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PRECAUTIONARY SPATIAL PROTECTION TO FACILITATE THE SCIENTIFIC STUDY OF HABITATS AND COMMUNITIES UNDER ICE SHELVES IN THE CONTEXT OF RECENT, RAPID, REGIONAL CLIMATE CHANGE

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Abstract

Recent rapid climate change is now well documented in the Antarctic, particularly in the Antarctic Peninsula region. One of the most evident signs of climate change has been ice-shelf collapse; overall, 87% of the Peninsula's glaciers have retreated in recent decades. Further ice-shelf collapse will lead to the loss of existing marine habitats and to the creation of new habitats, with consequent changes in both ecological processes and in community structure. Habitats revealed by collapsed ice shelves therefore offer unique scientific opportunities. Given the complexity of the possible interactions, and the need to study these in the absence of any other human-induced perturbation, this paper highlights why commercial fishing activities should not be permitted in these habitats, and suggests that areas under existing ice shelves in Subareas 88.3, 48.1 and 48.5 should be preserved and protected for scientific study. The boundaries of these areas should henceforth remain fixed, even if the ice shelves recede or collapse in the future. Designation of areas under ice shelves as areas for scientific study would fulfil one of the recommendations made by the Antarctic Treaty Meeting of Experts in 2010.

Introduction

Regional climate change is now known to be well established in the Antarctic, particularly in the Antarctic Peninsula region (Solomon et al., 2007). Details of the underlying drivers of climate change are increasingly well accepted and the physical consequences increasingly well known. Changes in the physical properties of the marine system are especially important for CCAMLR and include, inter alia, changes in ocean temperature (Gille, 2002) and ocean acidification (Bednaršek et al., 2012), reductions in the extent and timing of seasonal sea-ice (Stammerjohn et al., 2008) and the retreat and collapse of ice shelves, glaciers and ice tongues (Cook and Vaughan, 2010; Cook et al., 2005; Gutt et al., 2010, 2013; Rignot et al., 2013). Nevertheless, the implications for biological systems remain poorly understood, above all, for how rapidly physical changes might cascade through marine foodwebs. It is therefore important that long-term reference areas are established to facilitate scientific study of the effects of such changes, primarily in the absence of any effects caused by other human activities. In this respect, ice-shelf collapse is of special importance as it opens up new habitats for biological colonisation and ecological succession.

Climate change has the potential to impact upon a diversity of physical properties. How such physical effects will then lead to changes in ecosystems, communities and species is as yet difficult to predict. A recent SCAR (Scientific Committee for Antarctic Research; www.scar.org) synthesis of the effects of Antarctic climate change on the environment (Turner et al., 2009a) summarises some of the most important physical effects. Of particular importance for ice shelves, the study highlights how:

(i) the ozone hole has delayed the impact of greenhouse gas increases on the climate of the continent (Turner et al., 2009b)

(ii) the Antarctic Circumpolar Current has warmed faster than the global ocean as a whole (Gille, 2002)

(iii) ice shelves in the Antarctic Peninsula have changed rapidly in recent decades (Cook and Vaughan, 2010; Cook et al., 2005,). Warming has caused retreat of ice shelves on both sides of the peninsula. Loss of ice on the eastern side results from warm air being brought over the peninsula by the stronger westerlies forced by changes in the Southern Annular Mode, driven ultimately by the development of the ozone hole. Ice-shelf retreat results from increased fracturing via melt-water infilling of pre-existing crevasses and the penetration of warm ocean masses beneath ice shelves. Removal of ice shelves has led to the speeding up of glacier flow from inland

(iv) by the end of the current century, the full effects of greenhouse gas increases are expected to be felt across the Antarctic as the ozone hole heals, with a predicted warming of about 3°C across the continent (Turner et al., 2009b)

(v) on the Antarctic Peninsula, most of the effects leading to loss of ice are confined to the northern part. Increased warming will lead to a southerly progression of ice-shelf disintegrations along both coasts. These may be preceded by an increase in surface melt-water lakes and/or progressive retreat of the calving front. Prediction of the timing of ice-shelf disintegration is not yet possible. Removal of ice shelves will cause glaciers to speed up

(vi) when ice shelves collapse, the changes from a unique ice-shelf-covered ecosystem to a typical Antarctic shelf ecosystem, with high primary production during a short summer, are likely to be among the largest ecosystem changes on the planet.

Ice-shelf collapse and retreat

Ice shelves are floating platforms of land ice that form where glaciers or ice sheets flow towards a coastline and onwards over the ocean surface. They vary in thickness, depending upon, inter alia, their catchment area and terrain, their rate of movement, and the distance from their grounding line; they may vary from 100 to 1 000 m in depth. Their movement is mainly driven by gravity, driving the seaward front of the ice shelf out from the land and out over the continental shelf towards the ocean. The primary mechanism of mass loss is iceberg calving. Typically, a shelf front will extend forward and it may be years or decades between major calving events. Other changes in the mass balance of an ice shelf include, inter alia, snow accumulation on the upper surface and melting/accretion from/to the lower surfaces. Changes in mass balance will affect the extent the ice shelf reaches from land.

One of the most evident signals of climate change has been ice-shelf retreat and collapse; regional warming caused by intensification of the westerly winds has led to ice-shelf collapse along the eastern edge of the northern Antarctic Peninsula (Cook and Vaughan, 2010). Overall, 87% of the peninsula's glaciers have retreated in recent decades (Cook et al., 2005). Retreat can be: gradual, such as the retreat of the northern edge of the George VI ice shelf (67.840°W 71.692°S) which lost ~993 km^2 over a number of years between 1974 and 1995 (Scambos et al., 2000); rapid, such as the retreat of the Wilkins ice shelf (72.500°W 70.416°S) which lost ~1 098 km^2 in 1998 (Scambos et al., 2000); or it can be dramatic, such as the final collapse of the remnants of the Larsen A (60.000°W 64.750°S) which disintegrated in late January 1995 losing ~4 200 km^2 (Rott et al., 1996), or the Larsen B (61.000°W 65.500°S) which disintegrated within a period of just a few days in 2002 losing ~3 370 km^2 (MacAyeal et al., 2003). The collapse of the Larsen B followed a series of warm summers on the Antarctic Peninsula, which culminated in an exceptionally warm summer in 2002 (MacAyeal et al., 2003). Significant surface melting due to warmer air temperatures created melt ponds on the surface of the Larsen B which acted like wedges to deepen the crevasses and eventually caused the shelf to splinter. As the surface melt ponds began to fracture the shelf, strong winds or waves might have caused the shelf to flex, helping trigger catastrophic break up (Scambos et al., 2000, 2003).

Other factors may also have exacerbated the unusually rapid and near-total disintegration of the Larsen B. For example, warmer ocean temperatures in the Weddell Sea occurred during the same period

(Robertson et al., 2002) and might have caused thinning and melting on the underside of the ice shelf (Shepherd et al., 2003). Although basal melting rates under the Larsen B are uncertain, Shepherd et al. (2003) concluded that basal melting was feasible given the oceanographic data. Indeed, beneath the Filchner-Rønne ice shelf (40.000°W 79.000°S – 61.000°W 78.500°S), melt rates are substantial where warm waters are transported beneath floating ice (Rignot and Jacobs, 2002; Hellmer et al., 2012). Elsewhere, evidence of the importance of basal melting is accumulating; in the Amundsen Sea, the temperature and volume of deep water in Pine Island Bay has increased in recent years. Faster basal melting under the Pine Island glacier (100.000°W 75.000°S) seems to have resulted mainly from stronger circulation under the ice shelf (Jacobs et al., 2011). Both increased air temperatures and increased ocean temperatures therefore have the potential to impact upon ice-shelf stability.

Ice shelves and glaciers in different geographic locations have different developmental histories and may react differently to the ongoing processes of regional climate change. For example, there may be differences for individual ice shelves depending upon bed morphology and grounding lines (Schoof, 2007), or because of latitudinal or regional differences, given the regional nature of climate change. Until ice shelves actually collapse, marine habitats and communities beneath them remain fully protected as they are difficult to access other than by remote technology.

Ice-shelf retreat or collapse will lead to new marine habitats and to biological colonisation. Peck et al. (2010) showed that the loss of ice shelves and retreat of coastal glaciers around the Antarctic Peninsula in the last 50 years has exposed at least 2.4×10^4 km^2 of new open water (see also Vaughan and Doake, 1996). These newly revealed habitats have allowed new phytoplankton blooms to be produced (Bertolin and Schloss, 2009) resulting in new marine zooplankton and seabed communities. This has now resulted in around 900×10^3 tonnes of new carbon being taken up by biological systems every year, which is around 10% of that taken up by new Arctic forests, but 10 times greater than any other identified natural feedback reducing atmospheric carbon dioxide (Peck et al., 2010). New production affords new feeding opportunities in the pelagic domain for mid-trophic and upper-trophic level species. New available habitat on coastlines may also afford breeding or haul-out sites for land-based predators, especially if these are close to sites of predictable production.

In general, the fauna under existing ice shelves exists in oligotrophic conditions, and because ice-shelf collapse may lead to greater nutrient input, there may be consequent loss of some species or communities (Gutt et al., 2010, 2011). Ice-shelf collapse will potentially allow increased levels of marine snow and benthic-pelagic coupling that will alter the nutrient status of the benthos. Further, terrigenous material may also be deposited in these habitats, potentially impacting upon the existing benthos and modifying conditions for future colonisation. The benthic communities of the Antarctic shelf show high levels of gigantism, longevity, slow growth, late maturity and endemism (Brandt, 2012), features (particularly the latter three) that mean that these species are susceptible to disturbance. However, these communities are also potentially much more dynamic than so far assumed and can show surprising rates of change, even over relatively short time periods (Gutt et al., 2010, 2013; Dayton et al., 2013). Nevertheless, they remain susceptible to climate variability and change (Brandt and Gutt, 2011), including from ocean acidification (Orr et al., 2005; Brandt, 2012). Therefore, the regional nature of climate change (Vaughan et al., 2003) coupled with the high levels of endemism (Brandt, 2012) mean that community processes will vary across a range of sites.

The Antarctic shelf ecosystems that form following ice-shelf collapse will be susceptible to colonisation by species from areas that are immediately adjacent to the new habitat; however, other complex processes may also take place as warming waters may create opportunities for species to return that were last present in the last interglacial, a warmer period than at present. In addition, altered ecosystem dynamics may also allow non-native species to invade, as ocean warming potentially removes physiological barriers that have previously led to the isolation of the Antarctic benthos (Clarke et al., 2004; Barnes and Peck, 2008; Aronson et al., 2009; Smith et al., 2011). Potentially, species that have their southernmost distribution in the sub-Antarctic and which may be able to extend their range further to the south, may be possible invaders to these new habitats (Aronson et al., 2007; Thatje and Fuentes, 2003; Griffiths et al., 2013). Ocean transport through directional current flow fields may also help isolate the Antarctic benthos, but raised temperature will probably increase survival rates, if invading species can cross these physical barriers. The breakdown of such thermal barriers also has the potential to impact pelagic communities as well as benthic communities.

Habitats previously covered under ice shelves present outstanding opportunities to undertake science related to habitat colonisation. Studying these habitats when they become available will provide valuable scientific insights into how communities develop over timescales ranging from years to decades. Habitats under ice shelves have been closed to both terrestrial and pelagic community interactions over recent geological timescales. If exposed, they would offer a range of opportunistic study sites, often with contrasting ecological scenarios. Some ice shelves have already collapsed, for example the Larsen B and Wilkins ice shelves (see Figures 1b and 1c), others are known to be thinning, for example the Pine Island glacier (Jacobs et al., 2011). Others are predicted to thin over the course of this century, for example the Filchner-Rønne ice shelf (Hellmer et al., 2012). Thus, different glaciers or ice shelves present different opportunities for the study of colonisation as regional climate change proceeds over the course of this century.

If colonisation processes for infaunal, epifaunal, demersal and pelagic organisms are to be studied, a variety of different sampling equipment must be used. Where possible, it would be advantageous to develop methods of non-destructive monitoring for detecting changes in community structure. For example, video recording methods and sampling from remotely operated vehicles is now feasible and is already providing extensive new evidence about changes in benthic community structure in areas where ice shelves have collapsed in the past, including on changes in the population size of selected macrobenthic organisms (e.g. Gutt et al., 2013; Dayton et al., 2013). However, some species may only be studied by use of more traditional core samplers, grabs and sledges.

Climate change is known to be regional and can occur rapidly (Vaughan et al., 2003); consequently, investigating how different parts of the Antarctic will respond has to be carried out over a variety of spatial scales. Improving our levels of understanding across the whole continent and across all possible physical and biological interactions is beyond the scope of operation of any single scientific body. Therefore, to increase levels of understanding and develop new monitoring methods, it will be necessary for a variety of stakeholders to work together, including CCAMLR Members, National Antarctic Operators and international organisations and programs such as SCAR, especially the new SCAR science programs Antarctic Thresholds-Ecosystem Resilience and Adaptation (AnT-ERA) and State of the Antarctic Ecosystem (AntEco), ICED (Integrating Climate and Ecosystem Dynamics in the Southern Ocean; www.iced.ac.uk), SOOS (The Southern Ocean Observing System; www.soos.aq) and Sentinel (Southern Ocean Sentinel; Constable and Doust., 2009).

Precautionary protection for marine areas under ice shelves

Based on Recommendation 26 of the Antarctic Treaty Meeting of Experts (ATME) in 2010 (ATCM, 2010), there is a clear need to provide automatic interim protection to newly exposed areas of ocean following ice-shelf retreat or collapse; this recommendation essentially advocates following a precautionary approach to protect newly exposed areas. In addition, the protection of marine areas under ice shelves is consistent with the objectives for protection set out in CCAMLR Conservation Measure 91-04 (CCAMLR, 2011b; www.ccamlr.org/measure-91-04-2011), which includes, inter alia, the protection of scientific reference areas and areas to maintain resilience, or the ability to adapt, to the effects of climate change. Though the establishment of a system of marine protected areas would provide such protection, long-term protection for these areas could also be agreed through other means, as the text of the CAMLR Convention allows for protection under Article IX.2(g), that is the designation of the opening and closing of areas, regions or sub-regions for purposes of scientific study or conservation, including special areas for protection and scientific study. Protecting areas under existing ice shelves through either of these mechanisms would be a significant achievement in the context of CCAMLR's commitment to work towards the development of a representative system of protection within the Convention Area (CCAMLR, 2009a, paragraph 7.19), and under CCAMLR's resolution to achieve increased consideration of climate change impacts in the Southern Ocean to better inform CCAMLR management decisions (CCAMLR, 2009b; www.ccamlr.org/resolution-30/xxviii-2009).

(a)

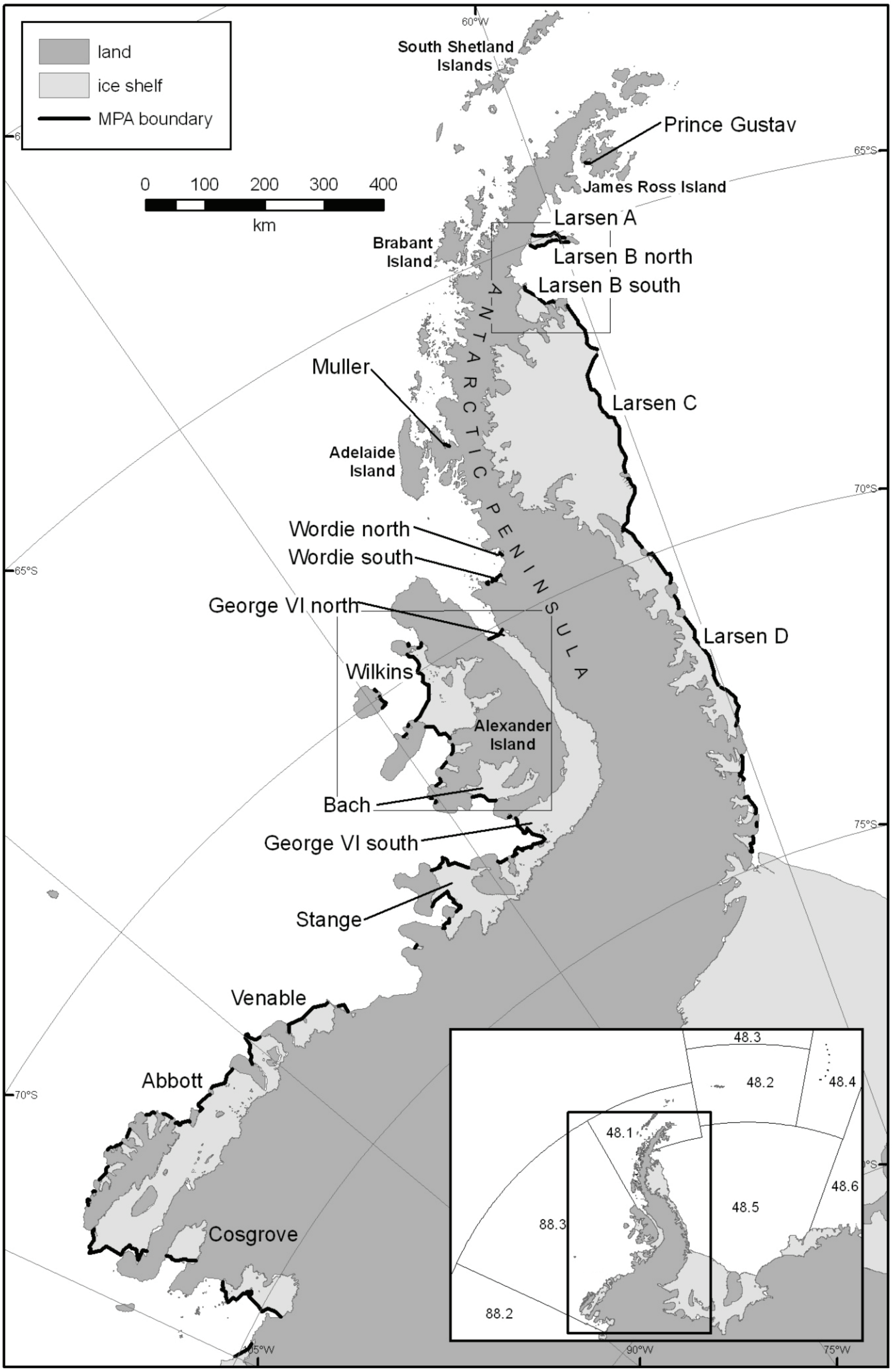
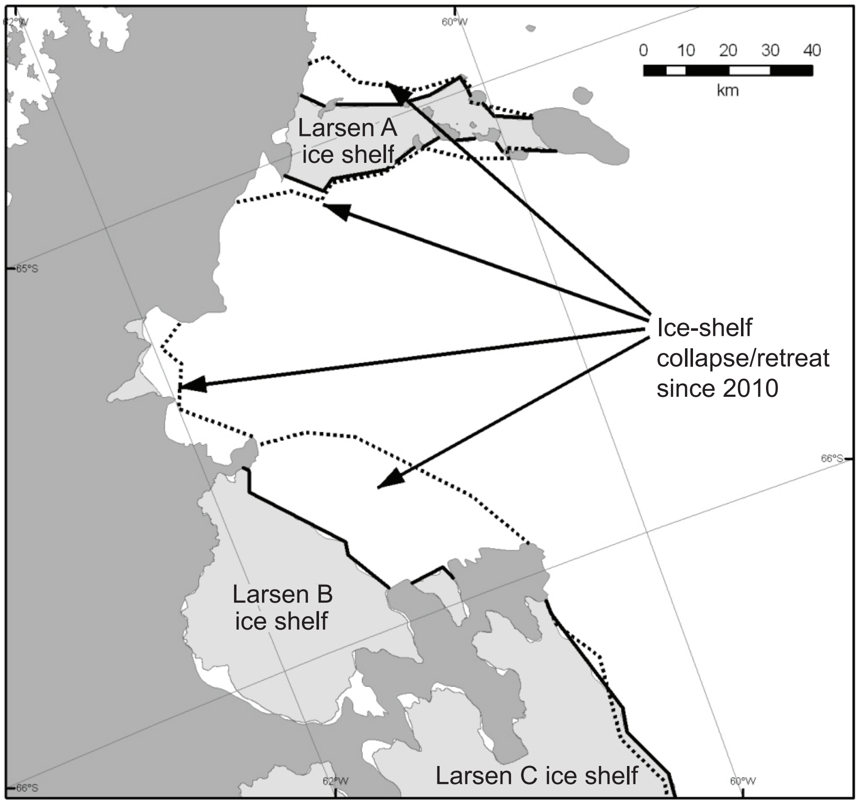


Figure 1: (a) Proposed boundaries for areas of scientific study (heavy black lines) for ice shelves, glaciers and ice tongues in Subareas 88.3, 48.1 and 48.5 (subareas shown in inset map). The boundaries of these areas would henceforth remain fixed, even if the ice shelves recede or collapse in the future. The proposed boundaries are indicated by the coastline and positions of ice shelves and ice tongues from the Scientific Committee for Antarctic Research (SCAR) Antarctic Digital Database (ADD), 2012.

(continued)

(b)



(c)

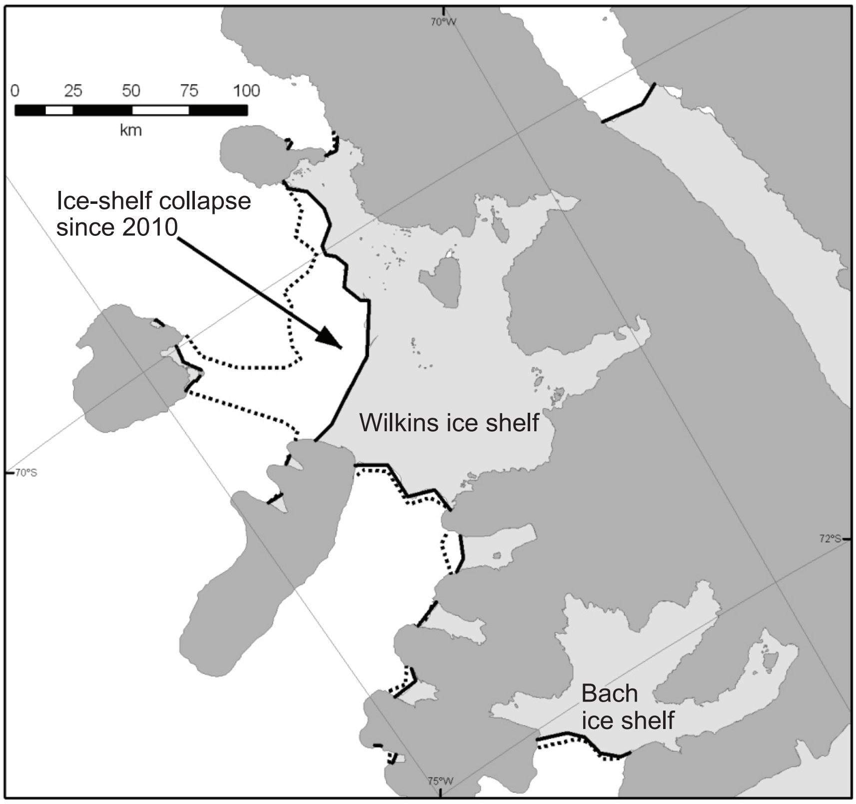


Figure 1 (continued): (b) regional map showing the proposed area boundaries for the Larsen A and Larsen B ice shelves, with ice front boundaries from the ADD (2010) shown as dotted lines and boundaries from the ADD (2012) as solid lines; (c) regional map showing proposed area boundaries for the Wilkins ice shelf, with 2010 and 2012 ice fronts shown as dotted lines and solid lines respectively.

Providing automatic interim protection to the whole of the Antarctic coastline would necessitate a considerable amount of operational effort. However, focusing on areas where regional climate change is known to be taking place, and where ice shelves have already collapsed or receded in the recent past, is a realistic proposition. This paper therefore suggests that CCAMLR, as a first step, should focus its attention on the Antarctic Peninsula region.

Discussions within CCAMLR

Precautionary protection for habitats and communities under ice shelves, and in areas where ice shelves might retreat or collapse in the future, has been discussed during a number of CCAMLR meetings (SC-CAMLR, 2011a, paragraphs 3.6 and 3.7; SC-CAMLR, 2011b, paragraphs 5.67 to 5.77; CCAMLR, 2011a, paragraphs 7.31 to 7.36; SC-CAMLR, 2012a, paragraphs 3.26 to 3.34; SC-CAMLR, 2012b, paragraphs 5.42 to 5.56; and CCAMLR, 2012, paragraphs 5.63, 7.62 and 7.86 to 7.90). There has been general agreement that there are important scientific objectives associated with studying areas revealed by collapsing ice shelves and retreating glaciers. However, there has been no resolution about the best way to achieve this. The recent changes in ice shelves are significant, so the issue needs urgent resolution by CCAMLR. For example, the area of the Wilkins ice shelf in 2010 was 13 432 km^2 (based on the SCAR Antarctic Digital Database (ADD), 2010), whereas in 2012 the area was only 10 108 km^2 (based on the ADD, 2012[1]), meaning that the area of new open water (exposed since 2010) is 3 324 km^2; this is equivalent to a reduction of almost 25% in the ice shelf in just two years. Similarly, the area of the Larsen B south ice shelf in 2010 was 3 375 km^2, whilst in 2012 it was 1 884 km^2, representing a loss of 44%.

In the proximity of the Antarctic Peninsula in Subareas 88.3, 48.1 and 48.5, there are 47 individual ice-shelf areas, ranging in size from less than 1 km^2 to 71 213 km^2. The total area covered by these ice shelves is 165 032 km^2 (based on the ADD, 2012). This is equivalent to only 3% of the total combined area of Subareas 48.1, 48.5 and 88.3. Subarea 48.1 has eight individual areas, with a total area covered by ice shelves of 1 032 km^2 (equivalent to 3.9% of Subarea 48.1); Subarea 48.5 has nine individual areas, with a total area under ice shelves of 75 706 km^2 (equivalent to 0.2% of Subarea 48.5); and Subarea 88.3 has 30 individual areas, with a total area under ice shelves of 88 538 km^2 (equivalent to 2.8% of Subarea 88.3). Thus, these areas are not large and the potential scientific benefits of having long-term protection for these rapidly retreating areas are likely to be substantial.

Recommended management provisions

It is therefore recommended that locations under existing ice shelves (as indicated by the ADD (2012) for the Antarctic Peninsula, Weddell Sea and Bellingshausen Sea regions) should receive long-term protection for scientific study in accordance with Article IX.2(g) of the CAMLR Convention, and that future commercial fishing[2] activities should be restricted. The duration of this protection should be commensurate with the type of long-term studies envisaged. The boundaries of these areas should remain fixed, even if the ice shelves recede or collapse in the future (see the hypothetical example in Figure 2). The areas will allow natural ecological processes such as iceberg scouring (e.g. Gutt, 2001), colonisation and/or community development (Gutt et al., 2013; Dayton et al., 2013), etc. to be studied in the absence of commercial fishing activity. Such protection is proposed for ice shelves in Subareas 48.1, 48.5 and 88.3 (Figure 1), as this is the region where climate change is occurring most rapidly, although climate change is predicted to occur more widely across the continent as this century proceeds (Turner et al., 2009a).

The boundaries of ice shelves and ice tongues are complex, often with numerous small-scale creeks, they also move over decadal time scales (Ferrigno et al., 2006). Therefore, for ease of management, the seaward boundary of these areas has

[1] Antarctic Digital Database (2012). (www.add.scar.org/index.jsp) Scientific Committee on Antarctic Research.
[2] This includes fishing activities regulated under CCAMLR conservation measures, transhipment of commercial product, bunkering, vessel discharge or dumping, or exploratory activities undertaken with the intention of developing future commercial fishing opportunities.

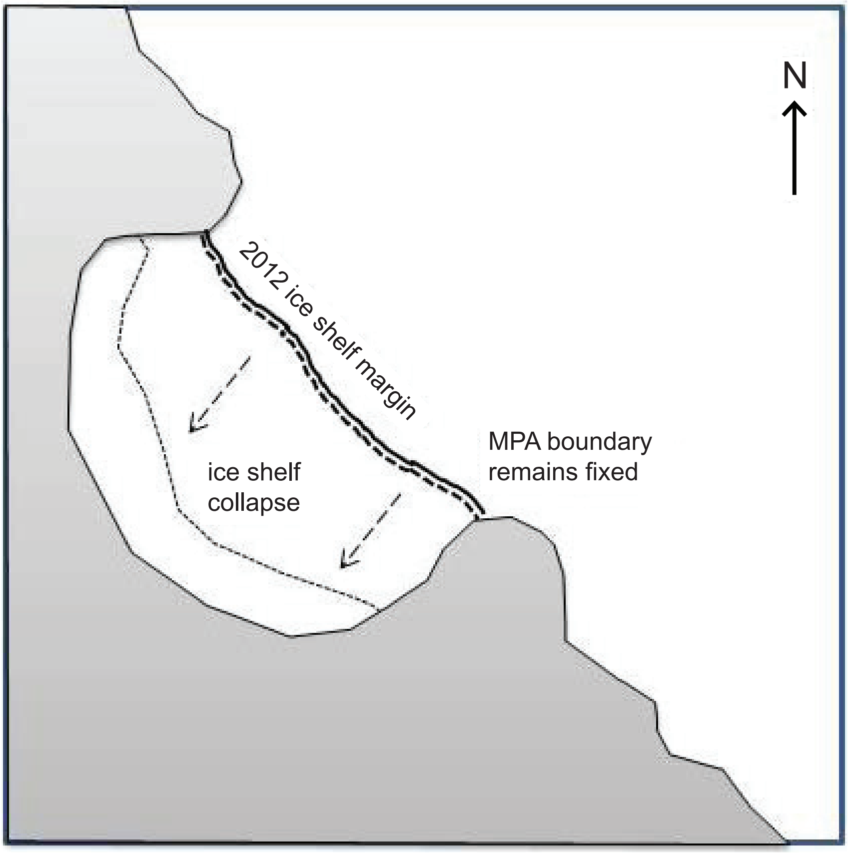


Figure 2: Hypothetical illustration showing how an area protection boundary would remain fixed following collapse of an ice shelf. The dotted lines show the position of the ice shelf in 2012 and its collapse (arrows) to a new marginal extent at some time in the future. The boundary of the protected area (heavy black line) would remain fixed if such a collapse occurred.

been represented by a simplified line[3] derived from the most recently documented ice front position (ADD, 2012).

The dynamics of ice shelves and glaciers are complex; some ice fronts are known to be in retreat, others are stable, while some are known to be extending. Of the 244 marine glaciers that drain the ice sheet and associated islands of the Antarctic Peninsula region, 212 (87%) have shown overall retreat since 1953 (Cook et al., 2005). The other 32 glaciers have shown small advances, though these advances are generally small in comparison with the scale of retreats observed. Therefore, information about ice-shelf extent (from satellite remote sensing), ice-shelf collapse (from the scientific literature) and the ecological merit of maintaining long-term protection (also from the scientific literature), should be reviewed by the CCAMLR Scientific Committee at regular intervals, at which date the seaward boundaries could be reconsidered in the light of updated information on climate change and ice-shelf position. The ADD is updated at least annually, at least partially (A. Fleming, BAS, pers. comm.), so the frequency of revision is an operational question for CCAMLR.

The positions of the Larsen A and Larsen B ice-shelf fronts from the ADD are shown in Figure 1(b); however, ship-based observations in these areas (Gutt et al., 2013) highlight how dynamic the movement of ice-shelf fronts can be. The studies described by Gutt et al. (2013) suggest that the compilation of information in the ADD might sometimes lag behind observations on the ground. Consequently, the operational frequency of revision should reflect the precautionary objectives identified by Recommendation 26 of ATME in 2010 (ATCM, 2010).

[3] Line simplification was performed using the 'simplify polygon' (point remove) tool in ArcGIS, with a maximum offset of 2 km.

Figures 1(b) and 1(c) demonstrate the scale of recent ice-shelf collapse and retreat (since 2010) in two specific locations in the Antarctic Peninsula region, and illustrate the rapid nature of such changes. Although not included in the current recommendations, recently exposed areas such as these might also warrant future consideration for designation as protected areas.

It is recommended that, should any ice-shelf or glacier tongue collapse, protection for the new open-water habitat should remain in place for a minimum period of 10 years in order that the benthic fauna may begin to develop naturally. Such interim protection is consistent with the precautionary approach advocated by Recommendation 26 of ATME in 2010 (ATCM, 2010). A period of 10 years is insufficient time to understand how benthic colonisation might proceed, even in temperate regions (Smith, 1994; Grassel and Morse-Porteous, 1987). However, 10 years is potentially sufficient time for scientific studies to be initiated, assuming seasonal sea-ice conditions do not impede access to research vessels. In such cases, the initiation of scientific studies may take more time. Thus, delays in obtaining research funds and/or ship time, or because of unforeseen logistic difficulties, might mean that a longer period of interim protection should be considered.

Interim protection could be removed (and the area deleted from the list of protected areas) after the interim period has elapsed; however, it may also be appropriate for an area where an ice-shelf retreat or collapse has occurred to remain closed for longer to commercial fishing. Maintaining such a closure might be warranted, for example, because new communities continue to show ongoing development in their succession of different stages, no new equilibrium has been observed, or because monitoring data are too short to provide detailed results.

All types of commercial fishing activities should be prohibited within these defined areas as bottom gear types are known to have adverse impacts (Kilpatrick et al., 2011; Shannon et al., 2010) that may affect developing benthic communities. Similarly, pelagic fishing for species such as krill, which are important prey for meso- and top-predators, may affect feeding opportunities and/or the establishment of new predator breeding colonies. In a warming ecosystem, predator populations may be already vulnerable and populations may be expected to change their feeding and breeding distributions as a response to climate change (Trathan et al., 2007; Forcada and Trathan, 2009). Thus, new habitats, such as afforded by new open-ocean and new coastlines, may be significant for their future security. No discharges and no dumping of any type of waste by any fishing vessel shall take place within these defined areas as some such discharges are known to have adverse effects on marine life, including upon seabirds and marine mammals (CCAMLR, 2009b; www.ccamlr.org/measure-26-01-2009).

Impact on commercial fishing

Protection of areas under existing ice shelves would have little impact upon commercial fisheries managed by CCAMLR. Commercial fishing activities with catches of several tens of thousands of tonnes of finfish in some years were conducted around Elephant Island and the South Shetland Islands (Subarea 48.1) between 1978/79 and 1989/90. Most fishing occurred in the two seasons 1978/79 and 1979/80 targeting marbled rock cod (*Notothenia rossii*) and mackerel icefish (*Champsocephalus gunnari*). A third species, spiny icefish (*Chaenodraco wilsoni*) was also taken in the Antarctic Peninsula region (Subarea 48.1) during several seasons after 1978/79. All of the finfish fisheries in Subarea 48.1, to the extent known, were conducted within 20 n miles of glaciers on the islands and the tip of the Antarctic Peninsula. No commercial fishing took place south of Antarctic Sound at the tip of the western Antarctic Peninsula. CCAMLR closed the fisheries after the 1989/90 season in order to allow the depleted stocks to recover (Kock, 1992). These over-exploited fisheries still remain closed some 23 years later. No commercial catch has ever been conducted east of the Antarctic Peninsula (Subarea 48.5), and only a few research hauls in the 2006/07 season using a commercially sized bottom trawl have been carried out there (Kock et al., 2007).

Limited exploratory longlining operations for Antarctic toothfish (*Dissostichus mawsoni*) in the Amundsen Sea (Subarea 88.3) have yielded less than 300 tonnes during the past three fishing seasons (SC-CAMLR, 2011b), while exploratory longlining for Antarctic toothfish in the eastern Weddell Sea (Subarea 48.5) has only taken place in the 2012/13 season.

Fishing for Antarctic krill (*Euphausia superba*) has occurred in the west Antarctic Peninsula region since the 1970s, with the majority of catches taken along the shelf edge of the South Shetland Islands and Elephant Island and in the Bransfield Strait. Krill fishing has not occurred in close proximity to any of the ice shelves proposed for protection in this paper.

Conclusion

Long-term biological research carried out with collaboration across the scientific community will be necessary for determining how ecosystems, communities and species adapt to new environmental conditions. Protecting new communities that are in the process of developing after ice shelves have disintegrated is important, as they will form long-term reference areas where colonisation processes may be studied in the absence of harvesting. As ecological succession continues across these habitats and communities, long-term protection would ensure that unique scientific opportunities could be maximised.

If CCAMLR is to disentangle the potentially confounding effects of climate change and harvesting (Ainley et al., 2007; Nicol et al., 2007), management methods should be structured in a manner that incorporates an experimental approach, setting aside reference areas of the ocean so that processes may be studied in the absence of harvesting. In the face of climate change, long-term reference areas could also potentially increase ecosystem robustness (Brand and Jax, 2007; Gallopín, 2006), particularly where other stressors, including science, tourism and harvesting, are absent.

Long-term protection of marine areas under ice shelves would secure and maintain important opportunities for scientific study, particularly of the complex ecosystem interactions in newly exposed habitats, and in the context of the effects of a rapidly changing climate. This would be consistent with the objectives of the CAMLR Convention for protecting scientific reference areas. It would also be a significant achievement in terms of CCAMLR's commitment to have increased consideration of climate change impacts in the Southern Ocean to better inform CCAMLR management decisions.

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