Polar Biol (2007) 30:769–779
DOI 10.1007/s00300-006-0236-0

ORIGINAL PAPER

The influence of depth, site exposure and season on the intensity of iceberg scouring in nearshore Antarctic waters

Dan A. Smale · David K. A. Barnes · Keiron P. P. Fraser

Received: 27 September 2006 / Revised: 6 November 2006 / Accepted: 19 November 2006 / Published online: 20 December 2006

Abstract Ice scour disturbance has a significant effect on the physical and biological characteristics of polar benthos. A series of grids, each consisting of 25 markers, were deployed along depth transects and replicated at two contrasting study sites at Adelaide Island, West Antarctic Peninsula. Markers were surveyed and replaced every 3 months for 2 years in order to assess the frequency and intensity of iceberg impacts. Depth, site, season and year were all highly significant factors influencing ice scouring frequency. We observed a high variation in the duration of winter fast ice between sites and years, which had a marked effect on ice scouring frequency. The ecological effects of the disturbance regime are likely to include depth zonation of benthic assemblages, patchiness of communities at varying stages of recovery and the near denudation of sessile fauna in the shallow subtidal.

Keywords Ice · Disturbance · Benthos · Mortality · Scour

Introduction

Icebergs are formed by the calving of ice from glaciers and ice sheets into marine waters and range in size from relatively small (~5 m height above the waterline) to massive tabular icebergs (~10,000 km^2). Ice scouring is caused by icebergs contacting the seabed, resulting in physical alterations to the substratum (Woodworth-Lynas et al. 1991). The ecological effects of ice disturbance on benthic communities have been fairly well documented. Depth zonation of shallow subtidal communities caused by ice scouring has been reported at sites on the Antarctic Peninsula and Sub-Antarctic (Gambi et al. 1994, 2000; Barnes 1995b; Brouwer et al. 1995; Nonato et al. 2000; Barnes and Brockington 2003) and Arctic coastlines (Conlan et al. 1998; Conlan and Kvitek 2005). Exposed polar sediments may be completely reworked in 50 years (Reimnitz et al. 1977), resulting in high faunal mortality (Conlan et al. 1998; Peck et al. 1999; Lee et al. 2001), skewed population structures (Peck and Bullough 1993; Brown et al. 2004) and a dominance of mobile taxa and secondary consumers (Richardson and Hedgepeth 1977; Conlan et al. 1998; Conlan and Kvitek 2005). It has been suggested that every square meter of the Antarctic shelf is disturbed once every 340 years (Gutt 2001) resulting in altered community structure and function (Gutt et al. 1996; Gutt 2000; Gerdes et al. 2003). Where ice disturbance is frequent and severe, communities can be held at early successional stages by chronic ice scouring (Dayton et al. 1974; McCook and Chapman 1993; Barnes 1995b; Pugh and Davenport 1997). However, intermediate levels of disturbance may promote biodiversity by preventing the monopolisation of space by dominant competitors (Barnes 2002, but see Bruno et al. 2003) and increasing habitat heterogeneity and niche separation (Brenner et al. 2001; Gutt and Piepenburg 2003).

The effects of depth and site on ice scouring frequency in the recent past have been inferred by seabed profiling of relict scour marks in both the Antarctic

---

D. A. Smale (✉) · D. K. A. Barnes · K. P. P. Fraser
British Antarctic Survey,
Natural Environment Research Council, High Cross,
Madingley Road, Cambridge CB3 OET, UK
e-mail: dasma@bas.ac.uk

(Gutt and Starmans 2001) and the Arctic (Conlan and Kvitek 2005). Although the role of ice in structuring marine communities is well recognised (Gambi et al. 1994, 2000; Sahade et al. 1998; Nonato et al. 2000; Barnes and Brockington 2003), there are very few data concerning present-day scouring frequency. This is because such studies are both difficult and time consuming, and as of yet there have been no fully replicated studies on the influence of spatial and temporal factors on ice-mediated disturbance. Two previous techniques have been developed to measure ice scouring. Scrosati and Heaven (2006) developed a field technique involving small metallic cages, which were used to quantify the intensity of ice scouring at an ice-laden rocky shore in the Canadian subarctic. In another study, Brown et al. (2004) deployed concrete markers at a location on the Antarctic Peninsula to assess the disturbance regimes at two contrasting shallow water sites. The current study was an expansion of the work carried out by Brown et al. (2004), which further developed the field technique and used the same study sites. It is important to note that it is not only icebergs that may disturb the area and 'sea ice' is present at these study sites in a variety of forms, each of which may have a different influence on the ecology of the benthos. Therefore, we refer to each form specifically, using accepted definitions from the World Meterological Organisation (Table 1). The aim of this study was to quantify the effects of depth, site exposure, and season on ice-mediated disturbance at a high-latitude polar location.

Table 1 Types and definitions of sea ice observed at study sites at Rothera Point, Adelaide Island, West Antarctic Peninsula

Icebergs			
Type	Height above waterline (m)	Relative size	Mass (tonnes)
Iceberg	>5	Merchant ship	180,000
Bergy bit	1–5	Small house	up to 5,400
Growler	<1	Grand piano	up to 120
Brash	–	Car tyre	<1

Seasonal sea ice	
Type	Definition
Fast ice	Consolidated solid ice attached to the shore, to an ice wall or to an ice front
Ice foot	A narrow fringe of ice attached to the coast, unresponsive to tidal oscillations
Sea ice floe	Any relatively flat (free floating) piece of sea ice more than 20 m across

Adapted from Haykin et al. (1994) and the World Meteorological Organisation (WMO)

Materials and methods

Study site

The frequency and intensity of iceberg impacts was assessed at two sites adjacent to the British Antarctic Survey research station at Rothera Point, Adelaide Island, West Antarctic Peninsula (WAP), 67°34.5′S, 68°07.0′W (Fig. 1). The two study sites used were Hangar Cove[1] and South Cove. Long-term meteorological records from Rothera Point show that the prevailing winds are from the north and as a result small icebergs and brash frequently accumulate in Hangar Cove during summer (BAS, unpublished data). In contrast, South Cove has a sheltered aspect and is therefore often free of ice during summer. During calm weather periods, ice tends to move into South Cove and away from Hangar Cove (personal observation). Currents probably drive this, although present knowledge of local current patterns is poor. Fast ice, defined as 'sea ice which remains fast along the coast' (WMO 1970), forms during winter at both sites. However, its extent has been extremely variable between years and records show that winter fast ice usually forms in Hangar Cove before South Cove (BAS, unpublished data). Both sites have similar bathymetry with inclines of ca. 30° but differ markedly in their substratum type. Hangar Cove consists of compacted cobbles with an overlying layer of silt whereas South Cove is a mixture of hard bedrock and areas of compacted cobbles. Iceberg scours of varying age, size and depth have been observed by SCUBA divers at both study sites, often acting as depositional sites for biogenic material and fine sediments. A preliminary investigation of ice scouring frequency (over a limited depth range and without replication) at these sites was conducted by Brown et al. (2004). They suggested ice scour frequency was typically three times greater at Hangar Cove than at South Cove.

Impact markers

Each marker consisted of a cuboid concrete base (9 cm × 9 cm × 4 cm, ca. 750 g) with a non-toxic PVC-based modeling clay block (5 cm × 5 cm × 2 cm, ca. 85 g) secured onto the upper side. The clay block was secured to the concrete base with aluminum pins and silicon sealant. Markers were positioned on the seabed in order to detect iceberg impacts (see below). The marker design facilitated a hierarchal system of impact intensity, which could be assessed during SCUBA

---

[1] N. B. Hangar Cove was referred to as 'North Cove' by Brown et al. (2004).

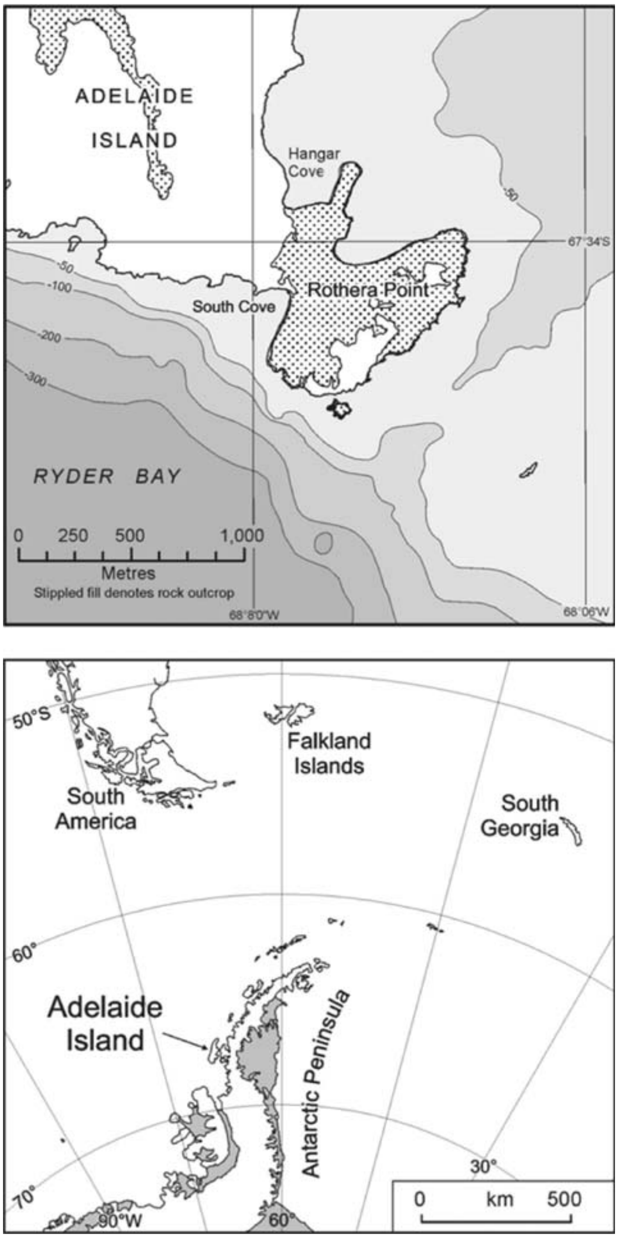


Fig. 1 Location of the South Cove and Hangar Cove study sites at Rothera Point, Adelaide Island, Antarctica. Large-scale map indicates position of Adelaide Island on the Antarctic Peninsula

diving surveys. The malleable modeling clay component of the marker was used to detect low intensity iceberg impacts as low energy collisions leave visible deformations on the surface of the block. High-energy impacts destroyed the clay block and damaged the concrete base (Fig. 2). SCUBA divers assigned each marker an 'impact score' of 0–4 during surveys: (0) no damage to marker; (1) <50% clay section damaged; (2) >50% clay section damaged; (3) concrete base damaged; (4) marker removed from experimental area or damaged beyond recognition (Fig. 2).

Experimental design

Each experimental grid designed to measure iceberg disturbance consisted of 25 individual markers placed 1 m apart to cover an area of seabed 4 m × 4 m (i.e. five rows of five markers). Each marker was clearly labeled with a unique code to facilitate in situ identification and assessment. Three replicate grids were laid at water depths of 25, 10, 5 and 0 m at both sites. These grids were laid along a depth gradient and therefore formed three replicate transects at each site. The 0 m depth grids were laid on the rocky shore at extreme low water spring tide level (ELWS) whilst SCUBA divers deployed the subtidal grids. The grids were surveyed at 3 month intervals and any damaged markers were recorded and replaced. The grids deployed at ELWS (0 m depth) were surveyed, but not rebuilt, more frequently during summer, as the frequency of impacts was consistently high at this time. Disturbance data was gathered for the period January 2004 to February 2006.

Statistical analysis

Two measures were analysed, disturbance frequency (F_d) and disturbance intensity (I_d). F_d is simply the total number of impacts recorded per grid. I_d is the mean impact score per grid; therefore each grid generated a value ranging from 0–4 (and hence relating to the scale defined above) at each sample point. The scores for replicate sets of grids were pooled and tested for normality (Kolmogorov–Smirnov normality test). Although our data were effectively a proportion, (i.e. number of hits per grid out of a maximum of 25) examination of the residuals showed minimal heterogeneity of variance and therefore untransformed data were analysed. Each grid (of 25 markers) was treated as one statistical unit, thereby providing 24 units generating data over eight time phases, all within a nested experimental design. Mean impact frequencies for depth were obtained by averaging depth replicates across all time phases. Means for sites and years were calculated by averaging across transects. All means are presented ± standard error (SE). The influence of depth, site, season and year on variance were analysed using a nested ANOVA design in Minitab 14.0.

Results

Depth, site season and year were all significant factors affecting the intensity of iceberg scouring, I_d at Adelaide Island, Antarctica. Depth, season and year

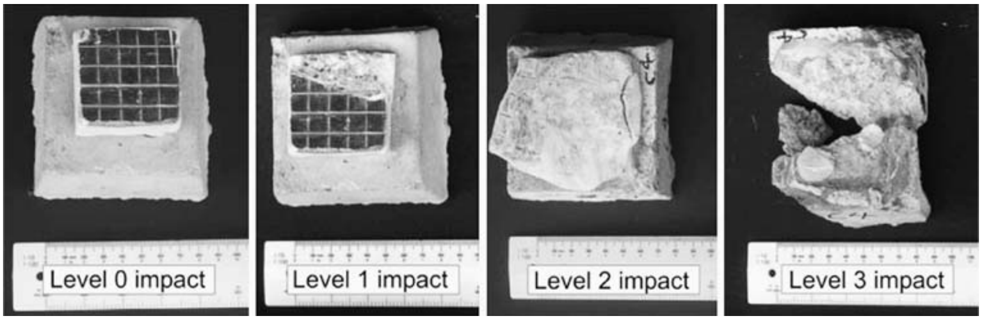


Fig. 2 The experimental markers used to detect iceberg impacts and the scale used to measure disturbance intensity. Each marker had a concrete base and a standardised clay block attached to the upper surface. A '*level 0*' score indicated no recorded impact; a '*level 1*' impact resulted in <50% damage to the clay block; a '*level 2*' impact resulted in >50% damage to the clay block; a '*level 3*' impact caused damage to the concrete base. An intensity value of 4 was assigned to markers that were either destroyed beyond recognition or removed from the experimental area entirely

Table 2 Results of nested ANOVA with disturbance intensity (I_d) the response to each factor and interaction

Source	DF	SS	MS	F	P
Site	1	1,598.52	1,598.52	10.85	0.030
Year	1	9,102.52	9,102.52	143.53	<0.001
Year × site	1	204.19	204.19	3.22	0.15
Season	3	14,890.94	4,963.65	40.67	<0.001
Season × site	3	5,312.94	1,770.98	14.51	<0.001
Season × year	3	1,125.02	375.01	4.70	0.022
Season × site × year	3	2,659.69	886.56	17.80	<0.001
Depth	3	15,349.35	5,116.45	23.90	<0.001
Depth × site	3	3,221.85	1,073.95	5.02	0.018
Depth × year	3	2,025.35	675.12	3.28	0.059
Depth × season	9	3,159.52	351.06	4.91	<0.001
Depth × site × year	3	2,018.02	672.67	3.27	0.059
Depth × site × season	9	2,874.35	319.37	4.47	<0.001
Depth × year × season	9	3,888.44	432.05	5.88	<0.001
Depth × site × year × season	9	5,647.44	627.49	8.54	<0.001

Table modified to allow for hierarchical structure of data due to transects nested within sites and repeated measures of year, season and depth within transects

were accepted at the >99.9% confidence level, whilst site was significant at the >95% level (Table 2). The same factors also significantly influenced disturbance frequency, F_d (all P values > 0.05). We therefore refer principally to I_d as it is relates to both the number and the intensity of iceberg impacts.

Depth

Disturbance frequency, F_d, decreased with depth at both study sites (Fig. 3a). At both South Cove and Hangar Cove the most frequently impacted grids were those laid at the ELWS level (0 m depth grids). During the fast ice-free summer months, when brash and small icebergs were most mobile, 100% of the markers laid at the ELWS level were damaged on several occasions. For example, in January 2005, all 75 markers laid at ELWS (0 m depth) at South Cove were impacted by ice within 24 h of placement. In contrast, impacts were recorded at the 25 m depth grids in just two of the eight SCUBA diving surveys at each site. The mean number of impacts per grid at the 0 m level (per 3 month survey) was 17.5 ± 0.1 at South Cove and 9.4 ± 0.0 at Hangar Cove, whilst the 25 m depth grids incurred an average of 1.5 ± 0.3 and 1.8 ± 1.7 hits per grid, at South Cove and Hangar Cove respectively. This indicates that floating ice impacted the rocky shore at Adelaide Island ~12 times more frequently than the seabed at 25 m depth at South Cove and ~5 times more frequently than 25 m depth at Hangar Cove (but see Discussion reg. ice foot disturbance). Depth also had a significant effect on disturbance intensity, I_d (Table 2). However, due to a number of high intensity impacts at deep grids at Hangar Cove, the 0 m depth I_d value was just 3.3 times greater than the 25 m value (Fig. 3b).

Low, medium and high-level impacts were recorded at every depth at both sites. The distribution of low intensity impacts (level 1) and high intensity impacts (level 3) was examined at each depth increment by

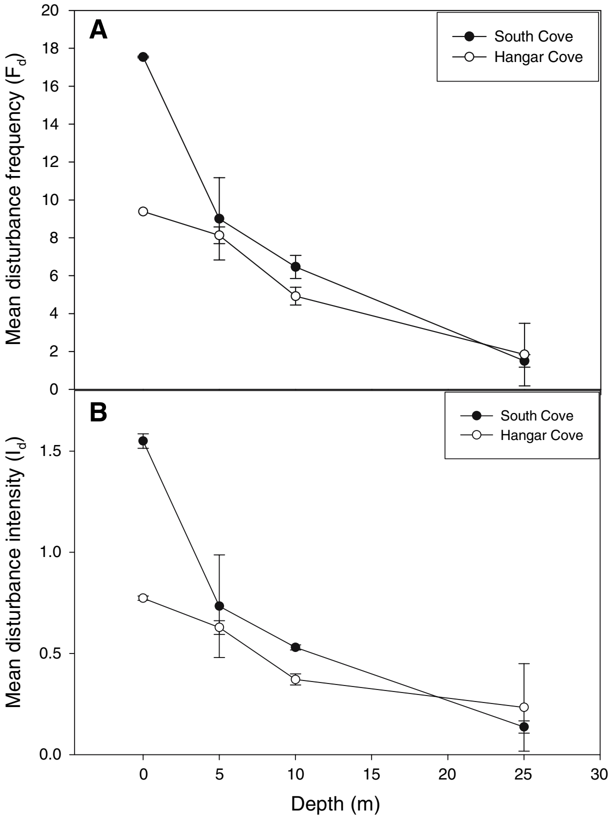


Fig. 3 **a** Mean disturbance frequency, F_d, (±SE) per grid and **b** mean disturbance intensity, I_d, per grid (±SE) plotted against water depth at both study sites, Rothera Point, Adelaide Island, Antarctica

calculating the contribution of these impact types to the total number of hits recorded. The proportion of low energy impacts showed no relationship with depth, whilst the percentage of high intensity impacts showed a significant correlation with water depth (Fig. 4). Regression analysis showed that the proportion of high intensity impacts was significantly greater at 25 m depth than at the ELWS (0 m depth) grids ($F = 6.53$, $P = 0.018$, $R^2 = 22.9$).

Site

The level of disturbance intensity, I_d, recorded at South Cove was significantly greater than at Hangar Cove ($F = 10.85$, $P = 0.03$). Both F_d and I_d were ~1.5 times greater at South Cove than Hangar Cove (Fig. 5). In terms of the number of markers hit during the study, 36% of the theoretical maximum were impacted at South Cove and 25% at Hangar Cove. The distribution of impacts was more homogenous at Hangar Cove, whilst at South Cove the gradient of depth and disturbance was more pronounced. These spatial patterns of total disturbance frequency (F_d) during the study period are illustrated in Fig. 6. Generally, there was little variation in disturbance scores between replicate grids. However, the exceptions were the 5 m depth grids at South Cove and the 25 m depth grids at Hangar Cove, where the standard deviations of I_d were considerably greater than at other depths (Fig. 7).

Two factors likely to have influenced ice scouring during the study were wind and the timing and duration of winter fast ice formation, both of which were recorded. The average wind direction was 006° and average speed was 12.5 knots (or 6.4 m s^{-2}; BAS, unpublished data). Therefore, Hangar Cove was more exposed to the prevalent wind and ice movements than South Cove. Winter fast ice formed in both years, but there was high variation between the study sites. In 2004, South Cove remained frozen for 81 days whilst fast ice was present at Hangar Cove for nearly 2 months more (135 days). The winter fast ice season was considerably longer in 2005, with 203 and 262 days of fast ice at South Cove and Hangar Cove respectively. In total, Hangar Cove had 1.4 times more sea ice days than South Cove (Table 3).

Season and year

Disturbance from iceberg impacts showed a strong seasonal pattern, which was closely related to the

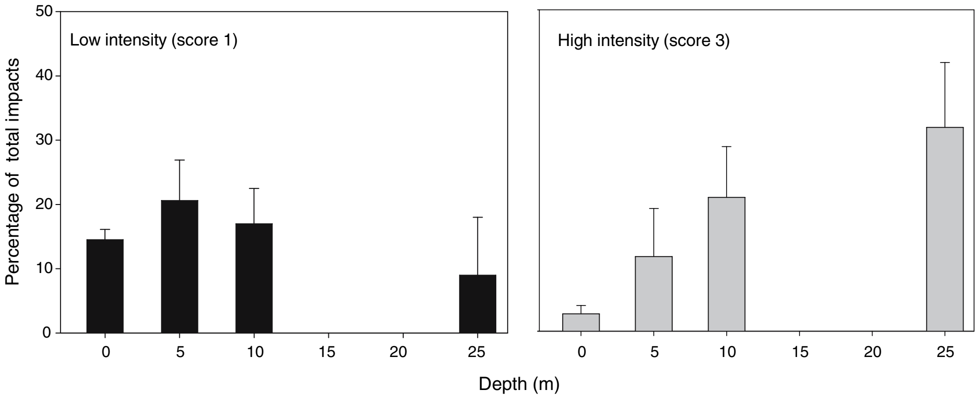
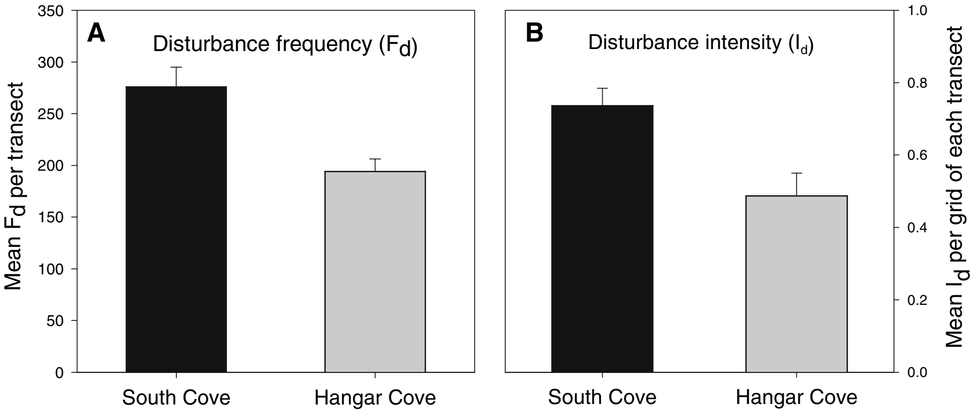


Fig. 4 Percentage of total impacts that were low intensity (*black bars*) and high intensity (*grey bars*) at each water depth increment. Data expressed as means of grids at both sites (±SE)

Fig. 5 **a** Mean disturbance frequency, F_d, (±SE) for each transect over entire study period. **b** Mean disturbance intensity, I_d (±SE) for each grid within replicate transects at South Cove and Hangar Cove, Rothera Point, Adelaide Island, Antarctica



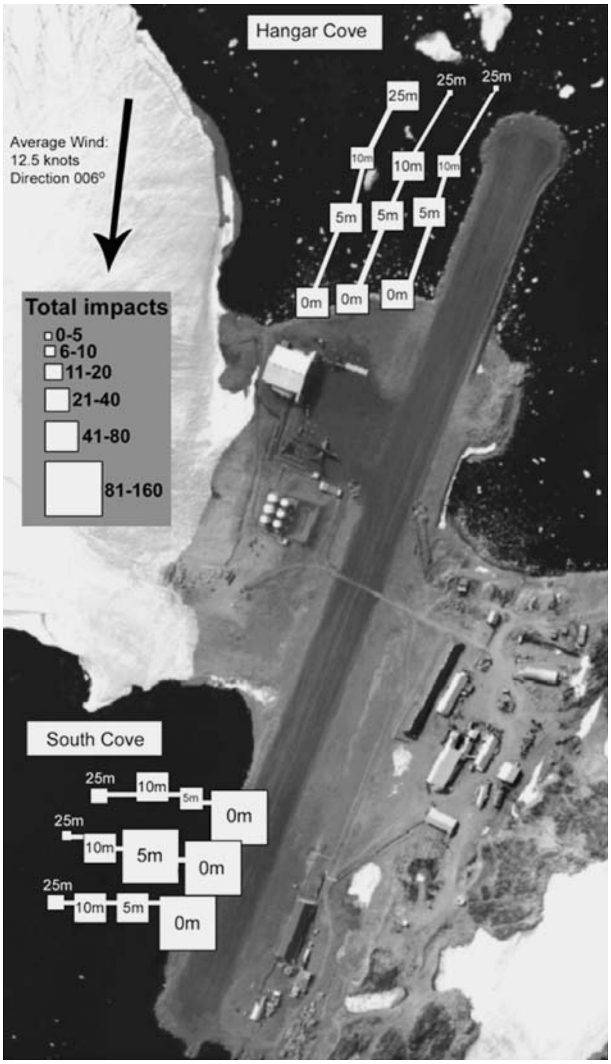


Fig. 6 An aerial photograph indicating the positions of each disturbance grid at Rothera Point, Adelaide Island, Antarctica. Accurate fixes of the grids were made using GPS. The area of the *white square* represents the total number of impacts (sum of frequency scores, F_d) recorded for each grid over the 2-year study

formation of winter sea ice (Fig. 8). At both sites and in both years, the periods of maximum disturbance were the austral summer (November–January) and autumn (February–April). Both the F_d and I_d response variables significantly decreased during the winter (May–July) and spring (August–October) in both study years. Zero impacts were recorded at both sites for 6 months during winter 2005. However, the 0 m grids were encased in an ice foot during this period, which may represent a further disturbance pressure (see Discussion). The greatest disturbance frequency was recorded at Hangar Cove in the 2004 summer survey, when 222 markers (74% of all markers) were hit. Season emerged as a highly significant factor influencing the disturbance score response ($F = 40.67$, $P < 0.001$) and interacted significantly with water depth, site and year (Table 2).

We observed high variation in disturbance between the two study years, with a 61% reduction in total I_d in 2005 compared with 2004 (Fig. 9). Year, like season,

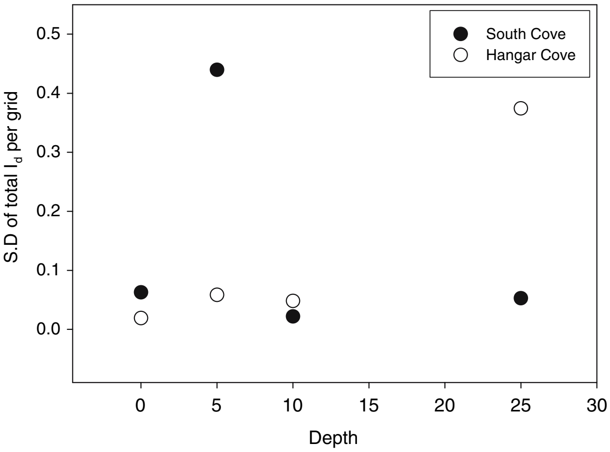


Fig. 7 Standard deviations of total disturbance intensity scores, I_d, recorded at the three replicate grids at each depth and site at Adelaide Islands, Antarctica

Table 3 Number of days of fast sea-ice at each study site and each year

	South Cove	Hangar Cove	Total
2004	81	135	216
2005	203	262	465
Total	284	397	

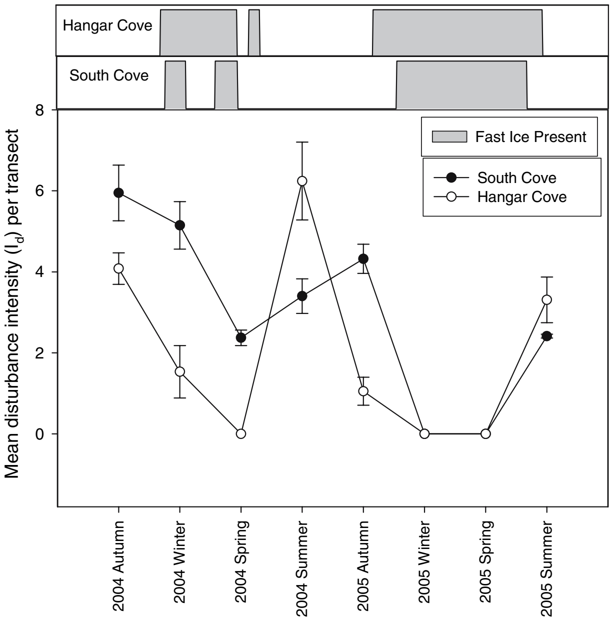


Fig. 8 Mean disturbance intensity, I_d (±SE) per transect plotted against each 3-month experimental phase at both study sites, Rothera Point, Adelaide Islands, Antarctica. *Upper axis plots* represent the presence of fast sea-ice at each site during the study period (*grey areas*)

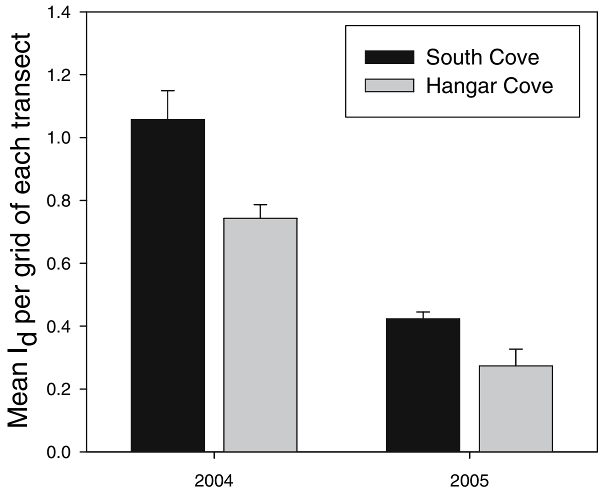


Fig. 9 Mean disturbance intensity, I_d (±SE) per grid at both sites and for both years of the study at Adelaide Islands, Antarctica. Means are averages of the three replicate transects at each site

also emerged as highly significant and interacted with all other factors (Table 2). There were over twice as many days of sea ice (sum of both sites) in 2005 compared with 2004 (Table 3) whilst differences in wind speed and direction between the study years were negligible.

Discussion

All the environmental factors had a strong and significant effect on the frequency of ice scouring. Although the influence of some of these factors on ice scouring frequency may seem intuitive, this is the first time these relationships have been quantified at any shallow subtidal location. Over 1,500 markers were impacted during the 2-year study and this figure alone suggests that ice disturbance has a major structuring role on the ecology of nearshore polar waters.

Depth

A negative correlation between depth and the number of iceberg scours in polar continental shelf regions has been known for 20 years, since the use of sidescan sonar to detect relict scour marks (Lien et al. 1989; Dowdeswell et al. 1993). We have, for the first time, measured the current frequency of ice scouring and observed a strong relationship between depth and ice disturbance in nearshore polar waters ranging from 25 to 0 m (ELWS) depth. In the Arctic, Hotzel and Miller (1983) observed a high frequency of icebergs with a low mass, height and length whilst large icebergs were less common. It seems likely that the size distribution of the iceberg population impacting the shores of the Antarctic Peninsula is also skewed towards a low mass. Thus the most likely explanations for a higher frequency of iceberg scouring at the shallow sites are twofold. Firstly (and most intuitively), shallower sites were hit more frequently than deeper sites because small icebergs with small draughts were probably more frequent. Secondly, shallow sites were more exposed to scouring by winter fast ice and sea ice floes during break out periods. The markers laid at ELWS were frequently exposed to large rafts of sea-ice (maximum draft of ca. 1 m) during the springtime deterioration of annual fast ice. Hence, a strong environmental gradient of disturbance frequency with depth was recorded. Anchor ice is another form of ice disturbance and, like iceberg scouring, it is both depth-related and has a major structuring role on shallow water benthic communities (Dayton et al. 1969, 1974). However, anchor ice was not observed at either site at any time during the current study.

The intensity of iceberg disturbance also varied with water depth, as high-level impacts (as a proportion of total hits) were more frequent at deep sites. A simple calculation of the kinetic energy, E_k (Eq. 1, where m is mass and v is velocity) of a typical iceberg impacting both the 25 m sites and the 0 m grids may explain this result.

$$E_k = \left(\frac{1}{2}\right) m v^2 \quad (1)$$

The mass of an iceberg with a draft of 25 m (the minimum size needed to impact the 25 m deep markers) is estimated at 2.35×10^7 kg (Hotzel and Miller 1983), whilst an iceberg with a draught of 1 m, a growler (Table 1), has a maximum mass of 1.20×10^5 kg (Haykin et al. 1994). To estimate the velocity of icebergs travelling into the study sites, the movement of six icebergs was monitored using time-lapse photography during a typical meteorological event with average winds of 22 knots. A mean velocity of 0.16 km/h ± 0.02 was observed. Inputting the data into Eq. 1 gives an estimated kinetic energy of 22.75 kJ for the larger iceberg and 0.12 kJ for the smaller growler, an almost 200-fold reduction in energy. Although these figures are crude estimates and are prone to some error, they support the study observation that disturbance events at deeper sites are generally more energetic and intense than events at shallow sites.

It is important to note that the 'disturbance' values for the ELWS (0 m depth) grids were not an attempt to estimate total disturbance, as the methodology did not measure the physical effects of wave action and encasement of the ice-foot during winter. The ecological effects of wave exposure on intertidal and subtidal communities have been extensively studied (Underwood and Jernakoff 1984; Denny 1988; Dexter 1992). In the current study, exposure to wave action was not directly quantified, although the markers laid on the rocky shore would have detected wave-induced ice movements. Even though the study sites were both fairly sheltered from local swell and had a short fetch, wave action was another disturbance pressure acting on the intertidal rocky shore, which was unmeasured. The ice foot is a 'narrow fringe of ice attached to the coast' (WMO 1970) and is formed during winter as seawater meets the cold rocky shore and freezes. This layer of ice extends seaward and covers the intertidal and shallow subtidal, and remains for longer durations than seasonal fast ice. The encasement of the biota by the ice foot has a physical effect as it restricts the exchange of gases and water, equalises the temperature of the zone with ambient air temperature and limits colonisation by new settlers to just a few months of the year (Barnes 1995a, 1999; Waller et al. 2006). However, the markers used to detect disturbance in this study were unaffected by the ice foot and most markers showed no signs of damage after up to 9 months of encasement. This contrasts with a study by Scrosati and Heaven (2006), which reported a widespread physical disturbance caused by winter sea-ice at an intertidal site in the Canadian subarctic. It seems probable that the crushing force of the ice foot at our study sites was disruptive, but not detected by the less-sensitive experimental markers deployed in this study. Effectively, we have only measured the abrasive action of brash, icebergs and fast ice on the rocky shore. If one considers (and measured) all the disturbance pressures acting on the intertidal zone, (i.e. wave action and the downward force and physical barrier produced by the ice foot) the degree of disturbance acting on this rocky shore is likely to be much greater relative to the subtidal zones than reported here.

Site

The level of disturbance at South Cove was 1.5 times greater than at Hangar Cove over the 2-year study. Icebergs are transported by both wind action and water movements caused by ocean currents and tides (Rearic et al. 1990). The Hangar Cove site was exposed to the prevailing wind direction and hence wind-driven ice, whilst South Cove was more susceptible to ice transported by local current systems (personal observation). Ice scouring occurs primarily during periods without winter fast ice when icebergs are not 'locked-in' and are free to be moved around and impact the seabed (Barnes 1999). During the study period fast ice was recorded at Hangar Cove on 135 days, whilst South Cove was frozen for 81 days, a 1.6-fold difference. During winter 2004, fast ice formed at South Cove for a short period before breaking up after strong northerly winds, therefore exposing the site to incoming icebergs and pieces of sea ice. In comparison, Hangar Cove was frozen for much longer periods. We suggest the longevity of winter fast ice is a principal factor determining ice scouring frequency at these two study sites, and probably in shallow polar seas generally.

Both Brown et al (2004) and the current study observed some heterogeneity in the distribution of iceberg impacts at each depth increment. Small-scale changes in topography affect the local frequency of ice scouring in both deep water (Gutt and Starmans 2001), and (as is now evident) in shallow water. Although there was a strong negative correlation between depth and disturbance, we observed high variation in disturbance scores between grids laid at the same depth at the same site, particularly at the 5 m depth increment at South Cove (Figs. 6, 7). For example, over the 2-year study there was a threefold difference in the number of hits recorded at two adjacent 5 m depth grids at South Cove. The grids were deployed about 20 m apart and we suggest this variation is the result of small-scale differences in topography, substrate type or aspect. Interestingly, disturbance scores recorded at the 25 m depth grids at Hangar Cove were also highly variable. Whilst one grid received no impacts during the whole study another grid (again only 20 m away) was impacted 41 times. The substratum at Hangar Cove is much more uniform than at South Cove and offers little protection from ice scour. At this depth iceberg impacts seem to be rare and stochastic, resulting in a highly patchy distribution of disturbance events. In ecological terms, this spatial heterogeneity of disturbance events creates a mosaic of benthic assemblages at different stages of recovery. At large spatial scales this 'patchiness' of disturbance may promote biodiversity by increasing the number of available niches (Sousa 1979; Gutt and Piepenburg 2003; Conlan and Kvitek 2005).

Temporal factors

The formation and duration of winter fast ice had a significant influence on the frequency and intensity of ice scouring. Fast ice formation typically reduces disturbance by 'locking-in' icebergs, thus limiting periods of ice scour, and by preventing wave erosion (Barnes 1999). For the first time, we have demonstrated the high degree of association between these two environmental factors. In 2005, we recorded twice as many days of sea ice and half the number of impacts compared with 2004. Even over a relatively short-term study, the intimate link between fast ice duration and ice scouring in shallow water habitats appears strong.

In the first study of its kind, Brown et al. (2004) estimated the frequency of ice scouring to be nearly three times greater at Hangar Cove compared with South Cove, which contrasts with the current study. Brown et al. (2004) deployed and monitored experimental marker for 2 years, from 2000 to 2002, over a limited depth range (ca. 10–15 m depth) and without replicated units. The reason for the higher frequency of ice scouring at Hangar Cove was inferred (but not stated) as being due to the exposure of this study site to prevailing northerly winds (and therefore ice movements). Even when disturbance values for only the 10 m depth grids from the current study were analysed (a comparable depth with the previous study), the results from the two studies still conflicted. As the materials and methods used in both experiments were similar, and therefore generated justifiably comparable data, we suggest that there is high inter-annual variation in the environmental conditions that govern the frequency of ice scouring at these high-latitude near-shore sites. Interestingly, the differences in inter-site scouring frequencies between Brown et al. (2004) and the current study cannot be explained simply by the number of fast ice days present during the study period. Fast ice was present for a total of 248 days at South Cove during 2001/2002 (BAS, unpublished data), whilst a similar number of 281 days was recorded during 2004/2005.

The duration of Antarctic fast ice varies between years (Clarke 1988; Jacobs and Comiso 1993) and decades (Murphy et al. 1995). Furthermore, there is some evidence that the extent and duration of Antarctic fast ice has decreased over the past century (Murphy et al. 1995; de la Mare 1997). Although estimates of sea ice cover from satellite observations available since the 1970s do not demonstrate a declining trend for total Antarctic sea ice (Jacka 1990; Cavalieri et al. 1997), satellite derived data have revealed a significant reduction in sea ice extent in the West Antarctic Peninsula region (Smith and Stammerjohn 2001). It is evident that the period of minimal seabed disturbance during the fast ice period is crucial for the development and growth of benthic communities (Barnes 1999). If there is a general decrease in the duration of fast ice at Adelaide Island, coupled with an increased scouring frequency, the implications for the already highly disturbed shallow water benthos may be both wide-ranging and severe.

Sources of error and concluding remarks

The experimental markers and survey methods used in this study facilitated the quantification of ice-mediated disturbance and comparisons of relative scouring intensity between different depths, sites, seasons and years. However, the values were estimates of disturbance and there were several potential sources of error. Each marker was surveyed once every 3 months and damaged markers could have been impacted more than once during that time. Also, markers were placed 1 m apart and it is possible that iceberg impacts occurred between markers and went undetected. Both of these eventualities would have resulted in an underestimation of ice scour frequency. Finally, each grid was treated as an independent unit for the purposes of replication and analysis. It is probable that scouring at one grid was not always independent of scouring at an adjacent grid, particularly when larger icebergs were causing the damage. Consequently, it is unclear how well correlated our experimental data are to the 'real' frequencies and intensities of ice disturbance at these sites. However, whilst this is a novel field technique, SCUBA divers for have extensively visited the study locations for 10 years. During this time divers have observed many scour marks and qualitatively reported on depth-related and seasonal patterns of scouring frequency, which are supported by our experimental data. We are confident that the methods developed for this study: generate representative data; can be repeated across spatial and temporal scales; are adequately sensitive to detect long-term changes in disturbance patterns.

In conclusion, the nearshore environment at Adelaide Island is disturbed by ice with great intensity and high frequency. Ice scouring has been described as one of the five most significant natural disturbances acting at the ecosystem level (Gutt and Starmans 2001) and it is undoubtedly a key structuring force acting at both small and large scales. The role of disturbance as a structuring force on natural communities has been well described (see Sousa 1984 for review). Although many disturbance pressures are difficult to quantify in space and time, the frequency of discrete disturbance events caused by ice scouring can be measured. The detailed quantification of ice-mediated disturbance we have presented has provided the opportunity to examine more fundamental ecological questions, such as the relationship between disturbance frequency and various parameters of community structure. A further study examining the influences of each disturbance regime on the richness, abundance and structure of the benthic community will follow.

Acknowledgments The authors acknowledge the essential work of Kirsty Brown concerning the development of the field technique. We thank Pete Rothery for statistical advice. We are grateful to all the members of the 2004 and 2005 marine teams at Rothera Research Station, but particularly for the hard work of the Dive Officers (John Withers and Matt Brown) during this project. Finally, we thank M. C. Gambi and two anonymous referees for their constructive comments.

References

Barnes DKA (1995a) Sublittoral epifaunal communities at Signy Island, Antarctica. I. The ice-foot zone. Mar Biol 121:555–563

Barnes DKA (1995b) Sublittoral epifaunal communities at Signy Island, Antarctica. II. Below the ice-foot zone. Mar Biol 121:565–572

Barnes DKA (1999) The influence of ice on polar nearshore benthos. J Mar Biolog Assoc UK 79:401–407

Barnes DKA (2002) Polarisation of competition increases with latitude. Proc R Soc Lond B Biol Sci 1504:2061–2069

Barnes DKA, Brockington S (2003) Zoobenthic biodiversity, biomass and abundance at Adelaide Island, Antarctica. Mar Ecol Prog Ser 249:145–155

Brenner M, Buck B, Cordes S, Dietrich L, Jacob U, Mintenbeck A, Schroder A, Brey T, Knust R, Arntz WE (2001) The role of iceberg scours in niche separation within the Antarctic fish genus *Trematomus*. Polar Biol 24:502–507

Brouwer PEM, Geilen EFM, Gremmen NJM, Van Lent F (1995) Biomass, cover and zonation pattern of sublittoral macroalgae at Signy Island, South Orkney Islands, Antarctica. Bot Mar 38:259–270

Brown KM, Fraser KPP, Barnes DKA, Peck LS (2004) Links between the structure of an Antarctic shallow-water community and ice-scour frequency. Oecologia 141:121–129

Bruno JF, Stachowicz JJ, Bertness MD (2003) Inclusion of facilitation into ecological theory. Trends Ecol Evol 18:119–125

Cavalieri DJ, Gloersen P, Parkinson CL, Comiso JC, Zwally HJ (1997) Observed hemispheric asymmetry in global sea ice changes. Science 278:1104–1106

Clarke A (1988) Seasonality in the Antarctic marine environment. Comp Biochem Physiol 90B:461–473

Conlan KE, Kvitek RG (2005) Recolonization of soft-sediment ice scours on an exposed Arctic coast. Mar Ecol Prog Ser 286:21–42

Conlan KE, Lenihan HS, Kvitek RG, Oliver JS (1998) Ice scour disturbance to benthic communities in the Canadian High Arctic. Mar Ecol Prog Ser 166:1–16

Dayton PK, Robbiliard GA, Paine RT (1969) Anchor ice formation at McMurdo Sound, Antarctica, and its biological effects. Science 163:273–274

Dayton PK, Robbiliard GA, Paine RT, Dayton LB (1974) Biological accomodation in the benthic community at McMurdo Sound, Antarctica. Ecol Monogr 44:105–128

de la Mare WK (1997) Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records. Nature 389:57–60

Denny MW (1988) Biology and the mechanics of the wave-swept environment. Princeton University Press, Princeton

Dexter DM (1992) Sandy beach communtiy structure: the role of exposure and latitude. J Biogeogr 9:59–66

Dowdeswell JA, Villinger H, Whittington RJ, Marienfeld P (1993) Iceberg scouring in Scoresby Sund and on the East Greenland continental shelf. Mar Geol 111:37–53

Gambi MC, Lorenti M, Russo GF, Scipioni MB (1994) Benthic associations of the shallow hard bottoms off Terra Nova Bay, Ross Sea: zonation, biomass and population structure. Antarct Sci 6:449–462

Gambi MC, Buia MC, Mazzella L, Lorenti M, Scipioni MB (2000) Spatio-temporal variability in the structure of benthic populations in a physically controlled system off Terra Nova Bay: the shallow hard bottoms. In: Faranda F, Guglielmo L, Ionora A (eds) Ross sea ecology. Springer, Berlin Heidelberg New York

Gerdes D, Hilbig B, Montiel A (2003) Impact of iceberg scouring on macrobenthic communities in the high-Antarctic Weddell Sea. Polar Biol 26:295–301

Gutt J (2000) Some "driving forces" structuring communities of the sublittoral Antarctic macrobenthos. Antarct Sci 12:297–313

Gutt J (2001) On the direct impact of ice on marine benthic communities, a review. Polar Biol 24:553–564

Gutt J, Piepenburg D (2003) Scale-dependent impact on diversity of Antarctic benthos caused by grounding of icebergs. Mar Ecol Prog Ser 253:77–83

Gutt J, Starmans A (2001) Quantification of iceberg impact and benthic recolonisation patterns in the Weddell Sea (Antarctica). Polar Biol 24:615–619

Gutt J, Starmans A, Dieckmann G (1996) Impact of iceberg scouring on polar benthic habitats. Mar Ecol Prog Ser 137:311–316

Haykin S, Lewis EO, Raney RK, Rossiter JR (1994) Remote sensing of sea ice and icebergs. Wiley, New York

Hotzel SI, Miller JD (1983) Icebergs: their physical dimensions and the presentation and application of measured data. Ann Glaciol 4:116–123

Jacka TH (1990) Antarctic and Southern Ocean sea-ice and climate trends. Ann Glaciol 14:127–130

Jacobs SS, Comiso JC (1993) A recent sea-ice retreat west of the Antarctic Peninsula. Geophys Res Lett 20:1171–1174

Lee HJ, Vanhove S, Peck LS, Vincx M (2001) Recolonisation of meiofauna after catastrophic iceberg scouring in shallow Antarctic sediments. Polar Biol 24:918–925

Lien R, Solheim A, Elverhii A, Rokoengen K (1989) Iceberg scouring and sea bed morphology on the easten Weddell Sea shelf, Antarctica. Polar Res 7:43–57

McCook LJ, Chapman ARO (1993) Community succession following massive ice-scour on a rocky intertidal shore: recruitment, competition and predation during early, primary succession. Mar Biol 115:565–575

Murphy EJ, Clarke A, Symon C, Priddle J (1995) Temporal variation in Antarctic sea-ice: analysis of a long term fast-ice record from the South Orkney Islands. Deep Sea Res 42:1045–1062

Nonato EF, Brito TAS, De Paiva PC, Petti MAV, Corbisier TN (2000) Benthic megafauna of the nearshore zone of Martel Inlet (King George Island, South Shetland Islands, Antarctica): depth zonation and underwater observations. Polar Biol 23:580–588

Peck LS, Bullough LW (1993) Growth and population structure in the infaunal bivalve *Yoldia eightsi* in relation to iceberg activity at Signy Island, Antarctica. Mar Biol 117:235–241

Peck LS, Brockington S, Vanhove S, Beghyn M (1999) Community recovery following catastrophic iceberg impacts in a soft-sediment shallow-water site at Signy Island, Antarctica. Mar Ecol Prog Ser 186:1–8

Pugh PJA, Davenport J (1997) Colonisation vs. disturbance: the effects of sustained ice-scouring on intertidal communities. J Exp Mar Biol Ecol 210:1–21

Rearic DM, Barnes PW, Reimnitz E (1990) Bulldozing and resuspension of shallow-shelf sediment by iceberg keels: implications for Arctic sediment transport trajectories. Mar Geol 91:133–147

Reimnitz E, Barnes PW, Toimil LJ, Melchior J (1977) Ice gouge recurrence and rates of sediment reworking, Beaufort Sea, Alaska. Geology 5:405–408

Richardson ME, Hedgepeth JW (1977) Antarctic soft-bottom, macrobenthic community adaptations to a cold, stable, highly productive, glacially affected environment. In: Llano GA (ed) Adaptations within Antarctic ecosystems. Smithsonian Institution Press, Washington, pp 181–196

Sahade R, Tatian M, Kowalke J, Kuhne S, Esnal GB (1998) Benthic faunal associations on soft substrates at Potter Cove, King George Island, Antarctica. Polar Biol 19:85–91

Scrosati R, Heaven C (2006) Field technique to quantify the intensity of scouring by sea ice on rocky intertidal habitats. Mar Ecol Prog Ser 320:293–295

Smith RC, Stammerjohn S (2001) Variations of surface air temperature and sea ice extent in the West Antarctic Peninsula (WAP) region. Ann Glaciol 33:493–500

Sousa WP (1979) Disturbance in marine intertidal boulder fields: the nonequilibrium maintenance of species diversity. Ecology 60:1225–1239

Sousa WP (1984) The role of disturbance in natural communities. Annu Rev Ecol Syst 15:353–391

Underwood AJ, Jernakoff P (1984) Effects of tidal height, wave exposure, seasonality and rock pools on grazing and the distribution of macroalgae in New South Wales. J Exp Mar Biol Ecol 75:71–96

Waller C, Barnes DKA, Convey P (2006) Ecological constraints across an Antarctic land–sea interface. Austral Ecol 31:656–666

WMO (1970) World Meterological Organization sea-ice nomenclature. Terminology, codes and illustrated glossary. In: WMO/OMM.BMO, vol 259, pp 145

Woodworth-Lynas CMT, Josenhans HW, Barrie JV, Lewis CFM, Parrott DR (1991) The physical processes of seabed disturbance during iceberg grounding and scouring. Cont Shelf Res 11:939–961