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Historical whaling records reveal major regional retreat of Antarctic sea ice

Cédric Cotté*, Christophe Guinet

Centre d'Études Biologiques de Chizé, Centre National de la Recherche Scientifique, 79360 Villiers en Bois, France

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Abstract

Several studies have provided evidence of a reduction of the Antarctic sea ice extent. However, these studies were conducted either at a global scale or at a regional scale, and possible inter-regional differences were not analysed. Using the long-term whaling database we investigated circum-Antarctic changes in summer sea ice extent from 1931 to 1987. Accounting for bias inherent in the whaling method, this analysis provides new insight into the historical ice edge reconstruction and inter-regional differences. We highlight a reduction of the sea ice extent occurring in the 1960s, mainly in the Weddell sector where the change ranged from 3° to 7.9° latitude through summer. Although the whaling method may not be appropriate for detecting fine-scale change, these results provide evidence for a heterogeneous circumpolar change of the sea ice extent. The shift is temporally and spatially consistent with other environmental changes detected in the Weddell sector and also with a shift in the Southern Hemisphere annular mode. The large reduction of the sea ice extent has probably influenced the ecosystem of the Weddell Sea, particularly the krill biomass.

Keywords: Sea ice; Environmental assessment; Long-term changes; Whaling; Antarctic zone

1. Introduction

Antarctic sea ice is of crucial importance to world-wide climate, but variations in sea ice extent (SIE) during the last century are still largely unknown for the Antarctic scale as a whole. Satellite passive microwave data enable the tracking of SIE in Antarctica since the 1970s (Parkinson, 1992; Cavalieri et al., 1997; Zwally et al., 2002; Comiso, 2003). However, scarce direct information concerning SIE is available for the previous decades of the 20th century (Murphy et al., 1995). This lack of information is strongly detrimental, because the sea ice coverage actually demonstrates a high regional and temporal variability in Antarctica (Zwally et al., 1983, 2002), and misinterpretation could occur from the extrapolation of records for which the time scale is shorter than the variability of the phenomenon. A long-term dataset is indeed required to study possible changes in Antarctic environmental parameters, and particularly in SIE (Curran et al., 2003).

In order to assess the past SIE, several proxies have been investigated. Pioneer studies on ice core proxies were carried out from aerosol records of biogenic sulfur compounds in recent south polar precipitation, which were linked to ENSO events in terms of atmospheric and oceanic circulation

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*Corresponding author. Tel.: +33 5 49 09 78 39; fax: +33 5 49 09 65 26.
E-mail addresses: cecotte@cebc.cnrs.fr (C. Cotté), guinet@cebc.cnrs.fr (C. Guinet).

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(Legrand and Feniet-Saigne, 1991). Later the methane sulfonic acid concentration in sea ice proved to be a useful proxy for quantifying changes in SIE (Curran et al., 2003). Another emerging original indicator of SIE can be found in historical whaling records. This method, devised by de la Mare (1997), consists in determining the historical position of the ice edge from the location of the past southernmost whale catches. These different approaches have revealed a steep decline of SIE since the 1950s in the Southern Ocean. However, all these studies were conducted either only at regional scale or only at global scale without investigating possible inter-regional differences in the change of summer SIE.

During the intensive whaling period, pelagic fleets concentrated their effort along the Antarctic ice edge (Hjort et al., 1933; Shimadzu and Katabami, 1984), a major feeding ground for whales because of high krill densities (Brierley et al., 2002). Krill require sufficient food year-round, and the role of sea ice has only recently been investigated through the recognition of the importance of the sea ice algal community (Lizotte, 2001; Constable et al., 2003) on krill recruitment (Siegel and Loeb, 1995; Loeb et al., 1997, Brierley and Thomas, 2002) and population size (Atkinson et al., 2004). The survival of these long-lived zooplankton is actually related directly to the ephemeral sea ice habitat (Lizotte, 2001), which acts as a particularly important nursery for krill larvae. This life stage is the most vulnerable to food shortage, and the ice algal community is the most obvious food source (Ross et al., 2000). The ice edge also creates a favorable environment for algal bloom development through the seeding of the upper ocean with phytoplankton cells, the formation of a stable surface layer created by melting sea ice and the release of iron, a limiting element for phytoplankton growth (Sedwick and DiTullio, 1997).

Through these Antarctic ecosystem processes, the positions of the southernmost catches constitute a proxy to locate the ice edge, and we use this method to reconstruct past SIE. We propose to use the unequalled whaling records database to investigate circum Antarctic change in SIE through the 20th century and underline possible inter-regional differences. However, the accuracy of the whaling method and the validity of the de la Mare circumpolar prediction have been subject to controversy. Vaughan (2000) has questioned the quality of the data, but the discrepancies reported by this author inadequately challenge the precision of the whaling method proposed by de la Mare (2002). Nevertheless an important bias overlooked by previous analyses of whaling records is the existing offset between the summer ice edge locations established from satellite and ship-derived measurements, including the whaling ship (Ackley et al., 2003; Worby and Comiso, 2004).

In this paper we first estimate the inherent bias of the whaling method and compare it with the bias estimated in the previous studies (de la Mare, 1997; Ackley et al., 2003). We then examine the variation of the circum-Antarctic SIE through summer from 1931 to 1987 and investigate possible inter-regional changes in SIE.

2. Methods

Since the 1930s blue, fin and minke whales were successively exploited, and we propose to examine past SIE from blue and fin whale catches previous to 1960, and recent SIE from minke whale catches and satellite data (after 1972). The International Whaling Commission (IWC) provided the dataset, and we used only pelagic whaling data (excluding whaling data from land stations, especially at South Georgia, and altered or falsified catches). Extensive whaling operations depleted 700 000 blue and fin whales from Antarctic waters between 1931 and 1960, i.e., more than 95% of the populations (Brown and Lockyer, 1984), and 105 000 minke whales from 1973 until 1987, i.e., 15% of the recently estimated population (IWC, 1999). In 1987 the JARPA program of the IWC delivered special permit for random minke whaling within the Southern Ocean, which may result in a disconnection between the catch position and the ice edge since this date.

We calculated the mean latitudes of the 10 southernmost whale catch positions for $36 \times 10^\circ$-longitudinal circum-Antarctic sectors, from November (the beginning of the major whaling season) to February (when the SIE is minimal, from Parkinson, 2004), and from 1931 to 1987 (with no whaling data from 1941 to 1945 and from 1961 to 1971). As in de la Mare (1997), for a given sector, month and year, any catch positions more than 3° north of the southernmost catch position were excluded from the computation. The data consisted of 16 124 records (because of the restriction of the 10 southernmost whale catches) and the number of validated records is detailed by latitude (Fig. 1a), by longitude

(Fig. 1b), by year (Fig. 1c) and by month (Table 1). A mean monthly southernmost catch latitude was calculated for every year encompassed by this study.

Satellite sea ice extent was established from the Hadley Centre sea ice and sea surface temperature (HadISST) dataset for the period 1973–1987 (Rayner et al., 2003). This dataset essentially utilizes passive microwave data (successively ESMR from 1973 and SMMR from 1978). From 1973 to 1978, the National Ice Center charts (NIC, previously named the Joint Ice Centre), a mixture of data from observations and several satellites, were used as the main data source. Since 1978, the HadISST dataset uses passive microwave data mainly from the Goddard Space Flight Centre (GSFC), derived using the NASA Team algorithm. As the NIC chart-derived data had very high concentrations within the ice edge relative to the GSFC data, the HadISST dataset calibrated the NIC data with the GSFC dataset (Rayner et al., 2003). Proper definition of the ice edge from passive microwave data is important since the distance from 0% to 100% sea ice concentration can reach several degrees, especially in summer because of the diffuse ice conditions and surface flooding snowmelt. These conditions can cause sea ice either to be unresolved at low concentrations or to be misidentified (water instead of ice) in passive microwave applications (Ackley et al., 2003). For these reasons we used a clear signature of the ice edge given by the northern limits of 80% ice concentration, defined as the closed pack ice.

Relationships between whaling and satellite-derived ice edge were investigated and estimated by linear regression between the southernmost catch positions and direct satellite-derived ice edge. In order to connect our results with those obtained in other studies, we used the modified Student's t-test for comparison of two slopes of linear regressions (Zar, 1999). Circumpolar monthly mean latitudes of ice edge were estimated by pooling data over the satellite era and over each whaling period. The effect of the month factor (November to February) on the distance between whaling and satellite-derived ice edge was tested with an analysis of variance (ANOVA) and the normality of the residuals was verified with a Kolmogorov–Smirnov test (with $p > 0.01$). The contribution of a regional change (D_r) relative to the circumpolar monthly mean difference (D_m) between whaling and satellite-derived ice edge is estimated by

$$(D_r \times l)/(D_m \times L),$$

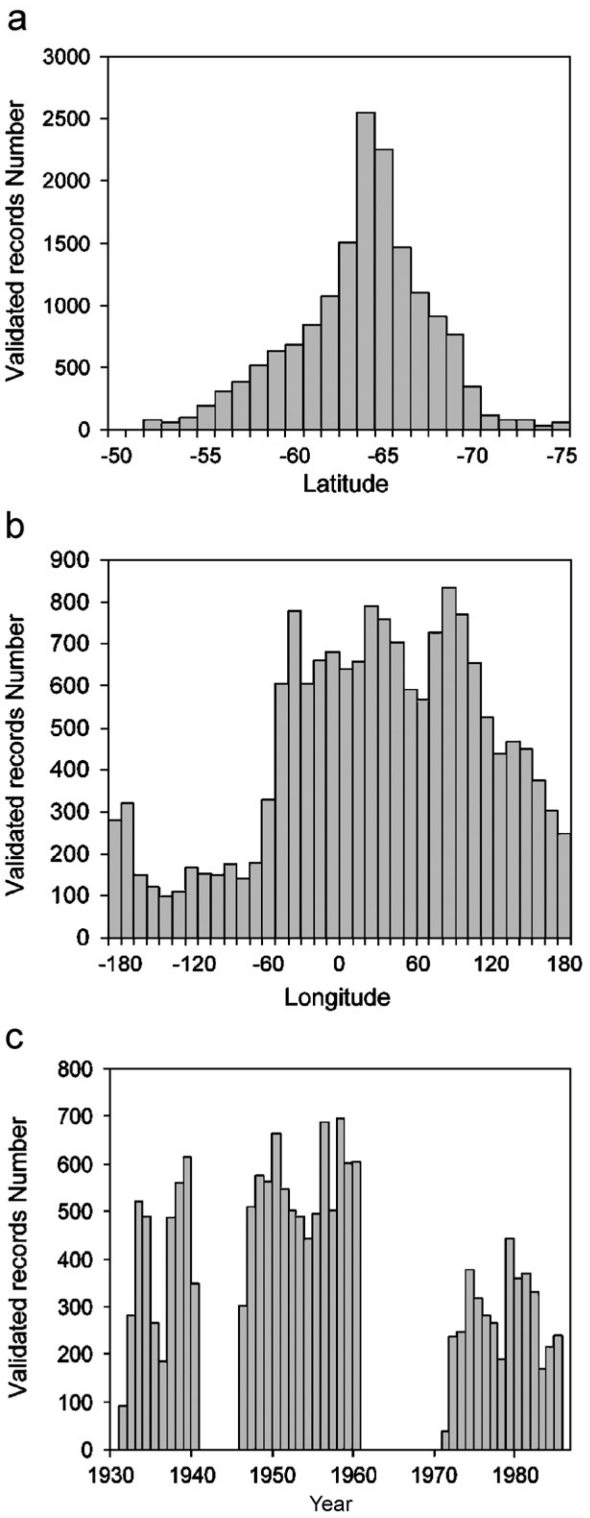

Fig. 1. Number of validated whale catch records from the combination processing represented by (a) latitude, (b) longitude, (c) year.

Table 1
Number of validated whale catch records from the combination processing by month

Periods	November	December	January	February	Total
Pre-1960 (blue-fin whales)	706	2403	4586	4344	12039
Post-1972 (minke whale)	566	1168	1111	1240	4085
Total	1272	3571	5697	5584	16124

where *l* is the longitudinal sector (in degrees) where the change in SIE occurred and *L* is the sum of the sectors where the SIE was estimated from whaling data. Standard errors (±s.e.) are indicated within brackets.

3. Results and discussion

Southernmost catch positions of minke whale were closely correlated to the direct satellite-derived ice edge from November to February, providing the most powerful justification of the validity of the whaling-derived ice edge (Fig. 2). However, the whaling-derived ice edge is further north by an average of 2.4° (±1.5°) latitude as shown by the offset of the correlation line from the one-to-one line (Fig. 2). Despite the relationship between satellite and whaling-derived ice edge is not one-to-one (due to the distance of whales to the closed pack ice and also to the misidentification of the ice edge during summer melting), we can nevertheless reconstruct the historical SIE since we have estimated the distance corresponding to the offset. This whaling-satellite distance is in close agreement with the 1.6° latitude difference between satellite and whaling-derived ice edge determined by Ackley et al. (2003), because they based their ice edge on the 15% ice coverage while we used the 80% coverage, which corresponds to an additional difference of nearly 1° latitude (Worby and Comiso, 2004). These authors argued that the satellite-derived ice edge is found southward when direct whaling-derived location of the ice edge and also direct ship observations are used (similar value given by Worby and Comiso, 2004). The 2.4° latitude difference we found is more than the de la Mare's 0.14° with a different slope of the linear regression (t-test = 3.26, $p > 0.01$). However, this discrepancy is explainable by the fact that de la Mare used the 15% ice coverage from NIC charts while we used here the 80% ice coverage from passive microwave data. Indeed Harangozo (1998) reported that the NIC ice edge data is generally located north of the passive microwave-derived ice edge and estimated an average discrepancy of 0.8° in November for a given year in the Indian Ocean. This author suggested that this discrepancy between the NIC and the passive microwave-derived ice edge may be most prevalent when retreat takes place, affecting the ice edge location during intense melting in summer. Accounting for these differences (0.8° for the NIC-passive microwave discrepancy, and 1° for the distance between 15% and 80% ice coverage), the resulting ~2° from de la Mare (1997) is close to the distance of 2.4° (±1.5°) we found between satellite (for 80% ice concentration) and whaling-derived ice edge.

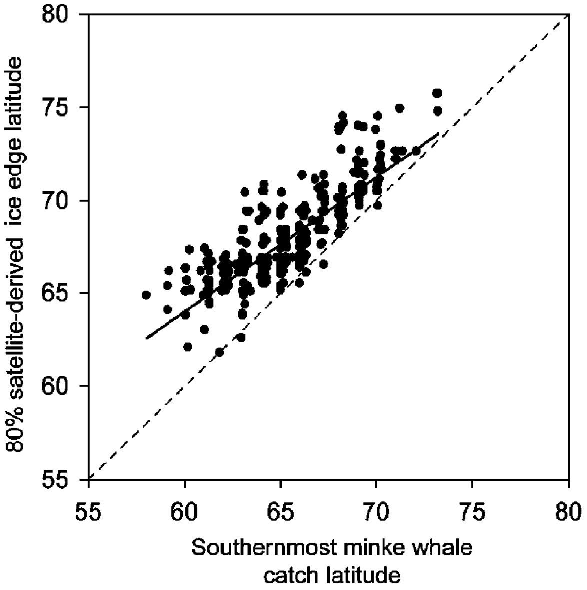

Fig. 2. Correspondence of minke whaling and direct passive microwave satellite data for ice edge location from 1973 to 1987 ($y = 0.72x + 20.81$, $r^2 = 0.68$, $p < 0.001$, $n = 381$, s.e. of the slope: 0.021) and from November to February. The dotted line indicates the one-to-one correspondence between southernmost whale catches and the position of the ice edge derived from satellite data (80% sea ice concentration). The correlation line deviates by a mean distance of 2.4° latitude from the one-to-one hypothetical correspondence.

Furthermore, Ackley et al. (2003) inferred that the bias in the whaling derived data vs. the satellite data is of the same order as that of the ship observations relative to satellite data (Worby and Comiso, 2004). As we chose the satellite passive microwave measurements as the referential location of the ice edge, this means that the 0.6° distance estimated by de la Mare (1997) between the southernmost catch latitude before 1960 and the ice edge derived from direct ship observation in the 1930s (Mackintosh and Herdman, 1940) has to be added to the 2.4° distance corresponding to the distance between ship-derived ice edge and virtual satellite-derived ice edge if such technology had been available in this period. The resulting 3° distance corresponds to an offset we have to take into account when considering whaling data before the satellite period (i.e. the blue-fin whaling). The different offset before 1960 (3°) and after 1972 (2.4°) relative to the satellite-derived ice edge location is consistent with the change in whale species hunted from blue and fin whales to the pagophilic minke whale found further into the marginal ice zone (van Franeker, 1992).

From whaling records, the ice edge location could not be calculated for some longitudinal sectors because of the lack of data. Monthly mean whaling-derived latitudes of ice edge from November to February were also calculated across years for the sectors where whaling data were available and compared to the mean 80% SIE extent determined from satellite measurement (1973–1987) for the corresponding sectors for the post-1972 minke whaling period (Fig. 3a) and the pre-1960 blue-fin whaling period (Fig. 3b). The mean latitude of the satellite-derived ice edge plotted in Fig. 3 corresponds thus to the monthly mean latitude of SIE across longitudes where whaling data was represented. Both minke (Fig. 3a) and blue-fin (Fig. 3b) whales followed the ice retreat through summer with no significant difference of the distance between whaling and satellite-derived ice edge over months for blue-fin whales ($F = 2.24$, $p = 0.09$), but with a significant one for minke whales ($F = 9.45$, $p<0.01$), probably due to the proximity of the ice edge to the continent in January and February (see next paragraph). But the important point is that, once the offset latitudes between whaling and satellite-derived ice edge previously estimated (indicated by the bars in Fig. 3) has been applied, the minke whaling-derived ice edge corresponds closely to the monthly corrected satellite-derived ice edge (very similar to the results of Ackley et al. (2003), while blue-fin whaling-derived ice edge estimates are further north. This suggests that, even though we apply the necessary offset, a difference still exists between whaling-derived mean ice edge before 1960 and satellite-derived mean ice edge. This difference corresponds to a distance of 2.3° (±1°),

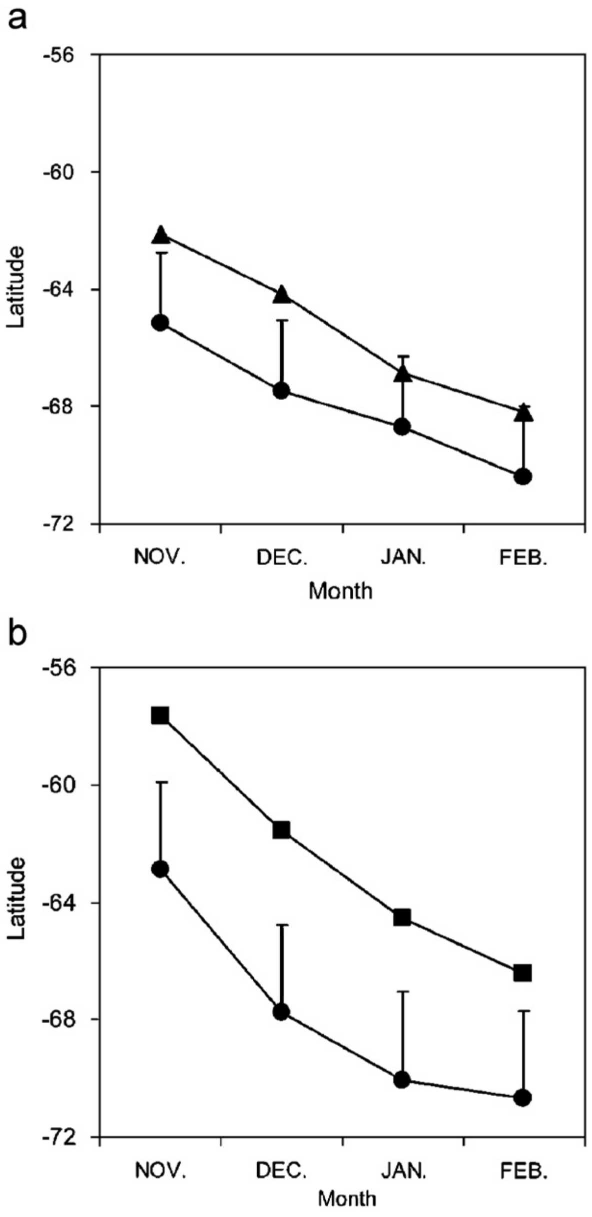

Fig. 3. Circumpolar monthly mean latitude of 80% satellite-derived ice edge (filled circles) estimated consistently (i.e., same sectors) with (a) minke (post-1972) whaling-derived ice edge (filled triangles) and (b) blue-fin (pre-1960) whaling-derived ice edge (filled squares) (Fig. 4 displays the monthly represented sectors). Bars indicate the estimated (a) 2.4° and (b) 3° offsets corresponding to the difference between satellite-derived ice edge and minke and blue-fin whaling-derived ice edge.

3.2° (±2.8°), 2.5° (±3.3°) and 1.3° (±2.8°) latitude for each month, respectively, from November to February. The mean difference over these 4 months (2.4°) is similar to the 2.8° latitude change found by de la Mare (1997).

These mean estimated distances between whaling before 1960 and satellite-derived ice edge are detailed in the maps from November to February presented in Fig. 4a–d showing the circumpolar monthly ice edges from blue-fin whaling (pre-1960), from minke whaling (post-1972), and from satellite data. Because of the high interannual variability in SIE, changes are considered significant when the error bars (defined as ±1 s.e.) of the pre-1960 whaling-derived ice edge do not overlap the errors bars of either the post-1972 whaling-derived ice edge or the satellite-derived ice edge (the ±1 s.e. of satellite data are represented by dotted lines in Fig. 4); the significant changes are reported in Table 2. In November, a significant difference between the pre-1960 whaling-derived ice edge and both post-1972 whaling and satellite-derived ice edge is observed for a 40° sector in the western South Indian Ocean. This difference increases dramatically (80° longitude and a mean 6.2° latitude) in December and is found in a sector of the South Atlantic Ocean corresponding to the Weddell Sea, while a sector of the Ross Sea is also affected during this month. In January, the difference is large (mean 7.3° latitude) for the Weddell sector while the difference in the Ross Sea seems to increase (60° longitude and a mean 5.9° latitude). In February, the difference is still important (mean 7.9° latitude) in the Weddell sector but affected only a sector in the Ross Sea. The large difference observed in the Ross sector between 190°W and 130°W in January remains uncertain as the scarcity of data (about 3 years only of consecutive data in the sector between 160 and 70°W), compared to the Atlantic and Indian sectors (Figs. 1b and 5), does not allow us to take into account the interannual variability of the SIE in this region. Note that the SIE is minimal for February; this suggests that the correction applied in the sectors where pack ice totally vanished (mostly Atlantic and Indian sectors) explained why the whaling-derived ice edge is found inland. In this case, whales are limited to the south by the coast and no more by the ice edge, making the offset unnecessary.

From a compilation of expedition records in the late 18th and early 19th centuries, Parkinson (1990) found some evidence of a larger summer SIE during this period in the Weddell Sea, although no strong "Little Ice Age" signal is found for the Southern Ocean. Whaling-derived ice edge from November to February revealed here that a major change occurred from western South Indian Ocean in November to western South Atlantic Ocean corresponding to the summer receding of the ice edge, and suggesting that the ice melting after 1972 is more intense than before 1960. The distance between past southernmost blue and fin whale catches and recent southernmost minke whale catches does not reflect an equivalent difference in foraging location between these species in the Weddell Sea as recent surveys reveal that these whales displayed similar southernmost distributions in this region (Kasamatsu et al., 1996). A smaller signal of SIE retreat is also noticeable in the Ross sector, but its reliability is difficult to estimate with the whaling method. Fig. 5 shows the complete combinations represented in January. Satellite-derived ice edge is in general agreement with post-1972 whaling-derived ice edge, even in terms of variability. The main point is the abrupt regional change occurring between the pre-1960 (blue-fin) whaling-derived ice edge and both the post-1972 (minke) whaling-derived ice edge and satellite-derived ice edge, when no data was available, neither from satellite, nor from whaling.

Once the contributions of the previously estimated regional changes in the Indian and Atlantic sectors are removed from their monthly mean difference, a difference of 0.6–1.4° between whaling and satellite-derived ice edge persists from November to February. This difference is in agreement with the long-term MSA data (Curran et al., 2003) revealing a 1.5° decrease in SIE in the 80–140°E sector that the whaling method does not detect here. The sources of the change, which is still unexplained by the whaling method, could come from the scarce data available for the region between 160° and 70°W making uncertain the difference observed in this sector, or the bias represented here by the non-negligible standard errors due to the strong interannual variability of the SIE.

While de la Mare (1997) provided a mean circum-Antarctic value for the reduction of SIE, our analysis reveals major regional differences between past and recent SIE which were not investigated by this author. The drastic environmental shift we report here is consistent with a decline of fast-ice duration occurring in mid-century in the Weddell Sea (Murphy et al., 1995), a net warming

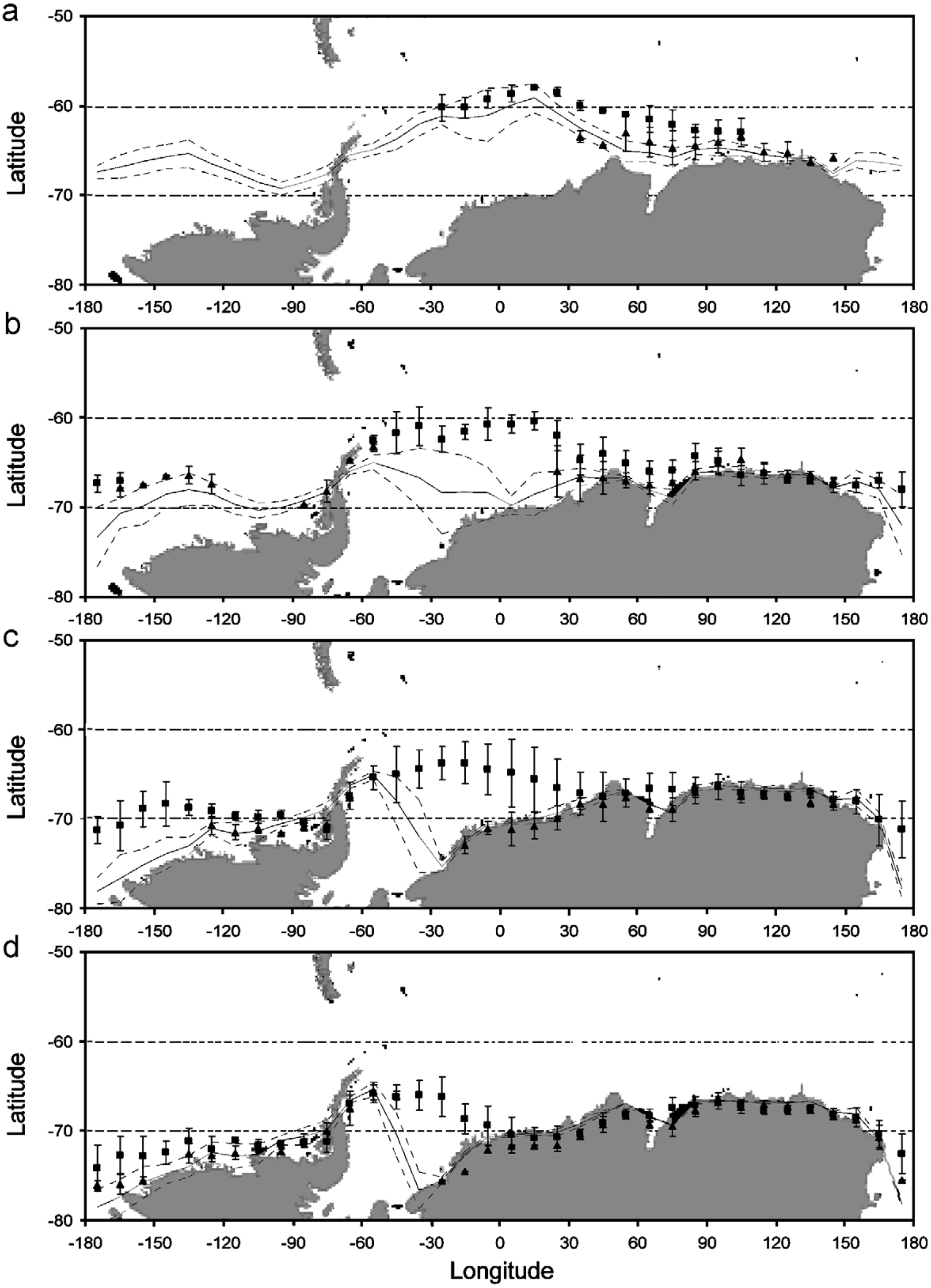

Fig. 4. Whaling and satellite-derived ice edge in Antarctica in (a) November, (b) December, (c) January and (d) February. The filled squares correspond to the monthly blue-fin (pre-1960) whaling-derived ice edge taking into account the 3° offset. The filled triangles correspond to the monthly minke (post-1972) whaling-derived ice edge taking into account the 2.4° offset. Bars indicate ±1 standard error for the whaling data. The solid line represents the monthly 80% satellite-derived ice edge and the dotted lines indicate ±1 standard error. East and west longitudes are plotted, respectively, as positive and negative values.

Table 2
Significant changes of SIE between pre-1960 and post-1972 period from November to February

Months	Sector (*l*)	Mean regional change (deg)	Contribution
November	20E–60E	3	0.9° (37%)
December	180W–170W	6	0.2° (7%)
	60W–20E	6.2	1.9° (60%)
January	190W–130W	5.9	1° (39%)
	40W–20E	7.3	1.2° (49%)
February	40W–10W	7.9	0.7° (41%)
	170E–180E	5.5	0.2° (10%)

The estimation of the regional changes contribution is detailed in the methods section (in brackets is given the percent of this contribution), and the mean monthly differences are given in the text.

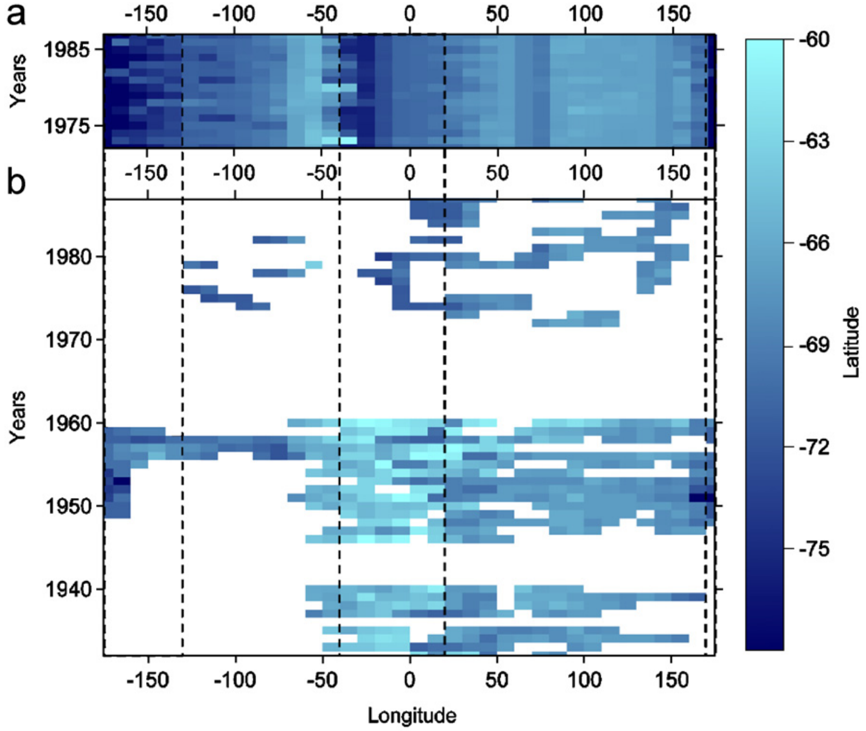

Fig. 5. January satellite and whaling-derived ice edge. (a) 80% satellite-derived ice edge from 1973 to 1987, and (b) blue-fin (pre-1960) and minke (post-1972) whaling-derived ice edge for each 10°-longitudinal sector. Dotted lines indicate the areas affected by the shift (see Fig. 4c). East and west longitudes are plotted, respectively, as positive and negative values.

measured in mid-depth Antarctic water (Gille, 2002) particularly noticeable in the Weddell Sea since 1970 (0.012±0.007 °C/yr in Robertson et al., 2002), and associated with a net warming trend (0.026–0.027 °C/yr at 11.50°E) of the surface ice in this region during the 1954–98 period (Comiso, 2000). Nevertheless, the step shift of SIE we depict here is non-linear compared to progressive trends of some environmental parameters as the warming of waters. An analysis of isotopic variability from coastal Antarctic ice cores carried out by Masson-Delmotte et al. (2003) indicates a sharp increase in deuterium excess in the early 1970s, resulting from an abrupt change in the local meridional atmospheric circulation. These authors found a warming of the sea surface temperature as early as 1965, before the warming of the Antarctic coast in the early 1970s, consistent with a negative trend in the sea-level pressure. This shift in 1970 corresponds to an increase of westerlies around Antarctica mediated by an intensification of the circumpolar vortex circulation (Thompson and Wallace, 2000). Fluctuations in the strength of the circumpolar vortex are induced by a large-scale pattern of climate variability at high latitudes called the Southern Hemisphere annular mode (SAM). The SAM shift recorded since 1969 has been related to the temperature trend and was thought to partly drive the regionally varying trends in Antarctic sea ice, especially the decrease in SIE near the peninsula (Thompson and Solomon, 2002). Ackley et al. (2003) discussed the influence of southward extension of warmer air by the winds near 60° due to SAM shift, coinciding to the past (before 1960) northernmost location of the ice edge we have reconstituted in the Weddell Sea. Other mechanisms have been proposed to explain the variability of ice edge retreat in the Weddell Sea, such as the ice streaming which constantly fed the ice edge along the constraint boundaries of the eastern part of the Weddell Sea and also the complex and highly variable Weddell ice tongue (de la Mare, 2002; Ackley et al., 2003).

These ocean-climate shifts could affect the regional absorption of solar radiation and ocean–atmosphere exchanges through the increase of atmospheric CO_2 drawdown (Parkinson, 2004) and could also affect Antarctic Bottom Water production and thereby impact, in the longer term, much larger regions of the world's oceans (Jacobs, 2004). Such major changes have important repercussions on the Antarctic ecosystem, as the Weddell sector was estimated to contribute 50 percent of the primary production associated with sea ice (Arrigo et al., 1997) and houses most stocks of Antarctic krill (Atkinson et al., 2004), a major species in the Antarctic marine ecosystem. Indeed the twofold decrease of the krill biomass since the 1970s recently described for this sector (Atkinson et al., 2004) is temporally and spatially consistent with the major decline of SIE we report here. Among other potential impacts, this SIE reduction may complicate the recovery of populations of large whales, which face considerable environmental changes in their sensitive Antarctic habitat.

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