Progress towards a representative network of Southern Ocean protected areas

Cassandra M. Brooks1*, Steven L. Chown2, Lucinda L. Douglass3,4, Ben P. Raymond5, Justine D. Shaw4, Zephyr T. Sylvester1, Christa L. Torrens1

1 Environmental Studies Program, University of Colorado, Boulder, Boulder, CO, United States of America, 2 School of Biological Sciences, Monash University, Melbourne, Australia, 3 Centre for Conservation Geography, Sydney, New South Wales, Australia, 4 Centre for Biodiversity and Conservation Science, School of Biological Sciences, The University of Queensland, Brisbane, Queensland, Australia, 5 Australian Antarctic Division, Department of the Environment, Kingston, Tasmania, Australia

* cassandra.brooks@colorado.edu

Abstract

Global threats to ocean biodiversity have generated a worldwide movement to take actions to improve conservation and management. Several international initiatives have recommended the adoption of marine protected areas (MPAs) in national and international waters. National governments and the Commission for the Conservation of Antarctic Marine Living Resources have successfully adopted multiple MPAs in the Southern Ocean despite the challenging nature of establishing MPAs in international waters. But are these MPAs representative of Southern Ocean biodiversity? Here we answer this question for both existing and proposed Antarctic MPAs, using benthic and pelagic regionalizations as a proxy for biodiversity. Currently about 11.98% of the Southern Ocean is protected in MPAs, with 4.61% being encompassed by no-take areas. While this is a relatively large proportion of protection when compared to other international waters, current Antarctic MPAs are not representative of the full range of benthic and pelagic ecoregions. Implementing additional protected areas, including those currently under negotiation, would encompass almost 22% of the Southern Ocean. It would also substantially improve representation with 17 benthic and pelagic ecoregions (out of 23 and 19, respectively) achieving at least 10% representation.

Introduction

Global threats to ocean biodiversity have generated worldwide momentum to improve its conservation and management. Marine protected areas (MPAs), areas of ocean where human activities are limited or prohibited, have been increasingly promoted by policy-makers, scientists and conservationists as a tool for mitigating ocean threats, conserving biodiversity, and managing fisheries [1–3]. Numerous studies demonstrate that MPAs, especially no-take MPAs (also known as marine reserves), lead to increases in biomass, density, and diversity of life in the MPA [4–6]. Notably, these MPA benefits can extend to fisheries. MPAs have been shown to facilitate the recovery of depleted fisheries, provide spillover effects, and lead to larger fish [7–9]. Furthermore, because they maintain all trophic levels of the ecosystem and increase...
both species and genetic diversity, MPAs can enhance resilience to environmental impacts, including those related to climate change [10–12].

Several international targets have recommended the adoption of representative networks of MPAs in national waters and in areas beyond national jurisdiction. At the 2002 World Summit on Sustainable Development, participating States agreed to designate a representative global network of MPAs by 2012 [13]. This call was further reiterated at the 2003 International Union for the Conservation of Nature (IUCN) World Parks Congress, which called for protected areas encompassing 20–30% of all marine habitats also by 2012 [14]. The 2010 Aichi Biodiversity Targets, adopted by the Convention on Biological Diversity as part of its Strategic Plan for Biodiversity 2011–2020, offered a new deadline of 2020 to designate 10% of the global oceans in ecologically representative MPAs [15]. Then, in 2014 the IUCN World Parks Congress recommended that 30% of the ocean be protected in an ecologically representative network [16]. Finally, in 2015 the United Nations adopted the Sustainable Development Goals, including goal 14 which aims to conserve 10% of coastal and marine areas by 2020 [17]. Evidence-based conservation science research often suggests protection targets of at least 30% and often higher are required to effectively conserve biodiversity and ecosystems [18, 19].

A major criteria for conservation, including Aichi target 11, is that protected areas be ecologically representative since their efficacy is substantially enhanced when they are representative of the biodiversity of a region [20]. A widely used method for examining representivity is by determining coverage of ecoregions by the protected area network [21, 22]. Ecoregions are spatial regions, typically within a large spatial domain, defined in such a way that each ecoregion defines a characteristic set of species communities and habitats that are distinct from those of other ecoregions within the domain [23, 24]. Direct sampling of biodiversity at large spatial scales is generally impractical, necessitating the use of proxies or modelling approaches to achieve broad spatial coverage. Species distribution and related modelling methods can be used to infer broad-scale biodiversity patterns based on spatially-limited sampling (e.g.[25, 26]). However, such approaches present difficulties for our purposes of assessing Southern Ocean MPA representativeness. Predictions of species distributions would need to be available at circum-Antarctic scale, and from a sufficiently diverse suite of species in order to be suitably representative of broader Southern Ocean biodiversity To date, Southern Ocean applications of such models have tended to be regional in scope (but see e.g. [25, 27–30] for circum-Antarctic applications), and focused on a relatively restricted number of species. Here we therefore use heterogeneity of habitats and geomorphic features as proxies for biodiversity. This approach is well established in the terrestrial and marine realms (see e.g., [31–35]).

In line with global MPA goals, roughly 18.45% of national waters, globally, have been protected to date. Meeting these targets in areas beyond national jurisdiction has proven a more difficult challenge, with only 1.18% of the high seas protected thus far [36]. Further, MPAs have generally been found to not be ecologically representative, especially within waters under national jurisdiction [37, 38].

National governments and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) have successfully adopted multiple MPAs in the Southern Ocean despite the challenging nature of establishing MPAs in international waters. The Southern Ocean encompasses roughly 10% of the global oceans (Fig 1), most of which is considered high seas. This area is primarily governed by a multi-lateral Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR Convention). This Convention is carried forward by CCAMLR, a Commission of 25-Member States plus the European Union. Within CCAMLR’s waters are five sets of sub-Antarctic islands that fall under national jurisdictions (Fig 1), which are managed in accordance with Convention rules [39]. CCAMLR has the explicit objective to conserve marine living resources and employs a science-based
precautionary and ecosystem-based management approach [39]. In doing so CCAMLR is arguably the world’s most successful international management body for marine living resources [40–43].
In 2002, in an effort to meet global MPA targets and in recognition of the value of MPAs as a biodiversity conservation and fisheries management tool, CCAMLR committed to designating a network of MPAs in the Southern Ocean [44]. Since 2002, CCAMLR and its Member States have held a variety of MPA workshops [44]. CCAMLR scientists, independent experts and conservation organizations have also conducted extensive Southern Ocean regionalizations, identifying areas of potential importance for biodiversity and ecosystems [24, 45, 46]. These benthic and pelagic regionalizations have helped guide CCAMLR towards identifying priority areas to be incorporated into a representative network of Southern Ocean MPAs [47].

Over the last two decades, CCAMLR and states with jurisdiction over sub-Antarctic islands have been designating MPAs (Fig 1; Table 1). First in 2002, Australia declared an MPA around the sub-Antarctic Heard Island and McDonald Islands, which was expanded in 2014 (~71,000 km²) [52]. In 2006, France designated MPAs around the sub-Antarctic Crozet and Kerguelen Islands which were extended in 2017 (combined ~ 580,000 km²) [53]. In 2009, CCAMLR adopted its first high sea MPA south of the South Orkney Islands (~94,000 km²) [54]. In 2012, the United Kingdom declared a large MPA around the South Georgia and South Sandwich Islands, which were extended in 2019 (~1.24 million km²) [55]. Furthermore in 2013, South Africa designated an MPA around the sub-Antarctic Prince Edward Islands (161,000 km²) [56, 57]. In 2016, CCAMLR adopted the world’s largest international MPA in the Ross Sea (~1.5 million km²) [58]. Additionally, CCAMLR has been negotiating a large MPA network in the East Antarctic, the Weddell Sea, and the Antarctic Peninsula (Fig 1). Adjacent to the CCAMLR Area other sub-Antarctic MPAs exist (e.g., Macquarie Island Marine Park, 162,000 km² declared in 1999) however these are outside of CCAMLR jurisdiction.

Here we assess progress towards establishing a representative network of MPAs, including its level of protection, in the Southern Ocean. We examine CCAMLR and nationally governed protected areas that have been adopted as well as those currently under negotiation. We map the location of existing and proposed MPAs and calculated no-take areas. We then assess whether these proposed and existing MPAs are representative of Southern Ocean biodiversity.

### Table 1. Established and proposed MPAs in the CCAMLR Area, including sizes, no-take areas, and benthic ecoregions and pelagic clusters encompassed by the MPAs (all constrained to the CCAMLR Area).

| EXISTING MPAS | area (km²) | no-take area (km²) | Benthic ecoregions | Pelagic clusters |
|---------------|-----------|--------------------|--------------------|-----------------|
| Ross Sea region | 1,525,651 | 1,092,788 | A, O, PAR, PB, RS | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16 |
| South Orkney Islands | 93,751 | 93,751 | AB, SOI | 1, 3, 7, 9, 10, 11, 12 |
| HIMI | 70,560 | 70,560 | K-DK, K-KP | 13, 14, 15, 16 |
| Prince Edward Islands | 160,784 | 4,433 | AB, DC | 13, 15, 16, 17, 19, 20 |
| Kerguelen | 567,978 | 110,650 | K-DK, K-KP | 13, 14, 15, 16, 17, 20 |
| Crozet | 410,450 | 9,158 | DC, OL | 13, 16, 17, 20 |
| SG & SSI | 1,241,295 | 284,197 | AB, SG, SOI, SSI | 1, 2, 3, 7, 9, 10, 11, 12, 13, 14, 15, 16 |
| **TOTAL** | **4,070,468** | **1,665,537** | | |
| % CCAMLR Area | 11.98 | 4.90 | |

| PROPOSED MPAS | | | |
|---------------|-------------------|-----------------|-------------------|
| East Antarctic | 969,000 | AB, CI-EK, CI-PB, CI-W, CI-WK, EIA, K-BB, K-DK, O | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15 |
| Weddell Sea | 1,968,175 | AB, AP, DM, SOI, WS | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 |
| Domain 1 | 466,000 | A, AP, SOI | 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15 |
| **TOTAL (Existing + Proposed)** | **7,473,643** | | |
| % CCAMLR Area | 21.99 | | |

1 The Ross Sea region MPA includes the area under the Ross Ice Shelf, however, due to lack of data under the Ice Shelf, we did not include this area in our analysis. The size of the Ross Sea MPA when including the area under ice shelves is greater than 2 million km².

https://doi.org/10.1371/journal.pone.0231361.t001
and ecosystems using existing benthic and pelagic regionalizations as a proxy for biodiversity [45, 46].

**Materials and methods**

Here, we use the CAMLR Convention Area as our study region (Fig 1). This region is circum-polar, with its northern boundary between 60 and 45°S aligning approximately with the Polar Front and its southern boundary aligning with the coast of Antarctica and ice shelf boundaries. Due to the lack of data under ice shelves, our study area does not include areas under ice shelves (thus it omits the area under the Ross Ice Shelf, which is technically part of the MPA) nor does it include some of the sub-Antarctic region situated above the Polar Front which falls outside the bounds of the CCAMLR Convention Area.

**Benthic regionalization**

Benthic ecoregion data representing 23 different categories [45] were downloaded from [59]. The benthic regionalization was based on a previously published hierarchical classification [31] and included ecoregions, bathomes and environmental types [45]. However, only the broadest scale unit—ecoregions—were included in this analysis. These previously published ecoregions were established based on patterns of endemism, recent biogeographic research and consideration of the influence of environmental drivers as potential barriers to dispersal [45]. A variety of previously published circumpolar datasets were used within the benthic classification, including depth [60], geomorphology [61], seafloor temperature [62], sea-surface chlorophyll [63], sea ice concentration [64] and frontal systems [65]. Previously defined regions and boundaries were also incorporated, including those regarding the Antarctic continental shelf and slope [24, 66–69], as well as patterns of endemism [66, 68] (Table 2). The data were bound by the CCAMLR Convention area. For further details on methods underpinning the generation of the benthic ecoregion data used in this analysis see [45].

**Pelagic regionalization**

Pelagic cluster data representing 20 different categories [46] was downloaded from [70]. Following the methods of two previous pelagic Southern Ocean regionalizations [24, 71], the pelagic regionalization data we used was based on a non-hierarchical clustering algorithm to reduce the number of grid cells, followed by further refinement using a hierarchical clustering algorithm [46]. During the latter, clusters comprised of only one datum were merged into parent clusters (which occurred in five instances in cluster groups 2, 3, 8 and 13). The regionalization used summer climatological sea surface temperature [63], depth [72] and the proportion of time covered by sea ice as input variables [64]. These data were originally calculated south of 40°S, but were bound to the CCAMLR Convention area for this analysis (Table 3). For further details on methods underpinning the generation of the pelagic regionalization data used in this analysis see [46].

**Total proportion of protected area**

Using ArcGIS (version 10.5) [73], we calculated the sizes, including of designated no-take areas, in kilometres$^2$, of all existing and proposed MPAs. Shapefiles for the CCAMLR Area boundaries, CCAMLR MPAs (South Orkney Islands Southern Shelf and Ross Sea region MPAs) and CCAMLR MPA planning domains were downloaded from [48]. Shapefiles for all nationally governed sub-Antarctic MPAs falling within in our study area (Kerguelen Island, Crozet Island, Prince Edward Islands, Heard Island and McDonald Islands, South Georgia
Table 2. Benthic ecoregions of the Southern Ocean, including abbreviations, descriptions (from [45]) and percentages of the benthic ecoregions included in: No-take zones of existing MPAs; existing MPAs; and existing and proposed MPAs combined.

| Benthic ecoregion                  | Abbreviation | Description                                                                                                           | % in no-take | % in existing MPAs | % in MPAs + proposals | Size of ecoregion (km²) |
|-----------------------------------|--------------|-----------------------------------------------------------------------------------------------------------------------|--------------|--------------------|------------------------|--------------------------|
| Amundsen                          | A            | Productive shelf & polynyas of Amundsen & Bellingshausen seas. Oceanic shallow environments of Peter I Island, De Gerlache Seamounts & Marie Byrd Seamount group. | 0.21         | 0.21               | 1.15                   | 1,550,758                |
| Antarctic Peninsula               | AP           | Shallow, productive shelf of west Antarctic Peninsula with a low duration of sea ice cover & warm seabeds relative to other Antarctic shelf areas. Island ecosystems of South Shetland Islands. 13 endemic molluscs. >10% of gastropods endemic. | 0            | 0                  | 46.46                  | 910,737                  |
| Atlantic Basin                    | AB           | Very deep & very cold rugose ocean floor & abyssal plain of South Atlantic Ocean Basin & Weddell Sea.                  | 1.54         | 2.36               | 11.26                  | 7,134,098                |
| Central Indian—East Kerguelen Subregion | CI-EK       | Central Indian region of East Antarctica influenced by Kerguelen Plateau including downstream productivity from frontal activity across Plateau. | 0            | 0                  | 50.67                  | 558,681                  |
| Central Indian—Prydz Bay Subregion | CI-PB       | Central Indian region of East Antarctica that contains the cold, productive waters of Prydz Bay & Prydz Gyre which oceanographically separates east & west Kerguelen Central Indian subregions. | 0            | 0                  | 16.41                  | 455,342                  |
| Central Indian—West Kerguelen Subregion | CI-WK       | Central Indian region of East Antarctica not influenced by Kerguelen Plateau nor Weddell Gyre.                      | 0            | 68.43              | 68.43                  | 173,536                  |
| Central Indian—Wilkes Subregion   | CI-W         | Central Indian region of East Antarctica oceanographically separated from East Kerguelen subregion.                  | 0            | 4.42               | 4.42                   | 486,762                  |
| Del Cano                          | DC           | Shallow, warm seabeds in sub-Antarctic Frontal Zone including South West Indian Ridge seamounts, Del Cano Rise & Crozet & Prince Edward Islands. | 1.50         | 56.91              | 56.91                  | 908,603                  |
| Dronning Maud                     | DM           | Maud Rise & associated open ocean polynya, Astrid Ridge, Gunnerus Ridge & canyons offshore Dronning Maud Land. Easternmost extent of Weddell Gyre. 20 endemic molluscs (19% of documented species). 21% of documented gastropods are endemic. | 0            | 0                  | 34.75                  | 673,365                  |
| East Indian Abyssal                | EIA          | The very deep and cold seabeds of rugose ocean floor & abyssal plains of South Indian Ocean Basin.                   | 0            | 0                  | 3.59                   | 2,880,769                |
| Kerguelen—Banzare Bank Subregion  | K-BB         | Shallower (mostly depths between 1000–3000 m), warmer seabeds of Banzare Bank, south of frontal activity of Fawn Trough. | 0            | 12.46              | 12.46                  | 270,266                  |
| Kerguelen—Deep Kerguelen Subregion | K-DK        | Deep (mostly depths >3000 m) ocean surrounding Kerguelen Plateau & Banzare Bank.                                    | 3.57         | 13.39              | 15.97                  | 1,807,252                |
| Kerguelen—Kerguelen Plateau Subregion | K-KP    | Shallow (mostly depths between 200–3000 m), warmer seabeds of Kerguelen Plateau, north of frontal activity of Fawn Trough. | 19.31        | 65.53              | 65.53                  | 605,000                  |
| Oates                             | O            | Oceanographically separated from Central Indian-Wilkes subregion with wind & sea ice vectors diverging at western border. Eastern border is adjacent to Ross Sea region. | 16.45        | 40.80              | 75.71                  | 543,586                  |
| Ob & Lena                         | OL           | Shallow, warm seabeds in Polar Frontal Zone, including Ob & Lena banks & seamounts east.                              | 0            | 0.39               | 0.39                   | 1,078,842                |
| Pacific Basin                     | PB           | Very deep rugose ocean floor & abyssal plains of South Pacific Ocean Basin warmer than other deep ocean basin regions of Southern Ocean. | 2.85         | 2.85               | 2.85                   | 3,988,040                |
| Pacific—Antarctic Ridge           | PAR          | Pacific—Antarctic Ridge region with large extents of shallower environments of depths <2000 m.                       | 11.58        | 17.89              | 17.89                  | 3,029,157                |
| Ross Sea                          | RS           | Very cold seabed & high sea ice duration of Ross Sea. 22 endemic molluscs (11.5% of documented species). 16% of documented gastropods endemic. | 64.60        | 77.82              | 77.82                  | 828,471                  |
| South Atlantic                     | SA           | Shallow environments of Mid Atlantic Ridge & associated seamounts                                                  | 0            | 0                  | 0                      | 1,908,771                |

(Continued)
The East Antarctic MPA proposal boundaries were drawn based on [49], Weddell Sea MPA boundaries were based on [50], and Domain 1 (Antarctic Peninsula) proposed MPA boundaries were based on [51] (the latter two with permission). All CCAMLR Area and MPA shapefiles were imported into ArcGIS and projected into ESRI:102020 projection, South Pole Lambert Azimuthal Equal Area [73]. Sub-Antarctic MPAs with boundaries extending outside the CCAMLR Area (Kerguelen, Crozet and Prince Edward Islands) were constrained to the CCAMLR Area. We then calculated the total area encompassed by each existing and proposed MPA in ArcGIS. The total proportion of protected area is given by:

\[ P_n = \frac{\sum_i A_{pi}}{A} \times 100 \]

where \( A_{pi} \) = area of each MPA, indexed by \( i \), located within the CCAMLR Convention area; \( n \) is the number of MPAs; and \( A \) is the total CCAMLR Area. This metric was calculated for each of the nine CCAMLR MPA planning domains as well as for the entire CCAMLR Area. To report the proportion as a percentage, we multiplied the total proportion by 100.

This metric was also calculated for the no-take areas in the CCAMLR Area. To calculate the total proportion of no-take area, \( A_{nt} \) = the no-take area of each MPA, indexed by \( i \), located within the target CCAMLR Convention area. As with the total MPA area, we calculated the no-take metric for each CCAMLR MPA planning domain as well as the entire CCAMLR Convention area.

### Fraction of ecoregion protected

We calculated the area and proportion of each benthic and pelagic ecoregion that falls within the boundaries of existing and proposed MPAs, including ecoregions encompassed by no-take zones. Benthic ecoregion and pelagic cluster files (see above) were downloaded and projected into the ESRI:102020 projection, South Pole Lambert Azimuthal Equal Area [73]. The pelagic regionalization was originally projected out to 40°S, thus we constrained the data to the CCAMLR Area. Pelagic cluster 18 fell outside the area of analysis as it only occurs north of the CCAMLR Area. The benthic and pelagic ecoregion data files were intersected with the MPA shapefiles. We then calculated ecoregion areas included in each existing and proposed MPA.

### Table 2. (Continued)

| Benthic ecoregion | Abbreviation | Description | % in no-take | % in existing MPAs | % in MPAs + proposals | Size of ecoregion (km²) |
|-------------------|--------------|-------------|--------------|-------------------|----------------------|------------------------|
| South Georgia     | SG           | Productive, shallow environments in Polar Frontal Zone including island ecosystems of South Georgia & seamounts of North Scotia Ridge. 65 endemic molluscs (32.7% of documented species). 15% of documented Cheilostomata endemic. 13% of documented bivalves endemic. 36% of documented gastropods endemic. | 1.98 | 34.05 | 34.05 | 1,727,252 |
| South Orkney Islands | SOI         | Island ecosystems of South Orkney Islands & seamounts & plateaus of South Scotia Arc, many which underlie Southern Antarctic Circumpolar Current Frontal Zone. 22 endemic molluscs | 13.17 | 32.75 | 43.19 | 863,550 |
| South Sandwich Islands | SSI        | Highly productive island ecosystems of South Sandwich Islands & deeper waters of South Sandwich Trench. | 35.23 | 99.95 | 99.95 | 340,884 |
| Weddell Shelf     | WS           | Very cold seabed & high sea ice duration of Weddell shelf, usually rather deep, −500–1000 m. 55 endemic molluscs (19.7% of documented species). 26% of documented gastropods endemic. | 0 | 0 | 83.72 | 1,257,192 |

https://doi.org/10.1371/journal.pone.0231361.t002
including areas encompassed by no-take zones. Mean fraction of each ecoregion protected =

$$\sum_{i}^{n} \left( \frac{\sum_{j}^{m} A_{pj} / A_{ij}}{n} \right)$$

(2)

Where \(m_j\) is the number of MPAs in ecoregion or pelagic cluster \(j\) and \(A_{pj}\) is the area of each MPA, \(i\), overlapping areas of ecoregion or pelagic cluster \(j\). \(A_{ij}\) is the total area of ecoregion or pelagic cluster \(y\). We calculated this for both existing and existing + proposed MPAs. This metric was also calculated for the no-take areas in each existing MPA. Note: \(n = 1–23\) for the

| Pelagic cluster | Description |
|----------------|-------------|
| 1              | Polynya margins on continental shelf, South Orkneys plateau & areas off Adelaide & Biscoe Island in west Antarctic Peninsula. Moderately shallow (to ~1000 m) with ice cover ~20–50% & SST (~2°C). |
| 2              | Polynyas on continental shelf & areas off Danco Coast of Peninsula & South Orkney Islands & part of Banzare Bank. Low ice cover (~0–20%) & cold SST (~2°C). |
| 3              | Shallow shelf areas with ~25–60% ice cover. Restricted distribution, generally limited to East Antarctica. |
| 4              | Shallow areas with high ice cover (~75–95%). Patchily distribution scattered around continental shelf |
| 5              | Shelf areas with almost perennial ice cover (~75–100%). |
| 6              | Similar to 7, but shallower & with lower ice cover. Widely but sparsely distributed around continental shelf |
| 7              | Moderate depths (~200–1000 m) & ice cover (~50–75%). Many areas correspond to regions around polynyas. Also southern Scotia Arc areas. |
| 8              | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover and decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. |
| 9              | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover & decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. |
| 10             | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover & decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. |
| 11             | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover & decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. |
| 12             | Moderate depth (~1000–2500 m) & sea ice cover (~40%). Restricted to parts of southern Scotia Arc & isolated pockets north of Balleny Islands & off West Ice Shelf. |
| 13             | Shallow (~200–1000 m) parts of northern Kerguelen, Crozet & South Georgia plateau areas, Conrad Rise. |
| 14             | Deeper (~500–2000 m) parts of same plateaus, also Bouvetøya & northern tip of southern Kerguelen plateau. |
| 15             | Deep oceanic waters, encompassing approximately southern Antarctic Circumpolar Current front & Polar Front. |
| 16             | Deep oceanic waters, bounded approximately on north by Sub-Antarctic Front. |
| 17             | Temperate waters |
| 18             | Temperate waters |
| 19             | Outer areas of South American, New Zealand & Tasmanian shelves & scattered temperate banks. |
| 20             | Broad distribution around South American, New Zealand, Tasmanian & Crozet shelves. Shallow, ice-free & with warm SST (~10–20°C). |

SST refers to sea surface temperature (note that cluster 18 is not within the CCAML R Area).

| Pelagic cluster | Description | % in no-take | % in MPAs | % in MPAs + proposals | Size of cluster (km²) |
|----------------|-------------|--------------|-----------|------------------------|----------------------|
| 1              | Polynya margins on continental shelf, South Orkneys plateau & areas off Adelaide & Biscoe Island in west Antarctic Peninsula. Moderately shallow (to ~1000 m) with ice cover ~20–50% & SST (~2°C). | 6.33 | 7.23 | 50.65 | 283,533 |
| 2              | Polynyas on continental shelf & areas off Danco Coast of Peninsula & South Orkney Islands & part of Banzare Bank. Low ice cover (~0–20%) & cold SST (~2°C). | 1.41 | 2.43 | 69.83 | 165,969 |
| 3              | Shallow shelf areas with ~25–60% ice cover. Restricted distribution, generally limited to East Antarctica. | 4.24 | 4.55 | 49.34 | 30,466 |
| 4              | Shallow areas with high ice cover (~75–95%). Patchy distribution scattered around continental shelf | 17.68 | 27.30 | 51.19 | 37,678 |
| 5              | Shelf areas with almost perennial ice cover (~75–100%). | 5.90 | 13.62 | 69.28 | 1,010,363 |
| 6              | Similar to 7, but shallower & with lower ice cover. Widely but sparsely distributed around continental shelf | 12.83 | 13.31 | 51.73 | 156,512 |
| 7              | Moderate depths (~200–1000 m) & ice cover (~50–75%). Many areas correspond to regions around polynyas. Also southern Scotia Arc areas. | 28.06 | 32.55 | 51.02 | 1,030,815 |
| 8              | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover and decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. | 23.48 | 30.98 | 54.21 | 1,676,534 |
| 9              | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover & decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. | 6.91 | 8.03 | 26.36 | 5,178,744 |
| 10             | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover & decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. | 1.73 | 5.66 | 13.04 | 3,440,399 |
| 11             | Sea ice zone. Clusters 8–11 form an approximately latitudinal, deep water continuum of increasing ice cover & decreasing SST. Northernmost limit (of cluster 10) is generally just south of mean maximum winter sea ice extent. | 2.13 | 4.03 | 15.39 | 3,575,726 |
| 12             | Moderate depth (~1000–2500 m) & sea ice cover (~40%). Restricted to parts of southern Scotia Arc & isolated pockets north of Balleny Islands & off West Ice Shelf. | 11.01 | 41.67 | 45.24 | 47,493 |
| 13             | Shallow (~200–1000 m) parts of northern Kerguelen, Crozet & South Georgia plateau areas, Conrad Rise. | 34.30 | 79.14 | 79.16 | 357,564 |
| 14             | Deeper (~500–2000 m) parts of same plateaus, also Bouvetøya & northern tip of southern Kerguelen plateau. | 3.19 | 25.93 | 34.61 | 322,906 |
| 15             | Deep oceanic waters, encompassing approximately southern Antarctic Circumpolar Current front & Polar Front. | 1.19 | 6.89 | 8.07 | 12,780,390 |
| 16             | Deep oceanic waters, bounded approximately on north by Sub-Antarctic Front. | 1.55 | 26.99 | 26.99 | 3,397,347 |
| 17             | Temperate waters | 2.74 | 6.98 | 6.98 | 255,758 |
| 18             | Temperate waters | 0.00 | 0.00 | 0.00 | 0 |
| 19             | Outer areas of South American, New Zealand & Tasmanian shelves & scattered temperate banks. | 93.28 | 93.28 | 93.28 | 657 |
| 20             | Broad distribution around South American, New Zealand, Tasmanian & Crozet shelves. Shallow, ice-free & with warm SST (~10–20°C). | 35.29 | 99.78 | 99.78 | 19,872 |
benthic analysis and 1–20 for the pelagic analysis (representing 23 benthic ecoregions and 20 pelagic clusters).

We also calculated the number of benthic ecoregions and pelagic clusters that have at least 10% of their total area protected (per Aichi Target 11 [15]) and at least 30% of their total area protected (per IUCN guidelines [16]). This is the number of times that \( \left( \sum_{i}^{n} A_{pi}/A_{j} \right) \geq 0.1 \) and \( \geq 0.3 \), respectively. We calculated this percentage for existing MPAs, existing + proposed MPAs, and no-take zones within existing MPAs.

**Protection equality**

Finally, we calculated the protection equality of the existing and proposed MPA system using parallel methods to [22]. These metrics were developed by [78] and are measures of how equally the different benthic ecoregions and pelagic clusters are represented in the MPA system (i.e., a Gini coefficient). We used the “ProtectEqual” package in R (version 3.5.1) [79], developed by [80], to calculate protection equality values based on the proportion of each ecoregion and pelagic cluster protected. Protection equality values can range from 0–1 with high numbers indicating a higher protection equality.

**Results**

**Total proportion of protected area**

Seven MPAs currently exist in the Southern Ocean resulting in 11.98% of the CCAMLR Area falling under general protection and 4.61% falling under strict no-take protection (Table 1; Fig 1). Of the 11.98% area protected, nationally managed MPAs account for more than half of this (7.21%) and CCAMLR-governed MPAs account for the latter (4.6%). MPAs implemented in the CCAMLR Area which fall under national jurisdiction are: the Heard Island and McDonald Islands (HIMI) marine reserve (~71,000 km\(^2\); adopted in 2002 and expanded in 2014; governed by Australia), the South Georgia and South Sandwich Islands MPA (~1.24 million km\(^2\); adopted in 2012 and expanded in 2019; governed by the United Kingdom), the Prince Edward Islands MPA (~180,000 km\(^2\); adopted in 2013; governed by South Africa), and the Crozet and Kerguelen Islands MPAs (~1.14 million km\(^2\); adopted in 2017; governed by France). Note that the northern boundaries of the Prince Edward Islands, Kerguelen and Crozet MPAs extend beyond the CCAMLR Convention Area boundary. CCAMLR has also collectively adopted two MPAs: the South Orkney Islands Southern Shelf MPA (~94,000 km\(^2\); adopted in 2009) and the Ross Sea region MPA (~1.55 million km\(^2\); adopted in 2016). Three large MPA proposals also remain under negotiation at CCAMLR in the East Antarctic (proposed at ~1 million km\(^2\)), the Weddell Sea (~2 million km\(^2\)) and in Domain 1 (~466,000 km\(^2\)) (Fig 1).

Of the nine planning domains established by CCAMLR (Fig 1), existing MPAs cover parts of Domain 1 (South Orkney Islands Southern Shelf MPA), Domain 2 (South Georgia and South Sandwich Islands MPA), Domain 5 (Prince Edward Islands and Crozet MPAs), Domain 6 (Kerguelen and HIMI MPAs), and Domain 8 (Ross Sea region MPA). Proposed MPAs would further cover Domain 3 and 4 (Weddell Sea MPA), Domain 7 (East Antarctic MPA), and additional areas in Domain 1 (Domain 1 MPA). Domain 9 remains un-represented (Fig 1).

**Fraction of ecoregion protected**

In the CCAMLR Area, 23 benthic ecoregions have been identified [45]. Of these, 12 benthic ecoregions are at least partially protected in no-take zones of existing Southern Ocean MPAs (0.21–64.0%; median = 7.58, mean = 14.33; Table 2). However, only six of these benthic
ecoregions have 10% or more no-take protection; only two benthic ecoregions have 30% no-take protection (Table 4). Across all zones of existing Southern Ocean MPAs, 13 benthic ecoregions are at least partially represented in existing MPAs (0.21–99.95%; median = 32.75; mean = 34.22; Fig 2; Table 2). Nine of these benthic ecoregions are at least 10% represented in existing MPAs; seven benthic ecoregions are at least 30% represented in the existing MPAs (Table 4). Ten benthic ecoregions are not represented in the current Southern Ocean MPA network (Fig 2; Table 2).

Table 4. Number of benthic ecoregions and pelagic clusters that have ≥ 10% and ≥ 30% represented (out of 23 benthic ecoregions and 19 pelagic clusters considered in this analysis). See Table 2 and Table 4 for names and descriptions of benthic ecoregions and pelagic clusters.

| 10% THRESHOLD | No-take zone (in existing) | Existing MPA | Existing + Proposed | Not at threshold (in existing + proposed) |
|---------------|---------------------------|--------------|---------------------|------------------------------------------|
|               | Total                     | 6            | 9                   | 17                                       | 6                                        |
| Benthic Ecoregions | K-KP RS DC RS AB           | K-KP A OL   |                      |                                          |
| O SOI K-DK SG AP |                          |              |                     |                                          |
| PAR SSI K-KP SOI CI-EK PAR EIA SA |              |              |                     |                                          |
| O SSI CI-PB RS |                          |              |                     |                                          |
| PAR CI-WK SG |                          |              |                     |                                          |
| DC SOI DM SSI K-BB WS |              |              |                     |                                          |
| K-DK |                          |              |                     |                                          |
| Total | 7            | 11           | 17                   | 2                                        |
| Pelagic clusters | 4 12 4 13 1 10 15 | 6 13 5 14 2 11 17 | 7 20 6 16 3 12 | 8 7 19 4 13 8 20 9 |
| 30% THRESHOLD | 2 7 12 11 | 2 6 13 6 | 13 7 19 8 9 15 10 16 11 17 | 4 14 5 19 6 20 7 |
| Benthic ecoregions | RS DC SG AP O A K-DK | K-KP SSI CI-EK RS AB OL | O SOI CI-WK SG CI-PB PB | RS K-KP WS K-BB |
| SSI | K-KP SSI CI-EK RS AB OL | O SOI CI-WK SG CI-PB PB | RS DC SSI CI-W PAR | DM SOI EIA SA |
| Total | 2 7 12 11 | 2 6 13 6 | 13 7 19 8 9 15 10 16 11 17 | 4 14 5 19 6 20 7 |
| Pelagic Clusters | 13 7 13 1 8 9 15 | 20 8 19 2 12 10 16 | 12 20 3 13 11 17 | 4 14 5 19 6 20 7 |

https://doi.org/10.1371/journal.pone.0231361.t004
Designation of the proposed MPAs in the East Antarctic, Weddell Sea and Domain 1 (Antarctic Peninsula) currently being negotiated by CCAMLR would provide representation of an additional nine benthic ecoregions. This would increase the total to 22 of the 23 benthic ecoregions (all except for the South Atlantic ecoregion), at least partially, within protected areas (1.15–99.95%; median = 34.40; mean = 37.44; Fig 2; Table 2). Inclusion of these additional
proposed MPAs in the Southern Ocean MPA network would result in 17 benthic ecoregions being at least 10% protected; 12 of these benthic ecoregions would achieve being at least 30% protected (Table 4).

In the Southern Ocean, 20 pelagic clusters have been identified [46], however only 19 of these fall within the CCAMLR Area (cluster 18 only occurs outside the CCAMLR Area). Of

Fig 3. Pelagic clusters of the CCAMLR Area and marine protected areas. Pelagic clusters [46], with existing and proposed MPAs overlain (in black outline and hashed line, respectively; no-take regions outlined in existing MPAs; see Fig 1 for delineation). Pelagic cluster numbers defined in Table 3 (note that cluster 18 only occurred outside the CCAMLR Area, thus outside the scope of this analysis).

https://doi.org/10.1371/journal.pone.0231361.g003
these, 18 pelagic clusters are at least partially protected in no-take regions of existing Southern Ocean MPAs (1.19–35.29%; median = 6.11; mean = 11.11; Table 3). However, only seven of these pelagic clusters are at least 10% protected in no-take zones; only two are at least 30% protected in no-take zones (Table 4). In all zones of established Southern Ocean MPAs, all of the 19 pelagic clusters are at least partially represented in the seven existing Southern Ocean MPAs (2.43–99.78%; median = 13.62; mean = 27.91; Fig 3; Table 3). Eleven of these pelagic clusters are at least 10% represented in existing MPAs; six are at least 30% represented in existing MPAs (Table 4).

Proposed MPAs in the East Antarctic, Weddell Sea and Domain 1 (Antarctic Peninsula) currently being negotiated by CCAMLR would increase representation of almost all pelagic cluster types (6.98–99.78%; median = 50.65; mean = 47.17; Fig 3; Table 3). Including these additional proposed MPAs in the Southern Ocean MPA network would result in 17 of the pelagic clusters being at least 10% protected; and 13 of the clusters being at least 30% protected (Table 4).

Protection equality

The protection equality of the no-take zones of existing MPAs were 0.18 and 0.41 for benthic ecoregions and pelagic clusters, respectively (Table 5). For all zones of existing MPAs, the protection equality values increased to 0.26 and 0.44 for benthic and pelagic regions, respectively. Including the existing and the proposed MPAs increased the protection equality values to 0.52 and 0.67 for benthic and pelagic regions, respectively (Table 5).

Discussion

CCAMLR has successfully adopted two MPAs in the Southern Ocean, with the Ross Sea being the world’s largest international MPA at ~1.55 million km². CCAMLR jurisdiction MPAs encompass 4.6% of the CCAMLR Area, mostly comprised by the large Ross Sea region MPA. Nationally implemented MPAs encompass 7.21% of the CCAMLR Area. Collectively almost 12% of the Southern Ocean is encompassed in MPAs, thus the region meets the 10% area targets of the Convention on Biological Diversity [15] and the United Nations Sustainable Development Goals [17], and in surpassing the proportion ice-free areas protected on the Antarctic continent [22]. No other high seas management body has achieved this level of protection. It exceeds the global average of 7.91% [36]. Many national waters have not reached the 10% target (e.g., Norway at 0.83%), however, others have far surpassed it (e.g., United States, France, and Australia all have greater than 40% of their national waters protected) [36]. Indeed, among the 66 large marine ecosystems in the world, the Antarctic has the 2nd largest area encompassed by MPAs and the Ross Sea MPA is considered to contain a high level of ecological representativeness for Antarctic biodiversity [37].

Despite having more than 10% of the Southern Ocean protected, only 4.61% is encompassed in no-take areas, largely comprised of the South Orkney Islands Southern Shelf MPA, HIMI marine reserve, and a large proportion (~70%) of the Ross Sea region MPA. Multiple

Table 5. Protection equality and integrated protection values of the existing and proposed MPA system, including no-take zones.

|                     | No-take | Existing MPA | Existing + Proposed |
|---------------------|---------|--------------|---------------------|
| Benthic ecoregion   | 0.18    | 0.26         | 0.52                |
| Pelagic cluster     | 0.41    | 0.44         | 0.67                |

https://doi.org/10.1371/journal.pone.0231361.t005
studies point to the importance of MPAs having no-take areas to be effective at conserving biodiversity, including fish populations [4, 5, 81–83]. Furthermore, the Ross Sea region MPA has a limited 35-year duration, meaning that this proportion might not receive protection after this time if the MPA is not renewed. Moreover, while some targets call for 10% protection, many studies suggest that less than 30% is insufficient to protect biodiversity, conserve ecosystem services—including sustaining commercial fisheries—and to achieve socioeconomic priorities set by these targets [9, 84, 85]. Others have argued that protection targets closer to 50% protection are required to curb biodiversity loss [18, 86, 87].

Beyond percentage targets, current protected areas do not provide a representative sample of the Southern Ocean’s biodiversity. Global targets call for protected areas to be ecologically representative [14–16], meaning that protection should encompass the full range of biodiversity present in a region [88]. Overall, current MPA distribution is largely biased towards sub-Antarctic regions and the Ross Sea. Thus, within currently established no-take areas in the Southern Ocean, only two benthic ecoregions have 30% protection. The Ross Sea ecoregion meets this threshold, due to the large-scale MPA in that region and the South Sandwich Islands ecoregions also has this level of protection due to recent (2019) expansions in no-take areas [55]. For pelagic clusters, only 13 (shallow parts of sub-Antarctic plateaus near Kerguelen and South Georgia) and 20 (Crozet shelves) have 30% protected in sub-Antarctic MPAs. At the 10% threshold, still only six benthic ecoregions and seven pelagic clusters are protected in no-take areas. Factoring in all existing MPAs, including no-take and multi-use zones, the Southern Ocean MPA network is still not representative of all benthic ecoregions and pelagic clusters, thus it is not representative of Southern Ocean biodiversity. This is in line with global MPA trends where, while there has been an overall increase in representation, overall 61% of the benthic ecoregions in national waters remain unprotected [38] and globally, most large-marine ecosystems do not have greater than 10% representation [37].

The adoption of additional proposed MPAs in the Weddell Sea, East Antarctic and Antarctic Peninsula would increase representation in the Southern Ocean MPA network. All of these regions encompass parts of CCAMLR’s MPA planning domains (Fig 1) and original priority areas [89]. With the addition of these proposed MPAs, roughly three-quarters of the benthic ecoregions and almost all pelagic clusters would be 10% represented. However, as noted above, to conserve biodiversity these additional MPAs should have no-take zones and further should have long duration (e.g., [81]). Even with the addition of pending MPA proposals, some areas remaining poorly represented. These include the benthic ecoregions of the South Atlantic (mostly in northern Domain 4), Amundsen (mostly in Domain 9), Central Indian-Wilkes subregion (in Domain 7), East Indian Abyssal (mostly in Domain 7), Ob and Lena (mostly in Domain 5), and Pacific Basin (largely in Domain 9). Additional MPAs (to those existing or currently being proposed) would allow for complete representation.

The Southern Ocean MPAs also do not have equitable protection in terms of proportionality protected across benthic ecoregions. For existing MPAs, the benthic ecoregions fall within the lowest quartile and the pelagic clusters are in the second lowest quartile for equality protection [78]. However these numbers are comparable to protection equality values for national MPAs globally [38]. While these values are much higher for the network of MPAs achieved by currently existing and proposed MPAs, protection equality still measures at less than 50% for benthic ecoregions and 60% for pelagic clusters which puts them in the second highest quartile [78]. While not completely equitable, these values are much higher than the values for MPAs globally inside national waters [38].

This assessment of representativeness was undertaken on the basis of large-scale benthic and pelagic regionalizations. The large-scale regions provide a helpful broad measure of progress but do not go far enough to plan for capturing biodiversity patterns, internal
heterogeneity, genetic diversity and cryptic species [45]. Although biological and ecosystem-level data are more difficult to work with, and typically do not have consistent circumpolar coverage, consideration of such data might also provide a more nuanced assessment of the strengths and gaps in current and proposed MPAs (e.g., [90–92]). Furthermore, at smaller scales, MPAs may be designed to protect vulnerable or critical habitats that are missed in broad-scale regionalizations. Ensuring protection of all ecoregions and replicated protection of particular ecoregions across different ocean basins is one possible means of addressing this.

The urgency of the threats to the Southern Ocean and the need for protection is critical now more than ever before. The Southern Ocean supports international commercial fisheries for Patagonian and Antarctic toothfish (*Dissostichus eleginoides* and *D. mawsoni*; sold as Chilean sea bass) and Antarctic krill (*Euphausia superba*) [44]. Pressure on these fisheries has increased in recent years [93] and is likely to continue, and at the same time climate change pressures on Southern Ocean ecosystems are also increasing [94–98]. The cumulative impacts of fishing and climate change are likely to have greater effect than either impact alone [99–101]. Increasing numbers of studies show that MPAs, especially no-take marine reserves, can be a proactive and precautionary tool to enhance resilience to environmental change, including climate change and warming [10–12, 102, 103]. Importantly, the MPAs need to be well designed, with representation being one of many elements. Key biodiversity areas, vulnerable and rare species should be considered in MPA design, as well as connectivity (e.g., [6, 104]). Further, the MPAs need to be well managed and enforced [105, 106], a significant challenge for large-scale MPAs in a place as large and remote as the Antarctic [107].

Nonetheless, protected areas alone will not suffice to conserve Antarctic marine biodiversity [108]. CCAMLR may need to enact other precautionary management measures targeted at reducing or even eliminating fish catch in some areas [109]. Given the international nature of climate change and threats to Antarctic biodiversity, successful deployment of such measures by CCAMLR will require collaboration with other appropriate international organizations and initiatives, including those of the United Nations [110–113]. Integration across these management bodies will broaden CCAMLR’s toolbox [114] for taking action on conserving the globally significant biodiversity and living resources of the Southern Ocean [115–118].

**Acknowledgments**

C.M.B., Z.S. & C.T. were supported by the Pew Charitable Trusts. Thanks to three anonymous reviewers whose comments and edits improved the manuscript.

**Author Contributions**

**Conceptualization:** Cassandra M. Brooks, Steven L. Chown.

**Data curation:** Cassandra M. Brooks, Lucinda L. Douglass, Ben P. Raymond.

**Formal analysis:** Cassandra M. Brooks, Ben P. Raymond, Justine D. Shaw, Zephyr T. Sylvester, Christa L. Torrens.

**Funding acquisition:** Cassandra M. Brooks.

**Investigation:** Cassandra M. Brooks, Steven L. Chown, Ben P. Raymond, Zephyr T. Sylvester, Christa L. Torrens.

**Methodology:** Cassandra M. Brooks, Lucinda L. Douglass, Ben P. Raymond, Justine D. Shaw, Christa L. Torrens.

**Project administration:** Cassandra M. Brooks.
**Resources:** Cassandra M. Brooks.

**Supervision:** Cassandra M. Brooks.

**Validation:** Cassandra M. Brooks.

**Visualization:** Cassandra M. Brooks.

**Writing – original draft:** Cassandra M. Brooks, Steven L. Chown, Lucinda L. Douglass, Ben P. Raymond, Justine D. Shaw, Zephyr T. Sylvester, Christa L. Torrens.

**Writing – review & editing:** Cassandra M. Brooks, Steven L. Chown, Lucinda L. Douglass, Ben P. Raymond, Justine D. Shaw, Zephyr T. Sylvester, Christa L. Torrens.

**References**

1. Lubchenco J, Palumbi SR, Gaines SD, Andelman S. Plugging a Hole in the Ocean: The Emerging Science of Marine Reserves. Ecological Applications. 2003; 13(1):S3–S7.
2. Lubchenco J, Grorud-Colvert K. Making waves: The science and politics of ocean protection. Science. 2015; 350(6259):382–3. https://doi.org/10.1126/science.aad5443 PMID: 26472764
3. Roberts CM, Hawkins JP, Gell FR. The role of marine reserves in achieving sustainable fisheries. Philosophical Transactions of the Royal Society London B Biological Sciences. 2005; 360(1453):123–32.
4. Lester SE, Halpern BS, Grorud-Colvert K, Lubchenco J, Ruttenberg BI, Gaines SD, et al. Biological effects within no-take marine reserves: a global synthesis. Marine Ecology Progress Series. 2009; 384:33–46.
5. Sciberras M, Jenkins SR, Kaiser MJ, Hawkins SJ, Pullin AS. Evaluating the biological effectiveness of fully and partially protected marine areas. Environmental Evidence. 2013; 2(4):1–31.
6. Laffoley D, Baxter JM, Day JC, Wenzel L, Bueno P, Zischka K. Marine Protected Areas. World Seas: an Environmental Evaluation. 2019. p. 549–69.
7. Hixon MA, Johnson DW, Sogard SM. BOFFFFs: on the importance of conserving old-growth age structure in fishery populations. ICES Journal of Marine Science. 2013;1:1–15.
8. FAO. Fisheries Management. 4. Marine Protected Areas and Fisheries. No. 4, Suppl. 4. FAO, Rome: 2011.
9. Gell FR, Roberts CM. Benefits beyond boundaries: the fishery effects of marine reserves. Trends in Ecology & Evolution. 2003; 18(9):448–55.
10. Olds AD, Pitt KA, Maxwell PS, Babcock RC, Rissik D, Connolly RM. Marine reserves help coastal ecosystems cope with extreme weather. Global Change Biology. 2014; 20(10):3050–8. https://doi.org/10.1111/gcb.12606 PMID: 24849111
11. Barnett LA, Baskett ML. Marine reserves can enhance ecological resilience. Ecological Letters. 2015; 18(12):1301–10.
12. Roberts CM, O’Leary BC, McCauley DJ, Cory PM, Duarte CM, Lubchenco J, et al. Marine reserves can mitigate and promote adaptation to climate change. Proceedings of the National Academy of Sciences USA. 2017; 114(24):6167–75.
13. United Nations. World Summit on Sustainable Development, Plan of Implementation. 2002.
14. IUCN. Vth World Parks Congress, Durban, South Africa 8–17 September 2003. http://enb.iisd.org/crs/worldparks/v/sdvol89num9e.html. 2003.
15. CBD. COP 10, Decision X/2 Strategic Plan for Biodiversity 2011–2020, Aichi Biodiversity Targets, Target 11. 2010.
16. IUCN. The Promise of Sydney, IUCN World Parks Congress. Sydney, Australia, http://worldparkscongress.org/about/promise_of_sydney.html. 2014.
17. United Nations. Sustainable Development Goals Report. New York: 2017.
18. Locke H. Nature needs half: A necessary and hopeful new agenda for protected-areas. The George Wright Forum. 2013; 31:359–71.
19. Svancara LK, Brannon R, Scott JM, Goves CR, Noss R, Pressey RL. Policy-driven versus Evidence-based Conservation: A Review of Political Targets and Biological Needs. BioScience. 2005; 55(11):989–96.
20. Moilanen A, Wilson KA, Possingham HP. Spatial Conservation Prioritization. Quantitative Methods and Computational Tools. Oxford: Oxford University Press; 2009.
21. Dinerstein E, Olson D, Joshi A, Vynne C, Burgess ND, Wikramanayake E, et al. An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. Bioscience. 2017; 67(6):534–45. https://doi.org/10.1093/biosci/bix014 PMID: 28608869

22. Shaw JD, Terauds A, Riddle MJ, Possingham HP, Chown SL. Antarctica’s protected areas are inadequate, unrepresentative, and at risk. PLoS Biology. 2014; 12(6):e1001888. https://doi.org/10.1371/journal.pbio.1001888 PMID: 24936869

23. Bailey RG. Ecoregions: The Ecosystem Geography of the Oceans and Continents. 2nd ed. New York Heidelberg Dordrecht London: Springer; 2014.

24. Grant SM, Constable A, Raymond B, Doust S. Bioregionalisation of the Southern Ocean: Report of Experts Workshop. Hobart: WWF-Australia and ACE CRC, 2006.

25. Pinkerton M, Smith A, Raymond B, Hosie G, Sharp B, Leathwick J, et al. Spatial and seasonal distribution of adult Oithona similis in the Southern Ocean: predictions using boosted regression trees. Deep-Sea Research Part I: Oceanographic Research Papers. 2010; 57(4):469–85.

26. Koubbi P, Moteki M, Duhamel G, Goarant A, Hulley P-A, O’Driscoll R, et al. Ecoregionalization of myctophid fish in the Indian sector of the Southern Ocean: Results from generalized dissimilarity models. Deep Sea Research Part II: Topical Studies in Oceanography. 2011; 58(1–2):170–80.

27. Freer JJ, Tarling GA, Collins MA, Partridge JC, Genner MJ. Predicting future distributions of lanternfish, a significant ecological resource within the Southern Ocean. Diversity and Distributions. 2019. https://doi.org/10.1111/ddi.12934

28. Xavier JC, Raymond B, Jones DC, Griffiths H. Biogeography of Cephalopods in the Southern Ocean Using Habitat Suitability Prediction Models. Ecosystems. 2015; 19(2):220–47.

29. Basheer Z, Costello MJ. The past, present and future distribution of a deep-sea shrimp in the Southern Ocean. PeerJ. 2016; 4:e1713. https://doi.org/10.7717/peerj.1713 PMID: 26925334

30. Pierrat B, Saucède T, Lafont R, De Ridder C, Festeau A, David B. Large-scale distribution analysis of Antarctic echinoids using ecological niche modelling. Marine Ecology Progress Series. 2012; 463:215–30.

31. Last PR, Lyne VD, Williams A, Davies CR, Butler AJ, Yearsley GK. A hierarchical framework for classifying seabed biodiversity with application to planning and managing Australia’s marine biological resources. Biological Conservation. 2010; 143(7):1675–86.

32. Harris PT, Baker EK. 64—GeoHab Atlas of seafloor geomorphic features and benthic habitats: synthesis and lessons learned. Seafloor Geomorphology as Benthic Habitat. London: Elsevier; 2012. p. 871–90.

33. Tews J, Brose U, Grimm V, Tielbörger K, Wichmann MC, Schwager M, et al. Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. Journal of Biogeography. 2004; 31(1):79–92.

34. Williams A, Althaus F, Dunstan PK, Poore GCB, Bax NJ, Kloster RJ, et al. Scales of habitat heterogeneity and megabenthos biodiversity on an extensive Australian continental margin (100-1100 m depths). Marine Ecology. 2010; 31(1):222–36.

35. De Leo FC, Vetter EW, Smith CR, Rowden AA, McGranaghan M. Spatial scale-dependent habitat heterogeneity influences submarine canyon macrofaunal abundance and diversity off the Main and Northwest Hawaiian Islands. Deep Sea Research Part II: Topical Studies in Oceanography. 2014; 104:267–90.

36. UNEP-WCMC. World Database of Protected Areas. 2020. https://www.protectedplanet.net

37. Fischer A, Bhakta D, Macmillan-Lawler M, Harris P. Existing global marine protected area network is not representative or comprehensive measured against seafloor geomorphic features and benthic habitats. Ocean & Coastal Management. 2019; 167:176–87.

38. Jantke K, Jones KR, Allan JR, Chauvenet ALM, Watson JEM, Possingham HP. Poor ecological representation by an expensive reserve system: Evaluating 35 years of marine protected area expansion. Conservation Letters. 2018; 11(6). https://doi.org/10.1111/conl.12460

39. The Convention on the Conservation of Antarctic Marine Living Resources. 1980.

40. Kock K-H. Antarctic Marine Living Resources–exploitation and its management in the Southern Ocean. Antarctic Science. 2007; 19(02):231.

41. Lodge MW, Anderson D, Lobach T, Munro G, Sainsbury K, Willock A. Recommended Best Practices for Regional Fisheries Management Organizations. London: Chatham House, 2007.

42. Diz Pereira Pinto D. Fisheries Management in areas beyond national jurisdiction. Netherlands: Martinus Nijhoff 2012. 207 p.
43. Miller D, Slicer NM. CCAMLR and Antarctic conservation: The leader to follow? In: Garcia SM, Rice J, Charles A, editors. Governance of Marine Fisheries and Biodiversity Conservation: Interaction and Coevolution. West Sussex, UK.: John Wiley & Sons, Ltd.; 2014.

44. Brooks CM. Competing values on the Antarctic high seas: CCAMLR and the challenge of marine-protected areas. The Polar Journal. 2013; 3(2):277–300.

45. Douglass LL, Turner J, Grantham HS, Kaiser S, Constable A, Nicoll R, et al. A hierarchical classification of benthic biodiversity and assessment of protected areas. PLoS One. 2014; 9(7):e100551. https://doi.org/10.1371/journal.pone.0100551 PMID: 25032993

46. Raymond B. Pelagic Regionalization. In: De Broyer C, Koubbi P, Griffiths HJ, Raymond B, D'Acoz C, van de Putte A, editors. Biogeographic atlas of the Southern Ocean. Cambridge: SCAR; 2014. p. 397–403.

47. Brooks CM, Crowder LB, Osterblom H, Strong AL. Reaching consensus for conserving the global commons: The case of the Ross Sea, Antarctica. Conservation Letters. 2019.

48. CCAMLR. CCAMLR GIS 2019. Available from: https://gis.ccamlr.org.

49. Division AA. A Marine Protected Area for East Antarctica: Australian Government. Department of the Environment and Energy. Australian Antarctic Division.; 2018 [04 May 2019]. Available from: http://www.antarctica.gov.au/law-and-treaty/ccamlr/marine-protected-areas.

50. Delegation of the European Union. EU proposal to establish the Weddell Sea MPA (WSMPA). CCAMLR-XXVII/29. 2018

51. Delgations of Argentina and Chile. Proposal on a conservation measure establishing a marine protected area in the Domain1 (Western Antarctic Peninsula and South Scotia Arc). CCAMLR-XXXVII/31 2018.

52. Welsford D, Constable A, Nowara GB. The Heard Island and McDonald Islands Marine Reserve and Conservation Zone—A model for Southern Ocean marine reserves? In: Duhamel G, Welsford D, editors. The Kerguelen Plateau: marine ecosystems and fisheries: Société française d'ichtyologie; 2011. p. 297–304.

53. MPA Atlas. Terres Australes Françaises. National Nature Reserve 2019 [04 May 2019]. Available from: http://www.mpatlas.org/mpa/sites/68808359/.

54. CCAMLR. Conservation Measure 91–03. Protection of the South Orkney Islands southern shelf. 2009.

55. Government of South Georgia and the South Sandwich Islands. South Georgia and South Sandwich Islands Gazette. Marine Protected Areas Order 2019 (SR&O No 1 of 2019). 2019.

56. Lombard AT, Reyers B, Schonegevel LY, Cooper J, Smith-Adao LB, Nel DC, et al. Conserving pattern and process in the Southern Ocean: designing a Marine Protected Area for the Prince Edward Islands. Antarctic Science. 2007; 19(01). https://doi.org/10.1017/s0954102007000077

57. Prince Edward Islands declared a Marine Protected Area. Environmental Affairs, Republic of South Africa; 2013; 9 April 2013. Available from: https://www.environment.gov.za/mediarelease/princeedwardislands_declaredmarineprotectedarea#

58. CCAMLR. Conservation Measure 91–05, Ross Sea Region Marine Protected Area. 2016.

59. Douglass L, Beaver D, Turner J, Kaiser S, Constable A, Raymond B, et al. Southern Ocean Benthic Classification (SOBC)—ecoregions, bathomes and environmental types. Australian Antarctic Data Centre2014, updated 2017. https://doi.org/10.4225/15/53A3760D4AFAA

60. Smith W, Sandwell D. Measured and Estimated Seafloor Topography Version 13.1, Research Publication RP-1: World Data Center-A for Marine Geology and Geophysics. 2010.

61. O’Brien PE, Post AL, Romeyn R. Antarctic-wide Geomorphology as an aid to habitat mapping and locating Vulnerable Marine Ecosystems. WS-VME-09/10. 2009.

62. Clarke A, Griffiths HJ, Barnes DKA, Meredith MP, Grant SM. Spatial variation in seabed temperatures in the Southern Ocean: Implications for benthic ecology and biogeography. Journal of Geophysical Research. 2009; 114(G3). https://doi.org/10.1029/2008jg000886

63. Feldman GC, McClain CR. Ocean Color Web, SeaWiFS Reprocessing, NASA Goddard Space Flight Center. In: Kuring N, Bailey, S.W., editor. 2010.

64. Spreen G, Kaleschke L, Heygster G. Sea ice remote sensing using AMSR-E 89-GHz channels. Journal of Geophysical Research. 2008; 113(C2). https://doi.org/10.1029/2005jc003384

65. Sokolov S, Rintoul SR. Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 1. Mean circumpolar paths. Journal of Geophysical Research. 2009; 114(C11). https://doi.org/10.1029/2008jc005108
66. Linse K, Griffiths HJ, Barnes DKA, Clarke A. Biodiversity and biogeography of Antarctic and sub-Antarctic mollusca. Deep Sea Research Part II: Topical Studies in Oceanography. 2006; 53(8–10):985–1008. https://doi.org/10.1016/j.dsr2.2006.05.003

67. Clarke A, Griffiths HJ, Linse K, Barnes DKA, Crame JA. How well do we know the Antarctic marine fauna? A preliminary study of macroecological and biogeographical patterns in Southern Ocean gastropod and bivalve molluscs. Diversity and Distributions. 2007; 13(5):620–32. https://doi.org/10.1111/j.1472-4642.2007.00380.x

68. Griffiths HJ, Barnes DKA, Linse K. Towards a generalized biogeography of the Southern Ocean benthos. Journal of Biogeography. 2009; 36(1):162–77. https://doi.org/10.1111/j.1365-2699.2008.01979.x

69. Spalding M, Fox H, Allen G, Davidson N, Ferdana Z, Finlayson M, et al. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. Bioscience. 2007; 57:573–83.

70. Raymond B. A circumpolar pelagic regionalisation of the Southern Ocean. Australian Antarctic Data Centre—CAASMD Metadata 2017, updated 2019. https://doi.org/10.4225/15/59001e9382f5c

71. SC-CAMLR. Report of the XXVI meeting of the CAMLR Scientific Committee. 2007.

72. Smith W, Sandwell D. Global seafloor topography from satellite altimetry and ship depth soundings. Science. 1997; 277:1957–62.

73. ESRI. ArcGIS Desktop, release 10.5. Redlands, CA: Environmental Systems Research Institute; 2017.

74. UNEP-WCMC. Protected Planet. Réserve Naturelle Nationale des Terres australes françaises (Périmètre de protection de la) in Terres australes et antarctiques françaises. 2018. Available from: https://www.protectedplanet.net/reserve-naturelle-nationale-des-terres-australes-francaises-perimetre-de-protection-de-la-protection-zone-around-nature-reserve.

75. UNEP-WCMC. Protected Planet. Prince Edward Island Marine Protected Area in South Africa. 2019. Available from: https://protectedplanet.net/prince-edward-island-marine-protected-area-marine-protected-area.

76. UNEP-WCMC. Protected Planet. South Georgia and South Sandwich Islands Marine Protected Area in South Georgia and the South Sandwich Islands. 2019. Available from: https://protectedplanet.net/555547601.

77. UNEP-WCMC. Protected Planet. Heard Island and McDonald Islands in Heard Island and McDonald Islands. 2019. Available from: https://protectedplanet.net/heard-island-and-mcdonald-islands-commonwealth-marine-reserve.

78. Barr LM, Pressley RL, Fuller RA, Segnan DB, McDonald-Madden E, Possingham HP. A new way to measure the world’s protected area coverage. PLoS One. 2011; 6(9):e24707. https://doi.org/10.1371/journal.pone.0024707 PMID: 21957458

79. R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2018.

80. Chauvenet AL, Kuempel CD, McGowan J, Beger M, Possingham HP. Methods for calculating Protection Equality for conservation planning. PLoS One. 2017; 12(2):e0171591. https://doi.org/10.1371/journal.pone.0171591 PMID: 28199341

81. Edgar GJ, Stuart-Smith RD, Willis TJ, Kininmonth S, Baker SC, Banks S, et al. Global conservation outcomes depend on marine protected areas with five key features. Nature. 2014; 506(7487):216–20. https://doi.org/10.1038/nature13022 PMID: 24499817

82. Lester SE, Halpern BS. Biological responses in marine no-take reserves versus partially protected areas. Marine Ecology Progress Series. 2008; 367:49–56. https://doi.org/10.3354/meps07599

83. Sala E, Giakoumi S. No-take marine reserves are the most effective protected areas in the ocean. ICES Journal of Marine Science. 2018; 75(3):1166–8. https://doi.org/10.1093/icesjms/fsx059

84. O’Leary BC, Winther-Janson M, Bainbridge JM, Altken J, Hawkins JP, Roberts CM. Effective Coverage Targets for Ocean Protection. Conservation Letters. 2016; 9(6):398–404. https://doi.org/10.1111/conl.12247

85. Gaines SD, White C, Carr MH, Palumbi SR. Designing marine reserve networks for both conservation and fisheries management. Proceedings of the National Academy of Sciences USA. 2010; 107(43):18286–93. https://doi.org/10.1073/pnas.0906473107 PMID: 20200311

86. Wilson EO. Half-Earth. New York, NY: Liveright Publishing Corporation; 2016.

87. Caffaro P, Butler T, Crist E, Cryer P, Dinerstein E, Kopnina H, et al. If we want a whole Earth, Nature Needs Half: a response to Büscher et al. Oryx. 2017; 51(3):400-. https://doi.org/10.1017/s0030605317000072
88. Possingham H, Wilson KA, Regan TJ. The roles of spatial heterogeneity and ecological processes in conservation planning. In: Lovett G, Jones C, Turner M, Weathers K, editors. Ecosystem Function in Heterogeneous Landscapes. New York: Springer; 2005.

89. WG-EMM. Report on the Working Group on Ecosystem Monitoring and Management. Hobart, Tasmania, Australia: CCAMLR, 2008.

90. Leaper R, Dunstan PK, Foster SD, Barrett NJ, Edgar GJ. Comparing large-scale bioregions and fine-scale community-level biodiversity predictions from subtidal rocky reefs across south-eastern Australia. Journal of Applied Ecology. 2012; 49(4):851–60. https://doi.org/10.1111/j.1365-2664.2012.02155.x

91. Raymond B, Lea M-A, Patterson T, Andrews-Goff V, Sharples R, Charrassin J-B, et al. Important marine habitat off east Antarctica revealed by two decades of multi-species predator tracking. Ecography. 2015; 38(2):121–9. https://doi.org/10.1111/ecog.01021

92. Reisinger RR, Raymond B, Hindell MA, Bester MN, Crawford RJM, Davies D, et al. Habitat modelling of tracking data from multiple marine predators identifies important areas in the Southern Indian Ocean. Diversity and Distributions. 2018; 24(4):535–50. https://doi.org/10.1111/ddi.12702

93. Brooks C, Crowder LB, Curran L, Dunbar R, Ainley D, Dodds K, et al. Science-based management in decline in the Southern Ocean. Science. 2016; 354(6309):185–7. https://doi.org/10.1126/science.aah4119 PMID: 27738163

94. Rintoul SR, Chown SL, DeConto RM, England MH, Fricker HA, Masson-Delmotte V, et al. Choosing the future of Antarctica. Nature. 2018; 558(7709):233–41. https://doi.org/10.1038/s41586-018-0173-4 PMID: 29899481

95. Swart N, Gille S, Fye J, Gillett N. Recent Southern Ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. Nature Geoscience. 2018; 11:836–41.

96. Montes-Hugo M, Doney S, Ducklow H, Fraser W, Martinson D, Stammerjohn S, et al. Recent changes in phytoplankton communities associated with rapid regional climate change along the western Antarctic Peninsula. Science 2009; 323:1470–3. https://doi.org/10.1126/science.1164533 PMID: 19286554

97. Atkinson A, Hill SL, PAKhmov EA, Siegel V, Reiss CS, LOeb VJ, et al. Krill (Euphausia superba) distribution contracts southward during rapid regional warming. Nature Climate Change. 2019; 9(2):142–7. https://doi.org/10.1038/s41558-018-0370-z

98. Ducklow H, Baker K, Martinson D, Quentin L, Ross R, Smith R, et al. Marine pelagic ecosystems: the West Antarctic Peninsula. Philosophical Transactions of the Royal Society B 2007; 362:67–94.

99. Halpern B, Frazier M, Potapenko J, Casey KS, Koenig K, Longo C, et al. Spatial and temporal changes in cumulative human impacts on the world’s ocean. Nature Communications. 2015; 6(7615). https://doi.org/10.1038/ncomms8615 PMID: 26172980

100. Fu C, Travers-Trolleb M, Velezc L, Grussue A, Bundy M, Shannoni LJ, et al. Risky business: The combined effects of fishing and changes in primary productivity on fish communities. Ecological Modelling. 2017; 368:265–76. https://doi.org/10.1016/j.ecolmodel.2017.12.003

101. Pinsky ML, Mantua NJ. Emerging adaptation approaches for climate-ready fisheries management. Oceanography. 2014; 27(4):146–59.

102. Hopkins CR, Bailey DM, Potts T. Perceptions of practitioners: Managing marine protected areas for climate change resilience. Ocean & Coastal Management. 2016; 128:18–28. https://doi.org/10.1016/j.ocecoaman.2016.04.014

103. Keller BD, Gleason DF, McLeod E, Woodley CM, Airame S, Causey BD, et al. Climate change, coral reef ecosystems, and management options for marine protected areas. Environmental Management. 2009; 44(6):1069–88. https://doi.org/10.1007/s00267-009-9346-0 PMID: 19636605

104. Lewis N, Day JC, Wilhelm A, Wagner D, Gaymer C, Parks J, et al. Large-scale marine protected areas: Guidelines for design and management. Best practice protected area guidelines series, No 26 Gland: IUCN, 2017.

105. Giakoumi S, McGowan J, Mills M, Beger M, Bustamante RH, Charles A, et al. Revisiting “Success” and “Failure” of Marine Protected Areas: A Conservation Scientist Perspective. Frontiers in Marine Science. 2018; 5. https://doi.org/10.3389/fmars.2018.00223

106. Gill DA, Mascia MB, Ahmadia GN, Glew L, Lester SE, Barnes M, et al. Capacity shortfalls hinder the performance of marine protected areas globally. Nature. 2017; 543(7647):665–9. https://doi.org/10.1038/nature21708 PMID: 28329771

107. Wilhelm TA, Sheppard CRC, Sheppard ALS, Gaymer CF, Parks J, Wagner D, et al. Large marine protected areas—advantages and challenges of going big. Aquatic Conservation: Marine and Freshwater Ecosystems. 2014; 24(S2):24–30. https://doi.org/10.1002/aqc.2499
108. Trathan PN, Wienecke B, Barbarud C, Jenouvrier S, Kooyman G, Le Bohec C, et al. The emperor penguin—vulnerable to projected rates of warming and sea ice loss. Biological Conservation. Biological Conservation. 2020. https://doi.org/10.1016/j.biocon.2019.108216

109. Brooks CM, Ainley DG, Abrams PA, Dayton P, Hofman R, Jacquet J, et al. Watch over Antarctic waters. Nature. 2018:177–80.

110. Chown SL, Brooks CM. The State and Future of Antarctic Environments in a Global Context. Annual Review of Environment and Resources. 2019; 44:1–30.

111. Montreal, UNEP/CBD/COP/DEC/X/2. https://www.cbd.int/decision/cop/?id=12268., (2010).

112. United Nations Framework Convention on Climate Change, (1992).

113. Resolution 71/312. Our ocean, our future: call for action., (2017).

114. Ban NC, Maxwell SM, Dunn DC, Hobday AJ, Bax NJ, Ardron J, et al. Better integration of sectoral planning and management approaches for the interlinked ecology of the open oceans. Marine Policy. 2014; 49:127–36. https://doi.org/10.1016/j.marpol.2013.11.024

115. Peck LS. Antarctic marine biodiversity: adaptations, environments and responses to change. Oceanography and Marine Biology: An Annual Review. 2018; 56:105–236.

116. Rabosky DL, Chang J, Title PO, Cowman PF, Sallan L, Friedman M, et al. An inverse latitudinal gradient in speciation rate for marine fishes. Nature. 2018; 559(7714):392–5. https://doi.org/10.1038/s41586-018-0273-1 PMID: 29973726

117. Nicol S, Foster J. The Fishery for Antarctic krill: Its current status and management regime. In: Siegel V, editor. Biology and Ecology of Antarctic Krill. Advances in Polar Ecology: Springer; 2016. p. 387–421.

118. Collins MA, Brickle P, Brown J, Belchier M. The Patagonian Toothfish: Biology, Ecology and Fishery. In: Lesser M, editor. Advances in Marine Biology. 58. Burlington: Elsevier Inc., Academic Press; 2010. p. 227–300.