Key climate change effects on the coastal and marine environment around the Polar UK Overseas Territories

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EXECUTIVE SUMMARY

- The UK Polar Overseas Territories comprise two geographically and environmentally distinct regions which will respond both differently and interconnectedly to climate change.

- This region is rapidly changing as a result of inter-related climate-driven changes to the environment, including temperature, sea-ice cover, and ocean chemistry. These changes will have a range of direct and indirect effects on the region's marine ecosystems as well as having widespread ramifications for the planet.

- The effects of these changes include observed and projected range shifts for many species depending on their tolerance for the changing conditions. Antarctic species have a more-limited physiological tolerance to variations in temperature compared to species elsewhere. Over time, changing conditions are likely to favour different assemblages of animals representing a potential regime shift in the structure of the Antarctic food web.

- The rate of change in this region, coupled with the potential susceptibility of its wildlife, means the ecological implications of these changes herald more-widespread change across the Southern Ocean and even further afield.

- Southern Ocean food webs support ecosystems with significant global value through the existence of charismatic wildlife, and through ecosystem services such as fisheries, tourism and carbon storage. The provision of these services will also be affected by climate-driven changes.

- Polar carbon sinks represent a rare negative feedback to global climate change with biological capture and storage of carbon increased by loss of ice and moderate ocean warming. Climate-driven regime shifts in biological communities and environmental disturbance (e.g. through increased iceberg scouring) will affect the rate and amount of carbon taken up and how efficiently it is transported to the seabed.

- Sea ice is a major modifying influence of the global climate system. Some regions of the Antarctic have experienced large decreases in sea ice, and in other areas there has been ice gain. It demonstrates significant inter-annual and decadal variability making it difficult to assess long-term, climate-induced trends. There is a high degree of uncertainty whether the recent decline in Antarctic sea-ice extent will continue.
- Sea ice has a significant influence throughout the Antarctic food web. Many animals are highly adapted to its presence, including krill and some species of penguins, seals and whales. It provides an essential habitat for breeding and feeding, as well as influencing important processes such as primary productivity.
- Addressing knowledge gaps will require an international co-ordination of effort and funding to obtain standardised datasets, provide improved data coverage and long-term time-series records.
- Improving our ability to predict future change in Antarctic ecosystems will enable us to be able to manage and conserve these ecosystems in the face of change. Understanding of observed changes and trends together with improvements in model parameterisations and capabilities, so that they capture the complex interactions between multiple stressors, will help facilitate this.

DESCRIPTION OF OVERSEAS TERRITORIES IN THE REGION

The UK Polar Overseas Territories (OTs) comprise two distinct territories: (1) South Georgia and the South Sandwich Islands (hereafter referred to collectively as 'SGSSI'), and (2) the British Antarctic Territory (hereafter referred to as 'BAT').

The SGSSI are an archipelago of sub-Antarctic islands that form part of the Scotia Arc, a predominantly submarine ridge that extends from the Terra del Fuego region of South America to the Antarctic Peninsula. The two island groups are distinctly different in character with South Georgia experiencing large inter-annual variability in temperatures and a mix of Antarctic and more-temperate South American species. The South Sandwich Islands archipelago is more Antarctic in character, with lower, more stable, annual temperature ranges and the presence of seasonal sea ice for up to about 200 days per year at the southern end of the archipelago. SGSSI are recognised as a globally important site of abundant and diverse marine fauna, and as an internationally important site for higher predators supporting vast colonies of penguins, seals, nesting seabirds and a recovering population of whales. The region's waters are protected by the 1.24 million km^2 SGSSI Marine Protected Area (MPA) established by the Government of SGSSI (GSGSSI), which aims to conserve marine biodiversity, as well as allowing some sustainable fishing. Fisheries are managed by GSGSSI within the framework

of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), with additional measures and standards imposed under GSGSSI licensing conditions.

BAT comprises the sector of Antarctica between 20°W and 80°W forming a wedge shape that extends from the Geographic South Pole north to 60°S. This region includes the South Shetland Islands and the remote South Orkney Islands at its most northerly extent. The shelf-sea habitat around Antarctica covers a broad bathymetric range, from shallow coastal waters to deep fjords and with deep average shelf depths of around 500 m. It is characterised by extreme seasonality in sunlight hours, primary production, and sea-ice cover. BAT is administered in London by the Polar Regions Department of the Foreign, Commonwealth and Development Office. All territorial sovereignty claims to Antarctica are held in abeyance under Article IV of the Antarctic Treaty 1959. The Antarctic Treaty and its Protocol on Environmental Protection provides for the management of human activities and protection of the Antarctic environment south of 60°S, while fishing is managed by CCAMLR.

MAIN CLIMATE CHANGE DRIVERS

The southern polar region is rapidly changing as a result of inter-related climate-driven changes to the environment, including temperature, ice, and ocean chemistry (Meredith *et al.*, 2019). These changes have a range of direct and indirect effects on the marine ecosystems of the region (Constable *et al.*, 2014; Gutt *et al.*, 2015) and widespread ramifications for the planet (IPCC, 2019). In turn, these changes affect ecosystem services such as the 'blue carbon pathway' (i.e. processes of carbon capture and fixation by marine organisms, through storage in organism bodies to sequestration), fisheries, and tourism (Cavanagh *et al.*, 2021).

The key driver of environmental change in the region is warming sea-surface temperatures (SSTs). Between 2005 and 2017, 45-62% of global ocean heat-gain took place in waters south of 30°S (Meredith *et al.*, 2019). SSTs at South Georgia and across the BAT (notably along the West Antarctic Peninsula) are among the fastest warming in the Southern Hemisphere (Turner *et al.*, 2005; Whitehouse *et al.*, 2008; Schmidtko *et al.*, 2014; Meredith *et al.*, 2019; Siegert *et al.*, 2019). Whilst at South Georgia, warming below about 100 m is not thought to have reached biologically significant levels (Whitehouse *et al.*, 2008), a poleward shift in southern hemisphere westerly winds has the potential for intense warming (in excess of 2°C) of subsurface coastal waters along the West Antarctic Peninsula at depths of 200–700 m (Spence *et al.*, 2014).

A globally important consequence of warming across the region is the accelerated rate at which ice shelves around the Antarctic Peninsula are retreating and thinning (Rignot *et al.*, 2019), and the degree to which the extent and duration of seasonal sea ice is changing (Morley *et al.*, 2020). The West Antarctic Ice Sheet (WAIS) is one of the world's most vulnerable ice

sheets (Bamber *et al*., 2018). Both its size and the rate of mass loss means ice loss will have significant implications for global sea level rise (Meredith *et al*., 2019). At lower latitude sites such as the South Orkney Islands, South Shetland Islands and SGSSI, glacial retreat has also been extensive with negative mass balance observed at South Georgia (Farías-Barahona *et al*., 2020) coupled with observed retreat in 97% of South Georgia's glaciers (Cook *et al*., 2010).

The waters of the Southern Ocean are relatively cold, and as such have relatively high levels of dissolved oxygen (Convey and Peck, 2019). Under climate-change scenarios, models predict an outgassing of oxygen from the ocean, with the Southern Ocean exhibiting the largest change in air-sea oxygen exchange as oxygen solubility decreases (Schmidtko *et al*., 2017). The cold waters also mean Southern Ocean waters are among the most vulnerable to ocean acidification due to the increased solubility of CO_2 at lower temperatures (Hancock *et al*., 2020).

Factors expected to affect Southern Ocean species arise predominantly from these three trends of a warmer, more acidic ocean with less ice (Convey and Peck, 2019). Antarctic species have a more-limited physiological tolerance to variations in temperature compared to species elsewhere (Peck *et al*., 2009). Adaptation is also more restricted due to slow development times, increased longevity and deferred sexual maturity (Peck, 2002). With projected increases in global CO_2 levels, organisms living in the Southern Ocean are likely also to be exposed to potentially damaging pH and calcium carbonate conditions earlier than elsewhere in the world. Reduction in ice will, in the case of ice shelves, ice sheets and glaciers (land-based ice), open up new potential habitats for both Antarctic and non-native species whereas, in the case of sea ice, fundamentally change the seasonal structure of the marine environment with significant implications for food web dynamics, species biogeography and ecosystem function.

In response to environmental change, to avoid local extinction, many organisms must migrate latitudinally, go deeper, or both (Barnes *et al*., 2009; Hogg *et al*., 2011; Griffiths *et al*., 2017). This will likely see a poleward shift with some species ranges contracting towards continent (Constable *et al*., 2014). The rate of change in this region coupled with the potential susceptibility of its wildlife means the ecological implications of these changes will herald more-widespread change across the Southern Ocean and beyond.

PRIORITY 1: CHANGES IN FOOD WEBS AND ECOSYSTEM FUNCTION

Southern Ocean food webs support ecosystems with significant global value through the existence of charismatic wildlife, and through ecosystem services such as fisheries, tourism, and the blue carbon pathway (Grant *et al*., 2013).

Research programmes such as the Scientific Committee for Antarctic Research (SCAR) Antarctic Thresholds – Ecosystem Resilience and Adaptation (AnT-ERA) programme, Climate and Ecosystem Dynamics in the Southern Ocean (ICED) programme, and the SCAR Horizon Scan (Chown *et al*., 2012; Xavier *et al*., 2016) have framed a number of cross-disciplinary questions which will need addressing to explain better the ecosystem response to natural climate variability and anthropogenic change (Gutt *et al*., 2015, 2018; Murphy *et al*. 2008).

WHAT HAS HAPPENED

Local and regional studies have taken place in recent years to attempt to assess faunal and ecosystem response to climate change. These efforts are hampered by limited long-term time series data (Morley *et al*., 2020), and even where time-series data are available there is often not clear consensus. Historical records of distribution and composition of zooplankton in the Scotia Sea region, for example, show that zooplankton communities have been resilient to long-term surface warming (Tarling *et al*., 2017). There is, however, evidence for a decline in Antarctic krill population density corresponding with changes in sea-ice extent since the 1980s (Constable *et al*., 2014; see also Hill *et al*., 2019; cf. Cox *et al*., 2018). With food webs also demonstrating regional specificity and adaptability to changes in energy source, however, there is inherent complexity and uncertainty in understanding the direct and indirect impact of climate change as its effects cascade through the Antarctic food web (Constable *et al*., 2014). As such, the ramifications of these changes across the wider Antarctic food web is unclear and complex. The long-standing paradigm of the Southern Ocean food web is one characterised by a short and efficient trophic pathway transferring primary production to top predators via a krill-dominated chain (Trebilco *et al*., 2020). It is increasingly being recognised however that alternate energetic pathways through mid-trophic level groups such as copepods, amphipods, salps, squid and mesopelagic fish may be equally or more important than the krill pathway (McCormack *et al*., 2019). These mid-trophic pathways can also act as an alternative pathway of energy flow, for example, in years of poor krill recruitment (Murphy *et al*., 2007; 2012; 2016). Lanternfish for example are a mesopelagic fish whose numerical dominance in the Antarctic means they play an important role as a trophic link between primary consumers (e.g. copepods and krill) and megafauna (e.g. seabirds, penguins and pinnipeds) (Saunders *et al*., 2015). In years when krill are scarce, lanternfish have a key role in ecosystem functioning as an alternative trophic pathway. Though also

subject to climate-driven changes, such alternate trophic pathways may act to buffer Antarctic food webs and maintain ecosystem stability during periods of long-term environmental change (Constable *et al*., 2014).

At higher trophic levels there is increasing evidence of climate-induced changes in populations. This is manifest in changes in the suitability of breeding habitats affecting changes in reproductive success, mortality, fecundity and body condition; and environmentally driven changes in spatial and seasonal prey aggregations that affect patterns of migration, distribution, foraging and reproduction (Hindell *et al*., 2016; Seyboth *et al*., 2016; Hinke *et al*., 2017; Santora *et al*., 2017). Long-term population shifts in predator species, however, are confounded by strong interannual environmental variability in good and bad years for prey and breeding habitat (Youngflesh *et al*., 2017). Furthermore, at sites such as South Georgia where some populations are still recovering from historic mass removals of seals, fish and whales, long-term population trends are hard to interpret.

Studies of the benthic environment along the Antarctic Peninsula have shown that an increase in iceberg scouring over the past 12 years corresponded to a halving in the probability of colonies of some species of benthic sessile invertebrates reaching two years of age (Smale and Barnes, 2008). Where time-series data is not available, studies using heated settlement plates *in situ* on the seabed and experiments in laboratories *ex situ* have provided insight into the physiological tolerances of certain benthic fauna (Barnes and Peck, 2008). Recent studies on the ecological effects of acidification in coastal waters near the Antarctic continent indicate a detrimental effect of acidification on primary production and changes to the structure and function of microbial communities (Deppeler *et al*., 2018).

Understanding changes in key ocean and sea-ice habitat characteristics are fundamental in determining future states of Southern Ocean ecosystems (Meredith *et al*., 2019). Central to this will be (i) evaluating regional differences in the rate and direction of responses as species may not be responding in a uniform way across the wider region, and (ii) quantifying how indirect responses may be promulgated through the food web.

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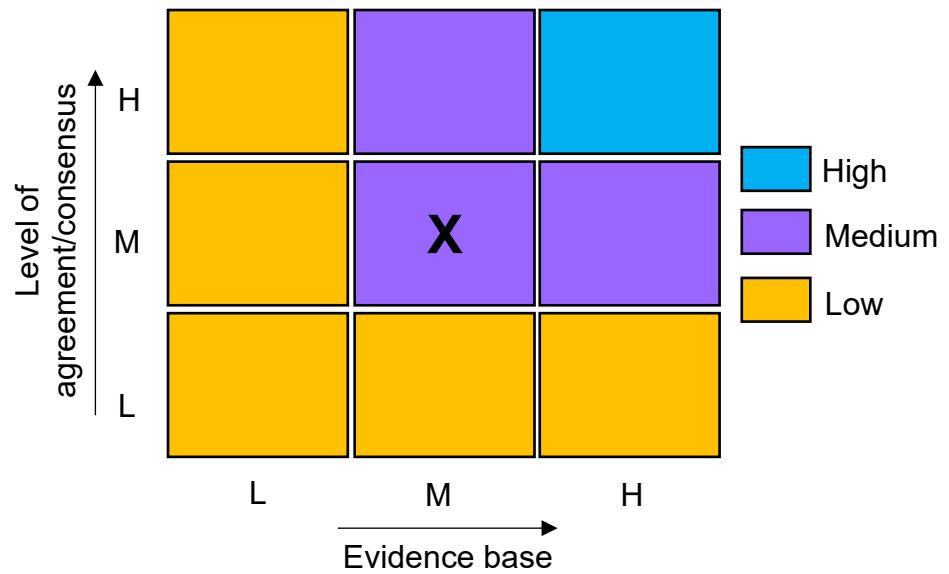
Changes in ecological systems at SGSSI and BAT are both documented and anticipated to occur more acutely in the future. There is however currently limited understanding of the preconditions or indicators of change that would help model/ pre-empt any regime shift in ecological systems (Meredith *et al.*, 2019; Rogers *et al* 2020). There is also a significant amount of uncertainty associated with natural variability and, in particular at SGSSI, the status of populations in terms of recovery from historical commercial exploitation.

WHAT MIGHT HAPPEN

Primary production is projected to increase in waters south of 65°S under 2100 RCP8.5 projections (IPCC, 2019). Lower trophic level primary consumers, such as krill, are expected to exhibit a corresponding southwards range shift into an ever-decreasing zone of cold (and increasingly acidified). water as the oceanographic conditions in which they are currently found move poleward (Constable *et al.*, 2014). In krill, changes in environmental conditions such as temperature and pH are likely to impede embryonic development and adult growth (Kawaguchi *et al.*, 2013; Perry *et al.*, 2020), and loss of habitat such as sea ice could negatively impact recruitment (Cavanagh *et al.*, 2021). Modelling for the Western Antarctic Peninsula suggests that potentially linked to declining krill biomass will be a contemporaneous increase in the biomass of gelatinous consumers such as salps (Suprenand and Ainsworth, 2017).

This geographical and compositional shift of lower trophic groups is likely to be matched by a disruption at higher trophic levels (Cavanagh *et al.*, 2021). For example, climate impacts on krill growth have been modelled for the Antarctic Peninsula and the Scotia Sea and shown to translate to an increased risk of declines in krill predator populations (particularly penguins), under multiple climate scenarios (Klein *et al.*, 2018). BAT and SGSSI are globally

important sites for marine mammals and seabirds hosting some of the largest concentrations of higher predators on Earth (Rogers *et al*., 2020). The degree to which climate change will impact on marine mammals and birdlife will depend significantly on diet, feeding strategies, foraging ranges, and biogeography. These changes are likely to be highly taxa and region-specific, with a high level of uncertainty in assessing present population status, much less future changes. One reason for this is that there is considerable variability in the diet of individuals between and within populations. For example, amongst penguins, generalist, near-shore foragers like gentoos exhibit flexibility to exploit alternative prey and to follow changes in prey distributions (Miller *et al*.,2010; Carpenter-Kling *et al*., 2019), whereas Adélie and chinstrap penguins, in contrast, rely more heavily on abundance of krill, demonstrating less plasticity in their prey selection (Cimino *et al*., 2016). Climate change will have direct impacts on the higher trophic species too based on their life history traits (e.g. preferred nursery grounds), habitat preferences (e.g. species that associated closely with ice habitats) and the availability of breeding grounds (e.g. glacial retreat has opened breeding habitat for king penguins on South Georgia).

Due to their numerical dominance in the Southern Ocean, mesopelagic lanternfish have a vital role in ecosystem functioning, representing a trophic link between primary consumers and megafaunal predators (Freer *et al*., 2019). Multiple climate models consistently predict a poleward distribution shift in these mesopelagic fish based on interplay between their thermal niche and biogeography (Freer *et al*., 2019). Modelling trends suggest that smaller sub-Antarctic species will become increasingly dominant across the Southern Ocean with implications for future trophic interactions (Freer *et al*., 2019). In larger demersal fish species, there is limited understanding of the consequences of climate change (Meredith *et al*., 2019). Differences in temperature tolerance of certain species (e.g. Patagonian vs. Antarctic toothfish). will likely also result in latitudinal range shift with implications for future fisheries.

The impact of climate change on benthic ecology will differ between shallow waters, shelf, slope and deep-sea ecosystems (Brandt and Gutt, 2011). Shallower shelf areas already experience significant disturbance caused by seasonal changes in Antarctic ice footprint which enables fast-growing macroalgal and early successional assemblages to establish in ice free summer habitats. With sustained ice loss and the associated increase in iceberg scouring, this trend seems likely to become more widespread with algal species in the shallows also benefiting from increased light attenuation resulting from sea-ice loss. Prevalence of algal and early successional species at the expense of reduced survivorship in long-lived, slow growing species could mean a net loss in benthic biodiversity. In deeper waters the timing of reproduction in many benthic invertebrates synchronise with spring phytoplankton blooms (Lohrer *et al*., 2013). As climate change impacts primary production, the magnitude and timing of the seasonal pulse of organic nutrients from surface phytoplankton blooms and pelagic biomass may change (Constable *et al*., 2014).

Extreme Antarctic conditions often sit at, or are beyond, the physiological limits of potentially invading marine species, limiting the survival of non-Antarctic species that reach Antarctica (e.g. Byrne *et al*., 2016). Climate-driven changes to ocean temperatures and circulation will have potentially significant implications on oceanic dispersal pathways influencing the ability for more temperate species to proliferate in the region and potentially improve the survivorship of non-natives (Hughes *et al* 2020). Such changes will vary according to local oceanographic, geographical and taxon-specific biological factors (Wilson *et al*., 2016) and will also be influenced by the opening of new ice-free environments. A circumpolar assessment of the environmental envelopes in which about 1000 native Antarctic invertebrate species currently live suggests more losers than winners under future warming scenarios (Griffiths *et al*., 2017), which could also decrease biotic resistance to non-native species (Hughes *et al.,* 2020). Conversely, when the capacity of species to adapt to changing environmental conditions is accounted for, more species (notably predators and deposit feeders) are suggested as likely to benefit under near-future climate forecasts (Morley *et al*., 2019).

Another key change in benthic and pelagic food webs over the next century is the predicted increase in acidification of the water (Henley *et al*., 2020) which will likely have adverse impacts on calcified marine invertebrates and coralline algae. It is suggested that ocean acidification will negatively impact growth and reproduction (Sewell and Hofmann, 2011) and reduce success in invertebrate early life-history stages (Ericson *et al*., 2012).

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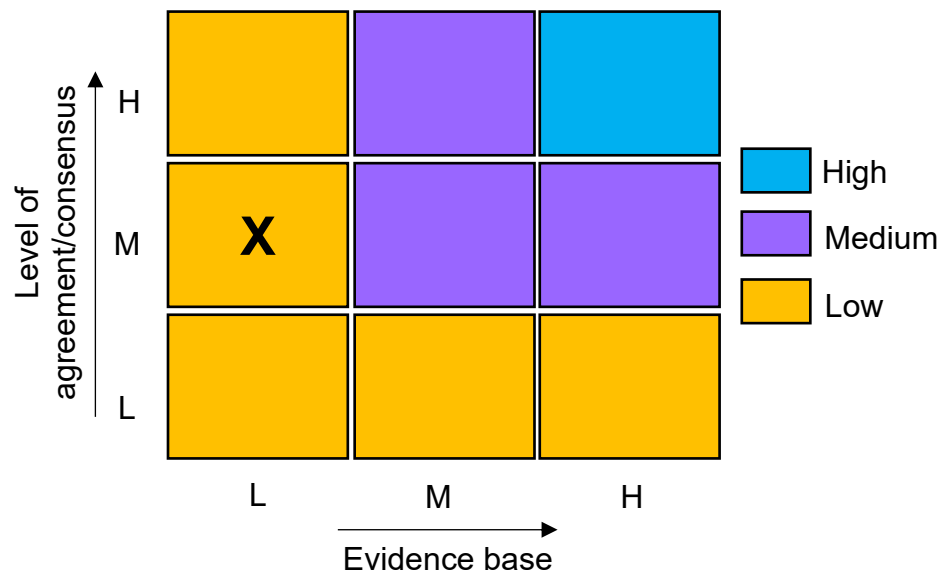
Over time, changing conditions are likely to favour different assemblages of animals, potentially representing a regime shift in the functional structure of the food web. Biodiversity projections and food web models are limited by uncertainty in the potential for organisms to tolerate or adapt to ecosystem change and the resilience of foodweb structures (Meredith *et al*., 2019).

PRIORITY 2: CHANGES IN CARBON UPTAKE, EXPORT AND SEQUESTRATION BY BIOLOGICAL PROCESSES

The blue carbon pathway is the process by which inorganic carbon in the form of dissolved CO_2 is captured in the world's oceans and coastal ecosystems through carbon capture and fixation by marine organisms. Long-term storage of this carbon occurs through two main pathways: (i) carbon storage in the bodies of organisms themselves, and (ii) carbon sequestration through burial of organic carbon at the seabed.

WHAT HAS HAPPENED

At SGSSI and BAT, high biomass species such as Antarctic krill and longer-lived species such as baleen whales and benthic invertebrates such as barrel sponges and corals are thought to be particularly important stores of carbon (Henley *et al*., 2020; Cavanagh *et al*., 2021). Longer-term (>100 years) sequestration of this carbon can occur through direct sinking of primary production to the seabed and through consumption of primary producers by zooplankton (which subsequently flows across the food web) with the carbon then stored through faecal pellets, and/or carcasses and moulted carapaces sinking to the seabed (Manno *et al*., 2020). Except for the heavily perturbated coastal environments in the BAT, which can experience significant ice scouring, Antarctica's continental shelves are large and deep and experience typically low levels of disturbance. Benthic invertebrates here grow slowly and are long-lived, facilitating considerable accumulation of benthic biomass and stored carbon.

In terms of total carbon storage budgets, the contribution of biological processes in polar oceans is relatively small, both in comparison to terrestrial analogues (e.g. forests). and lower latitude coastal habitats (e.g. mangroves), as well as in comparison to the physical storage of dissolved CO_2 in the water itself. The last point is particularly notable in the cold waters of the Southern Ocean, which facilitate greater levels of dissolved CO_2 than warmer seas at lower latitudes. Furthermore, within the blue carbon pathway, most carbon is recycled back into the system through the microbial loop (Henley *et al*., 2020; Cavanagh *et al*., 2021). Importantly however, biological storage and sequestration of carbon in polar environments represents a rare negative-feedback to climate change (Barnes *et al*., 2018; Pineda-Metz *et al*., 2020). Whilst other global carbon sinks are shrinking in size (e.g. through deforestation and coastal habitat degradation), blue carbon sinks at BAT (notably along the Western Antarctic Peninsula) are increasing considerably (Barnes, 2015). Furthermore, changes in carbon storage through physical processes, whilst fundamentally important climate drivers, are difficult to mitigate against at a local or regional level. In contrast, biological sequestration can, to a degree, be protected as a process through spatial protection measures (e.g. limiting direct anthropogenic threats that may damage or disturb the benthic environment).

There is significant regional variability in both carbon uptake, export and sequestration by biological processes and the degree to which it is changing. In the polar OTs this is manifest in key differences between SGSSI and the BAT, largely relating to the degree to which seasonal sea ice and ice shelf changes impact on the marine environment. In response to sea-ice loss in parts of the BAT over the past 25 years, stores of carbon on the seabed and in zoobenthos biomass have increased (Barnes, 2015). This has principally been driven by links between reduced sea ice and the timing, duration and size of phytoplankton blooms (Arrigo *et al*., 2008). Ice shelf collapse (i.e. land-based ice) has also been demonstrated to result in significant onshore (Peck *et al.,* 2010), offshore (Duprat *et al*., 2016) and overall carbon capture (Barnes *et al*., 2018). Retreating ice shelves and marine-terminating glaciers along the Antarctic Peninsula ice are enriching coastal waters as they melt with micronutrients such as iron (Constable *et al*., 2014), opening up new pelagic and benthic habitats and providing increased habitat for carbon sequestering organisms (Barnes *et al*, 2018). Conversely, some of these shallow coastal environments are now also experiencing significant ice scour (Barnes, 2017), resulting in perturbed benthic environments and limiting the capacity of the environment to support large sessile sequestering invertebrates such as corals and sponges.

North-west of South Georgia is the site of one of the largest spring phytoplankton blooms in the Southern Ocean. South Georgia is characterised by high biomass and productivity of phytoplankton, with the region supporting a bloom earlier in the season than elsewhere in the Southern Ocean (Prend *et al.*, 2019). This may result in significant carbon storage through direct sinking. Analysis of moulting in krill at South Georgia as a driver of pulses of carbon export to the seabed, suggests that temperature increases may also have a negative impact on krill growth and biomass (Manno *et al*., 2020), causing the growth season to end earlier and growth habitat to shift to cooler higher latitudes (Veytia *et al*., 2020). Conversely, studies on benthic invertebrates suggest that SGSSI have low levels of biogenic carbon storage (Barnes *et al*., 2016) in comparison to the Weddell and Bellingshausen seas (Antarctic Peninsula) and most notably compared with the South Orkney Islands, which are considered as a polar blue carbon hotspot (Barnes *et al*., 2016). However, SGSSI are still thought to have a key role in carbon storage because of their large shelf areas likely account for considerable carbon immobilisation (Barnes and Sands, 2017). Carbon immobilisation was shown to correlate to the duration (but not peak or integrated biomass) of phytoplankton blooms.

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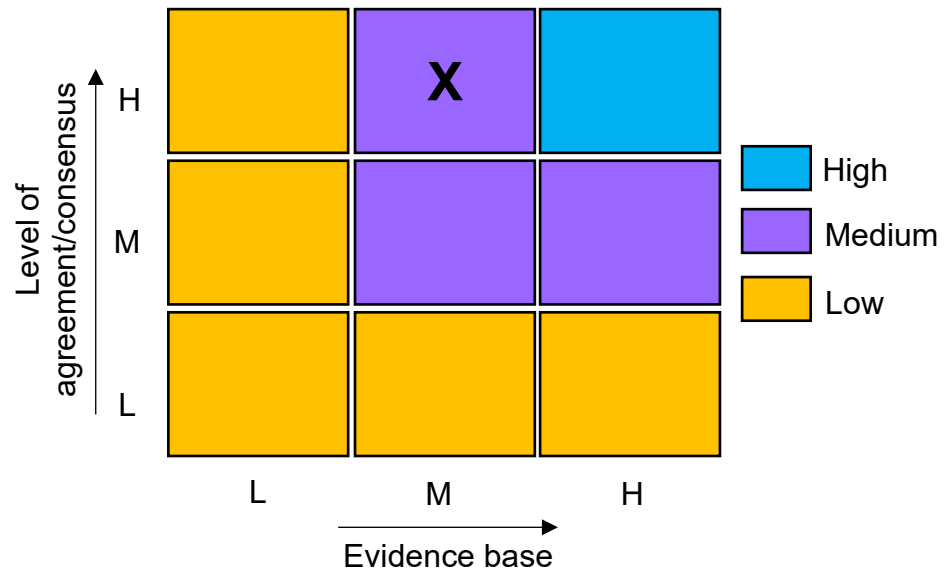
Analysis of carbon sequestration in benthic invertebrates is based on extrapolation of camera transect data to continental shelf-scale. As such, actual values of carbon drawdown will likely have a high associated error. It is also based on analysis of a subset of species. There are also limitations in quantifying the amount of carbon sequestered and duration of storage through direct burials of bodies, carcases and faecal matter. In the case of Antarctic krill, vertical seasonal migration, potentially below the depths on the sediment traps which collect the data, make it hard to quantify year-round carbon export to the seabed. Furthermore, carbon budget stored in the biomass of the food web is difficult to quantify with complex annual, interannual and long-term variability (e.g. recovery from historical exploitation in higher predators).

WHAT MIGHT HAPPEN

Future temperature increases of up to 1°C may enhance zoobenthos growth and carbon storage (Ashton *et al*., 2017). On the seabed, biological carbon storage is likely to increase with declining sea ice, increasing temperatures and increasing phytoplankton availability (Ashton *et al*., 2017; Barnes, 2015; Barnes *et al*., 2018; Pineda-Metz *et al*., 2020). These changes are however likely to be parabolic in nature (Cavanagh *et al*., 2021) as temperature warming above 1°C and associated acidification of the waters across the BAT and SGSSI may start to have physiological implications for animals in terms of optimal and survival envelopes (Ashton *et al*., 2017; Peck, 2018) and a reduction in efficiency of carbon storage and sequestration (IPCC, 2019). Furthermore, whilst there is the potential for a considerable reduction in sea ice during the summer months, this loss is finite and in the dark winter months across the BAT does not influence productivity levels.

A potential decrease in krill biomass is likely to impact marine biogeochemical cycles highlighting the sensitivity of carbon flux to rapid regional changes in temperature. Ocean acidification could also reduce sinking rates in phytoplankton, reducing the efficiency of carbon export in the coming decades (Petrou *et al*., 2019; Henley *et al*., 2020).

A further proposed risk of future warming at the seabed is the potential that it may catalyse the release of methane sequestered as gas hydrates in Antarctic (and sub-Antarctic). sediments resulting in a positive feedback to climate change (Archer *et al*., 2009; Ruppel and Kessler, 2017). Such hydrates have been shown to be present to some degree in the continental shelf around South Georgia (Bohrmann *et al*., 2017).

The marine environment of the Southern Ocean is predicted to change significantly under RCP8.5 and RCP4.5 scenarios. Changes in ocean temperature, salinity, acidity, sediment loading and ice scouring from melting land ice and a potential poleward shift in frontal systems will all act as drivers on marine ecosystems and food webs affecting the distribution, abundance of species, and as such the community and functional structure of ecosystems. Shifts in species composition are important for carbon pathways as some communities will be more effective at carbon draw down than others. In the benthic realm, for example, animals with calcifying structures, or those that are very long-lived are better at sequestering it. In the water column, the rate and efficiency of carbon transport to the seabed is influenced by the dominant species at the base of the food web. Climate change may influence these population dynamics differently across the region. For example, there have been different changes recorded in the size and type dominance of phytoplankton in the northern Western Antarctic Peninsula (WAP) compared to the mid and south WAP (Rogers *et al*., 2020). Regime shifts in biological communities will ultimately affect the rate and amount of carbon taken up and how fast it is transported to the seabed.

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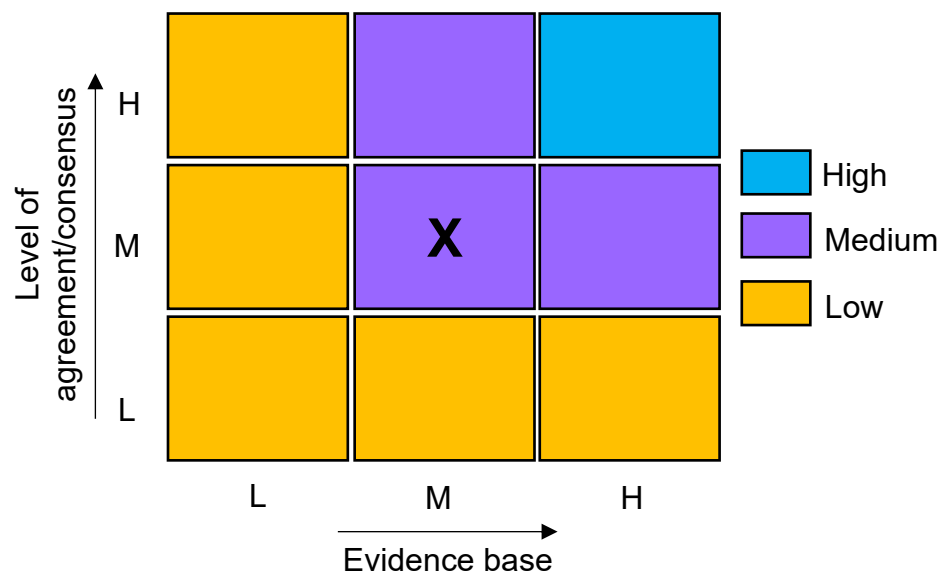
Uncertainty in future sea-ice projections (Cavanagh *et al*., 2017; IPCC, 2019) and physiological responses to environmental change means it is difficult to predict trends in future biological carbon pathways (Rogers *et al*., 2020). There is also significant regional variation in sea-ice change (see Sea Ice section, below). Understanding of Southern Ocean ecosystem services, especially carbon sequestration lags behind the rest of the world. There are also potentially regional differences in changes to phytoplankton population structure to consider which could drive very considerable (but at the moment unknown) changes in consumer populations.

PRIORITY 3: CHANGES IN THE DISTRIBUTION OF SEA ICE HABITAT

Sea ice is frozen water that form on the sea surface resulting in a sixfold change in total ice-covered area in Antarctica each winter (Morley *et al*., 2020). During the austral winter, sea ice extends across the BAT region to encompass the South Shetland Islands, South Orkney Islands and much of the South Sandwich Islands (though not South Georgia). It has a major modifying influence of the global climate system (Bintanja *et al*., 2013) because it is both highly reflective (of solar radiation), strongly insulating and restricts ocean-atmospheric exchange of heat and gases (notably CO_2). Its reflective properties also mitigate impacts on regional terrestrial ice (ice shelves, ice sheets and glaciers) with knock-on implications for global sea-level rise. Sea ice also provides a habitat for breeding, resting and feeding in many ice-associated species (Meredith *et al*., 2019).

WHAT HAS HAPPENED

Sea ice demonstrates significant inter-annual and decadal variability making it difficult to assess long-term, climate-induced trends (Turner and Comiso, 2017; Meredith *et al*., 2019). In the last decade, satellite records indicate Antarctica has experienced both its highest (Reid and Massom, 2015) and lowest (Stuecker *et al*., 2017) sea-ice extents. Some studies suggest a long-term increase in extent (Bintanja *et al*., 2013; Comiso *et al*., 2017), whilst others indicate that a decades-long overall increase has, since 2014, reversed into a rapid decrease (Parkinson, 2019). Sea ice also demonstrates significant regional variability. The Weddell Sea has experienced decreases in ice extent from 2015 to 2018 (Turner *et al*., 2020), whilst the Bellingshausen-Amundsen Seas are now experiencing an overall upward trend (Parkinson, 2019). Several explanations have been proposed for this temporal and regional variability. These include the influence of trends in atmospheric circulation (Stuecker *et al*., 2017), notably strong phases of the Southern Annual Mode (SAM). and variability in El Niño Southern Oscillation (ENSO); decadal trends in ocean circulation resulting in warmer water being moved upward in the column closer to the surface (Meehl *et al*., 2019); and links with cold, fresh surface-water from ice-shelf melt which paradoxically drives more sea ice resulting in a negative feedback to a warming Antarctic (Bintanja *et al*., 2013). Satellite datasets of sea-ice thickness are improving for the Antarctic

(Paul *et al*., 2018), definitive trends however, are not yet available (Meredith *et al*., 2019).

Sea ice is a major driver of energy flow through Southern Ocean food webs (Morley *et al*., 2020). Its extent, onset, duration and thickness affect the degree to which sunlight reaches shallow polar ecosystems (Clark *et al*., 2013). As the ice retreats in the warmer spring and summer months, there is increased light availability, stratification of the upper water column and meltwater enrichment of the water with limiting elements such as iron (Lannuzel *et al*., 2016; Henley *et al*., 2017). The resulting large phytoplankton blooms drive abundance and distribution patterns of pelagic zooplankton (notably Antarctic krill) with the influx of energy flowing through the food web from benthic invertebrates to higher predators such as whales, seals and penguins.

Sea ice also acts as a barrier to wind-driven mixing in the surface waters (Venables *et al*., 2013; Henley *et al*., 2017). As such, it influences vertical mixing in the water column and nutrient cycling and the supply of nutrients to deeper waters and the benthic environment. In shallow benthic ecosystems the presence of sea ice modulates iceberg disturbance at the seabed (Barnes *et al*., 2018). and seasonal light regimes (Clark *et al*., 2013).

Understanding the impacts of changing sea ice on Southern Ocean ecosystems is difficult due to a lack of long-term time-series data to monitor change (Morley *et al*., 2020), uncertainty associated with interactions between multiple environmental drivers, a mismatch between the temporal and spatial scale of climate projections and those of ecological processes (Cavanagh *et al*., 2021) and difficultly in accounting for natural variability of the climate system.

One example of observed ecosystem change attributed to reductions in winter sea-ice extent is the spatial distribution and size composition of Antarctic krill (Atkinson *et al*., 2019) resulting in different regional trends in numerical krill abundance (Cox *et al*., 2018; Atkinson *et al*., 2019). This has also been reflected in the seasonal shift in the Antarctic krill fishery with peak operations moving from summer to late autumn (Meredith *et al*., 2019).

Observations have also been made in the breeding success and population growth rates in some Antarctic flying birds, for which contraction of sea ice may be a key driver. It is however difficult to attribute these changes to one factor and is likely to reflect a combination of different factors.

CONFIDENCE ASSESSMENT
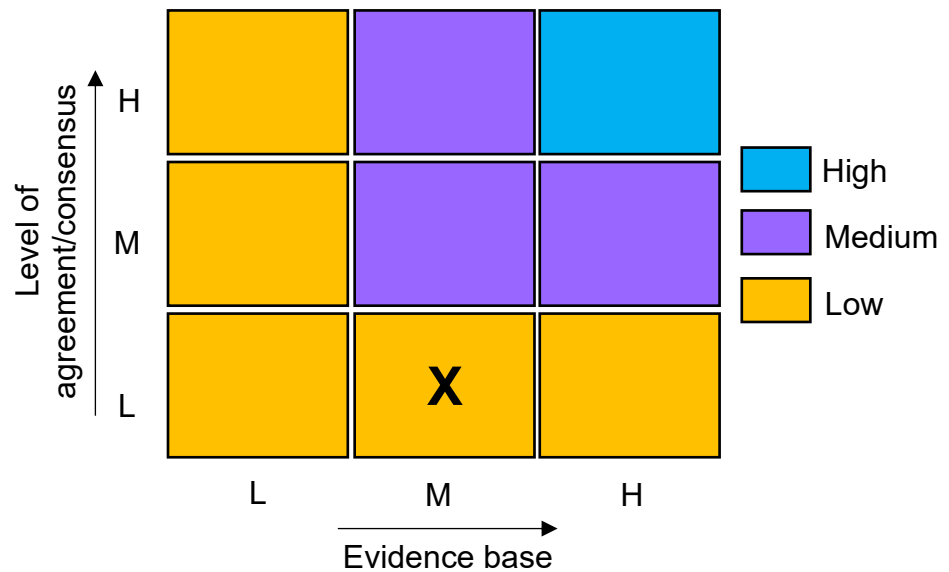
There is a high degree of spatial and temporal uncertainty in short-, medium- and long-term trends in sea-ice extent and duration with a move from net gain to net loss of sea ice only recently having taken place. Confidence about the current impact of sea ice change on ecosystems is low due to (i) a lack of long-term ecosystem monitoring, (ii) difficultly in accounting for natural variability of the climate system, and (iii) a mismatch in the timescales between climate projections and those of ecological processes.

WHAT MIGHT HAPPEN

There is a high degree of uncertainty in sea-ice projections, notably whether the recent decline in Antarctic sea-ice extent will continue or not (Cavanagh *et al*., 2017; IPCC, 2019; Meredith *et al*., 2019; Morley *et al*., 2020; Turner *et al*. 2020). Furthermore, change is unlikely to be homogenous or linear, with further uncertainty centred on regionally specific drivers.

If sea-ice coverage continues to contract and durations shorten, then an ecological tipping point may be reached resulting in a regime shift in shallow water polar communities (Clark *et al*., 2013). Early melt that brings the date of ice-loss closer to midsummer will cause an exponential increase in the amount of annual sunlight reaching some ecosystems. This is likely to drive a shift in coastal benthic communities, in which shallow-water, dark-adapted invertebrate communities are replaced by light-dependent communities such as algae. This could result in a reduction in coastal biodiversity and a fundamental change in ecosystem functioning (Morley *et al*., 2020).

In deeper waters, the reverse may be true. Sea-ice loss will likely impact nutrient cycling and supply to deeper waters environments. Ice acts as a barrier to wind driven mixing in the surface waters (Venables *et al*., 2013; Henley *et al*., 2017). With increased storm and wave activity predicted in

Southern Ocean under both RCP8.5 and RCP4.5 scenarios (Dobrynin *et al*., 2012), increased vertical mixing of the water column seems probable.

Sea ice has also been shown to strongly influence benthic biomass (Barnes, 2015; Barnes *et al*., 2018). With reduced sea ice, the nature of this relationship becomes depth dependent based on the net influences of increase primary production and increased iceberg scouring. In shallow waters along the Antarctic Peninsula, longer sea-ice durations reduce the chance of ice scour, which outweighs slower growth from the shorter phytoplankton blooms. At typical continental shelf depths iceberg scouring is rare. The main driver here is slower growth from shorter phytoplankton blooms. As such it seems likely that a reduction in sea ice will equate to net higher benthic biomass (Barnes *et al*., 2018).

The life cycle of Antarctic krill is closely linked with sea ice (Atkinson *et al*., 2019). In the winter months when food in the water column is scarce, the winter survival of krill larvae is dependent on algae inhabiting the underside of ice floes (Meyer, 2012). As such, krill recruitment success (and its importance to the Southern Ocean food web – see Priority 1 commentary above) has been closely linked with sea-ice habitat (Meredith *et al*., 2019; Cavanagh *et al*., 2021). However, recent studies have suggested that the relationship is more nuanced and that break up of sea ice can be beneficial to some krill larval stages (Melbourne-Thomas *et al*., 2016).

Changes in abundance, distribution and the timing of phytoplankton blooms and pelagic zooplankton such as krill will influence Southern Ocean food web ecology more broadly (Trathan and Hill, 2016). This could see changes in the foraging behaviour, population viability and population dynamics of predators both in the BAT region and at sites downstream of the Antarctic Curcumpolar Current (ACC) such as South Georgia, which rely on krill from the Antarctic Peninsula to support its diverse ecosystems. Antarctic fur seals at South Georgia, for example, prey mainly on krill (constituting about 90% of their diet). It has been suggested that previous observed declines in annual pup production could have been related to availability and variability of krill in South Georgian waters (Forcada *et al*., 2005). There is also concern for ice-dependent species of seal living on and around pack ice across the BAT (i.e. crab-eater, Weddell and leopard seals). These species inhabit a highly changeable environment that is particularly sensitive to climate change. Studies suggest crab-eater and Weddell seals will be negatively affected by changes in the extent, persistence and type of annual sea ice, whereas Ross and leopard seals will be the least negatively influenced by changes in pack ice characteristics (Siniff *et al*., 2008). Studies of penguin populations in BAT suggest declining success in both ice-associated and ice-avoiding species (Trivelpiece *et al*., 2011). Other ice-loving bird species such as emperor penguins and snow petrels may also be susceptible to climate-driven sea ice change (e.g. Ainley *et al*., 2017).

Sea-ice loss cannot be viewed in isolation and should be viewed in combination with losses to ice shelves, ice sheets and glaciers (land-anchored

ice). Sea-ice change can be considered as changing existing marine ecosystems. Marine-terminating land-ice retreat creates new coastal habitats as once ice-grounded seabed become available for colonisation. Both types of ice loss have a profound effect on the regional ecosystem and the global system. The impact of reduced sea ice may be expected to occur first at some of the lower latitude sites in the polar UKOTs such as the South Sandwich Islands and South Orkney Islands.

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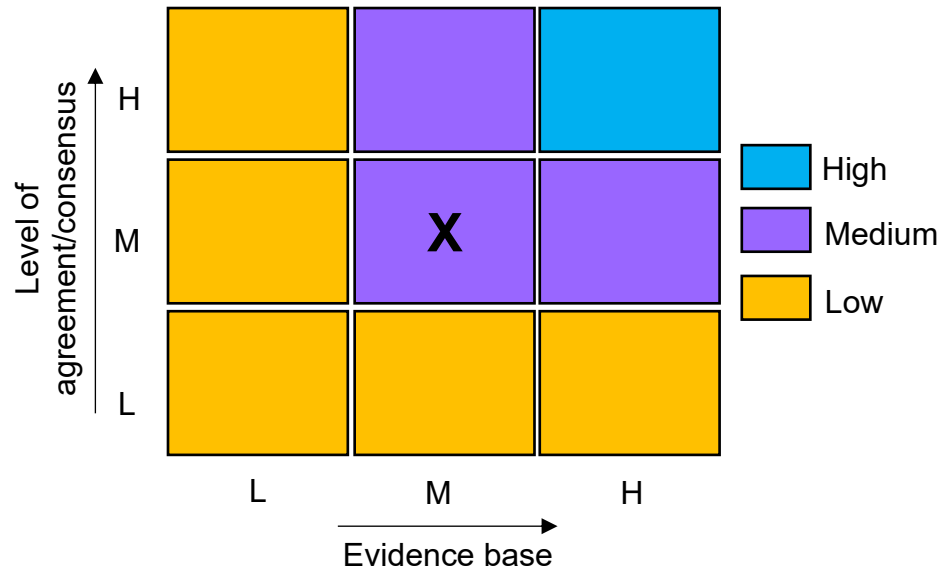
There is a high degree of uncertainty whether the recent decline in Antarctic sea-ice extent will continue or not (Morley *et al*., 2020) and uncertainty in sea-ice projections (Cavanagh *et al*., 2017; Turner and Comiso, 2017; IPCC, 2019; Turner *et al*., 2020). Models currently have low confidence in projections of Antarctic sea ice because of multiple anthropogenic forcings (ozone and greenhouse gases) and complex processes involving the ocean, atmosphere, and adjacent ice sheet. Key knowledge gaps include temporal data series of sea ice duration, thickness and extent. Change is not linear and often reaches critical tipping points. Furthermore, trends vary between regions within Antarctica.

REGIONAL NATURE-BASED SOLUTIONS: CASE STUDY

Climate-driven change in the Southern Ocean, as discussed here for SGSSI and the BAT, are largely part of broadscale changes across the whole-Earth system. As such, local and regional nature-based solutions to mitigate the impact of the priorities discussed here are difficult.

Ecosystem-based management is one mechanism that can enhance the resilience of ecosystems by reducing or managing other potential threats that may damage or disturb the environment. This can act to protect ecosystem services such as fisheries and blue carbon pathways and provide holistic

protection to regional food web ecology (e.g. limiting direct anthropogenic threats that may damage or disturb the environment).

In 2010, the South Orkney Islands became the site of the world's first Antarctic - and by internationally agreement - the first high seas Marine Protected Area. The maritime zone of South Georgia and the South Sandwich Islands was designated one of the world's largest MPAs in 2012, with further enhancements made in 2013 and 2019. CCAMLR members have also developed proposals for MPAs in different regions of the Antarctic as part of a representative network of MPAs across the Southern Ocean. A representative network of protection measures can help enhance connectivity between populations which is one way to increase/maintain resilience to climate change (e.g. through protecting sink and source populations and transport pathways). In 2021, CCAMLR members are also due to discuss Resolution 30/XXVIII on climate change which aims to minimise long-term (> two decades) risk to Antarctic systems.

Ecosystem-based management can also be responsive to environmental change and adaptive to potential future changes to the physical environment, regional biogeography, ecosystem service and function. For example, ice-shelf retreat or collapse around Antarctica is opening up new ice-free marine environments. This has led to the establishment of time-limited Special Areas for Scientific Study in newly exposed marine areas (CCAMLR Conservation Measure 24-04, https://www.ccamlr.org/en/measure-24-04-2017).

Ecosystem-based fishery management through sustainable use MPAs, quota systems on target species, the presence of fisheries observers and multilateral agreement on limiting impact on vulnerable marine ecosystems, are all practical solutions to better ensure that management of the region marine resources is sustainable and resilient to future change. The BAT lies within the area of jurisdiction of CCAMLR, to which the UK is a signatory. As such, all the fisheries in the area are subject to CCAMLR regulations (Darby *et al*., 2018). Fisheries at SGSSI are managed and licensed by the GSGSSI with a strict quota system for toothfish and icefish and access fees in the case of Antarctic krill in addition to both temporal and spatial restrictions (https://www.gov.gs/fisheries/overview/).

NEXT STEPS

There are significant uncertainties in the models used to project ecosystem response to climate-driven change in the Southern Ocean (Morley *et al*., 2020). Recent model predictions for sea-ice extent and duration, for example, have been poor at providing an accurate representation of observed change (Reid and Massom, 2015; Turner and Comiso, 2017; Turner *et al*., 2020), with high inter-model variability and low confidence in the rate of loss (Roach *et al*., 2020; Cavanagh *et al*., 2021). A better understanding is also needed on the sensitivity of marine ice-sheet instability in BAT and specifically whether

recent changes on the West Antarctic Peninsula represent a tipping point of irreversible change (Meredith *et al*., 2019).

Improvements in the ability to predict future change will only come from an improved mechanistic understanding of the observed changes and trends (Meredith *et al*., 2019; Cavanagh *et al*., 2021); direct measurements (that are currently lacking) on key drivers such as oceanic overturning circulation (Meredith *et al*., 2019); and improvements in model parameterisations so that they capture the complexity associated with interplay between multiple stressors (Henley *et al*., 2020). Another key consideration is spatial and temporal gaps in the data/ our knowledge. Direct sampling in the Southern Ocean is logistically challenging and expensive. It is typically restricted to the spring and summer months and to regions nearest to research bases and supply hubs. This biases our understanding of processes that occur in certain regions and/or at certain times of the year (Henley *et al*., 2020). To fill these gaps will require an international co-ordination of effort to work as part of integrated work programs (e.g. the Southern Ocean Observing System, Newman *et al*., 2019) to obtain standardised datasets (Henley *et al*., 2020) and provide improved data coverage. Innovations in technology such as autonomous vehicles, remote monitoring stations and the utilisation of improvements in satellite remote sensing will increase our ability to sample inaccessible regions (e.g. under ice sheets) and provide long term time series data with improved spatial-temporal coverage (Morley *et al*., 2020).

Given the model limitations and data gaps discussed, understanding ecosystem response to climate change is challenging. This is compounded by the mismatch between the temporal and spatial scale of climate projections and those of ecological processes (Cavanagh *et al*., 2021). Ecosystem-based management is considered on multi-annual/decadal timescales. Such timescales are dominated by natural variability of the climate system making it difficult to predict with present day climate models (Cavanagh *et al*., 2017). It is further compounded by limited long-term time-series data which limits our ability to differentiate natural variability, the influence of recovering populations from historical exploitation (such as at SGSSI), and global change impacts that may result in ecosystem regime shift (Morley *et al*.,2020). This uncertainty makes it is difficult to inform policy and decision makers. To address this, time and money must be allocated to maintain long-term sampling programs (Morley *et al*., 2020) and improve end-to-end ecosystem modelling (Cavanagh *et al*., 2021). This will improve understanding of the mechanisms that link physical variables to ecological processes, their interactive effects, and connections to ecosystem services and assist in addressing uncertainty about how ecosystem structure and function respond to change.

Conservation of mature undamaged habitats and ecosystems is more effective than restoration, remediation, and recreation. Spatial protection in the Antarctic represents a globally important opportunity to protect unique and diverse ecosystems which provide globally important ecosystem services. With the development of new, or adaptation of pre-existing MPAs, it is

important that they are 'future proofed' in terms of spatial coverage and connectivity to other reserves to ensure a connected, representative network of MPAs. This will require consensus between nations and including the establishment of protection in areas beyond national jurisdiction.

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