Decadal decrease of Antarctic sea ice extent inferred from whaling records revisited on the basis of historical and modern sea ice records

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In previous work, whaling catch positions were used as a proxy record for the position of the Antarctic sea ice edge and mean sea ice extent greater than the present one spanning 2.8° latitude was postulated to have occurred in the pre-1950s period, compared to extents observed since 1973 from microwave satellite imagery. The previous conclusion of an extended northern latitude for ice extent in the earlier epoch applied only to the January (mid-summer) period. For this summer period, however, there are also possible differences between ship and satellite-derived measurements. Our work showed a consistent summer offset (November–December), with the ship-observed ice edge 1 - 1.5° north of the satellite-derived ice edge. We further reexamine the use of whale catch as an ice edge proxy where agreement was claimed between the satellite ice edge (1973–1987) and the ship whale catch positions. This examination shows that, while there may be a linear correlation between ice edge position and whale catch data, the slope of the line deviates from unity and the ice edge is also further north in the whale catch data than in the satellite data for most latitudes. We compare the historical (direct) record and modern satellite maps of ice edge position accounting for these differences in ship and satellite observations. This comparison shows that only regional perturbations took place earlier, without significant deviations in the mean ice extents, from the pre-1950s to the post-1970s. This conclusion contradicts that previously stated from the analysis of whale catch data that indicated Antarctic sea ice extent changes were circumpolar rather than regional in nature between the two periods.

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In a letter to *Nature*, de la Mare (1997) stated that there had been a 25 % decline in summer (January) Antarctic sea ice between the mid-1950s and early 1970s. Figure 1 shows the 2.8° latitude apparent shift in sea ice extent for early January at 20 - 30° E longitude. Sea ice limits have been relatively constant in the era since then, although large year-to-year variability is seen on a regional basis. This conclusion was based on the use of whale catch records, as pelagic whaling was

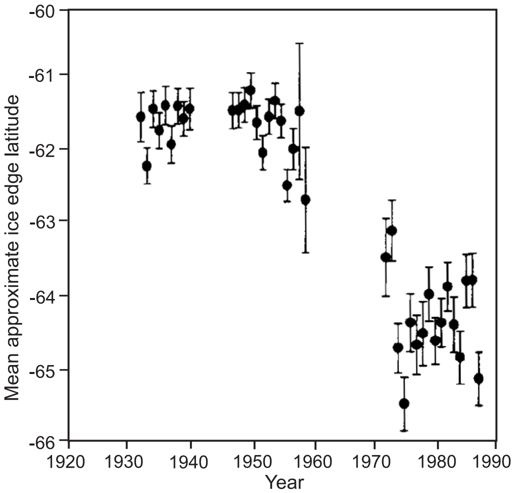

Fig. 1. The sea ice limit at 20 - 30° E for 1 - 10 January plotted as latitude vs. year covering the pre-1950s and post-1970s, based on de la Mare's analysis of whale catch records as a sea ice extent proxy (figure originally published in de la Mare 1997; used with permission of *Nature* and the author).

concentrated near the ice edge for certain species: blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales in the early era, minke whales (*B. bonaerensis*) for the modern era, as reviewed in Vaughan (2000). In this paper, we compare the historical (direct) record and modern satellite maps of ice edge position; show some recent findings on the relationship between surface-based and satellite ice observations; review some of the analyses used in the whale catch records; and discuss some recent physical findings on the atmospheric driving for sea ice variability in the modern era. These comparisons, in total, suggest instead that while some regional ice extent variations both may have occurred and continue to occur, interpetating a 25 % change (decline) in mean circumpolar ice extent between the 1950s and 1970s is unsupported.

Examining the direct historical record

From the 1920s to '30s, a series of cruises to the Southern Ocean was undertaken by the UK Discovery Committee with the ships *Discovery, Discovery II* and *William Scoresby.* The purpose was to investigate oceanographic properties and plankton distribution in relation to whale conservation, and results were published by the UK government in a long series of *Discovery Reports.* During this period, direct observations of sea ice extent were made when the ship encountered the pack ice. From these occasional observations, Mackintosh & Herdman (1940) compiled a circumpolar map of the monthly variation of the average ice edge. Mackintosh (1972) later updated these analyses with additional observations, probably including some made by whaling factory ships, and slightly revised the earlier maps. We note that due to the lack of whaling near the ice edge in the 1960s (de la Mare 1997) the observations used to construct these ice extent maps were exclusively from the period earlier than 1960.

To compare these historical maps to the modern record, the maps (Mackintosh 1972) were digitized and compared to the satellite data record derived from passive microwave satellite imagery from 1979–1998. As can be seen in Fig. 2, the January limits show relatively good correspondence in the mean except for about 170 - 180° E (Ross Sea) and 60° W to 0° (300 - 360° in Fig. 2) longitude (Weddell Sea). These two regions are also characterized by the greatest maximum-to-minimum differences, that is, they show the highest interannual variability, with a maximum-to-minimum greater than 10° latitude, in their January ice edge behaviour. As discussed later, the Weddell Sea apparent shift is also consistent with some recent evidence in atmospheric driving. This level of difference is relatively explainable and probably does not represent a circumpolar change, being dominated by an apparent regionally confined shift, primarily in the Weddell Sea. We also note that the variability in modern ice edge for the 20 - 30° E sector represented in Fig. 1 is 6 - 10° latitude from the maximum to the minimum.

Comparing in situ (surface-based) and satellite ice observations

Worby & Comiso (2001) conducted a study comparing ice observations from ships to the record from satellite microwave data. The ship data were taken from voyages of the Australian and US Antarctic research programmes between 1990 and 1998, using trained sea ice observers (Worby & Ackley 2000). Satellite passive microwave data were analysed from the SSM/I satellites to recover sea ice edge and concentration data (Comiso et

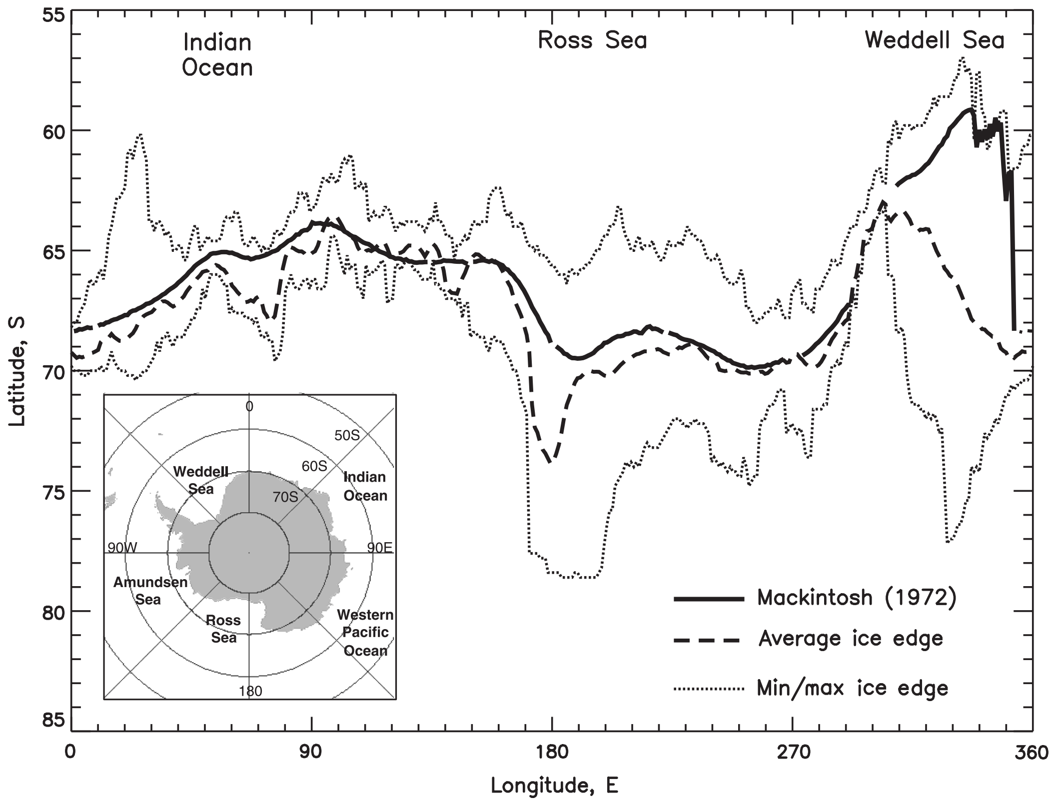

Fig. 2. Data digitized from the maps Mackintosh (1972) compiled from direct sea ice observations in the 1920s and 1930s, and mean, maximum and minimum sea ice extents for January (1979–1998) satellite passive microwave data.

al. 1997). Figure 3 shows the satellite data vs. the observed ice edge, for the observed years. As seen here the relationship and correlation between the satellite and in situ observations differ for the winter and summer periods. In the summer (November–December) period, the observed ice edge is further north by an average of 1.0 to 1.56° latitude as shown by the deviation of the correlation line from the one-to-one line. Worby & Comiso (2001) discussed the application of this result to historical comparisons, such as the whaling records study, and concluded that a range of several degrees northward of the plotted ice edge from satellite data could contain the actual ice edge in summer conditions. Physically, this discrepancy arises in summer conditions because of the diffuse ice conditions and surface flooding or snowmelt. These conditions can cause sea ice either to be unresolved at low concentrations or to appear as a water signature (disappear as ice) in passive microwave applications. Conversely, in winter, the surface has a very different microwave emissivity than water, and is more compact at the ice edge, leading to both better resolution and higher emissivities characteristic of cold sea ice and close correspondence between satellite and ship observations (Fig. 3a). Note also that in summer the discrepancy between ship-based and satellite ice edges is greatest where the ice edge latitude is lowest, again demonstrating that diffuse ice edges (whose occurrence will be relatively more frequent at low latitudes) are probably the source of the discrepancy. The ship data are also based on Australian cruises in the East Antarctic sector (see inset map in Fig. 2), so the Antarctic coastline generally lies between 66 and 67° S there. Sea edge ice observations at higher latitude (> 66° S) are therefore restricted to small amounts of residual sea ice that are close to the coastline at its minimum extent; these are naturally less frequently observed and, possibly, less diffuse due to the proximity of the coast.

Given the fewer data points for the summer period, however, an argument can be made that the deviation of the line from the one-to-one slope is not significant. In this case, it is easily seen that the line of slope 1 that best fits the data crosses the y-axis above the equal latitude crossing point, resulting in a similar latitudinal shift (satellite ice edge further south than ship ice edge) as we have estimated from the slope argument.

Comparing whaling-derived ice edge position and satellite-derived ice charts

One justification for the validity of the whaling-derived ice edge was a comparison between satellite-derived ice edges from the Joint Ice Center (JIC) charts and the period of whaling that overlapped with those data, 1973–1987 (Fig. 3 in de la Mare 1997, not shown here). A strong correlation ($R^2=0.83$) was found between the whale catch-indicated ice edge and the JIC chart position of the ice edge. The JIC ice edge is derived primarily from passive microwave satellite data because of the prevalence of cloud cover at the ice edge, limiting the use of visible imagery. However, the slope of the regression line is given as 0.87, rather than a value near 1.0 that is necessary. In Fig. 3b, where ship observations are compared to satellite values, the summer comparison has a higher correlation ($R^2=0.90$) than the whaling data, but the important point is the *slope* of the regression line (0.87), which lacks the one-to-one correspondence necessary to infer the actual ice edge position from the satellite data at all locations. On the other hand, in Fig. 3a the slope is near one, giving a near exact correspondence between the satellite and ship data for winter conditions and also a stronger correlation. Because of the statistical similarities, we infer the bias in the whaling derived data relative to the ice charts is of the same order as that of the ship observations vs. satellite data, on the order of 1.6° latitude, similar to that determined by Worby & Comiso (2001). Because the slope is less than one in both cases the bias is of similar sign, that is, the actual ice edge is northward of satellite-derived values when direct ship observations are used and northward of ice chart values when whaling-derived data is used, for summer conditions, defined here as October through March.

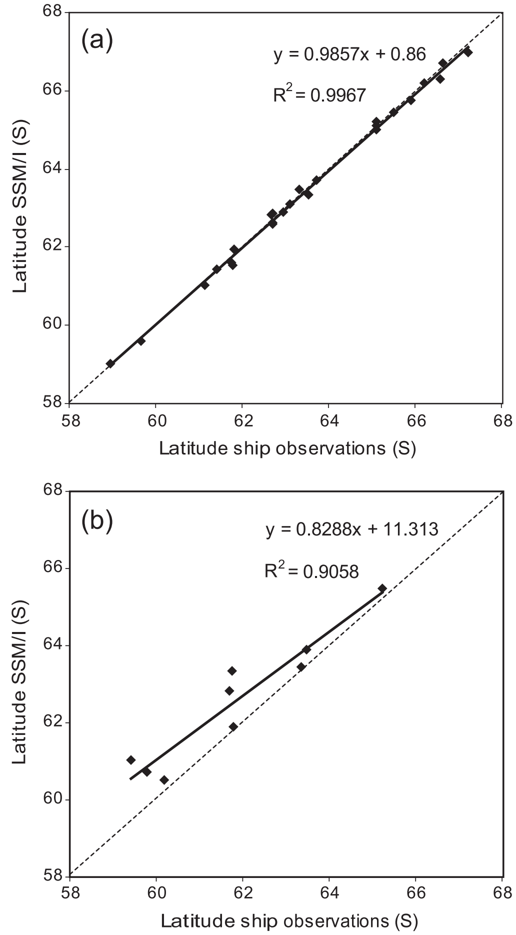

Fig. 3. Comparison of ice edge position from satellite data and ship observations: (a) winter (March–October) and (b) spring–summer (November–December). The dashed line in both is the one-to-one line (Worby & Comiso 2001).

Discussion

A circumpolar monthly average ice edge latitude was computed by averaging longitudinal data for the means from the satellite era and the ice maps for each month from October through March in Mackintosh (1972) (Fig. 2). In Fig. 4, we have plotted the computed average monthly latitudes of the ice edge against each month from October through March. On the lower curve the topside bar indicates an addition of 1.6° latitude to correct for the difference between the satellite-derived ice extent and surface observations, similar to the difference shown in Fig. 3b. We suggest

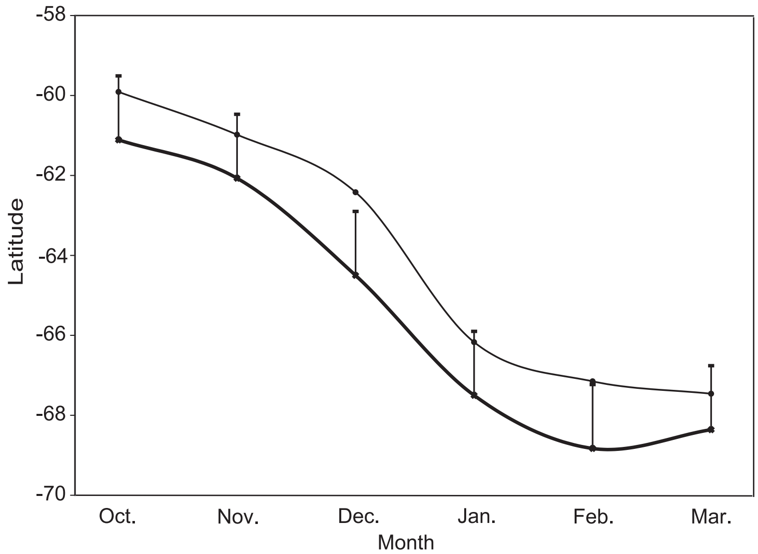

Fig. 4. Sea ice extent plotted as latitude against month, October–March. The lower curve shows the values from modern satellite data (1979–1998). The upper curve represents data from digitized maps in Mackintosh (1972) for 1925–1952. The topside bar on the satellite data is an estimate of 1.6° latitude northward, given the differences in ship observations and ice extent for the summer period.

that the relatively close correspondence between these two sets, after this correction, bears out the conclusion that little change is evident when the two periods are compared. Any difference is well within the modern era variability of 3 - 4° latitude, i.e. one half the longitudinal average difference between the maximum and minimum latitude extents shown (for January) in Fig. 2.

We suggested that there was some evidence for a regional change in ice extent for the earlier period, particularly for the Weddell Sea region (300 to 360° in Fig. 2). A discussion in Thompson & Solomon (2002) attributes some of this change to an air temperature-driven ice retreat effect, all within the period 1969–1998, caused by a shift in the Southern Hemisphere annular mode (SAM) in the atmosphere. This atmospheric effect can account for a portion of the warming and, consequently, recent sea ice reduction in the regions proximate to the Antarctic Peninsula. Although the recent SAM shift has also been characterized by cooling over east Antarctica, little difference is seen for the January sea ice extent between the modern or earlier eras (60 to 160° longitude in Fig. 2). Several factors are at work here. One is that the SAM is a change in tropospheric circulation affecting primarily the winds near 60° S, with extension of warmer air primarily occurring in these lower latitude regions, that also coincide with the position of the ice edge in the Antarctic Peninsula and Weddell Sea regions. The ice edge is further south in the east Antarctic region (> 64° S) than the 60° S typically seen in the Weddell Sea, i.e. somewhat removed from the strengthening or weakening in westerly wind flow associated with the SAM variability. Ice edge retreat in the modern era has shown different regional variability (Ackley & Keliher 1976) consistent with different mechanics for ice edge retreat. In the Weddell Sea, for example, the ice edge is constantly fed by ice transport along the Antarctic Peninsula, allowing a much lower latitude extent than the unconstrained boundaries in East Antarctica, where ice retreat nearly follows the onset of increased solar radiation in the summer period.

Even a circumpolar change in atmospheric driving (such as the SAM) can therefore cause either significant or no response in the sea ice edge retreat in different regions.

The documented SAM changes therefore do not provide the driving mechanism necessary for the large circumpolar increase inferred for the pre-1950s sea ice extent from the whaling data analysis, in the best case suggesting changes of opposite sign between the Weddell Sea and East Antarctica.

Whether whale catch data is usable as a sea ice edge proxy is still an open question. De la Mare claimed that the direct observations (that we also relied on here) were suggestive of a change between the 1930s and 1970s but that these observations had been regarded as inconclusive owing to limited spatial and temporal scope of these records. He then felt he was able to confirm change conclusively using the expand-

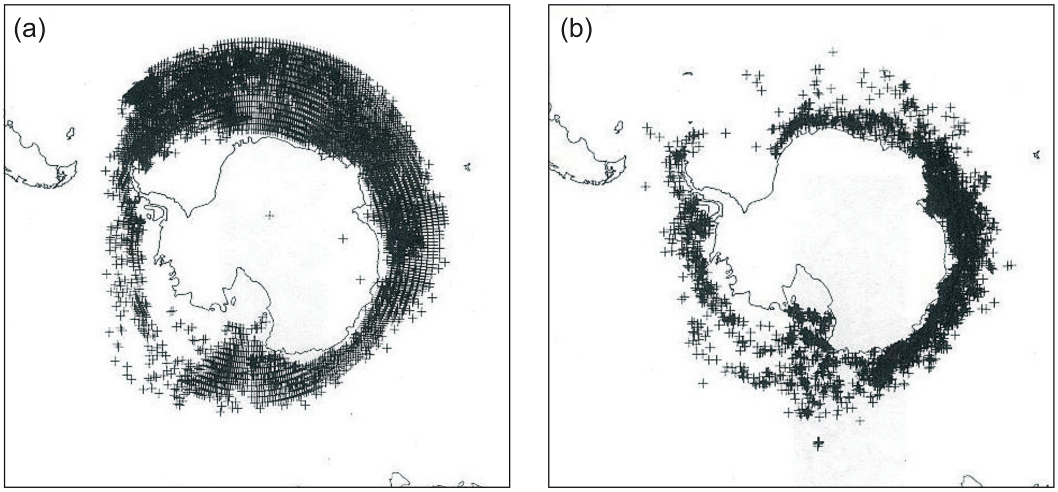

Fig. 5. Whale catch positions used in ice edge analyses from (a) pre-1970s and (b) post-1970s.

ed data from whale catch records. Confirmation of change, rather than detection of change, was, therefore, an underpinning principle in his analysis. He also chose regions and timing (early January) that are subjected to large fluctuations in ice extent to confirm his case, somewhat akin to choosing the highly variable air temperatures in spring in mid-latitudes to confirm trends in global warming. (The signal might be there, but the noise is also high.) These problems were further compounded by the change in whale species hunted and principal regions in which they were hunted between the two periods (Fig. 5). The minke whales (*Balaenoptera bonaerensis*) caught in the later period are an ice-associated species found throughout the year in the pack ice zone, while the earlier blue (*B. musculus*) and fin whale (*B. physalus*) species migrate to the spring–summer ice edge from outside the pack ice zone. There is also skewness in the catch data with a shift in the concentration of catches from the Atlantic side in the earlier era to the Indian Ocean (East Antarctic) side in the later period. The behaviour of the whale species and hunting at the ice edge may be similar, but species behaviour and data distribution might make the case inconclusive; in the absence of direct evidence for circumpolar change we believe it is insupportable.

Conclusions

We have relied on direct observation of ice edge position, as carried out by Mackintosh (1972) in the past, and summarized by Worby & Comiso (2001) for the present, and conclude that these must carry greater weight than observations of a quite different parameter which is affected by a host of whaling industry-based biases. We have shown in this paper that modern visual observations of ice edge position are well correlated with satellite-based data, but subject to a consistent mean offset due to diffuse ice edge satellite detectability in summer conditions. When the same offset is applied, there is good agreement between the range of modern (1979 onwards) satellite-based ice edge positions and the ship-based ice edges observed specifically by research vessels in the 1920s and 1930s for circumpolar mean latitude extent. Regional changes in summer sea ice extent between the two periods are also explainable by decadal changes in the SAM intruding warmer air and increased winds near the lower latitude ice edge in the Weddell Sea but neither increasing nor decreasing the ice extent elsewhere, due to the latitudinal asymmetry of the ice edge around Antarctica.

There is therefore no scope for a significant quantum transition in the circumpolar ice edge position in the 1960s as inferred by de la Mare from his analysis of whaling catch data as a sea ice edge proxy. Most of the difference between the earlier and later periods is explainable by the differences between ship and satellite observations and those significant changes seen are only regional variations with physical cause. We suspect the whale catch data as proxy evidence would come to a similar conclusion if the differences between ship and satellite observations are adequately accounted for and the analysis is done without an a priori assumption that circumpolar change has taken place.

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