Table S2. Summary of ecosystem services (ES) provided by the Southern Ocean (SO) and how they may be affected by change.

Ecosystem services (ES) are categorised in this table as provisioning, regulating, supporting and cultural (MEA, 2005); followed by a summary of the biological components deemed essential to the provision of each ES[1] (Grant et al., 2013); the key climate-related[2] drivers of change (IPCC, 2019); followed by summaries of potential future impacts on the biological components[3]. This information was used to assess the risk of climate-driven change affecting the capacity of the ecosystem to deliver the ES in the future (Tables 1 and 2 in the main text). Drivers in italics are those for which there may be potential biological impacts but there is currently insufficient evidence to include these as part of the risk assessment. Other key (non-climatic) drivers are listed here and discussed further in the main text (while noting that for each ES this could potentially include all the drivers that affect Southern Ocean (SO) ecosystem structure and processes[4]). Information is included on demand[5] and whether the ES (and/or the biological components) are explicitly considered by instruments of the ATS[6]. The table focuses on the circumpolar scale (unless otherwise stated) with regional-scale nuances discussed in the main text and case studies. The table is split into two parts: (a) the ES for which we undertook our risk assessment (Table 2 in the main text) and (b) additional ES that we identified but did not assess in this study (see Methods). We have not included the ES water or air quality regulation. i.e. the uptake of chemicals and pollutants from the ocean and atmosphere, or waste treatment, i.e. decomposition of organic wastes by bacteria and microorganisms. These are underpinned by a complex network of interacting ecosystem processes and merit separate studies. For information about levels of confidence, see Abram et al. (2019).

*the ES that form the detailed case studies in this study.

[1]The table does not include physical components of ES. The source of information on biological components is primarily Grant et al. (2013) with any additional references cited.

[2]The source of information on the drivers in this table is the IPCC SROCC (IPCC, 2019), predominantly Chapter 3 (Meredith et al., 2019), those included are those considered as the key drivers in the context of ecosystem change in the SROCC i.e. sea ice, ocean temperature, ocean acidification, stratification, retreating glaciers, ice sheets, and ice shelf loss, and circulation. Circulation refers to the key components of ocean circulation, especially the horizontal circulation and movement of fronts, and overturning circulation and water mass formation.

[3]The source of information on the drivers and impacts is the IPCC SROCC (IPCC, 2019), predominantly Chapter 3 (Meredith et al., 2019), with detail from other sources discussed in the case studies in the main text.

[4]Each ES is potentially influenced by all drivers that affect aspects of ecosystem structure and processes (including all those listed in both the climate-related and other drivers columns). For space and readability this general-level information is not included except where more specific information is lacking in part (b).

[5]We consider demand to be the societal need for these ES, ranging from the demand for fish as a food source to the reliance on the role of the blue carbon pathway in climate regulation. Based on global increases in human population growth, demand for food, atmospheric CO_2 concentrations and environmental degradation, we expect the demand for all the ES in this table to increase. However, the uncertainty in this expectation is explored further in the main text for each of the case study ES.

[6]For further information refer to https://www.ats.aq/index_e.html and http://www.ccamlr.org/en , and the main text. Note that additional fisheries and environmental management measures (i.e. not within the ATS) are established around some sub-Antarctic islands under national jurisdiction.

Table S2 (a) The ES for which we undertook our risk assessment

ES	**Description and importance/value**	**Ecosystem/ biological components essential to the provision of the ES**	**Key drivers of change (climate-related)**	**Potential future impacts on ecosystem / biological components (that underlie ES)**	**Other key drivers**	**Anticipated changes in demand for ES in the future**	**Consideration of the ES in ATS instruments**
Provisioning services							
Fishery products	*Antarctic krill (*Euphausia superba*) Used mainly in meal and krill oil production, and as the basis for various biochemical products. In the 2017/2018 fishing season, 11 vessels from 5 nations participated in the fishery catching 312,989 tonnes (CCAMLR, 2019), with a first sale value of $US100 to 416 million (based on the values in CCAMLR Commisison	Recruitment – including: availability of suitable habitat, e.g. sea ice – winter/spring krill habitat; dispersal/transport of larvae and juveniles via ocean current systems, e.g. transport of krill in ACC across the Scotia Sea, e.g. from spawning sites along western Antarctic Peninsula to South Georgia. Food availability – primary production – algae associated with sea ice (winter)	Sea ice Ocean temperature Ocean acidification *Circulation*	Regional sea ice changes will have an overall negative effect on Antarctic krill (*medium confidence*) (SROCC Fig 3.6). Some of the temporal and spatial shifts in the fishery have been attributed to reductions in winter sea ice extent (*low confidence*) (SROCC 3.2.4.1.2). Ocean warming and ocean acidification will have an overall negative effect on Antarctic krill	Fishing Population recovery of previously harvested krill-consuming species (e.g. whales)	Increase. Parts of the Southern Ocean other than the Scotia Sea region may become increasingly attractive to the industry as markets and supply chains change. While Antarctic krill is an important economic resource it is not a major source of fishmeal or polyunsaturated fatty acids (contributing <1% of global production of each), nor is it currently an important human food source.	Commercial fishery for Antarctic krill is managed by CCAMLR. CCAMLR principles of conservation: i) Prevention of decrease in size of populations, to ensure stable recruitment; ii) Maintenance of ecological relationships (associated & dependent species); iii) Prevention of changes to ecosystem which are not reversible

	Report 2016 and Grant et al 2013a). This accounts for 95% of the annual catch in the Southern Ocean but <0.5% of the global annual marine fisheries catch (GAMFC).	and phytoplankton blooms (summer). Distribution of adults (availability to fishery), associated with habitat quality/food availability.		(*medium confidence and low confidence, respectively*) (SROCC Fig 3.6). Projected climate-induced changes include changes in distribution, further habitat contraction and changes in abundance for Antarctic krill (*medium confidence*). Optimal conditions for krill are predicted to move southwards (*medium confidence*), with the decreases most apparent in the areas with the most rapid warming. Greatest projected reductions in krill due to warming and ocean acidification are predicted for SW Atlantic/Weddell Sea region (*low confidence*), which		However, this fishery is one of the few that are theoretically capable of supporting significantly higher catches and may therefore become important future food resources. Better prognostic information would be useful, including forecasts of future demand for krill products.	over two to three decades. Further development of CCAMLR's krill fishery management strategy aims to include regularly updated krill biomass estimates and the spatial allocation of krill catches, together with a risk assessment framework to consider impacts on krill-dependent species.

				is the area of highest current krill concentrations, contains important foraging grounds for krill predators, and is also the main area of operation of the krill fishery (SROCC 3.2.3.2.1).			
	Toothfish: Patagonian toothfish (*Dissostichus eleginoides*) and Antarctic toothfish (*D. mawsoni*), sold mainly as high-value fish for direct human consumption. In the 2017/2018 fishing season, vessels from 13 nations participated in the fisheries for Antarctic and Patagonian toothfish, with a total reported catch of 11,370	Recruitment - including availability of spawning areas in deep water and shallow nursery habitats. Food availability - including notothenids, myctophids, krill. Distribution of adults (availability to fishery).	Ocean temperature	Projected ocean warming may negatively affect cold-adapted fish (*low confidence*) (SROCC Fig 3.6). Increasing water temperatures may affect toothfish species differently due to differences in temperature tolerances for Patagonian toothfish (wide temperature tolerance) and Antarctic toothfish (limited by low tolerance for water temperatures above 2ºC), the	Fishing Population recovery of previously harvested species	Increase	Commercial fishery for toothfish is managed by CCAMLR (see principles of conservation above). Catch limits and other regulations for fisheries in each subarea are reviewed annually.

	tonnes (inside the CCAMLR Area; both species combined) (CCAMLR, 2019). Mean annual wholesale value of Southern Ocean toothfish fisheries: US$206.7 million per year 2011-2015. Publicly available information on the market value of toothfish products indicates a wide price range from US$10-50/kg (Grilly et al., 2015).			latter may be faced with reduced habitat and potential competition with southward-moving Patagonian toothfish (*very low confidence*) (SROCC 3.2.3.2.3). Recruitment has been shown to be inversely correlated with sea surface temperature for Patagonian toothfish at South Georgia (SROCC 3.2.3.2.3). Differences in temperature tolerance of toothfish species may have implications for future fisheries (SROCC 3.2.3.2.3).			
	Mackerel icefish (*Champsocephalus gunnari*).	Recruitment. Food availability (e.g. krill, copepods,	Ocean temperature	Increasing water temperatures may displace icefish (family Channichthyidae)	Fishing Population recovery of	Increase	Commercial fishery for mackerel icefish is

	In the 2017/2018 fishing season, total reported catch of mackerel icefish was 573 tonnes. (see also Table S2(b) - Previously and potentially harvested species)	myctophids, benthos). Distribution of adults (availability to fishery).		in marginal habitats (e.g., shallow regions around subantarctic islands) as they lack haemoglobin and are unable to adjust blood parameters to an increasing oxygen demand (*low confidence*) (SROCC 3.2.3.2.3). Lack of recovery of mackerel icefish stocks after cessation of fishing around the Antarctic Peninsula in 1995 has been related to anomalous water temperatures (~2°C increase related to a strong El Niño) in the subantarctic Indian Ocean and to availability of krill prey in the Atlantic region (*low confidence*) (SROCC 3.2.4.1.2).	previously harvested species		managed by CCAMLR.

Regulating services							
Climate regulation	*The blue carbon pathway is the capture and fixation of carbon by marine organisms, through storage in the bodies of organisms (for up to 100 years) to sequestration (which is removal of carbon from the carbon cycle for 100+ years).	Carbon capture from dissolved CO_2 by phytoplankton. Consumption of the phytoplankton and storage of this carbon by consumers (zooplankton and benthos). Burial (and subsequent sequestration) of pelagic and benthic biomass. Most carbon is recycled in the microbial loop by bacterial breakdown of phytoplankton and animals. The amount actually sequestered depends on factors such as bottom oxygenation (bioirrigation, bioturbation etc)	Sea ice Retreating glaciers, ice sheets, and ice shelf loss *Ocean temperature* *Ocean acidification* *Stratification* *Circulation*	Carbon uptake and storage by Antarctic benthic communities is predicted to increase with sea ice losses (SROCC 3.2.3.2.2). There is *high agreement* based on *medium evidence* that ice shelf retreat or collapse is leading to new marine habitats and to biological colonisation. These newly-revealed habitats have resulted in enhanced carbon uptake by coastal marine ecosystems (*medium confidence*) (SROCC 3.3.3.4). There is evidence that glacier retreat can impact the structure and function of benthic communities (*low*	Generally the drivers that affect SO biodiversity, e.g. disruption by non indigenous species establishments and fishing, e.g. longline bycatch.	Increase. The reduction of atmospheric carbon is a major societal goal with the blue carbon pathway is recognized as an important ecosystem service, and increasing interest in the polar regions.	There is currently no specific management or policy for this ecosystem service by the ATS. However fisheries management and other conservation measures (e.g. to reduce impact on Vulnerable Marine Ecosystems (VMEs)) under CCAMLR, and regulation of other human activities under the Environmental Protocol (e.g. to prevent pollution and the introduction of non-native species have the potential to influence biological carbon storage and its likelihood of sequestration, despite not being specifically aimed at this.

		what the organisms are made of, local microbial activity etc.		*confidence*) (SROCC 3.3.3.4).			
Supporting services							
Primary production	Assimilation of energy and nutrients by phytoplankton, as a food source for higher trophic levels.	Production of oxygen and uptake of CO_2 by phytoplankton. Summer phytoplankton blooms, growth of winter and spring sea ice algae. Upwelling of nutrient-rich waters. Role of metazoans, e.g. recovery of depleted whale populations, could enhance the recycling of iron in the upper water column and so increase primary production (Nicol et al., 2010).	Sea ice Ocean acidification Stratification Retreating glaciers, ice sheets, and ice shelf loss *Circulation*	Regional sea ice changes have mixed effects on phytoplankton (*medium confidence*). Projected changes in ocean acidification will have a negative effect on coastal phytoplankton (*medium confidence*) and mixed effects on open ocean phytoplankton (*low confidence*). Projected changes to stratification (mixed layer depth) will have mixed effects on phytoplankton (*medium confidence*). Increased light and iron have positive effects on phytoplankton at	Population recovery of previously harvested species (e.g. whales)	Increase	No specific recognition

				high latitudes (south of 65°S) (*low confidence*), associated with ice melt and changes in stratification. Ice shelf losses have positive effects on phytoplankton (*medium confidence*). E.g. exposure/creation of new habitat. (SROCC Fig 3.6)			
Nutrient cycling	Cycling of nutrients required for plant production such as nitrogen, phosphorus & silicon. The supply of limiting micronutrients for productivity (most commonly iron) is a dominant influence on Southern Ocean marine ecosystem dynamics.	Nitrogen fixation, microbial communities, decomposition of organic wastes. Role of metazoans, e.g. fertilisation by krill, myctophids and whales (Nicol et al., 2010; Cavan et al., (2019).	Retreating glaciers, ice sheets, and ice shelf loss *Sea ice* *Stratification* *Circulation*	Both polar ice sheets have the potential to release dissolved and sediment-bound nutrients and organic carbon directly to the surface ocean via subglacial and surface meltwater, icebergs, melting of the base of ice shelves, in addition to indirectly stimulating nutrient input via upwelling associated with subglacial	Population recovery of previously harvested species (e.g. whales)	Increase	No specific recognition

				meltwater plumes (SROCC 3.3.3.3).			
Cultural services							
Tourism and recreation	*Tourist cruises, yachts, scenic flights, adventure tourism, etc. Much of the tourim is based on wildlife present at established landing sites.	Antarctic wildlife, particularly marine mammals and birds, and their prey species, including Antarctic krill. Areas of particular aesthetic value.	Sea ice Retreating glaciers, ice sheets, and ice shelf loss	Climate-induced changes may change access to established visitor sites/facilitate access to new locations; and affect the wildlife present at established tourist sites: Regional sea ice changes are currently having and will have (in the future) mixed effects on marine mammals and penguins (*high confidence*). Krill-dependant predators may also be affected by changes in Antarctic krll populations (see above) (*medium confidence*) (SROCC 3.2.3.2.1, 3.2.3.2.4, 3.2.3.2.5);	Visitations Pollution Fishing (potential impacts on krill-dependent predators) Population recovery of previously harvested species (e.g. whales)	Temporary decline in response to COVID-19 pandemic, then increase.	The ATCM regulates tourism activities, in accordance with the ATS. All operators undertaking activities under the jurisdiction of nations that are signatories to the Protocol on Environmental Protection must also comply with the Protocol. They are also subject to Environmental Impact Assessments. Since the Protocol entered into force (in 1998) two Measures and several Resolutions have been adopted, including the ‘General Principles of Antarctic Tourism’.

				Changes to the presence of sea ice as a physical barrier, either allowing or restricting the movement and access of species (*medium confidence*) (SROCC 3.2.3.2.4), and fishing and tourism vessels (SROCC 3.2.4.2, Table 3.4). Newly available habitat on coastlines may provide breeding or haul out sites for predators such as penguins and seals (*low confidence*) (SROCC 3.3.3.4).			

Table S2 (b) Additional ES that we identified but did not assess in this study

ES	**Description and importance/value**	**Ecosystem/ biological components essential to the provision of the ES**	**Key drivers of change (climate-related)**	**Potential future impacts on ecosystem / biological**	**Other key drivers**	**Anticipated changes in demand for ES in the future**	**Consideration of the ES in ATS instruments**

				components (that underlie ES)			
Provisioning services							
Genetic resources. Biochemicals, medicines and pharmaceuticals.	Genetic diversity in all marine species, including harvested resources. Bioprospecting for biological resources (plants, animals, microorganisms) that can be used for e.g. pharmaceutical or industrial products.	A range of ecosystem components.	Essentially all the drivers that affect SO ecosystems	A range of effects on ecosystem structure and processes.	Drivers that affect SO ecosystem structure and processes	Increase	No specific recognition or legislation under the ATS, although the CCAMLR principles of conservation require the maintenance of harvested, associated and dependent populations, and the Protocol on Environmental Protection regulates human activities to minimse impacts on species and habitats (including requirements for Environmental Impact Assessment).
Previously and potentially harvested species.	Finfish species such as marbled rock-cod (*Notothenia rossi*) and Patagonian rockcod (*Patagonotothen*	Recruitment. Food availability.	Sea ice Ocean temperature	The Antarctic silverfish (*Pleuragramma antarctica*) has an ice-dependent life cycle. There have been documented	Population recovery of previously harvested species	Increase	Fishing for any of these species is not currently permitted by CCAMLR, but the development of future harvesting

	guntheri) were heavily exploited during the 1960s and 1970s, but stocks remain low. Antarctic silverfish (*Pleuragramma antarctica*) were also targeted in the 1970s and 1980s. Fishing for these species is not currently permitted by CCAMLR, but could resume in the future. Additional potentially harvested species (not previously exploited) could include myctophids, grenadiers, rays and copepods. Other species such as southern blue whiting (*Micromesistius australis*), squid and sub-tropical tuna species may migrate into the Southern Ocean			declines in the abundance of this species in some parts of the West Antarctic Peninsula (SROCC 3.2.3.2.3). Species distribution models for *Electrona antarctica*, a dominant myctophid species in the Southern Ocean, project habitat loss associated with increased sea surface temperature (SROCC 3.2.3.2.3).	Potential future fishing		could be regulated under existing CCAMLR frameworks.

	and be subject to harvesting in the future.						
Cultural services							
Spiritual and religious value Aesthetic value Education/science	Spiritual and symbolic value of Antarctica as a wilderness. There are a small number of religious sites operated by some nations. Wilderness areas, wildlife, undisturbed spaces. About 4400 people reside in Antarctic in the summer and about 1100 in the winter, predominantly based at research stations of which approximately 40 are occupied year-round. Southern Ocean as a 'natural laboratory'/ reference area.	A range of ecosystem components.	Essentially all the drivers that affect SO ecosystems	A range of effects on ecosystem structure and function.	Visitation and generally drivers that affect SO ecosystem structure and processes	Increase	Annex V of the Protocol on Environmental Protection recognises "areas of outstanding aesthetic and wilderness value" as areas to be included in the system of Antarctic Specially Protected Areas (ASPAs).

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