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Developing resilience to climate change impacts in Antarctica: An evaluation of Antarctic Treaty System protected area policy

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ABSTRACT

Antarctica is increasingly vulnerable to climate change impacts, with the continent predicted to warm by ~4 °C by 2100 under a 'business as usual' greenhouse gas emission scenario. Simultaneously, human activity, primarily in the form of scientific research and the fishing and tourism industries, is putting increasing pressure on Antarctic and Southern Ocean environments and ecosystems. We evaluate the effectiveness of the Antarctic area protection system in promoting resilience to climate change impacts. Under the framework of the Antarctic Treaty System (ATS), terrestrial and marine areas can be designated to protect locations of scientific, environmental, historic and intrinsic value and to facilitate operational coordination to minimise environmental impact. However, climate change is not mentioned explicitly in the Protocol on Environmental Protection to the Antarctic Treaty and is little considered in guidelines for the designation and management of the region's existing protected areas. Climate change impacts are considered in only 17% of Antarctic Specially Protected Area (ASPA) management plans and, at a time when threats to Antarctic environments are increasing, the last decade has seen an 84% decline in ASPA designation rate compared with levels in the 1980s. Nevertheless, momentum is building within the Scientific Committee on Antarctic Research (SCAR) and the ATS's Committee on Environmental Protection (CEP) to deliver an evidence-based, integrated response to climate change that includes the use of protected areas. The Antarctic scientific community is well-placed to support decision-makers in the use of existing conservation management tools through provision of climate change forecasts at sub-regional scales, data on anticipated environmental change, and predicted species and ecosystems responses. Ultimately, reducing global greenhouse gas emission will provide the greatest protection from climate change impacts within Antarctica.

1. Introduction

Human activities continue to cause unprecedented impacts upon the global climate, largely through fossil fuel combustion and deforestation (see: https://www.ipcc.ch). Rates of climate change vary regionally but are at their most rapid in the polar regions, with some associated impacts, such as ice melt and the resulting sea level rise, of global significance (IPCC, 2019). Ultimately, global action to limit greenhouse gas emissions will be essential to reduce further climate change impacts within Antarctica. However, use of available conservation tools may serve to minimise additional pressures produced by human activities in the region. Globally, protected areas have been identified as important tools to help manage the impacts of climate change on biodiversity by increasing connectivity between populations, protecting ecosystem services, conserving biodiversity and providing locations for climate change research (Hannah, 2008; Dudley et al., 2010). However, there has been no evaluation of the progress of the Antarctic Treaty System (ATS) in developing ecosystem resilience to climate change impacts through the Antarctic protected area system. While many definitions of 'resilience' have been developed, in this context, we use the term to mean the capacity of an ecosystem to persist or maintain function in the face of exogenous disturbance (Brand and Jax, 2007; Côté and Darling, 2010; Bastiaansen et al., 2020).

1.1. Antarctic climate change

Since widespread Antarctic meteorological records began in the 1950s, surface temperature trends within the area of Antarctic Treaty governance (south of latitude 60 °S) have been characterized by a marked warming of the Antarctic Peninsula and Scotia Arc archipelagos.

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Previously, little significant temperature change was observed across the rest of the continent, but recent research has detected a significant warming trend at the South Pole (Turner et al., 2019; Clem et al., 2020). Across Antarctica, the largest warming has been at Vernadsky station, where the annual mean temperature increased between 1951 and 2018 at a rate of 0.46 ± 0.15 °C decade^{-1} (equivalent to > 3 °C across the period). Along the Antarctic Peninsula and Scotia Arc archipelagos, the higher temperatures have resulted in the retreat of glaciers (Cook et al., 2005), the complete or partial collapse of a number of ice shelves (Mulvaney et al., 2012) and a greater frequency of precipitation occurring as rain rather than snow (Turner et al., 1997; Royles et al., 2012; Cannone et al., 2016). Since the late 1990s there has been a pause in warming, and even cooling, across at least parts of this region, but temperatures are still higher than in the 1950s (Turner et al., 2016) and models predict a resumption of the warming trends in the twenty-first century (Bracegirdle et al., 2019). However, it should be noted that the surface warming rate, as indicated by monthly mean air temperature, does not necessarily translate to other biologically relevant consequences of temperature change (Robinson et al., 2020).

That Antarctica has not experienced a broad-scale surface warming across the entire continent may be attributed, at least in part, to the anthropogenically-caused springtime loss of stratospheric ozone that has occurred each year since the early 1980s. The 'ozone hole' has increased the strength of the westerly winds around the Southern Ocean and reduced the poleward transport of heat towards the Antarctic, thereby to a degree 'shielding' the continent from much of the impact of increasing greenhouse gas concentrations. However, it appears likely that the concentrations of greenhouse gases will continue to rise, with their warming influence increasing as the expected 'healing' of the ozone hole takes place (Bracegirdle et al., 2019). Therefore, under a business-as-usual scenario of continued greenhouse gas emission increases, Antarctic surface temperatures are expected to increase by ~4 °C by 2100 compared with temperatures at end of the twentieth century (see Fig. 1). At a continent-wide scale, the higher temperatures are predicted to increase precipitation by about 30% and result in a 30% reduction in sea ice extent. Predicted warming could result in up to a three-fold increase in the area of ice-free ground in the central and northern Antarctic Peninsula, and ice retreat across coastal areas of continental Antarctica, with substantial impacts upon biological communities (Lee et al., 2017; Convey and Peck, 2019). Nevertheless, it is predicted that the surface temperature increase across the surrounding Southern Ocean will be amongst the smallest on Earth, as heat is drawn down into the ocean (see chapter 3.2 in IPCC, 2019).

1.2. Human impact in Antarctica

While climate change has resulted in profound and widespread changes in the Antarctic environment (Convey, 2011), scientific research and logistical activity have also led to significant local environmental impacts including non-native species introductions (Frenot et al., 2005; Hughes et al., 2015a), major one-off (e.g., ship wreck) and chronic pollution events (Bargagli, 2005) and destruction of terrestrial and marine habitats (Tin et al., 2009). Furthermore, some areas of Antarctica, and the northern Antarctic Peninsula region, in particular, have seen a rapid expansion of tourism industry activities (Bender et al., 2016), with for example, 74,401 tourists visiting during the 2019/20 summer season (IAATO, 2019), albeit that the COVID-19 pandemic reduced both national operator and tourism industry activity in the short-term (Hughes and Convey, 2020). Tourism and national operator activities in Antarctica are also currently highly reliant on the combustion of fossil fuels, with an associated contribution to global carbon emissions.

Direct human impacts have been largely concentrated within small areas of ice-free ground located near the coast, which are more accessible and favoured by national operators for station construction and the tourism industry for recreational visitation, yet are also home to the majority of the continent's vegetation and terrestrial diversity, charismatic marine vertebrate colonies (penguins and seals) and marine bird breeding sites (many of which have been designated as Important Bird and Biodiversity Areas (IBAs) by BirdLife (see: https://www.birdlife.org/worldwide/programme-additional-info/important-bird-and-biodiversity-areas-ibas)) (Hull and Bergstrom, 2006). Consequently, Antarctic biological communities and species have been damaged and displaced by human impacts (Tin et al., 2014; Coetzee and Chown, 2015), despite the requirement under the Protocol on Environmental Protection to the

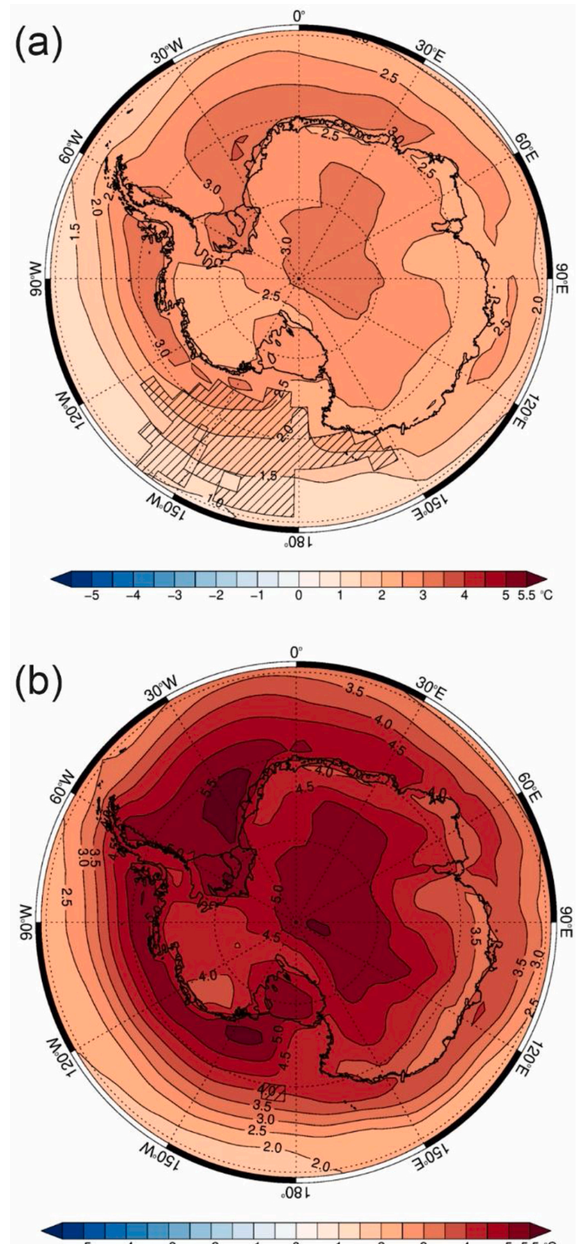

Fig. 1. The projected 2 m annual mean air temperature changes between the means of 1970-1999 and 2070-2099 as determined from the mean of one ensemble member from each of the currently available models used in the Coupled Model Intercomparison Project 6 exercise. Data are shown for Shared Socioeconomic Pathways (SSPs) 245 (a) and 585 (b). The hatched areas indicate where <50% of the models project significant change or where <90% agree on the sign of the change. SSPs 245 and 585 represent respectively a stabilization of radiative forcing at 4.5 and 8.5 W per square metre by 2100, which can be regarded as essentially moderate or high greenhouse gas emission scenarios (see IPCC, 2013 for details).

Antarctic Treaty for environmental impact assessments for all activities in Antarctica, in order to identify, avoid, minimise and mitigate impacts.

1.3. Synergistic impacts of climate change and human activity

Antarctic environments now face the dual and, in some cases, synergistic threats of climate change coupled with direct regional human impacts. For example, climate change has resulted in increasing surface temperatures and soil wetness as well as an expansion of ice-free areas, thereby increasing the likelihood of the establishment of non-native species introduced through increasing human activity in the region, as well as natural colonisation events (Chown et al., 2012; Duffy and Lee, 2019). Permafrost, snow and soil surface melting may cause mobilisation of soil pollutants from, for instance, waste dumps and other polluted sites associated with previous stations and activities, resulting in potentially adverse impacts upon local biological communities (Bockheim et al., 2013). Climate change has resulted in changes in sea ice distribution, and predictability and duration of the sea ice season, which has impacted upon penguin species' food availability and access to breeding habitat (e.g., Trathan et al., 2019), thereby making it important to minimize any further adverse impacts caused by human disturbance. Climate warming-induced changes in the permafrost layer, soil hydrology and environmental conditions may have negative impacts upon the foundations and fabric (e.g., cladding, insulation, finishes, etc.) of Antarctic stations and infrastructure, as already seen widely in the Arctic, with historic sites and monuments, in particular, potentially vulnerable (Barr, 2008; Blanchette et al., 2010).

1.4. The Antarctic protected area system

The Antarctic Treaty entered into force in 1961 and the Treaty area (the area south of latitude 60 °S) is now governed through consensus by the 29 Antarctic Treaty Consultative Parties. Building upon earlier conservation agreements (Bonner and Smith, 1985; Hughes et al., 2013), the Protocol on Environmental Protection to the Antarctic Treaty was agreed at the Antarctic Treaty Consultative Meeting (ATCM) in 1991 and entered into force in 1998. Through the Protocol, Parties prohibit mineral resource extraction within the Treaty area and commit themselves to the comprehensive protection of the Antarctic environment, designating Antarctica as a '*natural reserve, devoted to peace and science*'. The designation of protected areas within Antarctica has been possible since 1964 through the Agreed Measures for the Conservation of Antarctic Fauna and Flora (Recommendation VIII, 1964). However, the protected areas system was revised when Annex V to the Protocol (Area Protection and Management) entered into force in 2002 and established tools to facilitate protection of Antarctic locations from human impacts, including three protected area classifications: Antarctic Specially Protected Areas (ASPAs), Antarctic Specially Managed Areas (ASMAs) and Historic Sites and Monuments (HSMs). ASPAs represent the highest level of spatial environmental protection and can be designated to protect '*outstanding environmental, scientific, historic, aesthetic or wilderness values, any combination of those values, or on-going or planned scientific research*' (Annex V, Article 3(1)). The drafting and approval of a management plan is a requirement as part of the process for an area to be designated as an ASPA, and entry is only allowed in accordance with a permit issued by a national governmental authority. ASMAs are designated to '*assist in the planning and co-ordination of activities, avoid possible conflicts, improve co-ordination between Parties or minimise environmental impacts*' (Annex V, Article 4(1)). ASMAs are also required to have a management plan, but permits are not required for entry, and their regulations are hortatory rather than mandatory. From the Antarctic Treaty's inception, the Treaty Parties have recognised the need to protect sites or monuments of historic interest and, in 1972, established an official list of Historic Sites and Monuments (HSMs) which now includes 89 sites (five further sites have been de-listed or subsumed into other HSMs). HSMs of the most outstanding historic value can also be designated as ASPAs, such as ASPA 155 Cape Evans, Ross Island, which contains Scott's hut.

The Protocol also established the Committee on Environmental Protection (CEP), to provide advice and formulate recommendations to the Parties in connection with its implementation (Sánchez and McIvor, 2007). Management of protected area designation, including the required five-yearly review of management plans for ASPAs and ASMAs, has been coordinated by the CEP's Subsidiary Group on Management Plans (SGMP).

1.5. Status of the Antarctic protected area system

At present 72 ASPAs are designated. They cover an area of 3860 km^2, including 760 km^2 of ice-free ground and 1970 km^2 of near-shore marine environment (SCAR, 2019). Six ASPAs are wholly marine (1631 km^2) with a further five partly marine ASPAs having been referred to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) for further approval (see Decision 9 (2005); available at: https://www.ats.aq/devAS/Meetings/Measure/344) (Douglass et al., 2014). ASPAs are located mainly within the Antarctic Peninsula and its offshore islands and archipelagos, the Ross Sea region and on various coastal ice-free areas of East Antarctica (see Fig. 2). Fifteen of the 29 Consultative Parties to the ATCM are ASPA proponents and engage in the management of areas, including the revision of management plans. Independent of the national Consultative Parties, the CEP, the Scientific Committee on Antarctic Research (SCAR) and CCAMLR may also propose areas for protection, but have yet to do so. ASPAs have tended to be designated close to research stations (Hughes and Grant, 2017) with 28% of ASPAs located within 3 km of a station (Shaw et al., 2014). Furthermore, ASPAs are generally small, with c. 55% having an area of less than 5 km^2 (Hughes and Convey, 2010).

Estimates vary concerning the amount of Antarctic ice-free ground (Burton-Johnson et al., 2016: 21,745 km^2 *c.f.* Terauds and Lee, 2016: 45,886 km^2) but, using these values, only between 1.7 and 3.5% is included within ASPAs. Studies suggest that the ASPA system is some way short of maturity, with many of the values identified for protection within the Protocol currently under-represented (Shaw et al., 2014; Hughes et al., 2015b, 2016a; Coetzee et al., 2017). Protection of biodiversity is far from comprehensive, with almost one third of the 16 currently recognised Antarctic Conservation Biogeographic Regions (ACBRs; equivalent of eco-regions) having no ASPAs for the protection of biodiversity (Terauds et al., 2012; Hughes et al., 2016a, b; Terauds and Lee, 2016), while many species are not represented within the region's protected areas (Wauchope et al., 2019).

Antarctica currently contains six ASMAs, with up to six nations involved in the management of each area, sometimes with input from the tourism industry and non-governmental conservation organisations. ASMA size varies from c. 100 km^2 for ASMA 4 Deception Island, South Shetland Islands to 26,344 km^2 for ASMA 5 Amundsen-Scott South Pole Station. Some ASMAs also contain ASPAs and HSMs, and defined zones to restrict access for scientific or conservation reasons.

At the same time that there has been an increasing awareness of and evidence available for climate change impacts, ASPA designation has declined by 84% since the 1980s (1980−89 *c.f.* 2010–2019), (Supplementary Fig. 1; Hughes and Grant, 2018) and no new ASMAs have been designated since 2008. A recent assessment of the level of protection of Antarctic biodiversity, using the Aichi Biodiversity Targets that are applied within nations across the globe as a benchmark, showed that, despite the region often being assumed to be remote and apparently pristine, its biodiversity outlook is similar to that for the rest of the planet (Chown et al., 2017). Nevertheless, three new ASPAs are currently under consideration within the CEP, indicating a potential reversal of recent trends.

Here we evaluate the effectiveness of policy and environmental management practices for addressing climate change within the Antarctic protected area system, as coordinated by the CEP. We identify how climate change is considered within existing Antarctic

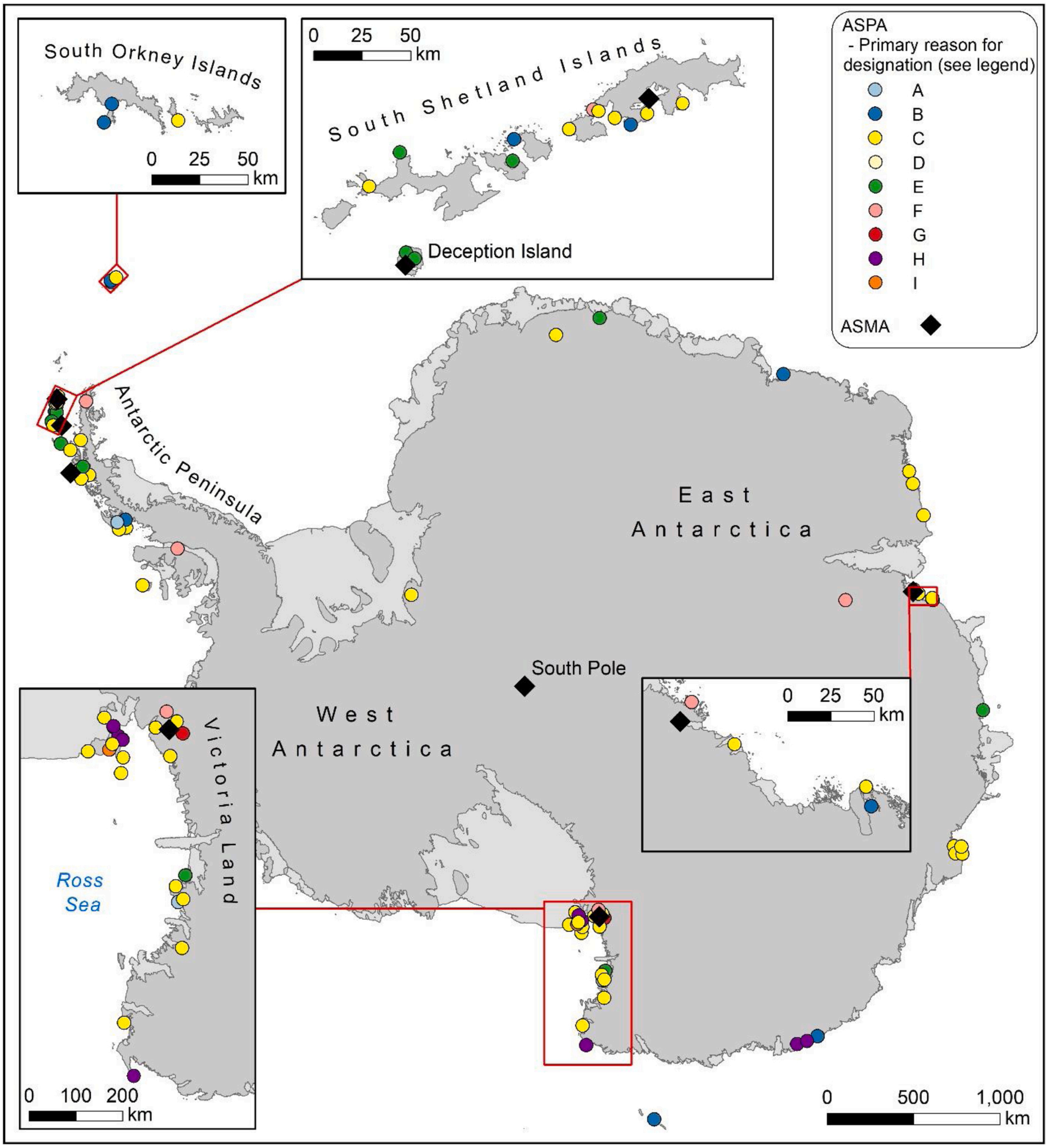

Fig. 2. Map of Antarctic showing the distribution of Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs). The ASPAs are represented according to the primary reason for their designation, using categories described in Annex V to the Protocol on Environmental Protection to the Antarctic Treaty: A – areas kept inviolate from human interference so that future comparisons may be possible with localities that have been affected by human activities; B – representative examples of major terrestrial, including glacial and aquatic, ecosystems and marine ecosystems; C – areas with important or unusual assemblages of species, including major colonies of breeding native birds or mammals; D – the type locality or only known habitat of any species; E – areas of particular interest to on-going or planned scientific research; F – examples of outstanding geological, glaciological or geomorphological features; G – areas of outstanding aesthetic and wilderness value; H – sites or monuments of recognised historic value; I – such other areas as may be appropriate to protect the values set out in Article 3 Paragraph 1 (i.e. 'to protect outstanding environmental, scientific, historic, aesthetic or wilderness values, any combination of those values or on-going or planned scientific research').

environmental agreements and addressed in current protected area management plans. Finally, we describe recent developments in climate change policy relevant to Antarctic area protection and highlight practical steps that may enhance Antarctic ecosystem resilience to climate change.

2. Methods

2.1. Assessment of climate change recognition within Antarctic Treaty System agreements and policy documents

Considerable effort has been put into analysing Antarctic climate and trends across a range of past, present and future timescales, culminating in the 2009 SCAR Antarctic Climate Change and Environment (ACCE) report, its 2014 update, and annual update papers requested by and provided to the ATCM (Turner et al., 2009, 2014). Consequently, there is a strong basis of climate-related knowledge available to inform governance processes and decision-making (see Discussion). Antarctic Treaty System (ATS) documents relating to ASPAs, ASMAs and HSMs were obtained from the Antarctic Treaty Secretariat webpages at https://ats.aq/devAS/EP/ToolsForDelegates?lang=e and https://www.ats.aq/devAS/EP/GuidelinesAndProcedures?lang=e. Each document was read and references to climate change were recorded. Protection of historic sites is of little relevance to maintaining ecosystem resilience to climate change, but it is a component of the Antarctic protected area system, as overseen by the Committee for Environmental Protection and, therefore, documents on this issue were included in the study for completeness.

2.2. Consideration of climate change within protected area management plans

The extent to which climate change is considered in protected area management plans was assessed for the 72 ASPAs and six ASMAs (available at https://www.ats.aq/devph/en/apa-database) by reading the documents fully and taking note of terms and topics relevant to climate change (e.g. use of terms such as 'climate change', 'warming', 'greenhouse', 'global' and discussion of topic including changes in sea-ice extent and ice retreat). Note was taken of the context in which climate change was discussed, i.e., in reference to climate change science, impacts or management action. We acknowledge the inherent biases present in our study, including those relating to limitations in the knowledge of the individuals undertaking the analyses. We also acknowledge that the issue of climate change is broad in nature and it may not always be a simple task to identify the extent to which an issue is directly related to climate change, as opposed to natural climate variability. We included in our analysis issues described in CEP guidance documents as relevant to climate change, e.g., changes in ice extent and sea ice-dependent penguin species (see Results). However, as a counter example, we excluded from our study consideration of the trampling impact on terrestrial habitats caused by the recently expanded fur seal population in the Antarctic Peninsula, South Shetland Island and South Orkney Islands, as climate change is likely to have been a more minor factor in this change, compared to others such the cessation of commercial sealing.

2.3. Protected area management plan compliance with CEP guidance concerning climate change

The '(Revised) Guide to the preparation of management plans for Antarctic Specially Protected Areas' recommends that the management plan section entitled 'Description of values to be protected' would be suitable for inclusion of any potential impacts likely to affect the ASPA in the context of climate change. Similarly, the 'Guidelines for the preparation of ASMA management plans' suggest that the 'Aims and objectives' sections of ASMA management plans should highlight any intention to consider climate change implications in the coordination and management of activities. Compliance with these recommendations within each of the ASPA and ASMA management plans was assessed, i.e., in terms of the degree to which climate change issues were discussed in the section 'Description of the values to be protected' in ASPA Management Plans, or the 'Aims and objectives' section of ASMA management plans.

2.4. Climate change affecting the boundaries of protected areas

The section 'Geographical co-ordinates, boundary markers and natural features' of ASPA and ASMA management plans was examined to see if consideration had been given to potential climate change impacts when establishing, revising or considering the boundaries of the area, in accordance with CEP guidance.

2.5. ASPAs designated for different primary reasons

In accordance with CEP guidelines, an ASPA management plan should state which of the nine primary reasons, set out in Annex V to the Protocol, the area was designated to protect primarily (see: Australia et al., 2019). Management plans were examined to determine the extent to which climate change was taken into consideration within ASPAs designated to protect different values.

2.6. Non-native species introductions

The CEP's '(Revised) Guide to the preparation of management plans for Antarctic Specially Protected Areas' identified that the likelihood/risk of establishment of non-native species was an important climate change-related issue that should be considered within ASPA management plans. The 72 ASPA management plans were examined to determine the extent and means by which the issue of non-native species establishment was addressed.

3. Results

3.1. Assessment of climate change recognition within Antarctic Treaty System agreements and policy documents

Climate change is not discussed in the Protocol or in guidance documents concerning HSMs, inspection of ASPAs, or consideration of new and revised draft ASPA and ASMA management plans (see Table 1). However, the '(Revised) Guide to the preparation of management plans for Antarctic Specially Protected Areas' notes that the management plan section 'Description of values to be protected' could describe the '*potential environmental changes faced by the protected area in light of rapid warming*', and gives examples including: (i) potential thinning of glaciers, rapid retreat of ice-shelves and exposure of new ice-free terrain; (ii) impacts on sea ice-dependent penguin species by ocean warming and declining sea ice extent; (iii) increasing risk of establishment of natural colonists originating from more northerly (and therefore less climatically severe) latitudes (in principle, these could also originate elsewhere in Antarctica) and (iv) increased establishment of anthropogenically-assisted non-native species (both from beyond or already established elsewhere within Antarctica).

Both the '(Revised) Guide to the preparation of management plans for Antarctic Specially Protected Areas' and 'Guidelines for the preparation of ASMA management plans' state that management plans should consider the likely future impacts of climate change when determining or reviewing the boundaries of a Protected Area, particularly where boundary features are vulnerable to change, e.g., due to glacial retreat, ice shelf collapse or lake level change. This guidance is provided to help ensure boundary features are static and constant, thereby avoiding confusion over boundary positioning.

3.2. Consideration of climate change within protected area management plans

Climate change was considered in 25 of the 72 ASPA management plans (35%) (see Table 2 and Supplementary Table 1). In almost all cases, climate change was considered primarily in the context of scientific research activities. Climate change impacts within a protected area (e.g., receding of glaciers) were described in 12 of the 72 ASPA management plans (17%). These comprised 10 of the 30 ASPAs in the Antarctic Peninsula and Scotia Arc (33%), but only two of the 42 continental ASPAs (5%). Overall, only 6% of management plans noted that climate change had already caused changes to the management of the protected area (e.g., revision to boundaries, as occurred in ASPA 126 Byers Peninsula, Livingston Island, South Shetland Islands), all of which were

Table 1
Text concerning climate change within Antarctic Treaty System international agreements and guidance documents relevant to protected areas[1].

	Antarctic Treaty System document	Text concerning climate change
1	Protocol on Environmental Protection to the Antarctic Treaty[2](https://www.ats.aq/documents/recatt/Att006_e.pdf)	None, although Article 3 (2) does state: 'To this end: activities in the Antarctic Treaty area shall be planned and conducted so as to avoid: (i) adverse effects on climate or weather patterns;'
2	Guidelines: A prior assessment process for the designation of ASPA and ASMAs (Appendix 4 CEP XX Report) (https://www.ats.aq/documents/atcm40/ww/atcm40_ww011_e.pdf)	'The CEP noted the benefits of a prior assessment process for potential new ASMAs and ASPAs, including:… … (iv) facilitating consideration of the further systematic development of the protected areas system in accordance with Article 3 of Annex V to the Protocol, and with consideration of climate change implications.'
3	Guidelines for the preparation of ASMA management plans. Annex B Resolution 1 (2017) (https://www.ats.aq/documents/recatt/Att626_e.pdf)	'3.1.5 Aims and objectives. For example, the aims of the Plan might highlight an intention to: consider climate change implications in the coordination and management of activities' '3.1.9.1 Geographical co-ordinates, boundary markers and natural features. Consideration should be given to the likely future impacts of climate change when determining or reviewing the boundaries of the Managed Area. In particular, thought should be given to the designation of boundaries using features other than ice-free ground. For example, future climate change induced glacial retreat, ice shelf collapse and lake level change will have an impact on ASMAs whose boundary definitions follow these features.'
4	(Revised) Guide to the Preparation of Management Plans for Antarctic Specially Protected Areas. Annex to Resolution 2 (2011) (https://www.ats.aq/documents/recatt/Att477_e.pdf)	'1. Description of values to be protected. The Antarctic environment is subject not only to natural variability in factors such as climate, ice extent and the density and spatial extent of biological populations, but also the effects of rapid regional climate warming (particularly in the Antarctic Peninsula region). Therefore this section could also, where relevant, give a description of the potential environmental changes faced by the Area in light of such rapid warming (e.g. potential thinning of glaciers; rapid retreat of ice-shelves and exposure of new ice-free terrain; impacts on sea ice-dependent penguin species by ocean warming and declining sea ice extent; the likelihood/risk of establishment of non-native species or natural colonists originating from more northerly (and therefore less climatically severe) latitudes, etc.)' '6. Description of the Area. 6(i) Geographical co-ordinates, boundary markers and natural features. Consideration should be given to the likely future impacts of climate change when determining or reviewing the boundaries of the Protected Area. Particular thought should be given to the designation of boundaries using features other than ice-free ground. For example, future climate change induced glacial retreat, ice shelf collapse and lake level change will have an impact on ASPAs whose boundary definitions follow these features.'
	Guidelines for implementation of the Framework for Protected Areas set forth in Article 3, Annex V of the Environmental Protocol. Annex to Resolution 1 (2000) (https://www.ats.aq/documents/recatt/Att081_e.pdf)	Table 6. Checklist of feasibility criteria for assessment of possible protected areas. Size: Is the area large enough to accommodate future changes (e.g. due to climate change?)

[1] Climate change was not mentioned in the following policy documents relevant to Antarctic protected areas: Guidance for assessing an area for a potential Antarctic Specially Managed Area designation (https://www.ats.aq/documents/recatt/Att625_e.pdf); Guidelines for CEP consideration of new and revised draft ASPA and ASMA management plans. Annex 4 to the CEP VI. Final Report (see CEP VI Final Report, page 331, https://www.ats.aq/documents/atcm31/ww/atcm31_ww001_e.pdf); Guidelines for handling of pre-1958 historic remains whose existence or present location is not known (https://www.ats.aq/documents/recatt/Att090_e.pdf); Annex: Checklist to assist in the inspection of Antarctic Specially Protected Areas and Antarctic Specially Managed Areas (https://www.ats.aq/documents/recatt/Att409_e.pdf); Guidelines for the designation and protection of Historic Sites and Monuments. Appendix to Resolution 3 (2009) (https://www.ats.aq/documents/cep/Guidelines_HSM_V2_2009_e.pdf); Guidelines for the assessment and management of Heritage in Antarctica. Resolution 2 (2018) Annex (https://www.ats.aq/documents/recatt/att643_e.pdf); or Procedures for forwarding draft Antarctic Specially Protected Area Management Plans to CCAMLR. Decision 9 (2005) Marine Protected Areas. (https://www.ats.aq/devAS/ats_meetings_meeting_measure.aspx?lang=e).

[2] Climate change was not mentioned in any of the Annexes to the Protocol, i.e.: Annex I: Environmental Impact Assessment (https://www.ats.aq/documents/recatt/Att008_e.pdf); Annex II: Conservation of Antarctic Fauna and Flora (https://www.ats.aq/documents/recatt/Att432_e.pdf); Annex III: Waste Disposal and Waste Management (https://www.ats.aq/documents/recatt/Att010_e.pdf); Annex IV: Prevention of Marine Pollution (https://www.ats.aq/documents/recatt/Att011_e.pdf); Annex V: Area Protection and Management (https://www.ats.aq/documents/recatt/Att004_e.pdf); and Annex VI: Liability arising from Environmental Emergencies (https://www.ats.aq/documents/recatt/Att249_e.pdf).

located in the Antarctic Peninsula and Scotia Arc.

Five of the six ASMA management plans mentioned climate change and four highlighted the use of the area for climate change-related research. Only the three ASMAs located on the Antarctic Peninsula reported climate change impacts. However, using the definitions of climate change impacts in CEP guidance documents, only the management plan for ASMA 1 Admiralty Bay, King George Island, reported management activities relating to climate change (i.e., non-native species management), albeit this would be important even in the absence of climate change.

3.3. Protected area management plan compliance with CEP guidance concerning climate change

Only 15 of the 72 ASPA management plans (21%) included some direct consideration of climate change/regional warming in the section entitled 'Description of values to be protected' as recommended in CEP guidance documentation (5 of 30 plans in the Antarctic Peninsula and Scotia Arc (17%) and 10 of 42 plans in the continental region (24%)). In contrast, climate change-related impacts featured in the 'Description of values to be protected' section for Antarctic Peninsula and Scotia Arc ASPAs more often than in those located within continental Antarctica (which may be attributed to the recorded warming in the Peninsula and Scotia Arc), with the only exception being the issue of non-native species (see Fig. 3). None of the ASPAs located in the continental region identified declines in sea ice extent and impacts on associated penguin

Table 2
Consideration of climate change in the management plans of ASPAs and ASMAs located on the Antarctic Peninsula and continental Antarctica.

		No. of protected areas	Text relating to climate change in management plan			
			Any	Climate change science	Climate change impacts	Climate change affecting area management
ASPAs	All	72	35%	35%	17%	6%
	Peninsula	30	40%	40%	33%	13%
	Continent	42	31%	31%	5%	0%
ASMAs	All	6	83%	67%	50%	17%
	Peninsula	3	100%	67%	100%	33%
	Continent	3	67%	67%	0%	0%

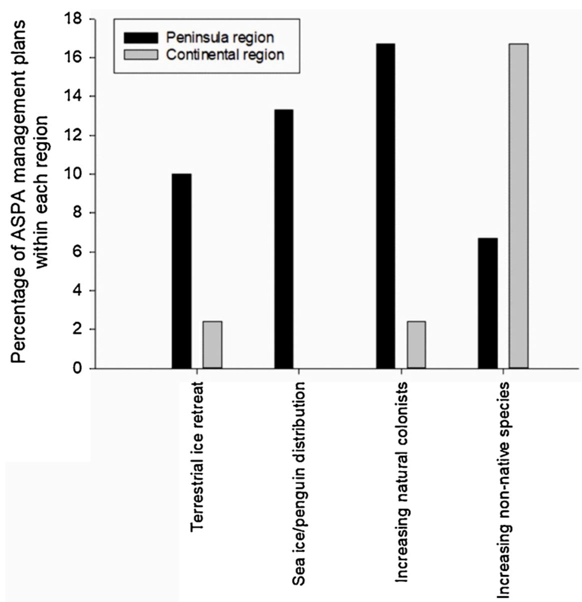

Fig. 3. Percentage of ASPAs with climate change-related impacts detailed in their management plan section 'Description of values to be protected' (as recommended in the '*(Revised) Guide to the preparation of management plans for Antarctic Specially Protected Areas*'). Of the 72 ASPAs currently designated, 30 are located in the Antarctic Peninsula and Scotia Arc, while 42 are located in continental Antarctica.

populations in the 'Description of values to be protected' section, despite the presence of many emperor and Adélie penguin colonies.

Contrary to CEP guidance documentation, text relating to climate change was not included in the 'Aims and objectives' section of any of the six ASMA management plans, albeit that this guidance was only agreed in 2017 (Resolution 1, 2017).

3.4. Climate change affecting the boundaries of protected areas

Recommendations within CEP guidance documents on the preparation of protected area management plans suggested that Parties consider potential climate change impacts when establishing or revising the boundaries of protected areas. Consideration of climate change impacts on boundaries within the management plan section 'Geographical co-ordinates, boundary markers and natural features' was evident in 10% of management plans for ASPAs in the Antarctic Peninsula and Scotia Arc region, compared with 5% for ASPAs located within continental Antarctica. Climate change influence on the area boundary was not considered in the management plan of any ASMA.

3.5. ASPAs designated for different primary reasons

The number of areas designated as ASPAs under each of the nine stated primary reasons for protection varied greatly (see Fig. 2 and Supplementary Table 2). For example, no ASPAs have been designated primarily to protect the type locality or only known habitat of a species (Category D) while 37 ASPAs (51%) have been designated to protect areas with major colonies of breeding birds or mammals (Category C).

None of the ASPAs primarily protecting aesthetic and wilderness values (Category G) or historic values (Category H) discussed climate change (in any context) within their management plans (Supplementary Table 2). Climate change impacts were reported in 22% of ASPAs protecting representative examples of major terrestrial and marine ecosystems (Category B), areas with major colonies of breeding birds or mammals (Category C) and areas of on-going or planned scientific research (Category E). However, climate change impacts were not discussed in management plans of any of the remaining categories (Categories A, F, G, H or I).

3.6. Non-native species introductions

Non-native species were considered in over 93% of ASPA and all six ASMA management plans, but rarely in the context of climate change or within the recommended section 'Description of values to be protected' (see Supplementary Fig. 2). Importantly, in most cases the management plans did not consider non-native species 'establishment', which may increase under climate change, but rather focused on non-native species 'introduction', which is itself largely unrelated to climate change and caused by direct human action. Nevertheless, two management plans did refer to planned eradication/control of non-native species within or adjacent to the area boundary.

3.7. Reported climate change impacts within protected areas

Several ASPAs show climate change impacts on the biotic and abiotic values identified within their boundaries. The reliance of most emperor penguin colonies on seasonal fast ice (Fretwell and Trathan, 2009), and their general dependence on this as a breeding habitat makes them vulnerable to climate change. ASPA 107 Emperor Island, Dion Islands, Marguerite Bay, Antarctic Peninsula, was designated in 1966 to protect the resident emperor penguin colony. However, an increase in local air temperature and a coincident decline in seasonal sea ice duration have been suggested to be associated with a decline in colony numbers and by 2009, and subsequently, no breeding population has been observed within the ASPA (Trathan et al., 2011). Recent modelling projections predict population declines of $\geq$ 50% over the twenty-first century, including colonies within the eight ASPAs designated primarily for their protection (Trathan et al., 2019), indicating the need for further protection of colonies located in areas predicted to be more resilient to climate change impacts.

On the Antarctic Peninsula, Adélie and chinstrap penguin populations have declined due to a reduction in extent and duration of sea ice, a decrease in krill abundance (which may have limited food availability), and an increase in the frequency and intensity of spring snowstorms that may have increased the mortality of chicks and eggs (Patterson et al., 2003; McClintock et al., 2008; Lynch et al., 2012). Within ASPA 113 Litchfield Island, Arthur Harbour, Anvers Island, Palmer Archipelago, the Adélie penguin colony disappeared over a

36-year period (1971/2–2007/8) (see Table 1 of ASPA 113 management plan) and Adélie and chinstrap penguin populations declined in ASPA 128 Western Shore of Admiralty Bay, King George Island, South Shetland Islands and ASPA 139 Biscoe Point, Anvers Island, Palmer Archipelago. In contrast, due to their greater adaptability to changing environmental conditions, gentoo penguin populations have been increasing within the Antarctic Peninsula region (Lynch et al., 2012). In ASPA 128, gentoo penguin numbers increased by 216% between the four-year periods of 1978−81 and 2014−18 (Korczak-Abshire, pers. comm., 2019, and Table 1 in ASPA 128 management plan; Ciaputa and Sierakowski, 1999) while a new colony that established within ASPA 139 in around 1992 had almost 3200 pairs by 2012/13 (Patterson--Fraser, pers. comm. 2010, 2014, detailed in ASPA 139 management plan).

Substantial ice retreat has been documented in some ASPAs. Within ASPA 128 the ice-free area increased from 20% in 1979 to more than 50% in 1999 (Battke et al., 2001). Some ASPA boundaries have been revised due to ice retreat, including ASPA 139. Others, including several in continental Antarctica, are subject to studies examining the impacts of climate change on ice extent or permafrost (e.g., ASPA 163, Dakshin Gangotri Glacier, Dronning Maud Land, ASPA 165 Edmonson Point, Wood Bay, Ross Sea and ASPA 174 Stornes, Larsmann Hills, East Antarctica). Ice shelf collapse has had little direct impact upon existing protected areas.

Climate change impacts on vegetation cover, diversity and community composition have been observed, particularly within the Antarctic Peninsula and Scotia Arc, with some of the most comprehensive studies occurring outside ASPAs (Fowbert and Smith, 1994; Parnikoza et al., 2009; Favero-Longo et al., 2012; Cannone et al., 2016, 2017; Amesbury et al., 2017). Consequently, reports of vegetation change within ASPAs may reflect the changes seen much more generally in the region (e.g., see Grobe et al., 1997 in relation to ASPA 113) and are not always evidenced by peer-reviewed references (e.g., changes in *Deschampsia antarctica* occurrence in ASPA 150 Ardley Island, Maxwell Bay, King George Island). Nevertheless, the increased distribution of lichen species within ASPA 151 Lions Rump, King George Island, South Shetland Islands, has been linked to glacial retreat and local water deficit (Angiel and Dąbski, 2012). Furthermore, climate-related changes in moss community composition and vegetation health have also been noted within ASPA 135 North-East Bailey Peninsula, Budd Coast, Wilkes Land, East Antarctica, in this case linked to regional cooling and drying due to an intensification in the positive phase of the Southern Annular Mode and higher wind speeds (Robinson et al., 2018).

The risk to Antarctic biodiversity of invasion by non-native species may be exacerbated by climate change, as warmer and wetter environmental conditions may increase the likelihood of introduced non-native species establishing (Frenot et al., 2005; Chown et al., 2012; Pertierra et al., 2017a) and may provide a competitive advantage over some, but not necessarily all, native species (Galera et al., 2017, 2019; Molina-Montenegro et al., 2019). As has already occurred in protected areas around the world (Lui et al., 2020), some ASPAs and ASMAs already contain non-native species (Hughes et al., 2015a). The non-native grass *Poa annua* has spread from an original introduction site within Arctowski Station to colonise parts of the deglaciated moraine in and around the area of ASPA 128 Western Shore of Admiralty Bay (Galera et al., 2017). In 2015, a slowly expanding patch of the non-native grass *Poa pratensis* was eradicated from near the boundary of ASPA 134 Cierva Point and offshore islands, Danco Coast, Antarctic Peninsula (Pertierra et al., 2017b). Nevertheless, the eradication of small mobile cryptic invertebrate species may be practically impossible with, for instance, one such previously reported from Cierva Point (Convey and Quintana, 1997). It is also a challenge that virtually no monitoring programmes are in operation that might target and allow status assessment of such species (although see Hughes et al., 2019), and extremely limited expertise is available to identify any encountered. ASMA 4 Deception Island is the most invaded area of Antarctica, having been colonised by non-native plants and micro-invertebrates (Smith and Richardson, 2010; Greenslade et al., 2012; Enríquez et al., 2019). However, here, geothermal heating of soils may mask the impacts of climate change on rates of non-native species establishment and exacerbate the challenge of separating natural colonisation events from human-assisted introductions (Hughes and Convey, 2012).

4. Discussion

Here we evaluate the Antarctic Treaty Consultative Meeting's progress in consideration of climate change within the Antarctic protected area system. Clearly, the success of Antarctic Treaty Party efforts to provide resilience to existing and predicted climate change impacts will be limited without global action to control greenhouse gas emissions. Nevertheless, while available local/regional conservation tools cannot reverse climate change impacts on Antarctic ecosystems, they can reduce potential additional pressures generated by human activities, such as scientific activity, tourism and fishing. Several environmental management tools, detailed in the Annexes to the Protocol, are available to reduce the impacts of human activities. These include the environmental impact assessment (EIA) process and the designation of protected areas and specially protected species (although currently only the Ross seal has this status). The capacity of these tools to afford resilience to climate change impacts will be limited by the nature, scale and extent of existing and anticipated climate change impacts but also by the efficiency and effectiveness with which they are utilised by the Treaty Parties. Creation of further protected areas encompassing a wider range of the marine and terrestrial environmental gradients would support greater climate change resilience, including by protecting species that have shifted their distribution in response to climate change (Loarie et al., 2009).

The Protocol on Environmental Protection to the Antarctic Treaty, including its Annexes, makes no reference to climate change, even though it was agreed after the establishment of the Intergovernmental Panel on Climate Change (1988) and the publication of the First IPCC Assessment Report (1990). Our research shows that guidance documents provided some limited consideration of the more 'administrative' elements of climate change management within protected areas (e.g., effects of climate change on area boundaries), but very little consideration of how protected areas could be used in an integrated manner to provide resilience to climate change on a regional scale.

Implementation of CEP guidance on climate change, at the scale of individual protected areas, has been patchy (at best), inconsistent and predominantly catalysed in response to ongoing changes in the Peninsula region (Table 1). Specifically, climate change issues were considered in 39% of the 72 ASPA and 6 ASMA management plans, most often with regard to scientific research efforts, rarely in terms of potential impacts, and even less concerning the implementation of management action to address the impacts (Table 2). The management action described was largely limited to the revision of the protected area boundary or the eradication or control of non-native species within or adjacent to the area. CEP guidance documents could be made more explicit and encourage Parties to move from a 'reactive' to a more 'pre-emptive' protected area management style, including forward planning for climate change impacts under anticipated scenarios (see Table 3).

Currently, the management of each individual protected area largely falls to one or a small number of proponent Parties (Hughes and Grant, 2017). Despite stated intentions to develop a systematic and integrated protected areas system, including to build climate change resilience (see Table 1), the level of international coordination has not yet been sufficient to advance beyond this rudimentary level. Rather, broader international efforts have focussed on climate change research, with slower progress on the use of existing environmental management tools to enhance ecosystem resilience to climate change impacts.

Several initiatives (showing variable levels of success) over the past decade or more have attempted to integrate climate change into

Table 3
ASPAs and ASMAs within the Antarctic Peninsula, South Orkney Islands and South Shetland Islands likely to be affected, or already affected, by identified impacts of climate change.

	Antarctic Peninsula response to the 1.5 °C scenario[1]	Protected areas likely to be affected	
		ASPAs	ASMAs
1	Temperatures will increase by 1–2 °C in winter and 0.5–1.0 °C in summer, with up to 130 days per year above 0 °C, leading to increased rain, melting and surface run-off	Nos. 107; 108; 109; 110; 111; 112; 113; 115; 117; 125; 126; 128; 129; 132; 133; 134; 139; 140; 147; 148; 149; 150; 151; 170; 171	Nos. 1; 4; 7
2	Ocean turbulence will increase and deliver heat to the sea surface and coast;	Nos. 107; 108; 109; 110; 111; 112; 113; 115; 117; 126; 128; 129; 132; 133; 134; 139; 140; 144; 145; 146; 149; 150; 151; 152; 153; 171	Nos. 1; 4; 7
3	Sea-ice extent will be highly variable west of the Antarctic Peninsula	Nos. 107; 108; 109; 110; 111; 112; 113; 115; 117; 126; 128; 129; 132; 133; 134; 139; 144; 145; 146; 149; 150; 151; 152; 153; 171	Nos. 1; 4; 7
4	Retreat of marine glacier margins will accelerate, increasing iceberg production	107; 111; 128; 144; 146; 151	Nos. 1; 4; 7
5	Meltwater production will increase on ice shelves, but will likely not lead to collapses	No. 147	–
6	Southward shifts in marine life distribution	Nos. 107; 108; 109; 110; 111; 112; 113; 115; 117; 126; 128; 129; 132; 133; 134; 139; 144; 145; 146; 149; 150; 151; 152; 153; 170, 171.	Nos. 1; 4; 7
7	Ice-free land will expand providing habitats for native and non-native plants; each is likely to benefit from warming	Nos. 107; 108; 109; 111; 125; 126; 128; 129; 132; 133; 134; 139; 140; 147; 149; 151; 170	Nos. 1; 4; 7
8	The threat to native biodiversity by non-native species	Nos. 107; 108; 109; 110; 111; 112; 113; 115; 117; 125; 126; 128; 129; 132; 133; 134; 139; 140; 145; 146; 147; 148; 149; 150; 151; 170; 171	Nos. 1; 4; 7

[1] See: Siegert et al. (2019).

policymakers' decision-making on protected areas more fully. In 2009, SCAR published the Antarctic Climate Change and Environment (ACCE) report, that presented the state of knowledge on climate change in Antarctica (Turner et al., 2009, 2014). Responding to this report, in April 2010, the Antarctic Treaty Meeting of Experts (ATME) on Climate Change met in Svolvær, Norway, and adopted 30 wide-ranging Recommendations (see Supplementary Table 3). Recommendations concerning the Antarctic environment, including area protection, were passed to the CEP, which subsequently produced a Climate Change Response Work Programme (CCRWP) to facilitate their advancement (Resolution 4 (2015)). In 2017, the ATCM established the CEP Subsidiary Group on Climate Change Response (SGCCR) to facilitate the efficient implementation of the CCRWP (Decision 1 (2017)). Climate change was also added to the ATCM Multi-Year Strategic Work Plan and the CEP Five-Year Work Plan (Supplementary Table 3).

Since the 2010 ATME on Climate Change, 21 working papers on climate change have been submitted to the ATCM and/or CEP (ATCM - 3, CEP - 13, both bodies - 5). For example, the ATCM has discussed how to respond to climate change impacts that are already evident within the region, and those that are inevitable, given recent warming (ATCM, 2019). However, progress on the use of new protected areas to respond to climate change has been limited. A proposed methodology to classify ASPAs according to their vulnerability to climate change was not developed further as Parties expressed concerns regarding the scope of the parameters under assessment (United Kingdom and Norway, 2011; CEP XIV Final Report). The CEP considered the potential utility of WWF's Rapid Assessment of Circum-Arctic Ecosystem Resilience (RACER) methodology for identifying sites with biological communities likely to be resilient to climate change (e.g., United Kingdom and Norway, 2012). A subsequent international trial identified locations on James Ross Island and concluded that ASPA designation was appropriate, but no protected areas have been designated linked to this proposal (United Kingdom and Czech Republic, 2015). Despite these stalled initiatives, momentum to develop an integrated and systematic protected area system is building, largely under the auspices of SCAR together with the CEP. At ATCM XLII (2019), a report was submitted to the CEP concerning the 'Joint SCAR/CEP workshop on further developing the Antarctic protected area system' held in Prague, Czech Republic, in June 2019 (Australia et al., 2019). Points raised at the workshop included the need to consider potential future environmental threats such as climate change in identifying sites for protection, and the value of efforts to address the synergistic pressures of climate change and other pressures associated with human activity in Antarctic. Subsequently, the CEP agreed to develop guidelines to progress the systematic development of the protected area system. In parallel, SCAR is working with the International Association of Antarctica Tour Operators (IAATO) to use systematic conservation planning tools to identify how best to concurrently manage biodiversity, science and tourism in the Antarctic Peninsula region, and contribute to the sustainable management of IAATO activities into the future, which will likely need to consider climate change impacts and existing and potential new protected areas (Margules and Pressey, 2000; SCAR and IAATO, 2019). Nevertheless, a comprehensive and systematic approach to Antarctic area protection at a regional scale has yet to be established and implemented.

5. Conclusions and recommendations

While the CEP recognises the value of an integrated protected area system to provide resilience to climate change (see Table 1), existing guidance on climate change impacts within protected areas has largely taken a limited view, focussing on protected areas as individual units. The provision of an integrated strategy that sets out the blueprint for the use of the wider Antarctic protected area system to provide climate change resilience has yet to be developed. The challenge for the Antarctic scientific community, potentially led by SCAR, will be to (i) help policy makers understand the scope of existing and future climate change impacts on Antarctic environments and ecosystems, and (ii) demonstrate, in a practical and implementable way, how existing conservation and management tools within the Antarctic Treaty System might be used to addressing these impacts at a regional level. Designation of a number of new protected areas (including a potential move toward designation of a smaller number of larger areas) and integration of existing areas are likely to be components of a practical solution. Facilitating this, researchers could provide information on the distribution of recognised biotic and abiotic values, the predicted spatial extent of climate change under different greenhouse gas emission scenarios and likely impacts upon biological groups, ecosystems and environments. Researchers could also consider the characteristics of locations that may act as climate change refugia, including candidate sites. Consultation with existing stakeholders (including the tourism industry, Antarctic national governmental operators and NGOs) will be essential for the effective designation of protected areas to provide resilience to climate change.

Recent dramatic declines in rates of ASPA and ASMA designation are a cause for concern due to the pressing need for use of these tools both to build a properly representative protected area system of appropriate scale (Coetzee et al., 2017) and to develop climate change resilience. The developing momentum within SCAR and the CEP to use available tools to enhance climate change resilience could improve the protection of Antarctica, and the values and features that make it unique. Nevertheless, the application of such tools within Antarctica can only ever support a limited degree of resilience, with the requirement for rapid global decreases in greenhouse gas emissions being the only realistic means of safeguarding Antarctica as we know it for future generations.

Author statement

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Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

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