. 3 in WET reveals that JIC autumn underestimation of total Antarctic extent relative to SMMR estimates after 1980 is usually most pronounced – reaching 6–10% – over periods of 1–2 months as in 1985 and 1986 and also in the early winter of 1984 and 1987. The JIC ice edge does locate south of the UB SMMR ice edge in June and, in

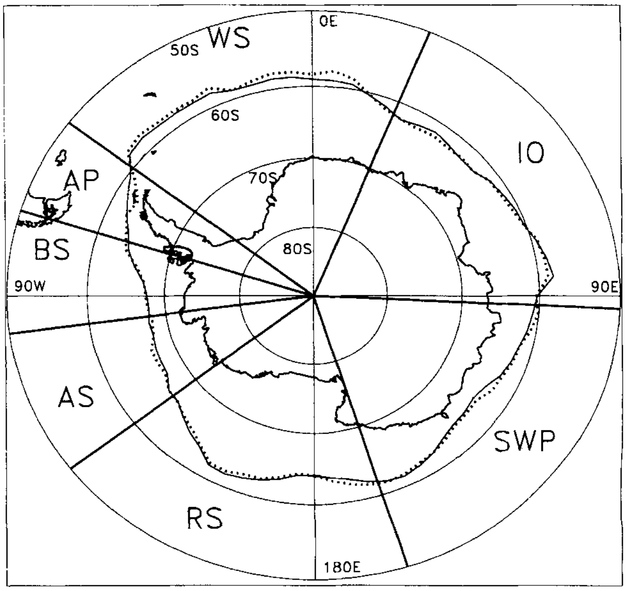

Fig. 4. Location of the JIC (solid line) and UB (dotted line) monthly average ice edge positions in July 1984.

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particular, July 1984 (Fig. 4) when displacements in the Weddell Sea, the Southwest Pacific and the western Ross Sea reach 0.5–1° latitude. June (not shown) is similar except that greatest displacements of about 1° latitude are in the Weddell and Bellingshausen seas. In contrast, no systematic southward shift of the JIC ice edge shows up in the 1987 winter or in the 1985 or 1986 autumns (not shown). In the autumn cases the JIC ice edge locates south of the UB ice edge in the Ross Sea but vice-versa in the Weddell Sea. Thus the previously suggested shortfall in autumn JIC ice extent only shows up occasionally in the ice edge data.

Distinct differences between earlier JIC-SMMR ice extent comparisons and present results also show up in spring and especially November (compare Table II with fig. 3 in WET). Thus while WET indicate close agreement in JIC and PM total Antarctic ice extent in many springs and, in particular, Novembers after 1980 the ice edge data generally show the JIC ice edge lying north of the UB ice edge, e.g. November 1986 (Fig. 5) when such a displacement is prominent from the Weddell Sea to 125°E, often exceeding 0.75° latitude.

Reconciling JIC-PM ice extent and ice edge intercomparison findings after 1980

The present JIC-PM intercomparison results seem to basically differ from those of WET after 1980. No differences have been found between the SIGRID coded JIC ice edge and those in the JIC charts. Even when ice edge positions correspond closely in different datasets, however, offsets in total Antarctic ice extent may arise from using different landmasks. The WET PM and JIC Antarctic ice extent estimates were separately derived (Weatherly, personal communication) and because of this it is not known what the magnitude of any offset introduced by different land masks might have been. Although separate ice extent series seldom completely agree this is not usually seen as a problem as different series capture the same temporal variability. Even the reported SMMR Antarctic total ice extents of WET and Gloersen *et al.* (1992) generally differ by about 5% (see their fig. 3), i.e. of similar magnitude to differences found by WET. Antarctic landmasks have also changed over time, e.g. three separate Antarctic landmasks have been shipped with the raw NSIDC SMMR and SSM/I PM datasets.

From the foregoing it does seem that a slight offset could exist between the JIC and SMMR Antarctic ice extents of WET. Thus the JIC values may be low relative to their independently derived SMMR estimates or the PM estimates slightly high or, perhaps most likely of all, a mixture of both. As fig. 3 in WET makes clear, JIC and SMMR Antarctictotal ice extent estimates systematically converge between autumn, when their estimates deviate most, and spring in all years after 1980 except 1981. If their estimates of Antarctic ice extent do contain an offset this would, if removed, give less JIC underestimation relative to PM data in autumn, close agreement in winter and more JIC overestimation in spring than shown in their fig. 3. Clearly, this pattern accords much more closely with the present ice edge intercomparison results.

Monthly ice edge position discrepancies in relation to ice extent alterations and ice extent anomalies in the Indian Ocean and Southwest Pacific

Given that PM data are thought to be least reliable in spring due to surface wetness it is slightly surprising that WET find little evidence of spring PM ice extent underestimation relative to JIC analyses that employ AVHRR data. In the present study the springtime prevalence of cases of the JIC monthly

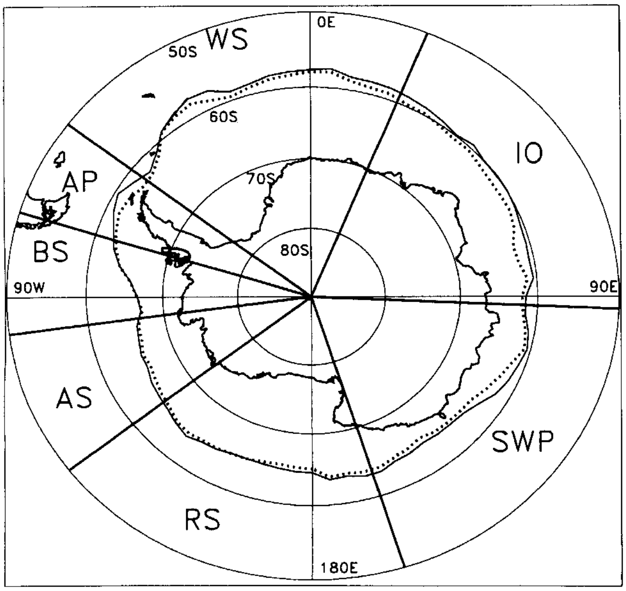

Fig. 5. As Fig. 4 but for November 1986

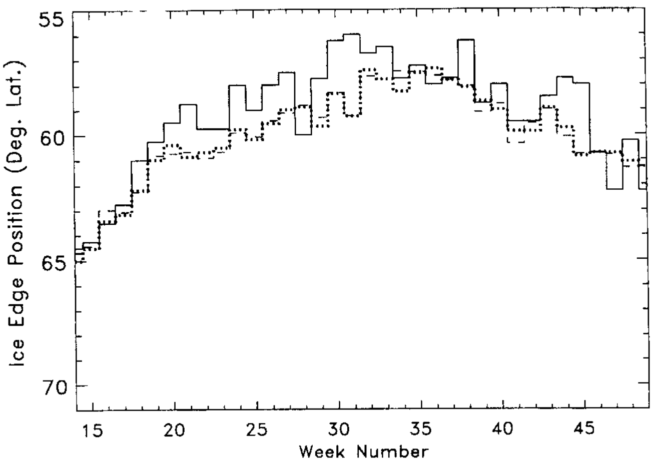

Fig. 6. Traces of weekly ice edge position (°latitude) from JIC (solid line) and UB based on all available daily data (dot) and data for the last four days of each week (dash) at 85°E from March to November 1982. The week number refers to the number of weeks from the start of the year.

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ice edge lying north of the UB ice edge in the Indian Ocean and Southwest Pacific from 1981–88 and their marked year-to-year variation may point to PM-based limitations when ice extent changes are rapid. Thus JIC-UB discrepancies may be most prevalent when retreat takes place perhaps producing negative ice extent anomalies, e.g. in the Indian Ocean (~85°E) region as shown for 1982 in Fig. 6. In two weeks (44–45) in November the UB ice edge is up to 2° latitude south of the JIC ice edge with an average discrepancy of 0.8° over the whole month. Similarly sized northward displacements of the JIC monthly average ice edge relative to UB appear throughout the Indian Ocean sector at this time (not shown).

Table III gives the percentage of cases of the JIC and UB monthly ice edge positions differing by at least 0.75° latitude (regardless of sign) that are attended by one or more weeks of ice edge movement (regardless of direction) of at least the same magnitude in the UB dataset for the Indian Ocean and Southwest Pacific for 1981–88. Data for 1979–80 are excluded as JIC ice extent underestimation found in the Ross Sea occasionally becomes more widespread at this time (Figs 1 & 3). The UB data are used to gauge ice edge movement solely as they are a single uniform data source (except for the change from SMMR to SSM/I in 1987). No assumption is made that they represent 'truth' any more than the JIC data. The weekly UB movement threshold exceeds the raw data resolution of about 0.5° latitude and, due to the heavy spatial and temporal averaging used to form weekly UB averages, is again conservative. In both regions frequencies of discrepancies of ≥ 0.75° latitude in monthly average positions attended by one or more weeks of ice movement are lowest from March–May falling to 12% or less in March. This rises to 60–78% in October and November but figures are also at least as high in winter in the Southwest Pacific. In other regionsthe small number of discrepancies in the 1981–88 period precludes a similar analysis.

There is therefore evidence in spring of an association between discrepancies in monthly ice edge positions and sub-monthly ice extent changes in the two regions where they are common in the 1981–88 period. In fact further analysis indicates that the ice is generally retreating in these regions at times of springtime discrepancies (not shown). In the Southwest Pacific JIC charts for the springs of 1984–86 when discrepancies are most frequent (Fig. 3) only show frequent estimated ice edge positions in October 1984. At this time discrepancies of ≥0.75° latitude are found between JIC and UB monthly averaged positions at 5 out of 14 measurement points and the UB data indicate widespread retreat (not shown). No estimated ice edge positions are found at the time of most prevalent discrepancies in the Indian Ocean in 1982 and 1986 (Fig. 3). Lack of real-time data at JIC thus does not appear to be a general cause of springtime discrepancies.

Limitations of PM data in spring, specifically in gauging retreat, could help explain the post-1980 cases of the UB ice edge lying south of the JIC ice edge but it is not obvious why these should mainly appear only in two regions. Noticeably, all the springs when such discrepancies are marked in the Southwest Pacific and Indian Ocean in the 1980s are attended by negative ice extent anomalies that either develop or intensify at the same time (see figs 4.1.25–4.1.27 in Gloersen *et al.* (1992)). No similar relation holds for the Weddell Sea in the spring of 1987 (Fig. 3) (SSM/I data), albeit the only other case found when such discrepancies are prevalent. Thus there does seem to be an association between years of increased relative springtime PM underestimation both with the occurrence of sub-monthly alterations in ice extent and the onset or intensification of ice extent anomalies, at least in the Indian Ocean and Southwest Pacific. This may suggest that they are prone to more springtime surface melt than the colder Ross and Weddell Sea regions.

Autumn PM ice extent underestimation relative to JIC charts in the Indian Ocean and Southwest Pacific sectors remains problematic owing to the climatological infrequency of ice retreat at this time of the year. Estimated JIC ice edge positions are again the exception at times when discrepancies are most prevalent. Also, the autumn discrepancies that most often appear in the Indian Ocean (Table I) are not generally accompanied by below-normal ice extent in the years 1981–

Table III. Monthly percentage of cases of the JIC and UB monthly ice edge positions differing by ≥ 0.75° latitude (regardless of sign) that are attended by one or more weeks of ice movement (regardless of direction) of the same magnitude in the UB dataset for the Indian Ocean (IO) and Southwest Pacific (SWP) for 1981–88.

Month	IO	SWP
Mar	12	10
Apr	38	33
May	50	13
June	53	71
July	73	80
Aug	50	100
Sept	45	80
Oct	63	60
Nov	78	70

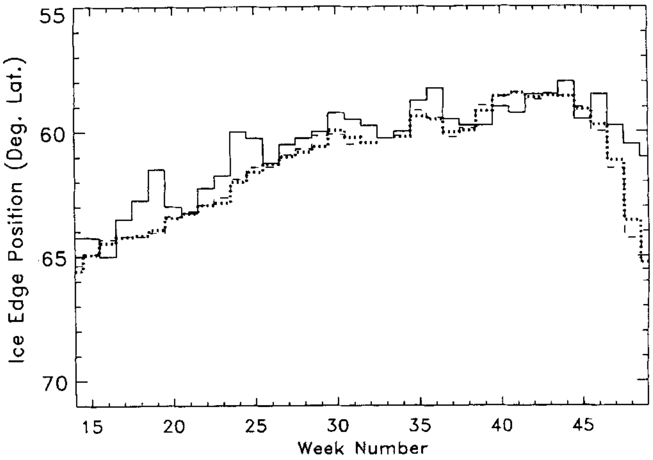

Fig. 7. As Fig. 6 but for 65°E from March to November 1984.

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84 when they are most frequent (Fig. 3). Instead, the JIC ice edge appears to go further north more quickly than in the UB case at the onset of the main ice advance season as in May 1984 centred on week 19 (Fig. 7). The use of AVHRR data by JIC may resolve ice stripes and patches not detectable in PM data but this would be unlikely to give the much greater JIC ice extent seen in Fig. 7 at this time.

In summary, it is not possible to unequivocally state why ice edge position discrepancies appear in the Southwest Pacific and Indian Ocean after 1980 but it seems likely that they are due to more than one cause. PM-retrieval limitations are a likely source of at least some in spring consistent with known climatological changes in ice extent at this time. Other reasons must be sought in the case of autumn and the possibility of JIC analysis limitations cannot be ignored. In agreement with SH, it is also clear from Figs 6 & 7 that the JIC and UB ice edge datasets cannot be used interchangeably on sub-monthly timescales.

Case study: relation of ice edge position discrepancies to meteorological conditions

In this section meteorological conditions in May 1984 in the Indian Ocean (Fig. 7) when the JIC ice edge lies north of the UB one more than might be expected just from using different remotely sensed data. In Fig. 8 the JIC and UB ice edges are mapped for the second week of May (week 19) when the JIC ice edge moves rapidly northward unlike the UB ice edge. The position of the -2°C isotherm at 1000 mb, i.e. near surface, and the mean sea level pressure field from the Australian Bureau of Meteorology numerical analyses are superposed. Climatologically, Antarctic sea ice does not generally locate north of the -2°C isotherm at any time of year (Comiso & Zwally 1984). In the case study period this is also true of the UB ice edge throughout the Indian Ocean. In contrast, the JIC ice edge lies north of this isotherm in the central part of the region where the JIC ice edge also lies north of the UB ice edge. The raised temperatures here are associated with poleward flows due to a mean cyclonic circulation centred over the western part of the region, a situation that favours warm air advection.

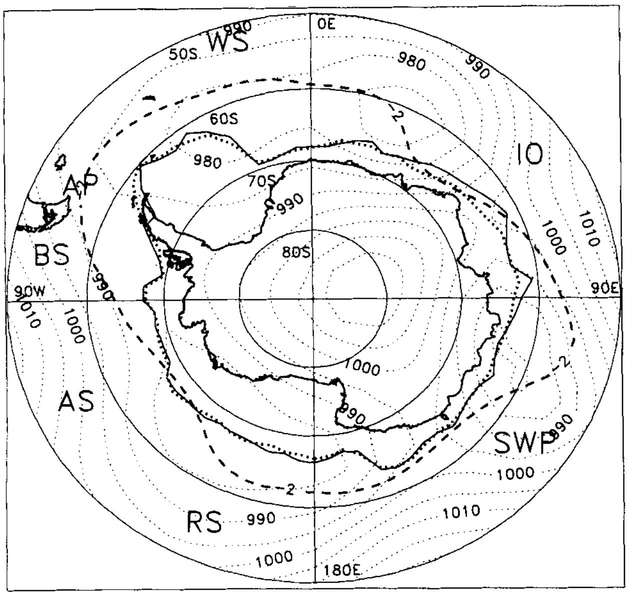

Fig. 8. Location of the JIC (solid) and UB (dotted) weekly ice edge positions and the weekly averaged -2°C isotherm (heavy dash) at 1000 mb and mean sea level pressure field (mb) (faint dot) in the second week of May 1984.

Meteorological conditions in the second week of May 1984 were thus not suited either to *in situ* ice formation or northward ice drift giving the observed JIC ice advance at this time. SH has found that a combination of poleward flow and warm air advection in fact favours ice retreat in the cold season in the Pacific. Assuming that the Australian meteorological analyses are accurate as they appear to be in the Pacific sector (SH), it is surmised that the UB ice edge position was probably more realistic than the JIC one in May 1984.

Climatological ice extent-air temperature relationships

Sea ice extent data have been used to study relationships between Antarctic surface air temperature and ice extent (WET, King 1994) and the degree of stability of these relationships across different ice edge products should be checked. Using station monthly air temperatures for Faraday in the Antarctic Peninsula and local ice edge positions based only on the mid-monthly JIC chart extracted by Jacka (1991) for 1973–89, King (1994) obtained correlation coefficients of 0.5–0.7 for most months of the year and peaking in winter. Using the monthly average UB ice edge position data from 1979 onward and JIC monthly values prior to this again produces highest correlations in winter but these all surpass 0.7 and reach 0.85 in July compared to King's 0.67, the highest value he found in any month. Also, correlation coefficients generally higher than those reported by King are obtained using only the present JIC monthly averages for 1973–88, e.g. 0.78 in July.

Present results thus suggest that using different monthly ice edge position datasets does not give stable ice-temperature correlations. It may be that the JIC mid-monthly position data of Jacka (1991) are not always representative of months as a whole. The datasets used in this study also give varying month-to-month changes in ice edge position. It is not obvious that the UB data are to be preferred over those from JIC but, in view of the differences in JIC-UB weekly ice edge positions – some of which likely exist for good reason especially in spring – climatological ice edge analyses based on monthly averaging are to be preferred over mid-monthly spot measurements.

Conclusions

A decade of monthly averaged Antarctic passive microwave and JIC chart-based sea ice edge position data have been compared to assess how far the two can be treated as interchangeable. Overall, the JIC and PM datasets do provide a sound basis for Antarctic sea ice extent analyses around the time of maximum ice extent and through most of the year in the Ross and Weddell Seas from 1981–88. Differences do arise in other years but are mainly confined to one embayment, at least on seasonal time scales. Outside the time of maximum extent agreement remains good in the major embayments. Two findings were, however, unexpected, namely, that the JIC and UB datasets are not interchangeable for Antarctica as a whole in transition seasons and a prevalence of UB spring extent underestimation in many years outside the main embayments. Differences between the present proxy ice extent results and previous Antarctic ice extent studies should also be kept in mind.

Although not a validation study, it has been surmized that at least some springtime PM ice extent underestimation relative to JIC data in the Indian Ocean and Southwest Pacific is likely due to PM data limitations. Year-to-year variations in this sort of discrepancy often coincide with ice retreat and negative sea ice extent anomalies. Lack of real-time data may also limit the accuracy of the JIC charts but it appears to be an uncommon problem. In autumn when ice retreat is rare JIC analysis limitations may also exist at least in the period under consideration. Monthly ice edge position-surface air temperature correlations are also generally higher when using the UB rather than JIC data at least in one area. Most caution is needed when using the JIC and UB data to look at sub-monthly ice extent changes and ice-atmosphere interactions, not least because of intrinsic differences in these datasets.

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