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CONTRIBUTORS TO VOLUME 70

Pippa Gravestock
Prospect House, Barnes, London, United Kingdom

Alex D. Rogers
Department of Zoology, University of Oxford, Oxford, United Kingdom

Christopher Yesson
Institute of Zoology, Zoological Society of London, London, United Kingdom

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CHAPTER ONE

A Biophysical and Economic Profile of South Georgia and the South Sandwich Islands as Potential Large-Scale Antarctic Protected Areas

Alex D. Rogers*,[1], Christopher Yesson†, Pippa Gravestock‡
*Department of Zoology, University of Oxford, Oxford, United Kingdom
†Institute of Zoology, Zoological Society of London, London, United Kingdom
‡Prospect House, Barnes, London, United Kingdom
[1]Corresponding author: e-mail address: alex.rogers@zoo.ox.ac.uk

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Abstract

The current hiatus in the establishment of a network of marine protected areas (MPAs) in the Antarctic means that other routes to conservation are required. The protection of overseas territories in the Antarctic and sub-Antarctic represents one way to advance the initiation of such a network. This review of the physical and biological features of the United Kingdom (U.K.) overseas territories of South Georgia and South Sandwich Islands (SGSSI) is undertaken to estimate the importance of the islands in terms of marine conservation in the Southern Ocean and globally. The economy and management of SGSSI are also analysed, and the question of whether the islands already have sufficient protection to constitute part of an Antarctic network of MPAs is assessed. The SGSSI comprise unique geological and physical features, a diverse marine biota, including a significant proportion of endemic species and globally important breeding populations of marine predators. Regardless of past exploitation of biotic resources, such as seals, whales and finfish, SGSSI would make a significant contribution to biological diversity in an Antarctic network of MPAs. At present, conservation measures do not adequately protect all of the biological features that render the islands so important in terms of conservation at a regional and global level. However, a general lack of data on Antarctic marine ecosystems (particularly needed for SGSSSI) makes it difficult to assess this fully. One barrier to achieving more complete protection is the continuing emphasis on fishing effort in these waters by U.K. government. Other non-U.K. Antarctic overseas territories of conservation importance are also compromised as MPAs because of the exploitation of fisheries resources in their waters. The possible non-use values of SGSSI as well as the importance of ecosystem services that are indirectly used by people are outlined in this review. Technology is improving the potential for management of remote MPAs, particularly in the context of incursion by illegal fishing activities and use of satellite surveillance for enforcement of fisheries and conservation regulations. The conflict between commercial exploitation and conservation of Antarctic marine living resources is explored.

1. ANTARCTICA: ECOLOGICALLY UNIQUE, A FRONTIER OF EXPLOITATION, ON THE FRONTLINE OF MARINE CONSERVATION

The Southern Ocean comprises about 6.5% of the world's ocean (Earle and Glover, 2009). It is defined on maps by a political boundary of 60 °S; however, the physical boundary is marked by the Antarctic Convergence which varies in position but can be as far north as 45 °S, and lies to the north of South Georgia/Shag Rocks. The region is characterised by extreme low temperatures (−1.8 to 0.5 °C winter, −1.0 to 3.5 °C summer in the Antarctic; 3.0–11.5 °C winter; 5.5–14.5 °C in the sub-Antarctic; De Broyer and Koubbi, 2014) and seasonality, with sea ice extending to cover up to >20 million km^2 in the winter (NOAA, 2014). Such extreme conditions have developed since the Late Mesozoic as continental drift caused the supercontinent of Gondwana to break up, and the Antarctic and surrounding Southern ocean became isolated some 40 million years ago (MYA; Scher and Martin, 2006; Lawver et al., 2014). The growth of the first Antarctic ice sheets commenced at the Eocene-Oligocene boundary (~34 MYA) coinciding with the further opening of Drake Passage and increasing thermal isolation of the Southern Ocean (Crame, 2014). One result of such climatic "deterioration" has been the elimination of taxa that failed to adapt to increasingly severe conditions, notably durophagous predators such as decapod crustaceans and sharks (reviewed in Rogers, 2012). Other taxa have evolved special adaptations to survive life in the cold and, as a consequence, have radiated within the Antarctic (e.g. notothenioid fish, octopus, peracarid crustaceans, penguins; reviewed in Rogers, 2012). Molecular phylogenetic studies have demonstrated that over millennia the Antarctic has acted as an origin of species that have invaded the deep oceans of the world via the thermohaline circulation (e.g. octopus; Strugnell et al., 2008), while also acting as crossroads for the movement of taxa between oceans, although one with a low-temperature selective filter (Herrera et al., 2015; Rogers et al., 2012; Roterman et al., 2013; Taylor and Rogers, 2015). As a result, the Southern Ocean and Antarctica comprise a unique biogeographic province (Spalding et al., 2007; UNESCO, 2009), with a unique ecology and evolutionary history (Rogers, 2012), as well as a highly endemic fauna (42–56% at class level with the exception of gastropods which are >78% endemic to the Southern Ocean; Griffiths et al., 2009). The short food chains that typify the region lead to abundant populations of marine predators, especially in sub-Antarctic regions (e.g. Murphy et al., 2007).

In this chapter, we detail past overexploitation of predators (including pinniped, cetacean and finfish species) in the Antarctic, with an emphasis on the seas around South Georgia and the South Sandwich Islands. Episodes of overexploitation are still evident today, with some populations of species showing recovery while others remain depleted. In addition, populations of some species are threatened with extinction resulting from human activities other than targeted hunting and harvesting. In particular, the effects of fisheries by-catch have led to the decline of some populations (e.g. some species of albatrosses and petrels). Antarctic marine species show lower rates of growth than temperate or tropical counterparts, as well as deferred age at maturity, higher longevities and slower rates of development (Peck et al., 2006). Many predators also show conservative life histories with low fecundity and extended development times (e.g. wandering albatross, *Diomedea exulans*). Thus, Antarctic marine species are highly sensitive to human impacts and the region requires strategic management and conservation. Moreover, conservation management for the region is becoming increasingly urgent as current and potential changes in populations of Antarctic marine species and ecosystems are increasingly driven by global climate change, including the effects of ocean warming and freshening, increasing strength of westerly winds, changes in the distribution of ocean fronts, ocean acidification and changes in sea ice duration and extent (Aronson et al., 2011; Constable et al., 2014; Flores et al., 2012; McBride et al., 2014). Climate envelope modelling of pelagic predators in the Antarctic suggests that many species will suffer from habitat degradation and will undergo range shifts by the end of the century (Huettmann and Schmid, 2014). Predictions also suggest a poleward shift in the distribution of biogeochemical provinces with variation across regions within the Southern Ocean (Reygondeau and Huettmann, 2014). Urgency in implementing conservation and management policies may be warranted given that the above predicted changes do not account for the possibility of invasions of species from further north (see Cheung et al., 2009) or changes in autecology in Antarctic communities.

Management and conservation of Antarctic marine species and ecosystems falls largely to two organisations, The Committee on Environmental Protection (CEP) and the Convention for Conservation of Antarctic Marine Living Resources (CCAMLR; Grant et al., 2014). The CEP advises the Antarctic Treaty Consultative Committee (ATCM) on the environmental impact of human activities, the prevention of pollution, introduction of invasive species and on climate change effects. In 1991, it was agreed that

the Antarctic Treaty, through the Protocol on Environmental Protection, Article 4, Paragraph 1, Annex V, would acquire the powers to designate "any area, including any marine area" as an Antarctic Specially Protected Area (ASPA) or an Antarctic Specially Managed Area (ASMA) during the Antarctic Treaty Consultative Meeting (ATCM). Annex V was adopted in 2002 and placed the Antarctic Treaty in the unique position of being able to designate any part of the marine environment, including the high seas within the Treaty Area, as an MPA. CEP therefore advises on the designation of specially protected or managed areas including in marine ecosystems (ASPAs and ASMAs; Grant et al., 2014). CCAMLR are effectively a Regional Fisheries Management Organisation (RFMO) that is aimed at regulating the harvesting of the marine resources of the Southern Ocean and Antarctic coastal seas in a manner that is sustainable and with consideration to the wider effects on the ecosystem, especially on species dependent on the targets of fishing (aquatic predators; see below).

The adoption of a regulatory framework to enable spatial protection of areas within the Antarctic, including in marine ecosystems, has been in line with broader measures and targets set by the international community. These range from targets for the establishment of global networks of protected areas within marine and terrestrial ecosystems such as the Aichi biodiversity targets (http://www.cbd.int/sp/targets/), to measures at regional scales (e.g. protection of areas of the Mid-Atlantic Ridge by the members of the Oslo-Paris Convention), or related to specific activities such as the protection of Vulnerable Marine Ecosystems from bottom fishing with active gears such as trawls (Rogers and Gianni, 2010). Such measures have been driven by the perception of widespread degradation of marine ecosystems resulting from human activities, especially fishing. Marine protected areas have become increasingly recognised as a primary tool in spatial or ecosystem-based management (EBM) of the ocean (Agardy et al., 2011; Gaines et al., 2010; Pollnac et al., 2010).

Here we follow the definition of EBM of Thrush and Dayton (2010) as having the goal of maintaining an ecosystem in a healthy, productive and resilient condition so that it can provide the services required by humankind. In the Antarctic, as elsewhere, these include ecosystem services that can be economically valued (provisioning services such as fisheries) and those that are beyond economic valuation at the present time (e.g. regulatory services such as climate regulation; Grant et al., 2013). Marine protected areas have been and are being established to conserve or restore species, fisheries, habitats, ecosystems and ecological functions and for the purposes of poverty

alleviation, or mitigation of, or adaptation to climate change (Fox et al., 2012). They may also be used as a scientific tool for monitoring changes in marine ecosystems. It would seem that as such, the establishment of a no-take MPA around SGSSI singly or as a network of marine protected areas in the Southern Ocean would be appropriate for protection of species and/or habitats or ecologically important areas that are sensitive to human impacts arising from resource extraction, pollution, disturbance or the effects of climate change.

A brief outline of recent activities governing implementation of MPAs in the Antarctic provides informative background for analysis of the usefulness of such spatial management in the region. The Scientific Committee of CCAMLR maintains that the whole of the convention area is a marine protected area as it falls within the definitions of the International Union for the Conservation of Nature's (IUCN) Category IV (CCAMLR, 2014a). Category IV protected areas aim to protect particular species or habitats and management reflects this priority (Dudley, 2008). Annex V, Article 6, Paragraph 2 of the Protocol on Environmental Protection to the Antarctic Treaty (1991) stipulated that no area was to be closed without prior approval of CCAMLR, although this was later modified to include areas where harvesting or the potential for harvesting existed, or where CCAMLR-related activities could be prevented or restricted. Effectively, this gave CCAMLR powers of veto over any MPA in the Regulatory Area where Contracting Parties could make a case that harvesting or some future possibility of harvesting existed. It also meant that any proposals for MPAs had to enter a process of dual consideration by the CEP and CCAMLR.

This placed CCAMLR in a unique position whereby states could use the Commission to refuse any proposals for MPAs that they considered might presently, or in the future, affect their commercial (fishing) activities. While some fisheries' protection measures were directed at specific areas of the Southern Ocean, for example the closure of the Ob and Lena Banks (seamounts; Statistical Division 58.4.4.) to fishing for grey rockcod (*Lepidonotothen squamifrons*; Conservation Measure 32-08, 1997; Lapsed in 2012; CCAMLR, 2014b), there was subsequently little effort by CCAMLR to increase spatial conservation areas in the Antarctic. This was despite recognition by CCAMLR in 2005 of the need to establish permanent spatial protection measures in the Antarctic for the purposes of: (i) protection of representative areas (ii) scientific study to understand the effects of fishing, environmental change and to further the understanding of Antarctic marine ecosystems (iii) to protect areas vulnerable to human impacts thus mitigating

those impacts and/or ensuring sustainable harvesting (iv) protection of important ecosystem processes (Trathan et al., 2014). The CCAMLR Review Panel (2008) identified that there were marked differences in views among Contracting Parties as to how to define ASPAs and ASMAs and indeed, despite the fact that CCAMLR had the power to close areas to fishing for conservation purposes, little action had been taken. Until 2009, the CCAMLR Regulatory Area was not as active as other RFMOs, such as the North East Atlantic Fisheries Commission (NEAFC) and the North West Atlantic Fisheries Organisation (NAFO), in the designation of networks of MPAs to protect VMEs, undermining the classification of Antarctic waters as a Category IV Protected Area.

In 2009, however, CCAMLR and CEP clarified their roles in relation to conservation activities, including the protection of the marine environment, at a workshop (CCAMLR, 2009a). During this meeting, it was agreed that CCAMLR and CEP would work more closely on the protection of marine areas by adopting harmonised approaches to data gathering and designation of protected areas. It was decided that the Scientific Committee of CCAMLR would lead future work on spatial protection and management of Antarctic marine biodiversity (CCAMLR, 2009a). In 2009, the Scientific Committee of CCAMLR agreed to work towards the goal of having a representative system of MPAs in place in the Convention Area by 2012 (CCAMLR Scientific Committee, 2009) and the recommendations of the Scientific Committee were agreed upon at the Commission meeting (CCAMLR, 2009b). Both organisations adopted a unified approach in the use of bioregionalisation methods to identify 11 priority representative areas in the Southern Ocean and coastal Antarctica (CCAMLR, 2008, 2009a; CCAMLR Scientific Committee, 2008). This bioregionalisation approach combined oceanographic, geomorphological and environmental data with information on species diversity and biogeography, to identify methods for distributing a system of MPAs that represent major, as well as rare, ecosystems. However, other approaches, for example, specific knowledge of rare or vulnerable ecosystems, can also be used for designation of MPAs. Two bioregionalisation workshops took place, the first in Hobart, Australia (Grant et al., 2006) and the second in Belgium (Penhale and Grant, 2007). These identified 11 priority representative areas in the Southern Ocean and coastal Antarctica (CCAMLR, 2008, 2009b; CCAMLR Scientific Committee, 2008). These areas were established not only on the basis of both their ecological and biological representativeness, but also on practical considerations and were not meant to be exclusive of other areas.

In 2009, the South Orkney Islands Southern Shelf Marine Protected Area was established following a systematic conservation planning exercise. Planning included use of the bioregionalisation data generated earlier by CCAMLR (Grant et al., 2006) and had the objective of protecting at least 20% of the bioregions present in the area (Grant et al., 2014). The South Orkney Islands are part of British Antarctic Territory and the proposal was driven by the U.K. Government and scientists. Since 2009, proposals for more marine protected areas, including for the Ross Sea, East Antarctica and areas exposed following the collapse of ice shelves in the Antarctic Peninsula region, have been put forward to CCAMLR. Planning is also underway for submissions related to the Del-Cano Rise, the Western Antarctic Peninsula and the Weddell Sea. These proposals met with objections from members of CCAMLR, notably Russia and China, on the following grounds (CCAMLR, 2014a):

- The proposed areas were not pristine.
- Issues with the design of MPAs.
- The MPAs were too large to monitor.
- Lack of information on which to base designation.
- Insufficient justification that there were threats that may cause irreversible damage to ecosystems.
- Disagreement over the application of the precautionary principle.
- Concerns over protection of the rights of fishing states (the balance between rational use and conservation).

In response, we offer the following observations. First, there are few areas, if any, on Earth that can be viewed as pristine. Further, as stated by the United States (U.S.) at the CCAMLR Commission meeting of 2014 (CCAMLR, 2014a), MPAs may be established anywhere where they will achieve the management objectives for which they are being used. With respect to lack of information, the argument could be made that the precautionary principle would suggest that no-take MPAs should be a priority and are likely to be large in areas where there is a dearth of scientific information. This is because of the risk of unforeseen or unrecognised impacts on species, habitats and ecosystems through harvesting activities. More data means that MPAs can be crafted to achieve more specific conservation objectives with less risk of failure and may therefore be smaller to achieve the same goals. Arguments for and against the use of spatial protection measures in CCAMLR represent very different views of how marine ecosystems should be managed and conserved at the international level. Such contentions are playing out on a wider scale elsewhere in the oceans. It is our view that they largely reflect efforts to

prevent conservation actions that reduce opportunities to fish both in the present time and in the future, actions which are inconsistent with the conservation priority accorded to a Category IV IUCN reserve.

To meet international obligations with respect to spatial protection of the oceans (e.g. the Aichi target of 10% spatial protection for the oceans by 2020), to conserve representative ecosystems before further exploitation of Antarctic marine resources occurs, and to reduce the rate of biodiversity loss regionally and globally (Barnes et al., 2011), there is urgency to progress the establishment of marine protected areas in the Southern Ocean which currently cover an area of ~1% of the region (Douglass et al., 2011). Given the success of the South Orkney's MPA proposal in 2009, one way to accelerate this process may be through the actions of individual states through CCAMLR to initiate the protection of sovereign territories in the Antarctic and sub-Antarctic. There are direct parallels with the SGSSI to the establishment of marine reserves around oceanic islands that are overseas territories and which are surrounded by the high seas (e.g. Hawaiian National Monument and the Chagos Archipelago). The United Kingdom, France, Australia, New Zealand and South Africa have all established protected areas around their sub-Antarctic territories, starting with the declaration of the Macquarie Island Marine Park in 2001 (Commonwealth of Australia, 2001). In this volume, we explore whether such an approach might meet part of the requirement for establishing a network of marine reserves in the Antarctic. We present a case study on the islands of South Georgia and the South Sandwich Islands, part of British Antarctic Territory. We note that the bioregionalisation scheme undertaken by CCAMLR identified both South Georgia and the South Sandwich Islands as priority areas within the entire Southern Ocean and Antarctic coastal seas. A subsequent bioregionalisation exercise, also incorporating data on predator foraging and species distributions, was undertaken on a circum-Antarctic basis by the World Wildlife Fund (WWF; Douglass et al., 2011). This study also identified South Georgia and the South Sandwich Islands (included within a larger Weddell Sea priority area) as areas that would form part of a representative network of marine protected areas for the Antarctic. Douglass et al. (2014) published a further study in which bioregionalisation of benthic ecosystems was undertaken on the basis of depth (partitioned into bathomes), geomorphological features, seabed temperature, sea ice concentration and chlorophyll *a* concentration. Information was also included on barriers to dispersal and endemism, as well as from previous bioregionalisations (Douglass et al., 2014). The authors identified 23 unique ecoregions,

including South Georgia and the South Sandwich Islands. The former was identified as having "Productive shallow environments in the Polar Frontal Zone including the island ecosystems of South Georgia Island and seamounts of the North Scotia Ridge" (Douglass et al., 2014). Reference was also made to the high endemism of the marine fauna (Douglass et al., 2014). The island arc of the South Sandwich Islands was identified as unique in the Southern Ocean (Douglass et al., 2014).

In the following sections of this review, we explore the geophysical and biological attributes of South Georgia and the South Sandwich Islands. We then provide an analysis of the current economics of the islands to better understand potential management, political and economic barriers to designation of all, or part, of the South Georgia and South Sandwich Islands Maritime Zone (SGSSI MZ) as a marine reserve. As such, we examine wider issues related to human exploitation of Antarctic living and non-living marine resources, as well as the possible non-use value and whether benefits to ecosystem services may arise from a partial or full no-take marine reserve.

2. SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS: THE GEOPHYSICAL SETTING

2.1 Geology

2.1.1 Region (Southern South America, Scotia Arc, Antarctic Peninsula, Ocean Basins)

South Georgia and the South Sandwich Islands are located in the Southern Ocean in a tectonically active area. The South Sandwich island arc is a typical intra-oceanic island arc (Vanneste et al., 2002), but is the only one in the Southern Ocean. The South American Plate converges with the Sandwich Plate, on which the South Sandwich Islands are situated, and the former is being subducted at the South Sandwich Trench at a rate of 70–85 mm year^{-1} (Figure 1). The plate melting associated with the subduction zone is responsible for the volcanic activity that has resulted in the island arc and associated submarine volcanoes and deep-sea hydrothermal vents. The vents have been found to host chemosynthetic communities.

Farther west, the Sandwich Plate is separating from the Scotia Plate at the East Scotia Ridge at a rate of 65–70 mm year^{-1} (Vanneste et al., 2002), and can be divided into nine segments (Segments E1-E9) trending approximately north to south. High temperature hydrothermal vents have been discovered on two of the East Scotia Ridge segments (E2 and E9), with fluids

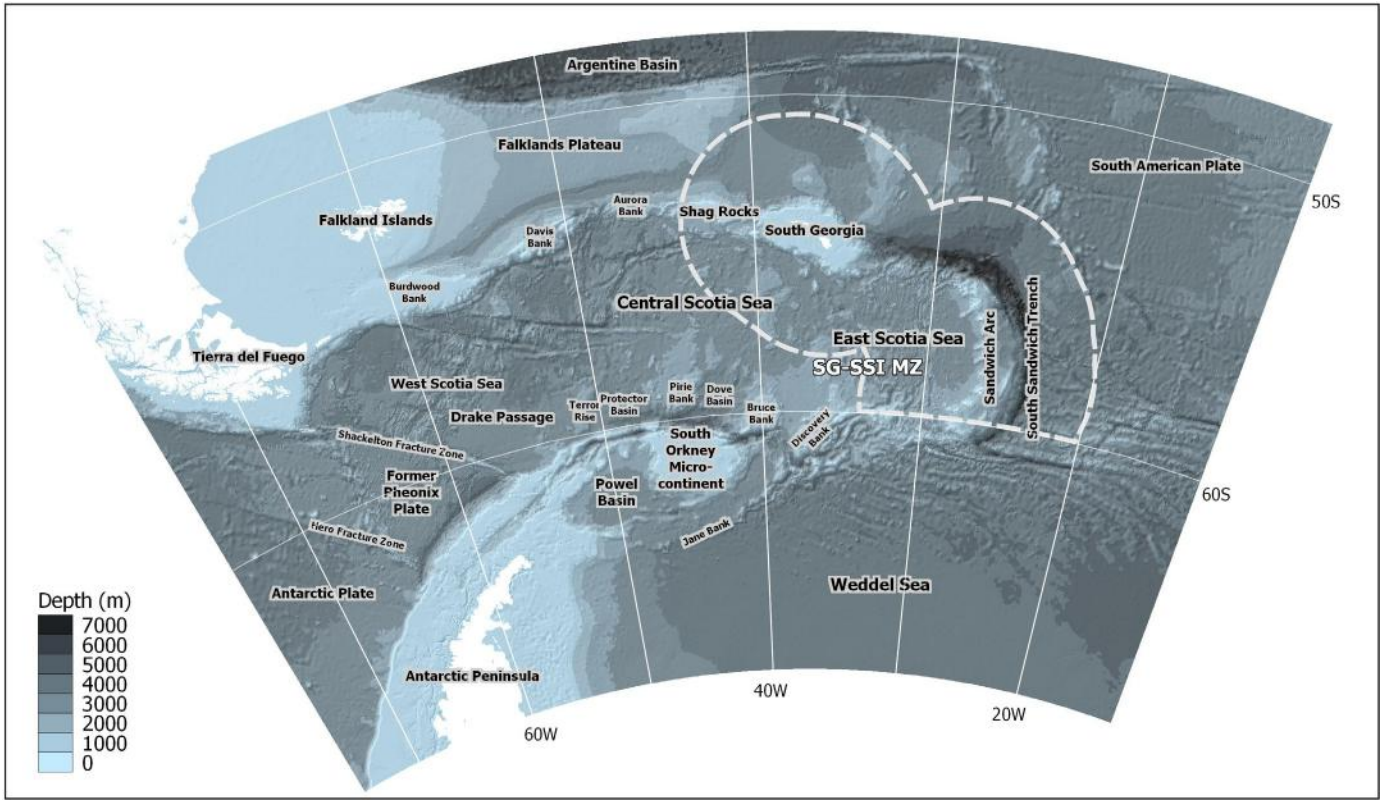

Figure 1 Scotia Sea bathymetric map showing large-scale geomorphology. White dashed line marks the boundary of the South Georgia and South Sandwich Islands Maritime Zone, SGSSI MZ.

emanating as "black smokers" at temperatures of up to 382.8 °C, in some cases, near phase separation, where gases escape from the vent fluid (Rogers et al., 2012). These vents host a newly recognised type of deep-sea hydrothermal vent community, unique to the Southern Ocean, and representing a new biogeographical province of the deep-sea vent fauna globally (Rogers et al., 2012).

To the northwest of the East Scotia Ridge, the North Scotia Ridge lies both inside and outside the South Georgia and South Sandwich Islands Maritime Zone (SGSSI MZ) and forms a series of banks, including the Burdwood Bank, Davis Bank, Aurora Bank and Shag Rocks terminating at South Georgia, the largest island of the Scotia Arc (see Figure 1; Graham et al., 2008). All of these banks, as well as South Georgia, host volcanic rocks that share a similar trace element chemistry and it is likely that they represent a volcanic arc of Cretaceous Patagonia/Tierra del Fuego. Thus, the banks and South Georgia are considered to be continental fragments of Cretaceous Period, or possibly even older (Pandey et al., 2010). The North Scotia Ridge is tectonically active and comprises a convergent boundary with sinistral, or left facing, strike-slip motion between the South American and Scotia Plates (Graham et al., 2008). Together with the South Scotia Ridge to the south, the North Scotia Ridge, East Scotia Ridge and South Sandwich Islands enclose three ocean basins, the West Scotia Sea, Central Scotia Sea and East Scotia Sea (see Figure 1).

2.1.2 South Georgia

South Georgia is located between latitudes 53°56′S and 54°55′S and longitudes 34°45′W and 38°15′W. It forms a roughly crescent-shaped landmass along a northwest-southeast axis and is about 175 km long and 2–40 km wide (Graham et al., 2008; Headland, 1984). The surface area of the island is about 3755 km^2, over half of which is covered in ice and snow. The main island is surrounded by several smaller islands, islets and rocks. These include Bird Island and the Willis Islands off the western part of the main island, Annenkov, and the Pickersgill Islands off the south-western coast and Cooper Island at the south eastern end (Figure 2; Headland, 1984). There are a number of other islands and groups of rocks within the vicinity of South Georgia. The latter include Clerke Rocks, about 65 km ESE from Cooper Island and Shag Rocks, 250 km NW from Willis Island, with Black Rock to their SE (Figure 3). South Georgia is 550 km from the South Sandwich Islands, 1550 km from the nearest point of Antarctica and 2050 km from Cape Horn (Headland, 1984).

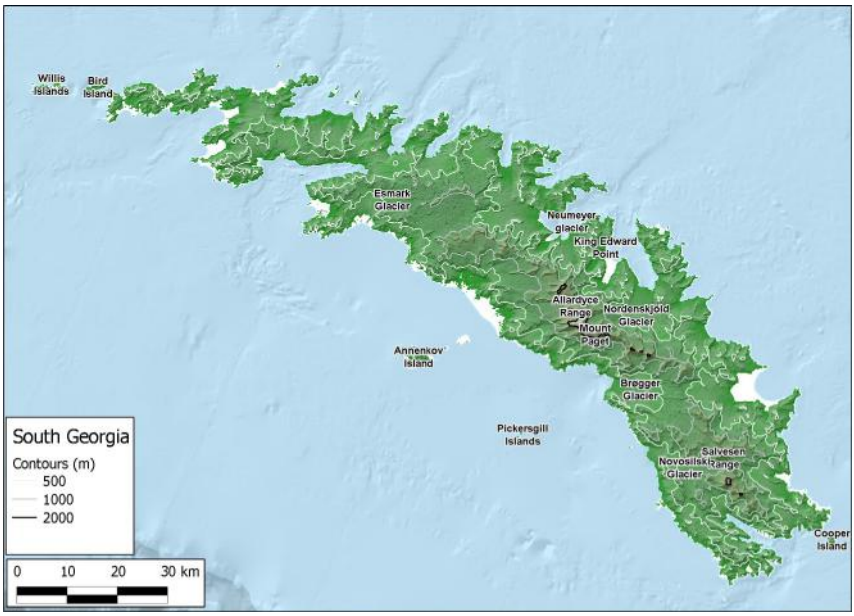

Figure 2 Map of the Island of South Georgia.

The South Georgia Island is very mountainous (e.g. Figure 4), the highest peak, Mount Paget reaching 2934 m above sea level (ASL), with 12 other peaks exceeding 2 km ASL (Headland, 1984). Two main mountain ranges, the Allardyce and Salvesen Ranges, form the island's spine (Headland, 1984). The mountains are dissected by a large number of glaciers (~163; Figure 5) and deep fjords. These interrupt a coast mainly formed by high sea cliffs, especially on the southern side of the island (Murphy et al., 2013).

Beaches on South Georgia, which are mainly located on the northern side of the island, and around Bird Island at the western tip, are mainly formed of shingle, although some are sandy and there are also wave-cut platforms. This is important as it determines the distribution of seal haul-out sites and bird nesting sites along the coastline of South Georgia (e.g. Murphy et al., 2013 for Bird Island). The five largest glaciers, the Brøgger, Neumeyer, Nordenskjold, Esmark and Novosilski have floating snouts and comprise ~25% of the ice cover of the island (see Figure 2). Most glaciers terminate at the coast. Glaciers have been in general retreat on the island since 1925 (Headland, 1984).

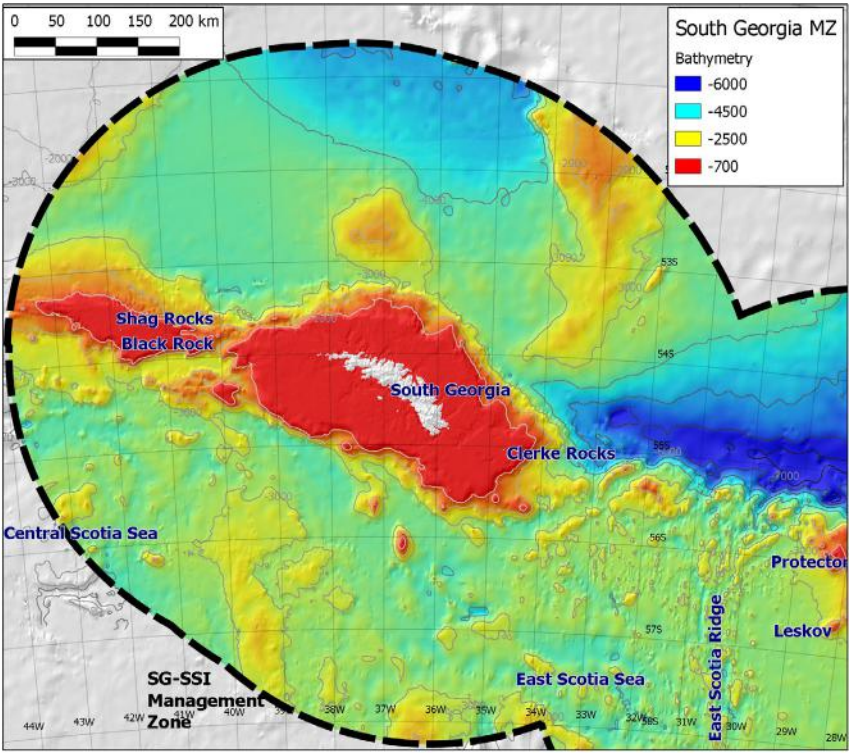

Figure 3 Western portion of the South Georgia and South Sandwich Islands Maritime Zone, SGSSI MZ, showing South Georgia and the positions of Shag Rocks, Black Rocks and Clerke Rocks.

Figure 4 Rugged coastline; southern coast of South Georgia showing mountainous terrain. *Photograph A.D. Rogers, 2010.*

Figure 5 Snow-covered mountains and glacier; northern coast of South Georgia. *Photograph A.D. Rogers, 2009.*

South Georgia Island is largely composed of ~8 km thick sequence of volcaniclastic sandstones and shales known as the Cumberland Bay Formation. The formation was derived from a series of active volcanoes situated in the SE of the area in the Late Jurassic–Early Cretaceous (140–110 MYA; Eagles, 2010; Headland, 1984) with the sandstones and shale formed by bottom-flowing currents laden with suspended sediments in a marine basin. A major fault zone separates the Cumberland Formations from another formation on the north east area of the Island, the Sandebugten Formation, which consists of sandstones and shales also deposited by turbidity currents. A third formation, known as the Cooper Bay formation, occurs as a promontory in the south east of the Island. This formation is thought to be a variant of the Cumberland Bay Formation, derived from a more basic source (Curtis et al., 2010). The oldest rocks on the South Georgia occur in the Drygalski Fjord Complex, are comprised of gneisses and schists, which are thought to underlie much of the island, and are remnants from the original continental rocks of Gondwana 200–186 MYA (Curtis et al., 2010; Eagles, 2010; Headland, 1984). Analyses of the geology of South Georgia suggest that it formed an extension of the Andean volcanic arc at the tip of South America (Curtis et al., 2010). During the Cretaceous period, increased seafloor spreading coupled with a change in the pole of rotation of South America and the convergence of the Pacific and South American Plates led to the opening of the Weddell Sea and the splitting of South Georgia away from the continent to form a micro-continental block (Curtis et al., 2010). The deformation, geochemistry and age of rocks on

South Georgia show a clear affinity to those of the Fuegian Andes in South America (Curtis et al., 2010).

The soils of South Georgia are heavily leached as a result of high levels of precipitation and low temperatures (podzols). Deep deposits of peat sometimes occur near the shore, and soil near seal or bird colonies are sometimes heavily enriched in nitrogen and phosphorus. Most of the island's soils are acidic. Some patterned ground, including stone stripes, soil polygons, circles and steps can occur associated with glacial till or fluvioglacial deposits, mostly relict (Headland, 1984).

Detailed bathymetric surveys of the South Georgia shelf and slope have been undertaken in recent years. This area, which covers about 44,000 km^2 (South Georgia and Shag Rocks shelf from 0 to 500 m depth), has a number of important geomorphological features that influence the distribution of benthic communities around the islands. The most notable of these features is a series of cross-shelf troughs 250–380 m water depth with intervening shallower banks of <80–200 m depth (Graham et al., 2008; see Deep Sea below). These are glacial features and extend from modern-day fjords to the shelf edge. There are at least 10 of these systems; seven discharging to the north of the main island and three to the south. However, data are at a lower resolution for the latter so the number may be underestimated (Graham et al., 2008). The troughs measure between 2 and 5 km wide in the inner shelf and fjords, widening to 12–26 km on the middle to outer shelf. They vary in length between 40 and 102 km and have maximum amplitudes ranging from relatively shallow (~80 m) up to ~250 m (Graham et al., 2008). Along the troughs, depths tend to decrease very gradually seaward. The troughs are U-shaped with steep sides and flat bottoms. Between the troughs, shelf profiles show reverse-gradient slopes with deeper inner to mid-shelf bathymetry and positive-relief banks at the outer shelf. These banks are moraine features and also occur at the shelfward limit of seven of the cross-shelf troughs, and along the axis of four of the troughs (Graham et al., 2008). These banks vary in size from lengths of a few km to ~36 km, widths of 1–12 km and vertical relief of up to >75 m in height and are often crescent-shaped with gently sloping inshore slopes and steeply sloping outer flanks continuous with the shelf break/slope. On the western shelf of South Georgia, these moraines take the form of ridges or banks rising at the edge of the shelf. To the seaward side of the troughs, trough-mouth fans are also visible on the slope. These are formed by focused delivery of sediment to the shelf margin and are usually formed by stacked sequences of glacigenic debris flows (Graham et al., 2008). Other bedforms, such as

drumlins, are also visible within some of the major cross-shelf troughs in South Georgia.

Canyons and gullies are also found on the slope and continental rise in at least two places on the margins of South Georgia (Graham et al., 2008). These canyons are sometimes large and may be straight or sinuous, with a length of >30 km, a width of 2–3 km and with a relief of 100–450 m. They may have been formed by the interaction of turbidity currents and contour currents. Smaller erosion gullies incise the flanks of the canyons (Graham et al., 2008). Large mounds between the gullies/canyons may be drifts formed by entrainment of sediment from turbidity currents or debris flows.

Shag Rocks (53°32.5′S, 42°01.7′W; see Figure 3) comprise two groups of islets about 200 m apart which are sharply pointed, up to 71 m above sea level, and steep on the north-facing side and less steep on the southern side. They are the only visible parts of a continental fragment which has an area of ~11,500 km^2. The block is separated from South Georgia by a channel >1500 m deep through which strong currents flow. The continental block is somewhat wedge-shaped, trending NW-SE with complex bathymetry, especially bordering the channel lying between it and South Georgia (NE corner) and with a distinct ridge running westwards from the western tip. The rocks are formed of a type of green schist with quartzose veins, which may be different from the rocks found on South Georgia, but more closely related to those found on the South Orkney and South Shetland Islands (Tanner, 1982). Black Rock lies about 18 km from Shag Rocks and only rises 3 m above sea level at 53°38′S, 41°48.1′W, with another rock lying to the east over which waves break. Clerke Rocks, lying 74 km to the SE of South Georgia, are also thought to comprise a continental fragment (Thomson, 2004).

2.1.3 South Sandwich Islands

The South Sandwich Islands lie on the small Sandwich Plate and are formed of seven main volcanoes from Zavodovski in the north to Southern Thule in the south (Figure 6). It is considered to be a "simple" intra-oceanic island arc system, and is free of complicating factors such as collision with seamounts, plateaus, ridges, older arc systems, or the occurrence of intra-arc rifting (Leat et al., 2013). Most of the volcanoes lie under the water and they rise some 3 km from the Sandwich Plate basement, which is thought to be ~10 MY old (Leat et al., 2013). In addition, there is a rear-arc volcanic island, Leskov Island and large groups of seamounts at either end of the arc; Protector Shoal at the northern end and Nelson and Kemp Seamounts in the south

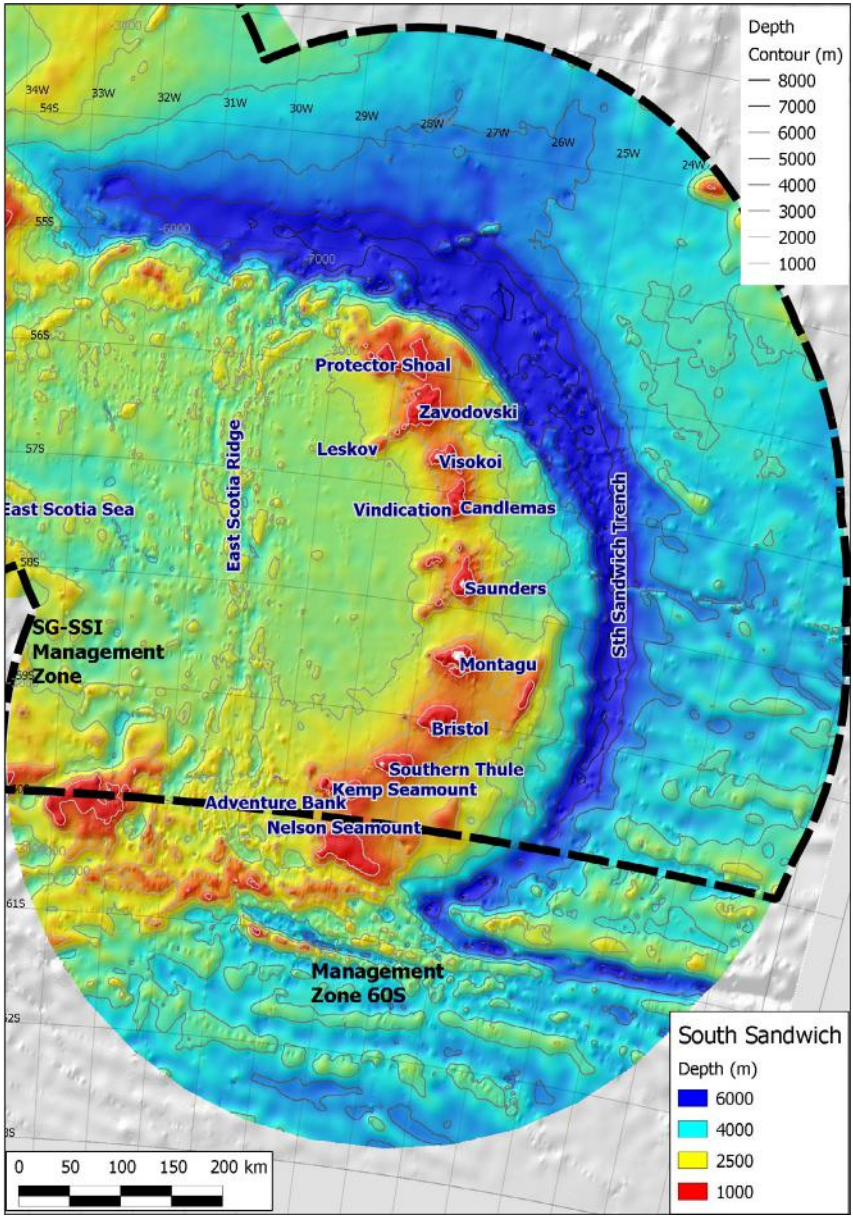

Figure 6 Eastern part of South Georgia and South Sandwich Islands Maritime Zone, SGSSI MZ, showing the South Sandwich Islands and associated seamounts, East Scotia Ridge and South Sandwich Trench.

(see Figure 6; Leat et al., 2013). To the north of the island arc, the South American plate is tearing as a result of the subduction process and the area is seismically active. The subduction trench is up to 8428 m deep (>5 miles; Meteor Deep) and is one of the deepest parts of the world ocean (ninth deepest trench). The islands are geologically young, probably not older than 5 million years (MY) (Thomson, 2004). However, rocks dredged from a bank to the NE of Montagu Island are reported to be much older (28.5–32.8 MY) and may represent a fragment of an older island arc that has shifted position eastwards from closer to the Pacific margin. The South Sandwich Islands represent the only island back-arc system in the Southern Ocean. The islands are predominantly basaltic and most show a recent history of volcanism with Bristol Island (eruption 1956; Holdgate, 1962), Protector Shoal (eruption 1962; Holdgate, 1962), Saunders Island (eruptions 1995–1998; Lachlan-Cope et al., 2001) and Montagu Island (eruptions 2001–2004; Patrick et al., 2005) all having erupted in recent history (Leat et al., 2013). Geologically, the volcanoes making up the seamounts and islands are comparable to those of the Tonga-Kermadec Arc, an area with significant hydrothermal activity and seabed massive sulphide deposition. The South Sandwich Islands are undergoing very rapid erosion, predominantly coastal, with sheer vertical cliffs, up to 350 m in height, pounded by the Southern Ocean. Glacial processes further contribute to the erosion, which is probably higher than other intra-oceanic island arcs globally, and which contributes to large sediment wave fields on the slopes of the islands (Leat et al., 2013). The islands comprise layers of easily eroded lava, scoria and ash and the highest is 1372 m high despite them being only <6 km in diameter. Stabilising vegetation is absent from the islands, although moss banks do occur around some fumaroles.

Protector Shoal comprises an east to west trending chain of eight distinct large seamounts and a plateau. These were initially named PS1–7, but were renamed later, with the exception of PS3 (Tula, Biscoe, Protector Shoal, Endurance, JCR Quest; Leat et al., 2010, 2013; Figure 7). The line of seamounts is approximately 55 km long, lying to the north and northwest of Zavodovski Island. The shallowest of these seamounts is PS4 (Protector Shoal) with a summit depth of 55 m, which is likely to be the site of the volcanic eruption that gave the shoal its name in 1962 after it was observed by *HMS Protector* (Leat et al., 2010). The seamounts have basal diameters from 9 to 15 km and the depth to the base is 700–1500 m. PS1 and PS2 (Tula, Biscoe) and PS3 have smooth outlines and may be older volcanoes, while Protector Shoal (PS4) has major slump features, PS5 (Endurance) has several satellite domes and PS7 (Quest) is a nested crater complex. A new

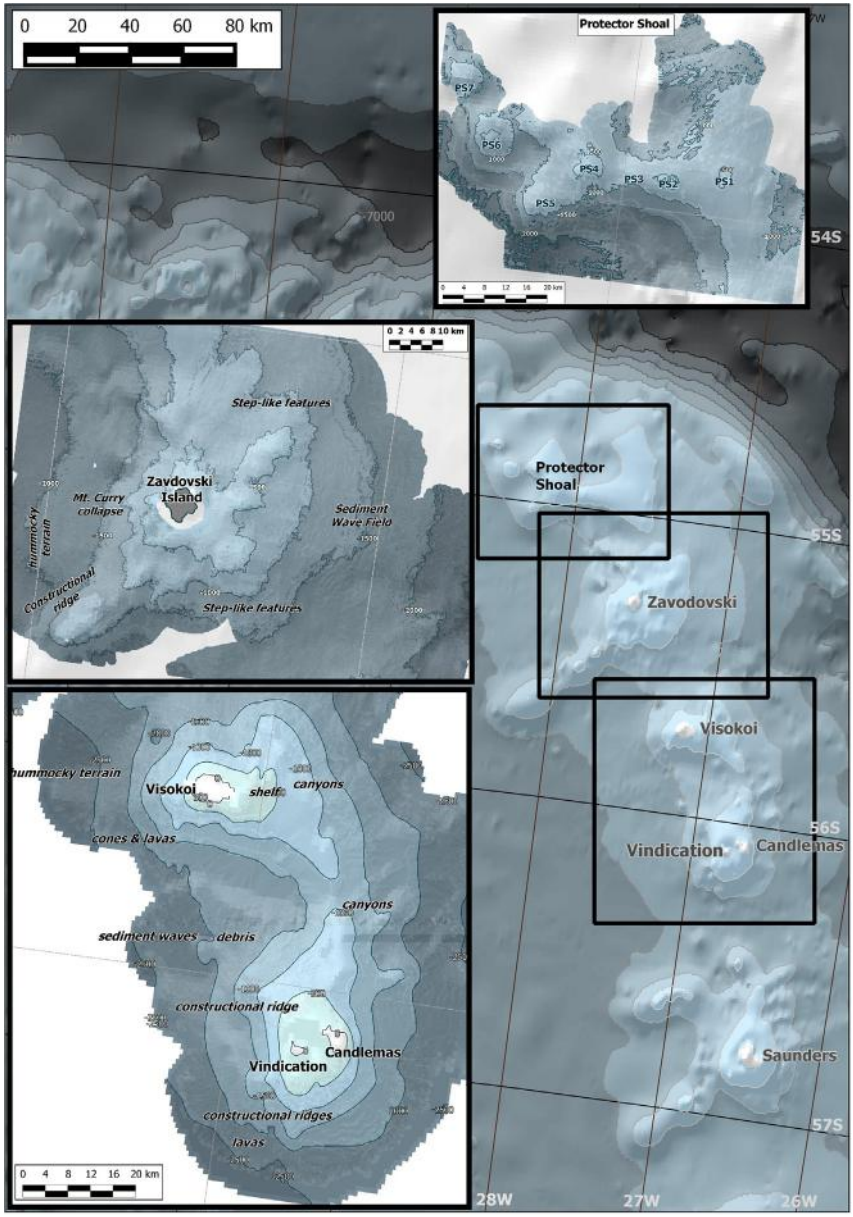

Figure 7 Northern South Sandwich Islands showing surrounding bathymetry of northern islands and submarine peaks of Protector Shoal (PS1–7). *From Leat et al. (2010)*.

seamount, Scoresby, has been identified lying to the west of PS7 (Quest; Leat et al., 2013).

The northernmost island, Zavodovski Island, is the top portion of a large volcano about 54 km across at the 1800 m isobath. The island is about 5 km across and is dominated by a single 551 m high peak, Mount Curry. Zavodovski Island has a permanent snowfield but no permanent glaciers. It is formed by scoria and ash and fumaroles are common on the main crater (there is a second non-active crater). The island is surrounded by a shelf that reaches 6 km in width and is between 70 and 160 m deep. The volcano as a whole is rather asymmetric in structure with submarine ridges to the west that are significantly steeper than the ridges to the east. The western ridges are formed by primary volcanic constructs while the eastern ridges are formed by heavily eroded volcanoes covered in sediment. The construction of these ridges is consistent with a shift of volcanism from the east to the west over time. A volcanic constructional ridge links Zavodovski Island with Leskov Island to the southwest (Leat et al., 2010). The ridge contains a number of volcanos/seamounts including Vostok and Mirnyi (Leat et al., 2013).

Visokoi Island is oval in shape and about 8 by 6 km in size. It rises steeply from low coastal cliffs to about 1005 m at the summit, forming Mount Hodson. Most of the island is covered in glaciers and the summit, which is plateau-like, may be formed of a crater filled with ice. Visokoi is a single large volcano about 40 by 33 km including its submerged slopes down to the 1800 m isobath. A shelf of 2.3–6 km wide surrounds most of the island at ~200 m depth. Most of the submerged north, west and south slopes of Visokoi are steep with rugged topography and many local topographic highs up to 350 m elevation and up to 2 km across. These features are formed by the eruption of domes or cones and the release of lava. The slopes extend approximately 11 km from the island and reach a depth of about 2400 m (Leat et al., 2010). The eastern side of Visokoi is formed by a gently sloping plateau that reaches from about 200 to 600 m in depth, and extends approximately 12 km from the island where it is cut by a number of deep canyons and gullies trending northeast. These canyons are separated by ridges that reach up to 600 m in height and extend as far as 20 km. The canyon floors reach 1800 m deep. These are likely to be erosional features generated by mass wasting of Visokoi (see Figure 7).

The islands of Candlemas and Vindication lie just 4.5 km apart. Candlemas Island is 6 by 4 km in size, and Vindication is 1.5 by 3 km. The edifice, of which the islands are part, is 32 km in diameter at the 1800 m isobath. Candlemas comprises an older sequence of lavas rising to 550 m in height

at Mount Andromeda, as well as a recently erupted group of lavas and scoria cones reaching 232 m height at Lucifer Hill, which is strongly fumarolic. Candlemas and Vindication islands are surrounded by an approximately 12 km wide shelf, housing numerous small islands, seastacks and shoals. The submerged flanks of the edifice slope steeply away on all sides of the island except to the north where the volcano joins with a ridge. Two submerged constructional ridges are located to the south of these islands. Other ridges are located to the west of the islands, with the one to the west terminating in a seamount rising to 950 m, which is a volcano. There are canyons located to the northeast of Candlemas and Vindication islands (see Figure 7).

Saunders Island lies about 73 km to the south-southeast of Candlemas Island. It is roughly hemispherical in outline and has an area of about 40 km^2 (length 8.5 km, width up to 5 km). The island is mainly ice covered and rises to 990 m above sea level at the Mount Michael peak. At the summit, there is a 700 m caldera (collapsed volcanic crater) that sometimes contains a lava lake and steam emissions have been reported from the island (Patrick et al., 2005). Surrounding Saunders Island to the north, northwest and southwest are several large seamounts, anti-clockwise Minke, Orca, Humpback, Fin and Southern Right (Leat et al., 2013).

Montagu Island is the largest in the South Sandwich Islands group and measures approximately 10 by 12 km. The island has a sub-circular to irregular shape, and rises to 1370 m above sea level at Mount Belinda. In the southeastern corner of the island is another satellite peak known as Mount Oceanite. The island is about 90% covered in ice with most of the exposed rock occurring on vertical cliffs on the islands coastline. Mount Belinda was recorded via satellite while it was erupting between 2001 and 2007, with levels of activity varying throughout this time (Patrick and Smellie, 2013; Patrick et al., 2005).

Bristol Island lies about 60 km south-southwest of Montagu Island. It is roughly rectangular in shape and is about 9 km by 10 km, rising to about 1100 m in height at Mount Darnley. The island is mostly ice covered with steep coastal cliffs and slopes. The island has a history of volcanic activity going back more than 150 years.

The islands of Thule (Figures 8 and 9), Cook and Bellingshausen form the Southern Group of the South Sandwich Islands collectively known as "Southern Thule". These islands lie on the wave-cut platform of a single large submerged volcano measuring about 30 km across at its base (Allen and Smellie, 2008). Thule Island is triangular in outline, about 6 km across and rises to about 725 m in height. Thule Island is dominated by a volcanic cone, Mount Larsen, and is largely comprised of inaccessible cliffs with the exception of low-lying headlands at Beach Point and Hewison Point (Allen

Figure 8 The northern part of Thule Island as viewed from the Cook Strait. *Photograph A.D. Rogers, 2009.*

Figure 9 The southern slopes of Thule Island showing the thick covering of ice and snow, as well as sheer cliffs. *Photograph A.D. Rogers, 2010.*

and Smellie, 2008). Cook Island, the largest of the three, is about 6 km in length and rises to about 1075 m in height. It is roughly rectangular with largely inaccessible rock cliffs and bluffs rising to several volcanic cones (Allen and Smellie, 2008). Bellingshausen Island is smaller and younger than the other two, measuring just 1.5 km in length and only rising to 253 m above sea level. It is dominated by a perpetually steaming crater about 500 m across. Thule and Cook Islands are largely covered with ice and snow, whereas Bellingshausen Island is mostly ice free. An eruption was recorded on Thule Island in 1962 when a 150 m wide crater opened up to the west of Mount Larsen (Allen and Smellie, 2008). Between Thule and Cook Islands lies a submerged basin covered on the bottom with a thick layer of sediment.

2.1.4 The Southern South Sandwich Arc Seamounts and Calderas

Just to the southwest of Thule lie several seamounts within the SGSSI MZ, including Kemp Seamount, Nelson Seamount and Adventure Bank (Figure 10). These seamounts represent the southernmost expression of the South Sandwich Islands. Kemp Seamount lies about 70 km to the west, southwest of the island of Thule and is 70 km north of the subducting edge of the plate (Leat et al., 2004). It comes to within ~80 m of the surface and slopes to at least 1800 m depth around its margins (see Figure 10). Nelson Seamount lies 90 km southwest of Thule and rises to within 500 m of the surface. It overlies the southernmost foci of earthquakes associated with the trench (Leat et al., 2004). Recent exploration of this area using acoustic mapping has identified at least two calderas adjacent to two of the seamounts in this group, Kemp Seamount and Adventure Bank. One caldera lies immediately to the west of Kemp Seamount. The caldera walls rise to about 800 m depth from a crater covered in a thin layer of sediment lying at down to 1600 m deep. The walls of the caldera are vertical in places with hexagonal pillar basalts resembling those of the Giants Causeway in Northern Ireland. Methane anomalies led to the discovery of an extensive area of hydrothermal activity located within this caldera on the flanks of a sub-cone lying in the western half of the crater. Hydrothermal vents characterised by hot fluids forming white smokers with white chimneys have been observed at this site along with an associated chemosynthetic community. The composition of this community has not yet been fully investigated, although it is quite different from those of the vents found on the East Scotia Ridge (Rogers et al., 2012; see below). Evidence of further venting has been discovered within the caldera but as yet the source of this has not been discovered. The Adventure Caldera was partially surveyed using a towed camera system

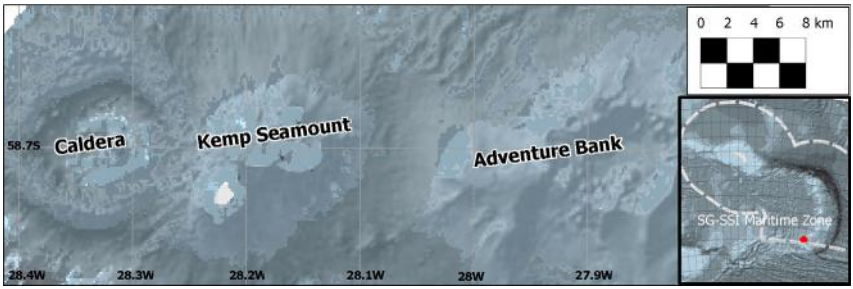

Figure 10 Kemp Seamount and a new caldera (denoted by black square). Lying to the east is Adventure Bank and another caldera. *After unpublished figures by Alistair Graham, British Antarctic Survey.*

in 2011 and at a depth of ~500 m, a 3 m tall chimney venting shimmering fluid surrounded by microbial mats was discovered (CHESSO, 2011).

2.2 Climate

Meteorological observations began on South Georgia with a German expedition to Royal Bay on the SE of the island in 1882 (Shanklin et al., 2009). The longest running series of climatological observations is for King Edward Cove, an inlet of Cumberland Bay on the north coast. The first whaling station was set up in Grytviken, Cumberland Bay in 1904, and weather observations began in 1905 (Shanklin et al., 2009). The observation station moved to King Edward Point (KEP), a distance of about a kilometre, in 1907 (see map Figure 2).

Weather at South Georgia is described as cold, wet, cloudy and windy subject to rapid change and without great seasonal variation (Headland, 1984). This changeable weather occurs because South Georgia lies in the path of depressions coming from the west. Gales occur throughout the year with a maximum of 30 recorded annually (Headland, 1984), with wind speeds recorded up to 96 knots at KEP, a topographically protected location (Shanklin et al., 2009). The strength of winds may be enhanced by local effects of the mountainous terrain and winds may be generated as cold, dense air flows down valleys (katabatic winds; Headland, 1984). These winds may give rise to violent squalls, known as "williwaws" that descend from the mountainous coasts to the sea (Headland, 1984). Warm Foehn winds also occur on South Georgia. These are generated when an air mass, heavily laden with water vapour, arrives on the windward side of South Georgia and is forced to rise over the steep mountains to heights of up to 3000 m (Headland, 1984). The air mass expands and cools and the water vapour condenses into clouds and precipitates as rain or snow. The humidity of the air is reduced and, as it descends towards the north-eastern side of the island, its pressure and temperature increase. These winds may increase temperature rapidly (as much as 10 °C in 10 min) in areas such as KEP in the north-eastern part of the island (Headland, 1984) such that records from this part of the island indicate that the climate is more benign than elsewhere on the island (Gordon et al., 2008).

Mean atmospheric pressure at KEP is around 1000 hPa, with the largest anticyclones having a pressure of ~1030 hPa and the deepest depressions approaching 950 hPa at their centre (Shanklin et al., 2009). Changes in atmospheric pressure occur frequently and over very short time periods as a result of passing depressions. Mean winter temperatures at KEP are around −1.8 °C with recorded extremes as low as −19.4 °C. In summer, temperatures can reach as high as +26.3 °C.

Interestingly, temperatures on the island are changing. A decrease of more than a degree in temperature was recorded from the 1920s to 1950s, followed by a rise of more than a degree after 1950 with most pronounced trends occurring in the summer months (Gordon et al., 2008; Shanklin et al., 2009). Also at KEP, precipitation occurs on an average of 200 days a year, with annual totals at around 1600 mm since the 1940s, and up to more than 100 mm falling in a single day. Overall there has been a recent but erratic trend in increasing precipitation over South Georgia (Gordon et al., 2008). The mountains and exposed south-western coasts are colder, wetter and windier than the leeward north-eastern coast (Gordon et al., 2008).

The changing climate of South Georgia is leading to a shift in environmental conditions on land. There is a general trend towards the retreat of glaciers on the island. Gordon et al. (2008) studied the frontal positions of 36 out of ~160 glaciers on South Georgia and found that 28 were retreating, while 2 were advancing, and 6 showed ambiguous trends. Some of the glacial retreats were dramatic and some smaller mountain glaciers were considered likely to disappear within a short period of time (Gordon et al., 2008). Glacier recession on the south-western windward side of South Georgia is less widespread, reflecting the different climatic conditions in this part of the island (Gordon et al., 2008). The retreat of glaciers potentially allowed further spread of invasive rats as the effects of climate change progress on the islands (see Section 4).

Little specific information is available on the climate of the South Sandwich Islands. Because these islands are further south than South Georgia, the climate is generally colder. The islands are surrounded by sea ice during the winter months. Temperatures permanently hover around freezing. Severe storms affect the islands with oceanic swells of up to 15 m in height lasting 24 h (A.D. Rogers, personal observation). Summer climate is reported to resemble that of the South Orkney Islands, with strong winds, low clouds, fog and rain (Shirihai, 2007).

3. THE ECOLOGY AND BIODIVERSITY OF THE MARINE ECOSYSTEMS OF SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS

3.1 The Pelagic Ecosystem

3.1.1 Oceanography and Ecosystem Productivity

The oceanography of the northern Scotia Sea and much of the Southern Ocean is dominated by the Antarctic Circumpolar Current (ACC; Figure 11). This current is bound to the north by a sharp boundary in

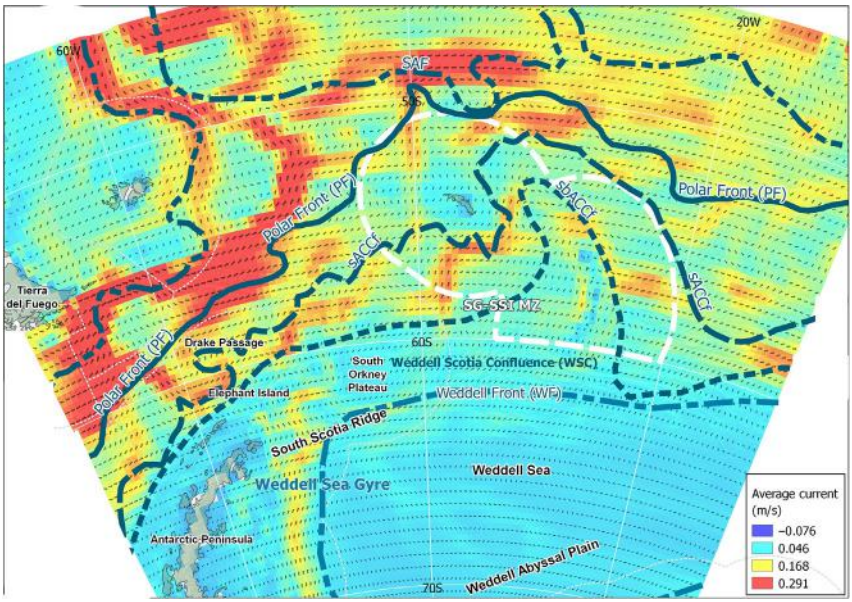

Figure 11 Atlantic Sector of the Southern Ocean showing the region from Drake Passage to the East Scotia Sea and Weddell Sea. Main current flows are shown (ms^{-1}) along with the oceanic fronts: SAF, Sub-Antarctic Front; PF, polar front; sACCf, Southern Antarctic Circumpolar Current Front.

oceanographic conditions, most noticeably temperature, known as the Polar Front (PF), which effectively isolates the frigid Southern Ocean water masses from warmer water masses of the South Atlantic Ocean. The ACC forms an eastward flowing pattern of circulation between latitudes 50° and 65°S (Orsi et al., 1995), transporting about 130–140 Sverdrups (Sv; million $m^3 s^{-1}$) through Drake Passage (Cunningham et al., 2003). The flow leads to relatively constant environmental conditions around the entire Southern Ocean with temperatures south of the PF remaining a consistent 4–5 °C in the north, to 0 to −1 °C south of the ACC Southern Boundary (sbACCf; see Figure 11). Within this circulation regime, changes in solar irradiance and fluctuations in sea ice cover lead to strong seasonal variations in light regime and temperature. Extreme seasonality allows only a brief period when phytoplankton can grow rapidly to produce blooms that lead to a burst of primary production. This production lasts for 2–3 months during the austral summer and aids the development of simple food chains. Thus, Southern Ocean food webs have been considered to be dominated by short food chains of: large diatoms > zooplankton > large predators. However, these food chains are likely more complex. This complexity is

exemplified by the ability of many predators to switch to alternative prey species, and also by observations of various other trophic pathways (e.g. protozoans > copepods > amphipods > large predators; Atkinson et al., 2012). Thus, environmental conditions lead to two extremes of life history and life style. At one extreme are small species that are able to develop quickly in response to favourable conditions, but also able to survive periods of low production. The other strategy is for large-bodied highly mobile predators capable of foraging over hundreds or thousands of kilometres in search of food and with sufficiently high longevity (>10 years) to enable successful reproduction in at least some years (Murphy et al., 2007).

An additional factor affecting species in the ACC region is that primary production is limited by availability of the micronutrient iron. Large areas of the Southern Ocean are classified as High Nutrient Low Chlorophyll areas (HNLC). Although levels of macronutrients (nitrogen, phosphorus, silicate) are high (pre-bloom surface concentrations for nitrate [NO_3], typically >30 mol m^{-3}, silicic acid [$Si(OH)_4$] >60 mmol m^{-3}, phosphate [PO_4] >2 mmol m^{-3}), with a gradient of reduced levels from south to north, levels of primary production are low (reviewed in Murphy et al., 2007). Near Drake Passage, where ACC waters emerge from the Pacific Sector of the Southern Ocean, chlorophyll *a* concentrations can be as low as 0.1 mg m^{-3}, whereas across the central Scotia Sea, they can reach moderate levels of 0.4–1.0 mg m^{-3}. However, some areas of the Scotia Sea are notable for enhanced primary production with chlorophyll *a* concentrations > 1.0 mg m^{-3}. Primary production mirrors chlorophyll concentrations with levels of 0.31 g C m^{-2} day^{-1} in central ocean areas, but over shelf areas, this increases to between 0.72 and 2.04 g C m^{-2} day^{-1} (reviewed in Murphy et al., 2007). In northern areas, such as around South Georgia, where the summer season is longer, annual primary production can reach 30–40 g C m^{-2} (Whitehouse et al., 1996). Near South Georgia, this enhanced primary production takes the form of large diatom blooms, and is thought to be the result of iron release from benthic sources around the islands (Korb and Whitehouse, 2004; Park et al., 2010; Venables and Moore, 2010; Whitehouse et al., 2008). Such enhanced production also occurs to a lesser extent around the South Sandwich Islands. The enhancement in primary production is dramatic and leads to megablooms of phytoplankton (e.g. Whitehouse et al., 2008) and high concentrations of krill (~70% of the entire Southern Ocean krill population occurs in the southwest Atlantic sector of the Southern Ocean; Atkinson et al., 2008) and historically, some of the largest and most diverse populations of seabirds and

marine mammals on Earth. These megablooms are particularly evident to the north/northwest of South Georgia and extend from the shelf eastwards out into the ocean for distances of up to 3500 km (Borrione and Schlitzer, 2013; Venables and Meredith, 2009; Figure 12). Of note, it has recently been discovered that krill can feed at the seafloor in deep waters and may subsequently release iron in surface waters (Schmidt et al., 2011). Analyses of a time series of satellite observations from 1997 to 2010 indicate that intense blooms occur every year to the north and northwest of South Georgia (and North of Shag Rocks) and are tightly constrained by current-topography interactions around the South Georgia Basin (Borrione and Schlitzer, 2013). These blooms generally have two peaks, December and February/March, with a low in January that is thought to be caused by silicate limitation of diatom growth (Borrione and Schlitzer, 2013). Within these blooms, there have been observations of a succession from large diatoms to small cryptomonads and flagellates (Murphy et al., 2013). It is also likely that upwelling of deep water spills onto the South Georgia shelf, and the nutrient rich waters may act to enhance production in the region (Murphy et al., 2013; Whitehouse et al., 2008).

Moderate levels of primary production have been observed in the northern and central Scotia Sea. The reasons for this are not fully understood, but may be related to an input of iron through terrestrial dust transported through the atmosphere from South America (Whitehouse et al., 2012).

The ACC is primarily a wind-driven current that is divided into a number of fronts, which are most narrowly constricted at Drake Passage. Moving

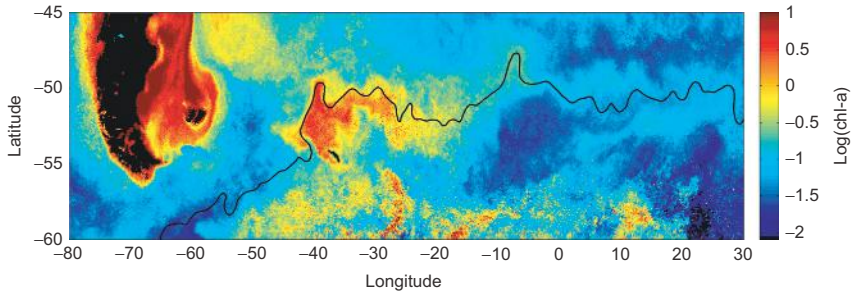

Figure 12 Log (chl *a*) image of mean spring (November–December 1997–2008) SeaWifs chl *a* in the Atlantic Sector of the Southern Ocean together with the mean 45 dyn cm dynamic height contour. The warm colours (red to yellow (dark grey to grey in the print version)) show high levels of chlorophyll and the overall pathway of large blooms originating around South Georgia is shown (Venables and Meredith, 2009).

from north to south these are: the Sub-Tropical Front (STF), the Sub-Antarctic Front (SAF), the Polar Front (PF), the Southern Antarctic Circumpolar Current Front (sACCf) and the Southern Boundary of the Antarctic Circumpolar Current (sbACCf; see Figure 11). The SAF and PF veer northward upon entering the Scotia Sea while the sACCf flows eastwards south of South Georgia (Smith et al., 2010). Although the bulk of the water moving across the North Scotia Ridge is transported by the ACC, water movement over the ridge is also associated with the SAF and PF, and has been estimated at 117–119 Sv. The SAF crosses the North Scotia Ridge east of the Burdwood Bank at a gap in the ridge called the 54–54 Passage (occurring at ~54°S, 54°W) while the PF moves through the Shag Rocks Passage, a 3100 m deep gap in the North Scotia Ridge lying 450 km west of Shag Rocks (Smith et al., 2010). The PF splits into two branches on the Falkland Plateau, one branch topographically associated with the south bank of the Maurice Ewing Bank, the other flowing northward over the plateau (Thorpe et al., 2002; Trathan et al., 1997, 2000). The sACCf moves eastward, but loops back around South Georgia anticyclonically from the south before forming a retroflection eastwards again. The sACCf is steered away from the shelf of South Georgia by the North West Georgia Rise, a bank lying to the north of South Georgia that rises 1500 m above the surrounding seabed centred at 52.5 °S, 37 °W (Meredith et al., 2003a). A complex eddy field is sometimes generated north of South Georgia, and a Taylor Column (a warm-core anti-cyclonic circulation) is frequently generated above the North West Georgia Rise. Taylor Columns are associated with the upwelling of nutrient-rich deep water around seamounts and banks (Rogers, 1994), and north of South Georgia, the feature is sufficiently long lived to generate enhanced primary productivity above the bank (Meredith et al., 2003b). However, the presence of this feature is influenced by the strength of the sACCf and it cannot be regarded as constant (Meredith et al., 2003b). The sbACCf flows mainly eastwards through the Scotia Sea, but is also deflected northwards around the South Sandwich Islands.

Lying south of the ACC in the Scotia Sea are the waters of the Weddell Scotia Confluence (WSC), the boundary between the Weddell Sea Gyre and the ACC (see Figure 11). The WSC is formed by waters spilling off the shelf of the tip of the Antarctic Peninsula, flowing into the oceanic waters that move eastwards (Murphy et al., 2007), and the western boundary of the Weddell Sea Gyre (Matano et al., 2002). Cold dense water also flows down the slope that is north of Elephant Island, and possibly contributes to

Antarctic Bottom Water. The WSC is bound to the south by the Weddell Front. In this region, the position of oceanic fronts can be convoluted as a result of interaction with the topography of the South Scotia Ridge. Overall, approximately 18 Sv are transported along the eastern boundary of the Antarctic Peninsula, and increase to 22 Sv along the northern part of the Weddell Sea Gyre to the east and south of the South Orkney Plateau (Matano et al., 2002). East of this plateau about 6–9 Sv of water escapes through the Powell Basin to the Scotia Sea via the ~3200 m deep South Orkney Passage (~38°W), reducing the overall flow eastwards of the gyre to about 10 Sv (Garabato et al., 2002; Matano et al., 2002). Some water probably also moves through the Philip Passage to the west of the South Orkney Plateau and through the Bruce and Discovery Passages to the east, but the South Orkney (or Orkney) Passage is by far the most important area of movement (Garabato et al., 2002). The water exiting the Weddell Sea moves around the northern part of the South Orkney Plateau before being entrained in the ACC and advected northeast into the Georgia Basin (Matano et al., 2002). The WSC is restricted in position by the South Scotia Ridge, but Weddell Sea Deep Water (WSDW) escapes from the Weddell Sea via a canyon into the South Sandwich Trench. However, most of the outflow from the South Sandwich Trench is recirculated to the south as well as being entrained in the ACC (Matano et al., 2002).

*3.1.2 Krill (*Euphausia superba*) and the Importance of Sea Ice in the South Georgia and South Sandwich Islands*

Antarctic sea ice cover ranges from approximately >20 million km^2 in September to 3–4 million km^2 in February (Massom and Stammerjohn, 2010; NOAA, 2014). It is a dominant seasonal force in the structure and dynamics of the marine ecosystems of the Southern Ocean. Sea ice comprises an assemblage of ice floes which vary in thickness, snow or ice cover, floe size, deformation and other properties and which move at rates of 15–20 km day^{-1} (Massom and Stammerjohn, 2010). The margin of the sea ice zone often includes a transitional zone that may be tens of kilometres wide, the structure of which is often determined by wind and wave action (Massom and Stammerjohn, 2010). The South Sandwich Islands lie within the seasonal sea ice zone. South Georgia does not occur within this seasonal zone, although it does lie in the path of tabular icebergs (sometimes as large as ~300 gigatonnes) originating from the Bellingshausen and Weddell Seas. These icebergs can get stranded on the slope/shelf of South Georgia and have a significant effect on regional hydrography (Brandon et al., 2010).

Ice, and in particular the timing and extent of sea ice, plays an integral role affecting the availability of krill (*Euphausia superba*) to the South Georgia and South Sandwich Island ecosystems. Antarctic krill are the main link between primary production and vertebrate predator populations in the Southern Ocean (Murphy et al., 2007). This is particularly relevant in the Scotia Sea/Atlantic Sector of the Southern Ocean, where about 75% the entire krill population occurs (Flores et al., 2012), and krill availability is responsible for the abundance of predators around South Georgia and to a lesser degree around the South Sandwich Islands (Murphy et al., 2007; see below). Krill population dynamics are strongly influenced by seasonal sea ice. In spring, the melting of sea ice is associated with the release of algal cells incorporated by the sea ice as it forms, as well as by iron taken up in sea ice and snow (Massom and Stammerjohn, 2010). Coupled with increasing light levels and stabilisation of the upper water column by meltwater this leads to a major austral ice-edge spring bloom of phytoplankton in the epipelagic zone (Massom and Stammerjohn, 2010). It appears that the development of the ovaries in female krill begins in the austral spring, and can only continue if sufficient lipids are stored in the body during this period. Thus, female krill rely on the spring ice-edge phytoplankton bloom to build up sufficient stores of energy and nutrients to reproduce in the summer (Quetin and Ross, 2009). Several batches of eggs are released (December–March) and sink rapidly as the embryos develop and hatch in deep water (Nicol, 2006; Quetin and Ross, 2009). The larval stages of krill, known as nauplii, swim towards the surface probably aided by relatively warm, upwelling water of the Upper Circum-Polar Deep Water (Murphy et al., 2007). Three weeks after hatching, the larvae metamorphose into the first feeding stage (Calyptopis I) and they must find sufficient food for continued development within a short period of time (within 6 days according to Nicol, 2006, or 10–14 days according to Quetin and Ross, 2009); otherwise they will die. The timing of the advance of winter sea ice is thought to be an important determinant in the survival of larvae at this early feeding stage (Massom and Stammerjohn, 2010). Larval krill are susceptible to starvation and microbial communities associated with the underside of sea ice (Sea Ice Microbial Communities, SIMCO) provide a critical habitat for larval krill to survive over winter (Quetin and Ross, 2009). The larvae metamorphose into juveniles in late-winter/early-spring and grow through the summer, autumn and winter before emerging the following spring as adults (Nicol, 2006). There appears to be some spatial segregation in the different life-history stages of krill; for example, larvae and juveniles occur inshore of adults during the spring (Nicol, 2006). Sea ice habitat retains

the larvae and transports juvenile krill as well as protects them from predators (Flores et al., 2012). There are many aspects of krill population ecology that are not well understood, as evidenced by the recent discovery of gravid female krill feeding on phytodetritus at depths as great as 3000 m (Clarke and Tyler, 2008; Schmidt et al., 2011).

Variation in seasonal sea ice dynamics has a major impact on the critical phases of krill life cycle, including egg production and larval survival. Thus the timing of the onset of seasonal sea ice, its duration and the timing of melting all have an impact on reproduction and recruitment (Quetin and Ross, 2009). In the Scotia Sea, upwelling waters of the Upper Circum-Polar Deep Water mainly occur along the western Antarctic Peninsula and a few places along the eastern Antarctic Peninsula (Murphy et al., 2007). However, it is not understood to what extent krill spawning and larval development occurs throughout the Scotia Sea, or whether it is mainly confined to the Antarctic Peninsula and southern Scotia Arc with dispersal occurring as krill develop over the following 1–2 years (Murphy et al., 2007). Around South Georgia, there have been observations of major fluctuations of krill abundance with serious impacts on the survival, reproductive success and recruitment of predators (e.g. Forcada et al., 2006; Reid and Croxall, 2001; Trathan et al., 2006, 2007). The driver of this fluctuation appears to be the influx, into the South Georgia region, of large cohorts of young krill that can dominate the population and maintain regional biomass for several years (Murphy et al., 2007). Strong recruitment is influenced by temperature and thus sea ice dynamics around the Antarctic Peninsula region (Atkinson et al., 2004). It is also likely to be related to the strength of winds and current in the region. Studies using a combination of drifter buoys and modelling indicate that strong westerly winds close to the tip of the Antarctic Peninsula can significantly increase advection and decrease travel time to South Georgia (Renner et al., 2012).

All of these phenomena are linked to large-scale atmospheric phenomena, particularly El Niño/La Niña and the Southern Annular Mode (SAM; Renner et al., 2012; Stammerjohn et al., 2008). Renner et al. (2012) found that over a period of 43 years, drifter travel time to South Georgia had decreased by 19%, probably as a result of an increasingly positive trend in the SAM. The influence of this on krill transport to South Georgia is not clear. Shorter transit times for krill from the Antarctic Peninsula to South Georgia may mean lower mortality as a result of shortened journey duration, but the krill may arrive at a smaller size, implying a lower biomass being delivered to the South Georgia Region (Renner et al., 2012).

3.1.3 Climate Change in the Atlantic Sector of the Antarctic and Changes in Food Webs

There is evidence of a general decrease in abundance of krill in the Atlantic Sector of the Southern Ocean since the 1970s, and a coincident increase in the occurrence of salps, a dominant group of gelatinous zooplankton, which are grazers of phytoplankton (Atkinson et al., 2004; Flores et al., 2012). Over this time, a statistically significant increase in the size of krill has been documented (Flores et al., 2012). These changes in krill abundance and size have occurred during a period when the western Antarctic Peninsula has experienced relatively rapid warming (6.5 °C rise in air temperature in July between 1950 and 2005; Stammerjohn et al., 2008). Temperatures of the upper ocean have also increased around South Georgia, and there is evidence of a negative correlation between temperature and krill abundance (Trathan et al., 2003; Whitehouse et al., 2008).

Recent observations have suggested that there is a slight increase in the extent of winter sea ice around Antarctica (e.g. Comiso and Nishio, 2008; Turner et al., 2009). However, there are differences in the extent of sea ice increase among Antarctic regions, and major shifts in temporal dynamics of sea ice (Comiso and Nishio, 2008; Massom and Stammerjohn, 2010). For example, along the western Antarctic Peninsula, there is a significantly later onset in the autumn, and earlier break up of sea ice, and thus a decreasing number of sea ice days (Stammerjohn et al., 2008). These shifts in the temporal and spatial dynamics of sea ice influence phytoplankton community composition and may effect zooplankton/micronekton communities, potentially reducing the reproduction and recruitment of krill in this region (Stammerjohn et al., 2008), thus affecting the supply of krill to South Georgia. In particular, there has been a statistically significant shift of higher chlorophyll concentrations towards the south with a diminishing component of large phytoplankton cells (diatoms) and an increasing component of cryptophytes (small algal cells without mineral shells; Massom and Stammerjohn, 2010). This shift in dominant algal types and size appears to be associated with increased glacial melt along the Antarctic Peninsula (Moline et al., 2008). Meltwater generates a lens of high temperature/low salinity water, which may extend 50 m deep and to approximately 100 km offshore, in the coastal waters of the Antarctic Peninsula. This lens stabilizes the upper water column by reducing mixing with deeper water. The shift in the size of phytoplankton cells has been linked to the increase in salps, which are better able to graze small algal cells than Antarctic krill (Flores et al., 2012; Moline et al., 2008).

The increase in salp populations has important implications for biogeochemical cycling in the Antarctic (Moline et al., 2008). Salps may be effectively considered as a "dead end" in the Antarctic food web because they are not generally preyed upon by higher trophic level predators (although some finfish feed on salps, e.g. the myctophid, *Electrona carlsbergi*; Shreeve et al., 2009). Salps reproduce asexually, which allows salp populations to respond to favourable changes in environmental conditions with the rapid production of offspring (Alldredge and Madin, 1982). Salps are also highly efficient consumers of phytoplankton cells and are able to retain particles as small as 4 μm (Moline et al., 2008). They can graze from 10% to 100% of all of the daily primary production of phytoplankton cells in various regions of the Antarctic (Dubischar et al., 2006). This switch in the Antarctic from a diatom/krill-dominated food web to one where small algal cells are important and salps are the dominant algal grazers may potentially lead to a decrease in transfer of carbon to higher levels of the food web (predators such as penguins, seals (pinnipeds) and whales) by 40–65% (Moline et al., 2008). Transfer of surface production to the seafloor, on the other hand, may be facilitated. Such a switch is likely to cause significant impacts on predator populations and major changes on Antarctic coastal food webs in the region (Moline et al., 2008).

In addition to krill and salps, other organisms can be important consumers of phytoplankton and microzooplankton. Around South Georgia, small copepod crustaceans, in particular, are thought to be the dominant grazers of phytoplankton and protozoans. Their production can exceed that of krill especially in western areas around the island (Atkinson et al., 2012; Murphy et al., 2007, 2013). In fact, copepods may be the most dominant secondary producers across the entire Southern Ocean (Shreeve et al., 2005). Whether krill or copepods are the dominant consumers in any one area may have important influences on biogeochemical processes. For example, krill produce large faecal pellets that sink quickly, whereas copepods produce small pellets that sink more slowly. However, copepods spend long periods in diapause at depths of up to 1000 m where they may die and sink, thus making a larger contribution to carbon flux to deeper water through an alternative route (Murphy et al., 2007). Large swarms of krill may also release large quantities of ammonia; this in turn may promote phytoplankton production as this is a favoured nitrogen source for phytoplankton cells (Murphy et al., 2007). Salps may also have an important influence on biogeochemical processes, since they are relatively unfavourable as a prey source for many predators (Massom and Stammerjohn, 2010). Predatory

amphipods, such as *Themisto gaudichaudii,* may also be important to these processes because they may affect population size of the species that they prey on, including copepods, pteropods and even krill (Atkinson et al., 2012; Murphy et al., 2007, 2013).

Although krill dominate energy flows to higher trophic levels, because of their abundance and size, alternative pathways exist in food webs in the Scotia Sea (Figure 13; Atkinson et al., 2012). Copepods for example may form an important component of the diet of myctophid or notothenioid fish and they are also important for seabirds such as prions, *Pachyptila* and *Halobaena* spp. and other petrels (Murphy et al., 2007). The amphipod *Themisto gaudichaudii* can also form an alternative prey species in years when krill abundance is low (Murphy et al., 2013). Fish, including notothenioids and myctophids, and squid may also provide alternative prey for vertebrate predators if krill are in short supply (see specific details for South Georgia/South Sandwich Island predators below). These alternative food web pathways may become increasingly important in the future if krill continue to decline in abundance and/or become more variable in terms of

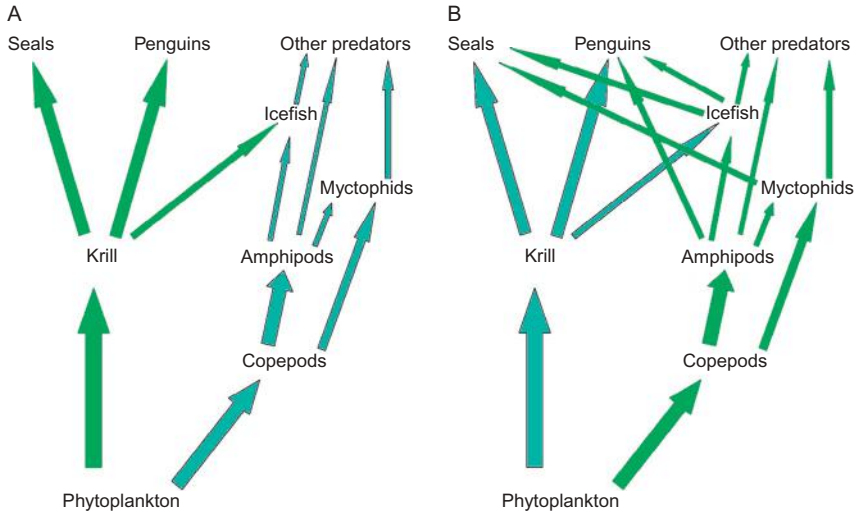

Figure 13 Alternative pathways through Scotia Sea food webs depending on the local/regional abundance of krill. When krill are plentiful (A), they form a direct link between primary production and predators, with other pathways involving grazers and intermediate predators less favoured. When krill are scarce (B), alternative pathways of energy flow occur where krill become less favoured and larger quantities of amphipods and fish are consumed by predators (Murphy et al., 2007).

abundance around South Georgia and the South Sandwich Islands (Murphy et al., 2007, 2013).

Finally, it is important to emphasise that krill are probably an important ecosystem engineer (Atkinson et al., 2012; Flores et al., 2012; Murphy et al., 2013). As has been mentioned already, they are likely to be important around South Georgia in the recycling of nutrients, especially iron and also nitrogen in the form of ammonium. Krill can also out-compete, or suppress, populations of smaller zooplankton, especially copepods through predation (Murphy et al., 2013), and can suppress concentrations of algae such as large diatoms (Atkinson et al., 2012). For these reasons, Antarctic krill is considered to be a keystone species within a "wasp-waist" like ecosystem, altering levels of primary production, effecting biogeochemical cycles and influencing plankton dynamics and predator populations with knock-on effects on the whole ecosystem (Atkinson et al., 2012; Flores et al., 2012; Murphy et al., 2013). Any long-term change in krill abundance in the northern Scotia Sea is likely to cause significant and as yet unpredictable changes in the ecosystem through a series of complex feedbacks resulting from these more subtle interactions of this species with other members in the food web.

Overall, many aspects of pelagic ecosystems in the Scotia Sea are poorly understood. This lack of knowledge includes the distribution of predators (especially in winter), specific components of pelagic food webs (e.g. gelatinous zooplankton, small pelagic fish such as myctophids), interactions between species and many other aspects of ecology. Regarding krill, there are many gaps in knowledge including understanding their recruitment, biomass, wider influence on food webs, the biomass consumed by predators, and their resilience and adaptability to environmental change, especially with respect to climate change (Flores et al., 2012).

3.2 Intertidal Zone

3.2.1 South Georgia

The intertidal and shallow subtidal ecosystems of South Georgia have only been poorly explored and little studied (e.g. John et al., 1994). Most of the work undertaken to date has been on the more sheltered northern side of the island. There, intertidal habitats are exposed to freezing temperatures and ice abrasion in winter and do not have a large tidal range (e.g. ~1.2 m at Husvik Harbour; John et al., 1994). In general, studies suggest that intertidal habitats lack strong zonation (e.g. Barnes et al., 2006). They are also relatively impoverished in fauna and flora (e.g. Davenport and Macalister, 1996; Headland, 1984). However, the insufficient amount of research in recent

years has led to a paucity of information regarding intertidal biota along the northern coast of South Georgia.

Although zonation on South Georgia shores is not strongly demarcated, it is present, at least in terms of algal distribution. John et al. (1994) studied the algal communities at Husvik, on the northern coast of South Georgia, and found that at this sheltered locality the upper limit of the littoral zone may be up to 1.7 m above chart datum on rocky shores and 1.2 m on boulder shores. The upper eulittoral zone in the sheltered localities at Husvik is sometimes dominated by red algae, *Porphyra* spp., which may reach a high abundance and cover on gently sloping shores (John et al., 1994). Other species of red algae associated with this zone, particularly in protected niches, were *Nothogenia fastigiata* and *Iridaea cordata*. The lower eulittoral zone in sheltered localities were dominated by *Palmaria georgica* along with lower quantities of *Porphyra* sp., *Schizoseris condensata* and *Adenocystis utricularis*. In the lower littoral zone, the widely distributed *Ceramium rubrum* can occur intermingled with *Schizoseris*. Below chart datum, small *Macrocystis pyrifera* and *Durvillaea antarctica* plants and encrusting calcareous red algae were observed. Overall, 12–13 algal species were found on the rocky shores at Husvik. Boulder shores in the same locality were found to harbour fewer species of algae (seven to nine) and in one of the two boulder shores investigated, the sides of rocks were covered in a brownish layer of colonial diatoms (John et al., 1994). This difference probably results from increased levels of disturbance associated with mobile substrata on boulder shores and other differences in habitat. Similar algal communities to those identified by John et al. (1994) have been described by Skottsberg (1941) at Maiviken, Cumberland Bay. Pugh and Bartsch (1994) also identified *Ulva* and *Acrosiphonia* to occur in Husvik. A recent preliminary report by Brewin and Brickle (2010), on the intertidal and shallow-subtidal communities of the northern coast of South Georgia, identified *Ulva* sp. present at, or near, the low tide level, along with filamentous green algae (c.f. *Acrosiphonia* or c.f. *Enteromorpha*), brown algae (c.f. *Adenocystis*) and mixed red algae such as *Palmaria* spp.

Fauna of the South Georgia shores are impoverished compared to those of the Falkland Islands and in the maritime Antarctic on Signy Island and the Antarctic Peninsula (Waller, 2008). Searches of cryptic habitat, such as in crevices, under boulders and in algal detritus or in coarse sands can reveal a higher diversity and abundance of invertebrates than is obvious from casual inspection of South Georgia's intertidal zone (Brewin and Brickle, 2010). Most reports describe amphipod crustaceans, gastropods (especially

Laevilitorina caliginosa, *Kerguelenella lateralis* and also *Nacella concinna* on the extreme lower shore) and bivalve molluscs (especially *Gaimardia trapesina*, *Kidderia bicolor*, and *Lasaea rubra*), spirorbid polychaetes and oligochaetes (Barnes et al., 2006; Brewin and Brickle, 2010; Davenport and Macalister, 1996; Waller, 2008). Mussels and barnacles, common in the Falkland Islands and Tierra del Fuego, are notably lacking from the intertidal environment in South Georgia and resident large predatory invertebrates are restricted to the occurrence of the muricid whelk, *Trophon brevispira* (Davenport and Macalister, 1996). In terms of abundance, mites of the Family Halacaridae are also important members of intertidal communities, particularly the species *Rhombognathus auster,* which occurs particularly on algae but also in crevices and under stones (Pugh and Bartsch, 1994). Similarly to algae, mites appear to be more diverse on rocky shores than on boulder shores (Pugh and Bartsch, 1994). Turbellarian flatworms are also reported as being abundant in some areas, with seven species currently known from South Georgia, one of which, *Allogenus sluysi*, is potentially endemic to the island, although the ecology of these animals is poorly known (Brewin and Brickle, 2010; Volonterio and Brewin, 2012; Waller, 2008). The harpacticoid copepod, *Tigriopus* (c.f. *angulatus*), has been observed in upper shore pools (Davenport et al., 1997). These copepods are part of a species complex and their status on South Georgia is unknown (Davenport et al., 1997).

Why the intertidal communities of South Georgia are species poor and in general show a lower abundance of animals than the Falkland Islands and locations further south (Waller, 2008) is uncertain. South Georgia is isolated from other locations with intertidal communities by a distance of about 1300 km (Waller, 2008). The presence of the Polar Front represents a significant barrier to dispersal of the marine fauna, both in terms of species distributions and genetically effective migration of individuals of conspecific populations located either side of the frontal zone (Rogers, 2007, 2012). The marine fauna of South Georgia is generally "Antarctic" in origin and it may be the case that relatively warm temperatures experienced in shallow and intertidal environments exceed the capacity of many intertidal species found further south in the maritime Antarctic (Waller, 2008). Physiological experiments have shown thermal adaptation of intertidal species according to their position on the shore at Husvik, South Georgia whereby upper shore species have a greater thermal tolerance than those from the lower shore (Davenport, 1997; Davenport and Macalister, 1996). Disturbance arising from the presence of glaciers (Pugh and Davenport, 1997), or disturbance caused by the presence of large numbers of aquatic predators, such as

Antarctic fur seals, *Arctocephalus gazella* (Waller, 2008), may also reduce the diversity of South Georgia shores, at least locally. In addition, high levels of freshwater run-off from snow, ice and glaciers and ice scour may also have a negative impact on the intertidal fauna of South Georgia.

3.2.2 South Sandwich Islands

Very little is known about the intertidal zone of the South Sandwich Islands. Accessible boulder shores are present on several of the islands including Thule, Saunders Island (Cordelia Bay), Vindication Island (Braces Point) and Candlemas Island (particularly Kraken Cove and the Gorgon Pool). Some of these locations may have limited rocky shore as well. Zavodovski is highly exposed and has a few accessible but small boulder shores at Reek Point, and between Pungent Point and Fume Point. The bivalve mollusc *Gaimardia trapesina* and gastropods of the genus *Patinogera* are reported from the South Sandwich Islands and may occur in intertidal habitats (Castilla and Guinez, 2000; Knox, 1960).

3.3 Shallow Subtidal Zone to 50 m Depth

3.3.1 South Georgia

Shallow subtidal communities around South Georgia often comprise multi-storied algal communities including large kelps such as *Macrocystis pyrifera,* with an understorey of algae such as *Desmarestia* spp., *Delesseria* spp., *Ballia* spp. and *Gigartina* spp. (Wells et al., 2011). Laminariales are absent from the Antarctic, and large areas of the sublittoral can be dominated by a canopy of Rhodophyta and Desmarestiales such as *Himantothallus grandiflorus* and *Desmarestia* spp., with an understorey of foliose and filamentous algae (Wells et al., 2011). Calcareous encrusting red algae may cover rock surfaces in many areas. The fauna is generally of an Antarctic origin and resembles that of the South Shetland or South Orkney Islands (Barnes et al., 2006). This is supported by observations of recent SCUBA dive surveys where there have been frequent observations of groups such as serolid isopods and Antarctic species including the large nemertean, *Parborlasia corrugatus*, the gastropod limpet, *Nacella concinna*, the nudibranch, *Austrodoris kerguelensis*, the giant isopod, *Glyptonotus antarcticus,* and the echinoderms, *Odontaster validus*, *Diplasterias brucei* and *Sterechinus neumayeri* (Barnes et al., 2006; Brewin and Brickle, 2010). Shallow subtidal communities occur in a variety of geological settings with various substrata from bedrock, rocks and cobbles to soft sediments. Particularly notable is a community located in Moraine Fjord, East Cumberland Bay described by Barnes et al. (2006), where a shallow sill

(~2 m depth) partially isolates the fjord from the open sea and leads to very calm conditions. The waters of the fjord may be subject to freshwater lensing and can be dark as a result of a dense layer of phytoplankton. The seabed is formed of pebbles, cobbles and rock grading to mud, and the invertebrate community is dominated by the stalked ascidian, *Molgula pedunculata,* with occasional hexactinellid sponges, *Rosella nuda* and *R. rascovitae*. Other taxa include large flustrid Bryozoa such as the species *Himantozoum antarcticum*, rare occurrences of the bivalves, *Cyclocardia astartoides* and *Laternula elliptica*, the seastar, *Acodontaster conspicuous,* and, in shallow water, the gastropod, *Nacella concinna*.

Barnes et al. (2006) noted that the shallow-water fauna of South Georgia lacks a high proportion of endemic species, with only the fish, *Harpagifer georgianus*, and the gastropods, *Margarella tropidophorides* and *M. steineni,* having been observed. This is in contrast to the deep-water fauna, which comprises a higher proportion of endemic species (see below). Brewin and Brickle (2010) note a paucity of fish in the subtidal surveys with observations mainly restricted to *Harpagifer* sp., *Lepidonotothen nudifrons*, *Parachaenichthys georgianus* and *Artedidraco mirus*.

Overall, knowledge of the current shallow subtidal communities of South Georgia is poor and restricted to the northern coasts of the island. Most recent SCUBA surveys of these communities undertaken by the Shallow Marine Surveys Group, based on the Falkland Islands, will likely contribute to our knowledge base. For example, 15 new species of sponges were described from a total of 22 sampled (Goodwin et al., 2012). These species are potentially endemics, and the work significantly increases knowledge of sponge diversity of South Georgia, even compared to recent biogeographic studies (e.g. Downey et al., 2012).

3.3.2 South Sandwich Islands

At present, there are no specific studies on the shallow subtidal benthic communities of the South Sandwich Islands. The kelp species *Himantothallus grandifolius* and *Ascoseira mirabilis* were reported from the South Sandwich Islands by Knox (1960), but a recent expedition to the islands did not report any large stands of kelp visible at the surface (as is the case at South Georgia).

3.4 Island Shelves to the Deep Sea (>50 m Depth)

3.4.1 South Georgia

The shelf and slopes of South Georgia and Shag Rocks have been relatively well studied, and much of this work has been for fisheries management

purposes (Agnew et al., 2007; Hogg et al., 2011; Wakeford et al., 2006). Work has included both dedicated fisheries trawl surveys and the sampling of by-catch from longline vessels fishing for Patagonian toothfish, *Dissostichus eleginoides*. Most of the sampling has used surface-deployed sampling gear, such as trawls, and has not targeted specific seabed features. The British Antarctic Survey (BAS) is continuing to conduct this research, and has recently initiated projects to investigate the benthic ecosystems of the South Georgia Shelf (British Antarctic Survey, 2015a).

The Spanish Antárdida 8611 cruise of 1986/1987 employed a fishing vessel with a commercial trawl to sample around the islands of the Scotia Arc. Twenty nine samples were taken around Shag Rocks and 104 around South Georgia (Ramos, 1999). Over the entire survey, sampling was from 26 to 643 m depth and thus restricted to the shelf and upper slope (Ramos, 1999). At Shag Rocks, the fauna was dominated by ophiuroids, echinoids and hydroids followed by asteroids, corals, sponges, actinians and octocorals (Ramos, 1999). Two large ophiuroids, *Astrostoma agassizii* and *Asprospartum gigas*, were particularly prevalent in the samples. Hydroids and octocorals were prevalent in two restricted western areas of Shag Rocks and ascidians were dominant in the southeast. Lithodid crabs from the genus *Paralomis* and polychaete worms from the family Aphroditidae were also notably abundant (Ramos, 1999). Brachiopods, cirripedes, pennatulids, large gammarid amphipods and crinoids were not found around Shag Rocks and asteroids were almost exclusively represented by the species *Labidiaster annulatus*. Ophiuroids were also dominant at South Georgia, being particularly prevalent in the central southern shelf of the island (Ramos, 1999). These were followed in abundance by echinoids, ascidians (particularly *Distaplia cylindrical*), sponges and asteroids. Lithodid crabs were also sampled, along with crinoids, caridean shrimps and brachiopods. An analysis of similarity among the sample sites identified South Georgia as being most closely related to the South Orkney Islands while Shag Rocks appeared to be an outlier (Ramos, 1999).

In addition to documenting the general benthic fauna of the shelf and upper slopes of South Georgia, the Antárdida 8611 cruise also discovered a remarkable serpulid reef formed by the species *Serpula narconensis*, located in the vicinity of Clerke Rocks at depths of 91–105 m (Ramos and San Martín, 1999). The seafloor in this area was reported to be comprised of sand and gravel. Approximately 1.5 t of serpulids were recovered from a single trawl. The serpulids were associated with large numbers of suspension feeding invertebrates including sponges, dendrochirotid holothurians, ascidians and bryozoans (including the species *Othimosia milliporoides*) as well as

actiniarians (described as abundant), ophiuroids, echinoids, isopods (e.g. *Glyptonotus antarcticus*), decapods, seastars, bivalves, gastropods (e.g. *Leucosyrinx paratenoceros*) and opisthobranchs (e.g. *Austrodoris kerguelensis*; Ramos and San Martín, 1999). To date only one similar serpulid reef has been documented in the Antarctic and this was described from Ellis Fjord at the Vestfold Hills, Antarctica (Kirkwood and Burton, 1988). Because *Serpula narconenesis* is brooding, and the prospects of dispersal from the Antarctic continent to South Georgia appear to be extremely low, Ramos and San Martín (1999) speculated that this remarkable biogenic habitat may be a relict that may date back to the Mesozoic. The serpulid reef fits the definition of a vulnerable marine ecosystem and the destructive effect of scientific trawl sampling is a cause for concern. The waters within 12 nm of Clerke Rocks are now a "no-take" marine reserve (Trathan et al., 2014).

Baited camera drops on the north and south slopes of South Georgia and Shag Rocks have attracted lithodid crabs. *Paralomis formosa* was by far the most frequent species observed at these traps but *Paralomis spinossisima*, *Neolithodes diomedeae* and an unidentified *Lithodes* spp. were also observed (Collins et al., 2002; Yau et al., 2002). Estimation of the density of *Paralomis formosa*, from their arrival rate at the bait, varied from 1100 to 25,600 individuals km^{-2} (mean density 8313 individuals km^{-2}; Collins et al., 2002). *Paralomis spinossisima* is endemic to deep waters off South Georgia (Thatje and Mestre, 2010). Other species attracted to the baited camera traps included Patagonian toothfish and other fish species as well as the decapod, *Thymops birsteini*, and octopus (*Paraeledone* sp.; Yau et al., 2002).

In 2004, the seabed around South Georgia and the South Sandwich Islands were sampled using Blake and Otter trawls from the research vessel *Nathanial B Palmer*. Precise depths were not published for invertebrate samples taken around South Georgia and Shag Rocks, but it is likely that the samples were taken from the same trawls as those from which fish were sampled on the same cruise (see Jones et al., 2008). If this is the case, samples were collected at depths of <500 m, with the majority of samples collected from between 100 and 300 m. Catch biomass of benthic invertebrates of the South Georgia/Shag Rocks region was consistently high on the north western shelf area of South Georgia, with estimated densities of invertebrates of 200–301 t $mile^{-2}$ in two sampling areas (Lockhart and Jones, 2008; Figure 14). The highest biomass was reported from a shallow bay (50–100 m) on the NW coast of South Georgia.

At two of the three Shag Rock stations, ascidians dominated the benthos, although echinoderms were also a significant component of the community

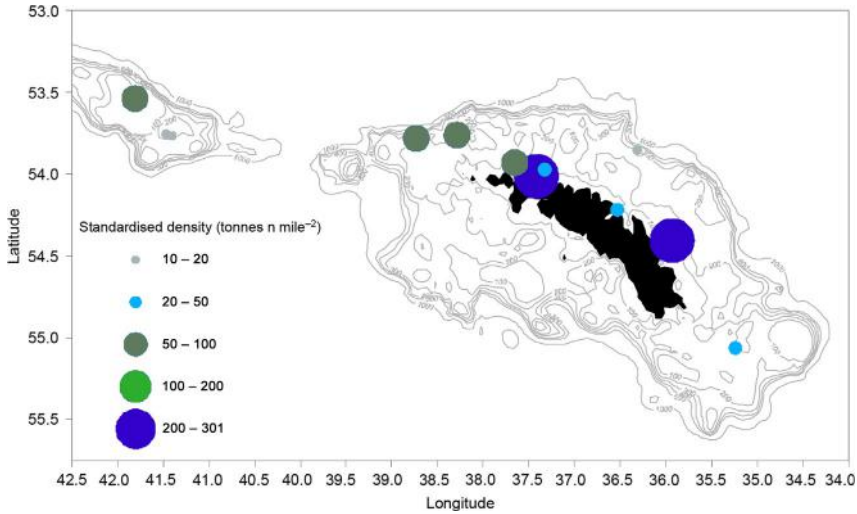

Figure 14 Biomass from trawl sampling stations around South Georgia and Shag Rocks (Lockhart and Jones, 2008).

at all three Shag Rock stations (Lockhart and Jones, 2008). The megafaunal invertebrate assemblages of South Georgia showed considerable variation, although a general trend was observed moving from west to east on the north western South Georgia Shelf region, of a shift from echinoderm-dominated communities to sponge dominated (Lockhart and Jones, 2008). Hexactinellid sponges were reported as dominating the two northern sponge dominated stations, while demosponges dominated the two more southerly stations in this area (Lockhart and Jones, 2008). It is also notable that one sample station was dominated by Cnidaria in this region. The two more southerly stations on South Georgia appeared to show a more mixed community with a significant component of bryozoans (Figure 15).

In 2006, the British Antarctic Survey Biopearl Cruise on the Royal Research Ship (RRS) *James Clark Ross* undertook a wide-ranging benthic survey of the Scotia Arc, from the Falkland Trough to Deception Island, including Shag Rocks, South Georgia and the South Sandwich Islands (Griffiths et al., 2008). This cruise deployed an Agassiz trawl to sample at four depths on Shag Rocks (200, 500, 1000, 1500 m) and at four depths on South Georgia (200, 500, 1000, 1500), the latter all on the north-western shelf region. At both South Georgia and Shag Rocks, there was a marked decrease in biomass of trawl catch with increasing depth, a trend that reflects decreasing food supply and which is found more or less globally (e.g. Rex

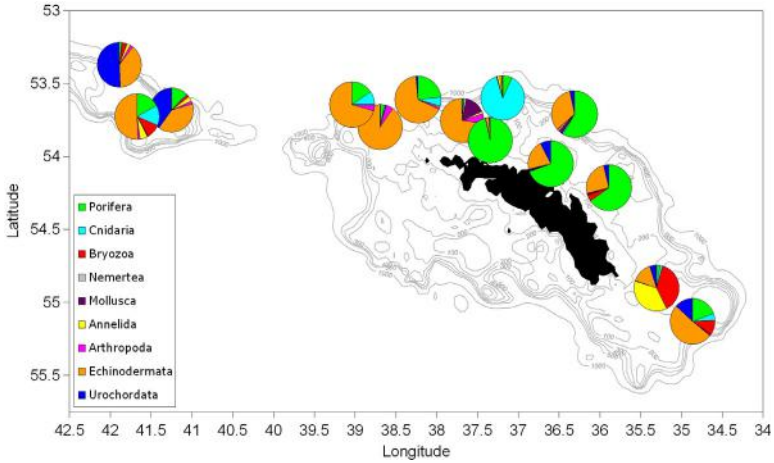

Figure 15 Distribution of the main faunal groups in trawl samples from the South Georgia and Shag Rocks (Lockhart and Jones, 2008).

et al., 2006). There was also a decrease in species richness with depth. At South Georgia, echinoderms, mainly echinoids, form a significant component of the catches at 200 m and dominate catches at 500 m depth (although Stelleroidea also form >20% of the catch by abundance and ~10% by biomass at 200 m). At 1000 m depth, the community is numerically dominated by polychaetes (but by crustaceans in terms of biomass) with a significant component of Cnidaria. At 1500 m depth, the community is formed mainly by polychaetes and crustaceans. Sponges decline in importance in terms of biomass in the South Georgia samples from 200 to 1000 m depth. The communities sampled at Shag Rocks are different with a much higher component of sponges, especially at 1500 m depth where they dominate the community by biomass, and a more important component of cnidarians. As with South Georgia, echinoderms are also important in shallow stations, but particularly at 200 m where the Stelleroidea are especially important.

Overall, analyses of similarity of the stations at Shag Rocks and South Georgia to each other and other stations sampled (by otter trawl) in the study reported by Griffiths et al. (2008) showed little relation to those sampled by Ramos (1999) (using Agassiz trawls). In both biomass and abundance comparisons, Shag Rocks appear most closely related to samples from the Falkland Trough. This similarity is also reflected in results obtained from analyses of the fish communities at Shag Rocks and South Georgia, and supports previous suggestions that South Georgia and Shag Rocks represent a significant biogeographic barrier within the region that is also demonstrated

by studies of communities, and studies of species at the genetic level (see below).

Barnes (2008) analysed the cryptofauna (fauna living on rocks) of Shag Rocks. Samples were collected from the shelf (~200 m) and slope (~1500 m), and a rich cryptofauna, dominated not only by bryozoans in terms of species richness but also including polychaetes, brachiopods, ascidians, corals, hydrozoans (including stylasterids), bivalve molluscs and sponges, were reported. Fauna occupied about 30% of the space on shelf boulders, but <5% on the slope boulders. Cheilostome bryozoa were represented by 60 species. Seven of the species collected were previously undescribed (including one that belonged to an undescribed genus), and the number of undescribed taxa was greater in the deeper samples (Barnes, 2008). Cyclostome bryozoa were also collected and many of these could not be identified, and may possibly also represent new taxa. Overall, the species accumulation curves for this investigation did not approach asymptote and 47% of the taxa were new to the South Georgia/Shag Rocks area. For the described cheilostome bryozoans, a third of the shelf species and a half of the slope species represented the northernmost records to date, which extends the known geographic range for these bryozoans. Barnes (2008) analysed cheilostome species richness of islands in the high latitudes of the southern hemisphere and showed a significant negative correlation between species richness and distance of the islands to the nearest continental slope. Interestingly, the species richness of South Georgia/Shag Rocks is an outlier to this relationship, showing a higher than expected diversity. Lopez De La Cuadra and Garcia Gomez (2000) also identified the high proportion of new species of bryozoans described at South Georgia/Shag rocks in their study as perhaps indicative of an anomalous situation arising from the isolation of this region and/or the mixture of two faunas (Antarctic and Magellanic).

Observers of the Patagonian toothfish fishery in South Georgia have documented by-catch of a variety of benthic invertebrates, including corals, crustaceans and brachiopods (Agnew, 2004). In 2005, observers of the South Georgia fishery were given identification guides to benthic invertebrates and asked to identify species to the highest taxonomic level possible (Wakeford et al., 2006). Samples of the by-catch were collected for subsequent systematic and genetic investigations. Over 13,000 benthic specimens were reported from the fishery in the 2005 season. Cnidarians made up 62% of the by-catch of which 96% were corals, the majority of which were octocorals followed by stylasterids, scleractinians and black corals

(Wakeford et al., 2006). While the corals were caught all around South Georgia and Shag Rocks, several areas were associated with a higher by-catch than others. These areas were western Shag Rocks, both sides of the channel between Shag Rocks and South Georgia, an area off north western South Georgia, an area off north-eastern South Georgia, and an area of south-eastern South Georgia (Wakeford et al., 2006). Overall, there were significant differences in coral by-catch between management areas around South Georgia, and in the levels of by-catch between vessels (Wakeford et al., 2006).

Based on results of research conducted to assess by-catch in the Patagonian toothfish fishery (Agnew et al., 2007), three areas around South Georgia, West Shag, West Gully and Northeast South Georgia, were closed as Restricted Impact Areas (RIAs) in 2009 (Figure 16). These areas had high by-catch per unit effort rates of coral, macrourids and rays (see below), and the closure protected toothfish spawning and juvenile habitats (Agnew et al., 2007). The West Gully RIA was expanded in 2010 to protect toothfish spawning areas. In 2011, two seamounts to the south of South Georgia were also closed to fishing (GSGSSI, 2012). This was a result of particularly large toothfish being caught in the vicinity of these seamounts and the management measure was aimed at protecting individuals that may be important to the reproductive capacity of the South Georgia stock.

Habitat suitability modelling based on the by-catch of octocorals from the South Georgia/Shag Rocks longline fishery (from 2005 to 2009) has been used to gain an understanding of how corals are distributed on the shelf and slope of these islands (Taylor et al., 2013). High-resolution bathymetry (150 m × 150 m grid) data (Fretwell et al., 2009) was incorporated in the modeling. This fine scale bathymetry layer was used to create a benthic habitat classification in Benthic Terrain Modeller (BTM) in ArcGIS 9.3.1 (Rinehart et al., 2004; Wright et al., 2005; Table 1). The habitat classification was used to develop a GIS layer (map) of the terrain features around South Georgia/Shag Rocks (Figure 17). Slope, orientation, curvature and aspect of the identified geomorphological features alongside rugosity (from BTM) were extracted from fine-scale bathymetry (150 by 150 m; Fretwell et al., 2009). In addition to these geomorphological derivatives, environmental and chemical layers were derived from the World Ocean Atlas (Antonov et al., 2006; Garcia et al., 2006a,b; Locarnini et al., 2006) and from the Global Data Analysis Project, GLODAP (Key et al., 2004), using the 'cookie cutter' up-scaling method of Davies and Guinotte

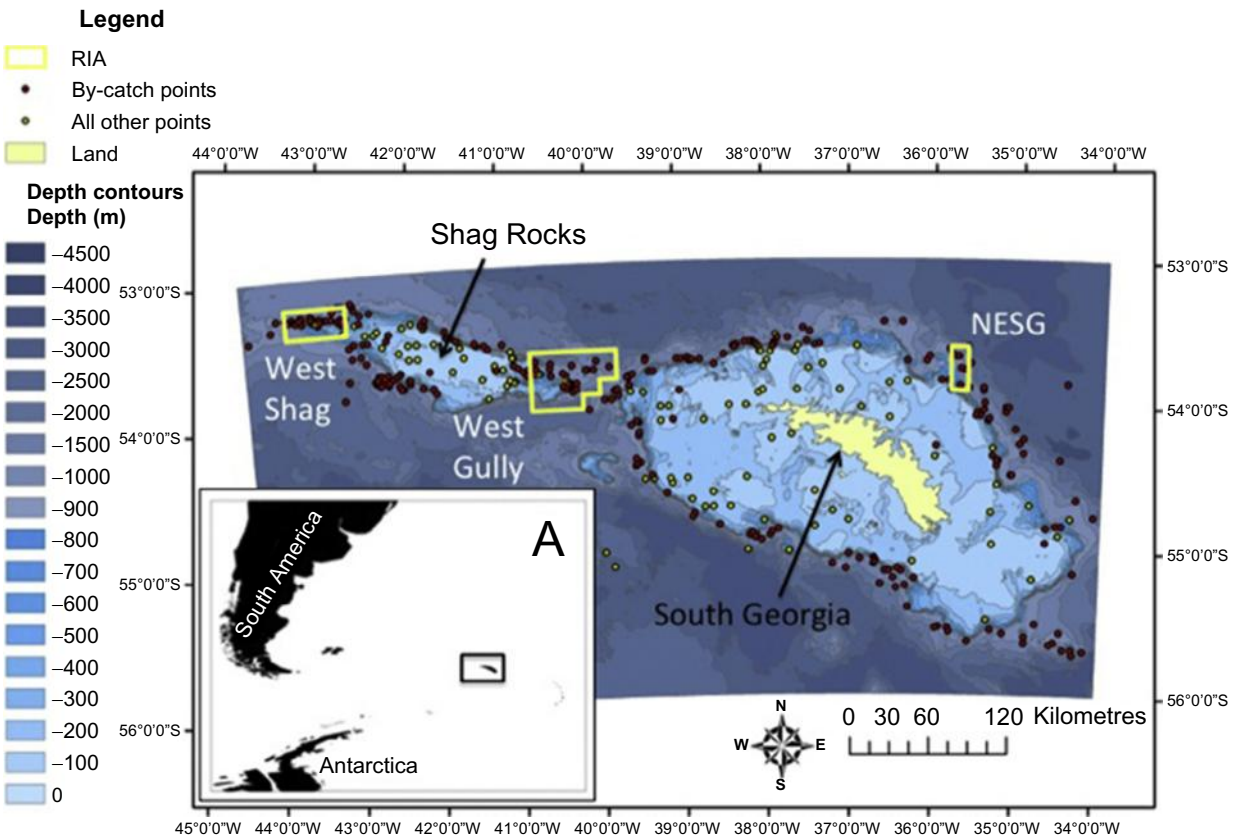

Figure 16 South Georgia and Shag Rocks bathymetry. Red (black in the print version) spots are by-catch samples, yellow (grey in the print version) spots indicate records of octocorals from museums and collections and Yellow (white in the print version) boxes indicate restricted impact areas (Taylor et al., 2013).

Table 1 Habitat Categories and Characteristics

Habitat Classification	Habitat Classification Characteristics
Narrow depression	Negative bathymetric position where both fine and broad terrain features are lower than surrounding by position index values greater than one standard deviation from the mean in a negative direction.
Broad flat	Broad flat area where terrain has few, nested, fine-scale features. Slope $\leq 5°$.
Shelf	As Broad Flat except below a depth of 300 m. Slope $\leq 5°$.
Escarpment	A steep slope of between 5° and 70°.
Narrow crest	Positive bathymetric position where both fine and broad terrain features are higher than surrounding by index values greater than one standard deviation from the mean in a positive direction.
Deep shelf	As shelf except depth of 300–1000 m. Slope $\leq 5°$.

Adapted from Lundblad et al. (2006).

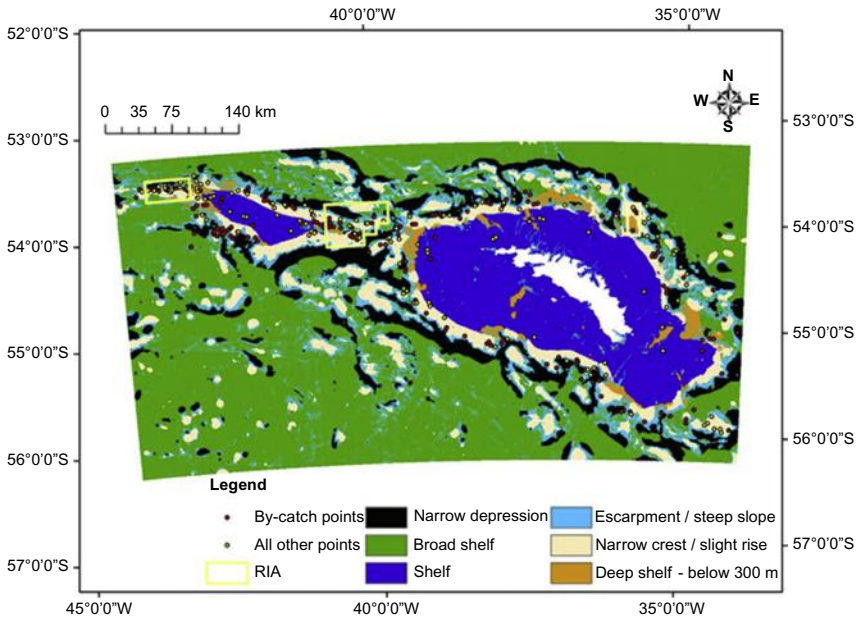

Figure 17 Megahabitat map of South Georgia and Shag Rocks (Shag Rocks located in the centre of west shelf area). Red (dark grey in the print version) spots are by-catch samples, yellow (white in the print version) spots indicate records of octocorals from museums and collections, and Yellow (white in the print version) boxes indicate restricted impact areas (Taylor et al., 2013).

(2011). This technique takes lower resolution depth-tiered environmental layers (i.e. the 1° depth grids of WOA) and estimates higher resolution values for the sea bottom at the resolution of the selected bathymetry grid.

Following the elimination of environmental parameters that were correlated, an Environmental Niche Factor Analysis (a form of Principle Component Analysis) was undertaken using the following physical attributes: slope, curvature, aspect, rugosity, calcite, temperature and nitrite. This analysis was undertaken using 980 records based on fisheries observations (940) and museum records (40; see Figure 16). The results of the Environmental Niche Factor Analysis are robust and indicate that corals are not uniformly distributed across the South Georgia and Shag Rocks shelf and slope areas (Figure 18). It is notable that the cross-shelf troughs identified from the high-resolution bathymetry (see Figure 17) appear to form suitable habitat for coral communities, along with the slopes associated with the shelf-edge moraines (e.g. on the western side of South Georgia), and the steep slopes and complex terrain such as canyons on Shag Rocks and South Georgia (see Figure 18). Broad areas of the shelf and the channel between South Georgia and Shag Rocks would appear to be relatively unsuitable for the occurrence of corals. Most of the fishing for Patagonian toothfish occurs between 1000 and 1500 m depth and is focused on steep slopes or ridge crests (Taylor et al., 2013; Wakeford et al., 2006). It is apparent from the habitat suitability maps that only a small proportion of the deep-water coral habitat around South Georgia is protected from fishing impacts below 700 m depth. Other habitats, such as the echinoderm and sponge-rich areas in shallower water, are likely to be protected by the general prohibition on bottom fishing in waters shallower than 700 m depth or within 12 nm of the shore.

3.4.2 South Sandwich Islands

Less is understood about the benthic fauna of the South Sandwich Islands than that of South Georgia. Ramos (1999) took eight samples from around the South Sandwich Islands. In each of the eight samples, two species of the ascidian family Molgulidae were the most abundant taxa, followed by echinoderms (ophiuroids and asteroids). Opisthobranchs and pennatulids were also abundant. Overall, the South Sandwich Islands appeared as an outlier in multidimensional scaling analyses of similarity of the sites investigated in the Scotia Arc (Ramos, 1999).

Lockhart and Jones (2008) also sampled the South Sandwich Islands using Blake and Otter trawls, but distribution patterns of taxa in the area

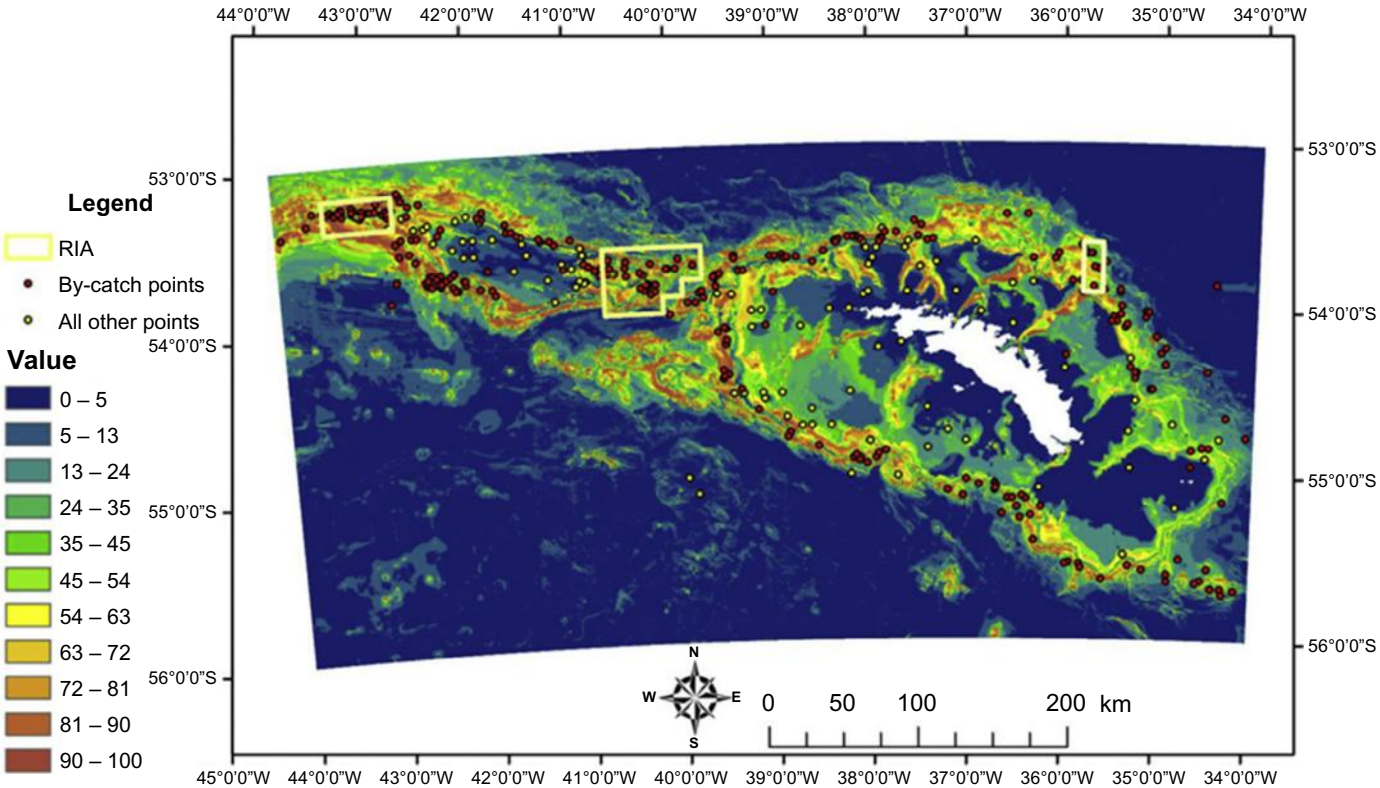

Figure 18 Habitat suitability for octocorals around South Georgia and Shag Rocks. Warm (different grey shades in the print version) colours indicate highly suitable habitat for octocorals, moving to green (grey in the print version) and blue (black in the print version) for successively less-suitable habitat. Red (dark grey in the print version) spots are by-catch samples, yellow (white in the print version) spots indicate records of octocorals from museums and collections, and Yellow (white in the print version) boxes indicate restricted impact areas (Taylor et al., 2013).

were poorly resolved because of depth variation of collected samples. It is notable that despite occurring further south than South Georgia, the biomass sampled from these islands was still high, reaching up to 100–200 t n mile^{-2} (Lockhart and Jones, 2008; Figure 19). At Zavodovski Island, two hauls collected at 330 m revealed a fauna similar to that of South Georgia and were dominated by echinoderms and sponges (Lockhart and Jones, 2008).

In shallower waters (118 m depth) around Candlemas Island, a diverse assemblage of echinoderms was sampled (Lockhart and Jones, 2008). In deeper waters at ~400 m depth at Montagu Island, cnidarians shared dominance with echinoderms (Lockhart and Jones, 2008). In shallow waters at Bristol Island, bryozoans were the dominant phylum (Lockhart and Jones, 2008; Figure 20).

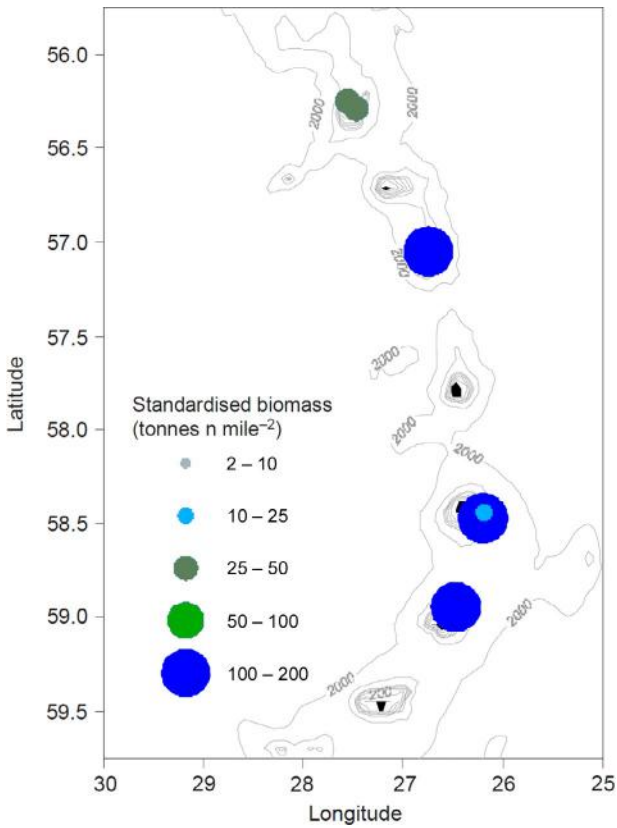

Figure 19 Biomass from trawl sampling stations around the South Sandwich Islands (Lockhart and Jones, 2008).

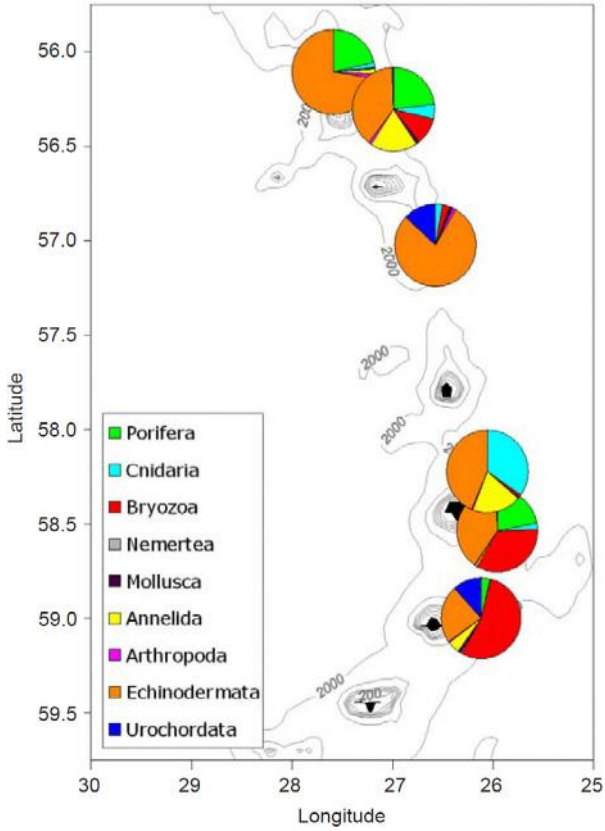

Figure 20 Distribution of the main faunal groups in trawl samples from the South Sandwich Islands (Lockhart and Jones, 2008).

The Biopearl 1 cruise (*James Clarke Ross* cruise JR 144) sampled an area off Southern Thule at 200, 500, 1000 and 1500 m depths using an Agassiz trawl (Griffiths et al., 2008). Abundance declined markedly from 200 to 500 m depth, but the trend was unclear between 500 and 1500 m depth (Griffiths et al., 2008). Biomass of the sampled fauna showed a decrease from 200 through to 1500 m depth (Griffiths et al., 2008). In agreement with results reported by Ramos (1999), ascidians and echinoderms were found to dominate samples at 200 and 500 m depth by abundance and biomass. In deeper waters, holothurians were particularly abundant along with lower numbers of Stelleroidea and Crustacea (Griffiths et al., 2008). Kaiser et al. (2008) reported the results of sampling during the same expedition using an epibenthic sledge at 300, 500, 1000 and 1500 m, and found a marked decrease of macrofauna from 300 depth to 1500 m. There was also

considerable variability among samples that were collected at similar depths (~500 m deep; Kaiser et al., 2008). Abundances were noted to be in the range of sampling elsewhere in the Scotia Sea (Kaiser et al., 2008). Molluscs (bivalves and gastropods), polychaete worms and crustaceans (especially Malacostraca and Copepoda) dominated the upper slope samples with nematodes not showing an obvious trend with depth but numerically dominating the deeper samples (Kaiser et al., 2008). Although the diversity at higher taxonomic levels was similar to other localities in Antarctica at the species level, Southern Thule was impoverished in groups such as the Malacostraca and echinoderms (Kaiser et al., 2008).

In January 2009, a towed video transect was undertaken across Kemp Seamount to the west southwest of Thule (see Figures 6 and 10). Video showed that the seamount summit was covered in a carpet of ophiuroids, with scattered pennatulids, large anemones feeding on scyphozoans (*Periphylla* sp.) and the seastar *Labidiaster* sp. In deeper waters around the seamount, octocorals and brachiopods were observed (A.D. Rogers unpublished data).

3.5 Biogeography of the Benthic Biota of South Georgia and the South Sandwich Islands

The overall picture arising of the biogeography of Shag Rocks, South Georgia and the South Sandwich Islands is complex. The South Sandwich Islands host an Antarctic fauna, and studies to date indicate these fauna have a lower diversity and lower levels of endemism compared to South Georgia/Shag Rocks (Table 2), possibly because they are geologically young and isolated. However, this conclusion should be viewed in the context of the much lower sampling effort around the South Sandwich Islands. Griffiths et al. (2008) identified a similarity in the benthic fauna of the islands of Southern Thule and Deception Island, particularly with regard to the occurrence of ascidians. It is likely that this similarity in fauna represents a community associated with disturbed habitats, in this case the recent destruction of the benthic fauna occurring as a result of volcanic eruptions and lava flows at Deception Island and the islands of Southern Thule (Griffiths et al., 2008). Ascidians were also observed at shallow locations exposed following the collapse of the Larsen B iceshelf (Gutt in Griffiths et al., 2008), lending support to the idea that they are early colonisers of newly exposed substrata.

The South Georgia shelf, in contrast, has been identified as the most speciose in the Southern Ocean and represents an anomaly to the low regional levels of endemism south of the Polar Front (Hogg et al., 2011).

Table 2 Number of Species of Non-Fish Groups Identified from South Georgia/Shag Rocks and the South Sandwich Islands, and Percentage of Species Estimated to be Endemic to Each Island Group

	South Georgia		South Sandwich Islands		
Group	**Number**	**% Endemic**	**Number**	**% Endemic**	**Reference**
Sponges	81	2.7			Hogg et al. (2011)
Cnidaria	78	44.2			Hogg et al. (2011)
Bivalve molluscs	49	29	25		Zelaya (2005)
Gastropod/bivalve molluscs (shelf)	199	32.7	40	5	Linse et al. (2006)
Molluscs	161	45.9			Hogg et al. (2011)
Ascidians	12	8	10		Tatian et al. (2005)
Ascidians	56	0	25	0	Primo and Vazquez (2009)
Ascidians	55	2	28	0	Ramos-Espla et al. (2005)
Bryozoa	94	16	43	5	Moyano (2005)
Bryozoa	112	55.6			Hogg et al. (2011)
Crustacea	283	23.7			Hogg et al. (2011)
Decapod Crustacea	5	20	5	0	Lovrich et al. (2005)
Polychaeta	20	0			Glasby and Alvarez (1999)

South Georgia and Shag Rocks appear to represent a zone of contact between the Magellanic fauna, which originates to the northeast, and the Antarctic fauna from the south (e.g. Downey et al., 2012). Such a boundary between two faunas may explain the anomalously high diversity of the fauna of these islands. High proportions of the species recorded at the islands are either at their northern or southern limits or are endemic (Hogg et al., 2011). Like South Georgia, the South Sandwich Islands also appear to be geographically the southernmost limit for some Magellanic species and northern-most limit for some Antarctic species (Kaiser et al., 2008).

The strong contrast in the fauna of Shag Rocks versus South Georgia is remarkable, and is also reflected in the fish fauna (see below) and in results

from genetic studies of samples from the two areas (Rogers, 2007, 2012). Further evidence of this zone of contact between Magellanic fauna and Antarctic fauna is provided by the analysis of similarity of communities around the Scotia arc by Griffiths et al. (2008), where Shag Rocks were found to be most similar to the communities sampled in the Falkland Trough. In addition, the fauna of South Georgia shows a high level of endemism (Table 2) possibly arising from the extreme isolation of the islands, its ancient history and perhaps unique environmental conditions, being the warmest shelf region within the Antarctic with the highest seasonal range of temperatures (Barnes, 2008; Hogg et al., 2011). For some groups of organisms, "endemic" species may represent pseudoendemic records because of a lack of exploration of the Southern Ocean (e.g. Goodwin et al., 2012). However, the fact that such high levels of endemism are recorded among relatively well-studied taxa such as molluscs suggests that this is a real feature of the marine biota of the area. It is important to emphasise that South Georgia and the South Sandwich Islands, and indeed the wider Antarctic, remains poorly sampled for many groups of marine organisms. Thus, even a single study can make a significant difference to knowledge of the diversity of a particular group (e.g. for sponges of South Georgia; Goodwin et al., 2012).

3.6 Diversity and Biogeography of Fish Communities Around South Georgia and the South Sandwich Islands

Much of the research on fish communities around South Georgia and, more recently around the South Sandwich Islands, is directed towards fisheries. Here, we summarise information from Gon and Heemstra (1990), who examined data on fish distributions around the Antarctic, and review more recent studies. These most recent studies focus on the diet of commercial or common species around South Georgia (Collins et al., 2007, 2008a), or on the species diversity of fish communities around South Georgia and the South Sandwich Islands (Collins et al., 2008b; Jones et al., 2008). As with the benthic invertebrate fauna, South Georgia/Shag Rocks has higher recorded species diversity than the South Sandwich Islands. It is apparent from examination of the fish species documented to occur at Shag Rocks, South Georgia, and the South Sandwich Islands (Table 3), and from general information on fish distribution (e.g. Gon and Heemstra, 1990), that many of the fish species recorded at South Georgia/Shag Rocks but not at the South Sandwich Islands, reach their southernmost distribution at the South Georgia/Shag Rocks within the Atlantic sector of the Southern Ocean.

Table 3 Summary of the Number of Fish Species from Shag Rocks, South Georgia, and the South Sandwich Islands

	Shag Rocks	South Georgia	South Sandwich Islands
Species	46	105	55
Endemic Species	0	10	0
% Endemic Species	0	9.5	0

Likewise, some species that occur at the South Sandwich Islands represent the northernmost occurrence of Antarctic endemic taxa in the Scotia Arc.

South Georgia/Shag Rocks also host a number of endemic species, representing about 9% of the total fish fauna observed to date; a figure within the range of levels of endemism observed for benthic invertebrates (see above). No endemic taxa have been observed at the South Sandwich Islands, reflecting the relatively young age of the islands and the fact that the fish fauna almost entirely represents Antarctic endemics found elsewhere to the south on the Scotia Arc and along the continental margin of Antarctica. The occurrence of endemics, especially some of the deeper water species, may simply reflect a lack of knowledge of the fish fauna within the region in general. However, some of the shallow-water species are almost certainly endemic, and some have a very small geographic range of occurrence. For example, the orange notothen, *Trematomus vicarius*, which probably has the most restricted distribution of all the notothenioid fishes (Gon and Heemstra, 1990) has been mainly recorded from Cumberland and Stromness Bays, northern South Georgia and Rosita Harbour in the Bay of Isles, although a single specimen was sampled in a recent survey of South Georgia and Shag Rocks but it is unclear where this specimen came from (Jones et al., 2008).

One remarkable result from recent studies of the fish communities around South Georgia and Shag Rocks is that there are significant differences in occurrence and abundance of species between the two areas. Despite being separated by a distance of only ~250 km (much less between the slopes of the two island groups), catches on a recent survey at Shag Rocks were dominated by the yellowfin notothen, *Patagonotothen guntheri*, but only a single specimen of this species was recorded at South Georgia and is the first record at this location (Jones et al., 2008). In a recent study, this species formed 85% of the diet of juvenile toothfish at Shag Rocks but was not found at all in the stomachs of fish from South Georgia. Yellowfin notothen was also found to be the most abundant species on the Burdwood Bank and

around the Falkland Islands, as well as Shag Rocks. This is the only known population south of the Polar Front for this species. The survey also found that yellowfin and painted notties, *Lindbergichthys nudifrons* and *Nototheniops larseni*, were the most abundant species (Jones et al., 2008) around South Georgia, although a previous study had found mackerel icefish, *Champsocephalus gunnari*, and humped rockcod, *Gobionotothen gibberifrons*, to be most abundant (Collins et al., 2007). Reasons for these differences in sampling results may relate to sampling gear, or to seasonal variation in species abundance, variation in behaviour, and/or inter-annual variation in relative abundance of species. As with the marine invertebrate fauna, South Georgia/Shag Rocks appear to represent a significant biogeographic boundary with southern species reaching their northern limit or Magellanic species and widespread oceanic species reaching their southern limit.

3.7 Chemosynthetic Communities

The East Scotia Ridge was the first location in the Antarctic where communities of vent-endemic chemosynthetic organisms were discovered around high-temperature black smokers (Rogers and Linse, 2014; Rogers et al., 2012). Another community has been identified on the Australian-Pacific Ridge at Segment KR1 (~62°S, 160°E), which is also likely to be hosted on high-temperature hydrothermal vents and has been sampled using dredges (Interridge, 2011, 2013; Korea Polar Research Institute, 2013). The East Scotia Ridge is an inter-oceanic spreading centre associated with the subduction of the South American Plate beneath the Sandwich Plate, which gives rise to the South Sandwich Trench to the East, a unique feature in the Southern Ocean. The ridge has an intermediate spreading rate (60–70 mm year^{-1} depending on position on the ridge; Thomas et al., 2003), but its morphology is more like a slow spreading ridge including a deep-median valley associated with reduced mantle temperature and melt production (Bruguier and Livermore, 2001; Livermore et al., 1994, 1997). The ridge is divided into nine segments, and the two on which deep-sea vents have been discovered (E2 in the north and E9 in the south) have an inflated appearance associated with higher rates of magma injection into the crust, which is more typically found in fast-spreading ridges. The tearing of the South American Plate and the rollback of the subduction zone eastwards are thought to lead to flow of mantle around the edge of the arc where it converges with the spreading centre (Leat et al., 2004). This is thought to be coupled with other processes, including the melting of sediments along the edge of the subducting slab (Leat et al., 2004). A melt lens

has been seismically imaged beneath the E2 segment, while one is suspected at E9 (although the large collapse crater located just to the south of the identified vent sites may represent a magma chamber that has drained and subsequently collapsed; Bruguier and Livermore, 2001).

These two areas of hydrothermal vents on the East Scotia Ridge are located on axial volcanic ridges (AVRs; Segment E2 between 56°5.2′ and 56°5.4′S and between 30°19′ and 30°19.35′W at ~2600 m depth and on Segment E9 at 60°02.5′ and 60°03.00′S and between 29°59′ and 29°58.6′W, at ~2400 m depth; Figure 21). At E2, focused venting occurs as high temperature "black smokers" from chimneys up to 10 m in height with maximum measured vent fluid temperatures of 352.6 °C. Some of the chimneys have expanded tops with hot vent fluid (>300 °C) emanating from the underside, similar to flanges found at vents in the North East Pacific (Rogers et al., 2012). Diffuse flow of vent fluids also occurred in various settings around the vent at temperatures from 3.5 to 19.9 °C. The chloride concentration of fluids was close to seawater and the pH ~3.0 (James et al., 2014) while H_2S concentration of end-member fluids was ~7 mM (James et al., 2014). At E9, the vent fluids reached a higher temperature of up to 383 °C and were depleted in chloride compared to seawater indicating phase separation. pH was slightly higher than E2 at ~3.3, but H_2S concentrations ranged from ~9.5 to 14 mM (James et al., 2014). Overall, the physical and chemical characteristics of these vents were fairly typical for basalt-hosted mid-ocean ridge systems (Cole et al., 2014) with little evidence of outgassing of magmatic volatiles (James et al., 2014).

Visually, huge densities of new species dominate the hydrothermal vents on East Scotia Ridge. These include a recently described yeti crab, *Kiwa*

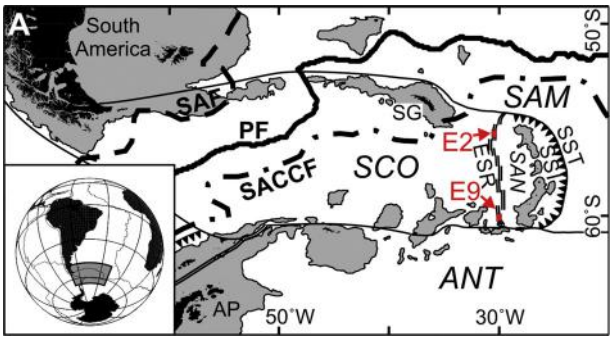

Figure 21 Scotia sea topography showing the position of the East Scotia Ridge and ridge segments E2 and E9 (Rogers et al., 2012).

tyleri (>700 individuals m^{-2}; Figure 22; Marsh et al., 2012; Thatje et al., 2015), a recently described peltospiroid gastropod (>1500 individuals m^{-2}; Marsh et al., 2012; Chen et al., in press), a new stalked barnacle, *Vulcanolepas scotiaensis*, from the family Eolepadidae (>1500 individuals m^{-2}; Figure 23; Buckeridge et al., 2013; Marsh et al., 2012) and limpets of the genus *Lepetodrilus* (Rogers et al., 2012). Other members of the community include vent-endemic sea spiders (*Sericosura* sp.), a new predatory

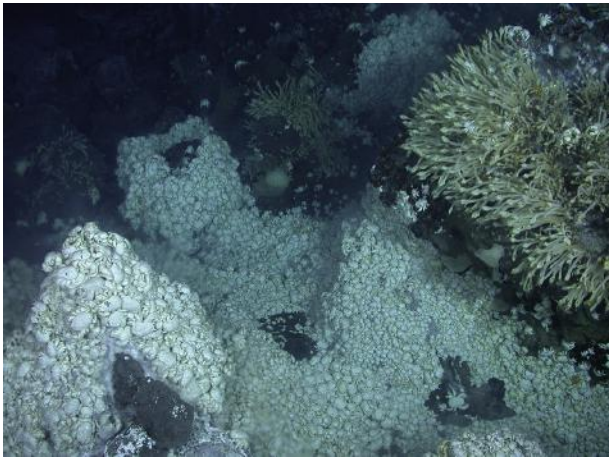

Figure 22 The E9 hydrothermal vent showing huge densities of *Kiwa* nov. sp. (Rogers et al., 2012).

Figure 23 East Scotia Ridge, Southern Ocean, E9 ridge segment, hydrothermal vent chimney showing Vulcanolepas scotiaensis and vent anemones (Rogers et al., 2012).

seven-armed sea star *Paulasterias tyleri* (Mah et al., 2015), small gastropods (*Provanna* sp.) and several species of sea anemone (see Figure 23). In contrast, several groups of animals commonly found on deep-sea vents elsewhere are notably absent from the East Scotia Ridge vents. These include alvinocarid shrimps, siboglinid tube worms such as the giant tube worm, *Riftia pachyptila*, alvinellid polychaetes, vent mussels, and vent clams. The vent fields host a distinct community of vent-endemic taxa that probably represent a new vent biogeographic province, distinct from those identified elsewhere in the world (Rogers et al., 2012). It is interesting to note that animals sampled by dredge from the KR1 Segment of the Australian-Antarctic Ridge include a yeti crab and a seven-armed seastar similar in appearance to *Paulasterias tyleri*, possibly indicating a closer affinity to the East Scotia Ridge vent communities than with those in the Pacific (Korea Polar Research Institute, 2013). The ecology of the East Scotia Ridge vent communities have been described in terms of spatial distribution of species (Marsh et al., 2012) and food webs (Reid et al., 2013).

Deep-sea hydrothermal vents have also been found within a submarine volcano, known as the McIntosh Caldera, next to Kemp Seamount centring at 59°42′S, 28°20′W (referred to as Kemp Caldera in Amon et al., 2013, 2014) and in another caldera lying next to Adventure Bank (see Figures 8 and 13). The McIntosh Caldera contains a small sub-cone, lying on the caldera floor at a depth of approximately 1400 m at ~59°41.6′S, 28°21′W (Great Wall and Winter Palace sites; Cole et al., 2014). Within this small sub-cone are extensive areas of hydrothermal venting, including friable white chimneys venting white smoker type fluids at temperatures up to 212 °C, as well as diffuse fluids issuing from seafloor fissures at <28 °C (Figure 24; Amon et al., 2013, 2014; Cole et al., 2014). The end-member fluids have very high levels of fluoride and (~1000 μM), H_2S (200 mM) and a pH ~1, suggesting input of magmatic volatiles. This is consistent with trace element analysis of the basalts of Kemp Seamount, which indicate that it is derived from melt in the subduction zone (Leat et al., 2004). The seafloor is covered in ash and sulphur suggestive of a recent volcanic event (Cole et al., 2014). Deposits of the latter are also consistent with the input of the volatile magmatic gas SO_2 which undergoes disproportionation to form native sulphur (Cole et al., 2014). Other volatiles influencing the geochemistry of the McIntosh Caldera fluids include H_2O, CO_2, HCL and HF (Cole et al., 2014).

It is therefore unsurprising that the community of vent-endemic species at the McIntosh Caldera site are markedly different from those at E2 and E9,

Figure 24 Sulphur chimney, Macintosh Caldera hydrothermal vents, South Sandwich Islands (NERC CHESSO Consortium).

Figure 25 *Calyptogena*-like bivalves on the sub-cone of McIntosh Caldera, South Sandwich Islands (NERC CHESSO Consortium).

a situation that is consistent with the idea that the geomicrobiological template of vent fields drives the characteristics of communities of vent megafauna (Nakamura and Takai, 2014). This fauna is currently still under investigation but it includes limpets and barnacles of the same species as at the East Scotia Ridge (*Lepetodrilus* sp. and the deep-sea stalked barnacle, *Vulcanolepas scotiaensis*; Buckeridge et al., 2013), a *Calyptogena*-like bivalve (Figure 25), anemones and sea spiders, but does not include yeti crabs or

peltospiroid gastropods of the type observed on the East Scotia Ridge. A minor area of diffuse venting, including a slender chimney venting hydrothermal fluid, was also discovered in the crater next to Adventure Bank (CHESSO, 2011).

3.7.1 Other Chemosynthetic Communities in the South Georgia South Sandwich Islands Maritime Zone

An Antarctic minke whale, *Balaenoptera bonaerensis,* skeleton was also found on the slopes of the sub-cone in the McIntosh Caldera at 59°41.671′S, 28°21.089′W, at a depth of 1444–1447 m (Figure 26; Amon et al., 2013). Natural whale falls on the sea floor are difficult to discover, and are rarely well studied. This one was colonized by a variety of animals including nine new species (an amphipod, the isopod *Jaera tyleri*, several polychaete worms and gastropods; Amon et al., 2013; Linse et al., 2014). The polychaetes included two new species and one existing species of the "bone-eating" *Osedax* (*Osedax rogersi*, *Osedax crouchi, Osedax antarcticus*; Amon et al., 2014), and the gastropods, a species of *Lepetodrilus*, also found on the nearby McIntosh Caldera vents (Amon et al., 2013; Figure 27).

The northern shelf of South Georgia has been found to be a site of methane emissions. To date 133 gas flares have been detected using ship-mounted echo sounders originating from the seabed at depths of 130–390 m (Römer et al., 2014). The gas flares occurred within the Cumberland Bay fjord

Figure 26 Natural whale fall decayed to a skeleton. This is the skull of a small baleen whale. Amphipods and polychaetes were found on the surface of the skeleton, and *Osedax* worms were burrowed into the skeleton (NERC CHESSO Consortium).

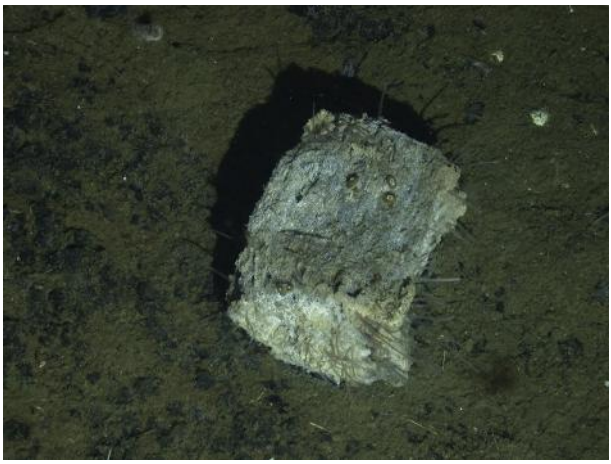

Figure 27 Close-up of a whale bone on the seafloor showing siboglinid worms, *Osedax* sp., and limpets, *Lepetodrilus concentricus* (NERC CHESSO Consortium).

system or were located in the cross-shelf depressions described earlier (Römer et al., 2014). Both the deeper water column and the sediments in the vicinity of the gas flares were enriched with methane which exhibited strongly negative $\delta^{13}C$-CH_4 values indicative of biogenic methane production (Römer et al., 2014). Low-relief mound-like structures with white patches, presumed to be bacterial mats, were located in the areas of gas venting along with the megafauna usually associated with the South Georgia Shelf, but no chemosynthetic fauna were observed in the area (Römer et al., 2014). This is the first active methane seep observed in the waters of the Southern Ocean, although inactive seeps with the remains of *Calyptogena*-like bivalves have been observed in the Weddell Sea where the Larsen B ice shelf used to cover the ocean surface (Domack et al., 2005; Niemann et al., 2009).

4. BIOLOGY OF PREDATORS FOUND AROUND SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS

4.1 Introduction

South Georgia and the South Sandwich Islands have an extremely rich predator fauna, which is sub-Antarctic in character. The predator fauna are primarily categorised into flying seabirds, penguins, pinnipeds and cetaceans. The region around South Georgia, in particular, is an important area for seabirds and marine mammals, hosting some of the largest and most diverse concentrations of these animals anywhere on Earth (Clarke et al., 2012;

Everson, 1977, 1984). It is estimated that over 100 million individual seabirds are based there, and that perhaps the number was far higher prior to the introduction of rats, which have possibly reduced numbers of petrels by an order of magnitude (Clarke et al., 2012). The waters of South Georgia are also important large whale habitat (e.g. Richardson et al., 2012). These aquatic predators are dependent on the highly productive ocean for prey. Importantly, during their respective breeding seasons, all of the predators around South Georgia and the South Sandwich Islands forage mainly within the SGSSI MZ, or, in the case of predators from South Georgia, forage to the north and west, along the Polar Front or on the Patagonian Shelf. The presence of fauna is generally highly seasonal, with most animals present on the islands during the austral summer when they breed, usually in large aggregations. Outside of the breeding season, some predators move away from the islands such as black-browed albatross, *Thalassarche melanophris*, grey-headed albatross, *T. chrysostoma*, white-chinned petrels, *Procellaria aequinoctialis,* and southern right whales, *Eubalaena australis* (Trathan et al., 2014). Others may be present but more diffusely distributed, or present as winter vagrants. Some predators, such as Gentoo penguins, *Pygoscelis papua,* appear to remain around the islands during the winter (Trathan et al., 2014). While none of these predators considered are endemic, the populations of at least two predator species, Gentoo penguins, *Pygoscelis papua*, and chinstrap penguins, *Pygoscelis antarctica*, in South Georgia and the South Sandwich Islands, respectively, are genetically distinct (Clucas et al., 2014), and this is likely to be the case in other, as yet unsurveyed, species.

There are a number of threats to the biodiversity of the islands in general, and to the predator fauna specifically. These threats include fisheries, either through by-catch or a reduction in prey, climate change and introduced species. Many predator species on South Georgia have shown substantial but as yet unexplained declines.

The South Georgia and South Sandwich Islands are exceptional for several reasons:

- Large breeding aggregations of many species. South Georgia is a highly important breeding site globally for: Antarctic fur seals (*Arctocephalus gazella*), southern elephant seals (*Mirounga leonina*), grey-headed albatross (*Thalassarche chrysostoma*), northern giant petrel (*Macronectes halli*), white-chinned petrel (*Procellaria aequinoctialis*), Antarctic prion (*Pachyptila desolata*) and common diving petrel (*Pelecanoides urinatrix*). South Georgia is also in the three top breeding sites globally for: king penguin (*Aptenodytes patagonicus*), gentoo penguin (*Pygoscelis papua*), macaroni

penguin (*Eudyptes chrysolophus*), wandering albatross (*Diomedea exulans*), black-browed albatross (*Thalassarche melanophris*), southern giant petrel (*Macronectes giganteus*), black-bellied storm petrel (*Fregetta tropica*) and South Georgia diving petrel (*Pelecanoides georgicus*).

- High proportions of the world population of many species of seabirds and of some pinniped populations.
- The undisturbed nature of large discrete areas such as the Willis Islands, Annenkov Island, Cooper Island, Bird Island and all of the South Sandwich Islands.
- Potential vulnerability to disturbance and to invasive species on land.

Here, we briefly summarise the occurrence and abundance of these predator species at South Georgia and the South Sandwich Islands, their influence and dependence on the surrounding marine environment, and known or potential threats. In some cases, very recent estimates of abundance are not available for South Georgia and the South Sandwich islands, therefore population trends as well as information on total species abundance is provided when possible. We include IUCN Red List status (available from http://www.iucnredlist.org/) for each of the main species discussed.

4.2 Population Size, Ecology and Distribution of Predators

4.2.1 Birds

4.2.1.1 Penguins

In the Antarctic, and in the sub-Antarctic in particular, penguins account for a substantial part of the avian fauna and may comprise up to 80% of the total avian biomass (Trathan, 2004; Williams, 1995). Although estimates of population size are problematic, numbers of the most abundant penguin species have been very high (Woehler, 1993), but in the last couple of decades some have shown considerable declines. Minimum breeding populations have been estimated at 1.23 million pairs for southern rockhopper penguins, *Eudyptes chrysocome* (BirdLife International, 2012a), 1.83–2.88 million pairs for Adélie penguins (*Pygoscelis adeliae*, BirdLife International, 2012b), 8 million individuals for chinstrap penguins (*Pygoscelis antarcticus*, BirdLife International, 2012c) and 6.3 million breeding pairs for macaroni penguins (BirdLife International, 2013). The ecology, life history and trends in populations for penguin species at South Georgia and South Sandwich Islands are briefly reported below.

4.2.1.1.1 King Penguin (*Aptenodytes patagonicus*)

- Location: South Georgia
- IUCN Red List Status: Least Concern.

- Population size: ~450,000 pairs.
- Population trend: increasing possibly as a result of recovery from human harvesting.
- Diet (South Georgia): mainly myctophids (lantern fish), although also take quantities of squid.
- Foraging range: mainly to the north of South Georgia at the Polar Frontal Zone in areas associated with mesoscale features such as warm-core eddies down to depths of 300 m.
- Breeding: extended breeding cycle lasting up to a year and a half so breed twice in 3 years. Single egg laid.

Foraging Ecology King penguins from South Georgia feed mainly on myctophid fishes during the summer, especially the species *Krefftichthys anderssoni*, *Electrona carlsbergi* and *Protomyctophum choriodon* (Olsson and North, 1997). Other species also occur in the diet, particularly the barracudina, *Notolepis coatsi* (Olsson and North, 1997) and squid, particularly *Martialia hyadesi*, but also *Moroteuthis knipovitchi*, *Kondokovia longimana* and *Psychroteuthis glacialis* (~3% total; Rodhouse et al., 1998). The relative proportions of fish and squid in the diet may differ outside the breeding season, as has been found elsewhere (Ratcliffe and Trathan, 2011; Rodhouse et al., 1998), and which is indicated by observations of Stonehouse (1956) on the feeding of king penguin chicks at South Georgia in winter. Elsewhere, king penguins have also been found to feed predominantly on myctophids, although other species, such as eel cods (*Muraenolepis* spp.), can form a significant proportion of the diet (e.g. Bost et al., 2002). King penguins are, along with emperor penguins (*Aptenodytes forsteri*), the most pelagic of penguin species, and spend roughly 50% of their time at sea, underwater (Scheffer et al., 2010). They are visual predators and forage at depths of up to 300 m by day (Rodhouse et al., 1998; Scheffer et al., 2010), but in much shallower water at night (Bost et al., 2002; Scheffer et al., 2010). Off Kerguelen Island, this diurnal behaviour has been studied using time-depth recorders coupled with trawl survey data from the foraging depth ranges, and indicated that most food was captured during daytime foraging at depth (Bost et al., 2002). This is consistent with the behaviour of king penguins from South Georgia that are most actively diving during the day or during twilight hours, with reduced foraging activity and dive duration during the night (Scheffer et al., 2010). These data suggest that king penguins are highly dependent on the light regime for location of prey (Bost et al., 2002).

Satellite tracking of foraging king penguins from South Georgia has shown that these birds use South Georgia as a base to forage to the north

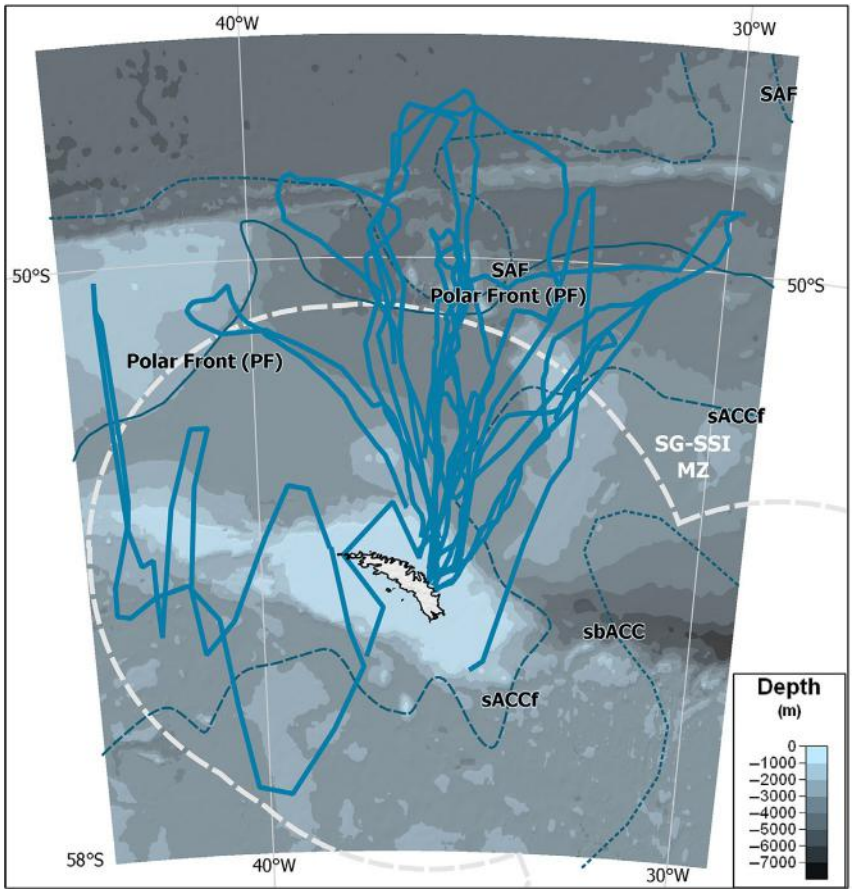

Figure 28 Tracks of king penguins, *Aptenodytes patagonicus*, foraging from South Georgia. *Data from Putz (2002) (one penguin tracked) and Scheffer et al. (2010) (11 penguins tracked).*

at the Polar Frontal Zone (Putz, 2002; Scheffer et al., 2010; Figure 28). In this region, the penguins appear to target mesoscale features such as warm-core eddies for foraging (Trathan et al., 2008). These features are probably associated with relatively high densities of the king penguin's myctophid prey. Two forms of foraging strategy have been detected using tracking. The first is a direct strategy, whereby the penguins move directly to the region of the front and remain within a relatively small area foraging (Scheffer et al., 2010). With the second of these two foraging strategies, the penguins exhibit a somewhat "circular" search pattern where they forage more continuously through the trip generally tracking temperature

gradients, presumably because they fail to locate a dense prey patch (Scheffer et al., 2010). The fact that such foraging strategies are present indicate that the penguins can find high densities of prey with a relatively high predictability in association with mesoscale features associated with the Antarctic Polar Front in this region. In general, foraging trips are in a clockwise direction, probably because this is energetically the most efficient strategy given the direction of the ACC (Scheffer et al., 2010).

Life History The breeding cycle of king penguins on South Georgia was described over 50 years ago. The remarkable feature of this cycle is that it extends over 14–16 months and may even last a year and a half (Stonehouse, 1956). Birds moult prior to breeding and courtship takes place over 3 weeks but can be as long as 6 weeks (Stonehouse, 1956). A site is selected in the colony and defended against encroachment by other members of the colony (Stonehouse, 1956). King penguins usually breed on flat beaches in large colonies (Croxall and Prince, 1980). A single egg is laid and incubated between the abdomen and the feet of the birds, as in Emperor penguins, over a period of 54–55 days (Stonehouse, 1956). Birds that have failed to rear chicks in the previous season, or that did not breed in the previous season, breed early, moulting in September and October and undergoing courtship from November (Stonehouse, 1956). Birds that were successful at rearing a chick the previous season, or that bred early but lost their chick, breed later, moult in December/January and undergo courtship from January, reaching peak laying in February (Stonehouse, 1956). By April the chicks of early breeders may reach close to the weight of their parents, with those of later breeders reaching a similar weight by May (Stonehouse, 1956). From May onwards, feeding becomes highly irregular with visits from the parents only occurring every 5–6 weeks (Stonehouse, 1956). The chicks are covered in thick down throughout the winter period, which lasts until October, to resist the weather but they starve during this period and lose a large proportion of their body weight (Stonehouse, 1956). The parents begin to feed their chicks more frequently in October and by December/January the chicks have increased their weight again, and moult prior to being abandoned by their parents and entering the sea (Stonehouse, 1956; Figure 29). Chicks of late breeders often perish in winter as they starve before feeding begins again in spring.

Population Trends Globally, king penguins have increased at many colonies, and recolonised some areas where they were previously exterminated, in particular at Macquarie Island, where they were hunted in the

Figure 29 King penguins, *Aptenodytes patagonicus*, moulting in early 2009, Grytviken, South Georgia. *Photograph A.D. Rogers, 2009.*

1900s. In South Georgia, there is some evidence that king penguins were also hunted for oil, although to date this remains anecdotal (Clarke et al., 2012). Because king penguins breed in large colonies, there have been very few attempts to monitor their populations. King penguin population size has increased in South Georgia from about 2000 pairs in 1914 to a total population count of around 57,000 in the mid-1970s (Lewis-Smith and Tallowin, 1979) to about 450,000 pairs today (Trathan et al., 2007). This is approximately half of the world's population. The other main breeding sites are the Kerguelen, Crozet islands and Maquarie Island. The signal of trends in this species may be confused by the removal of many direct threats of human exploitation, which may have allowed some recovery in the population. Whether their recovery will be checked or reversed by the same threats (e.g. overfishing, contaminants, habitat degradation) affecting other penguins is uncertain, and opinion differs as to whether king penguins are threatened by climate change (Barbraud et al., 2008; Le Bohec et al., 2008).

4.2.1.1.2 Chinstrap Penguin (*Pygoscelis antarctica*)

- Location: South Georgia and the South Sandwich Islands
- IUCN Red List Status: Least Concern.

- Population size: > 1.5 million pairs.
- Population trend: probably decreasing as a result of climate change impacts on krill.
- Diet (South Georgia): predominantly krill but also pelagic fish such as myctophids.
- Foraging range: not known in the vicinity of South Georgia and the South Sandwich Islands. Elsewhere over the shelf and out to over the shelf break/continental or island slope.
- Breeding: adults arrive in November and eggs hatch in January, with chicks fledging in 53–54 days. Generally two eggs are laid.

Foraging Ecology There are no specific studies on the foraging ecology of chinstrap penguins (Figure 30) from South Georgia or the South Sandwich Islands (Ratcliffe and Trathan, 2011). Information here is drawn from studies elsewhere in the range of the species. As is true for the closely related Adélie penguin, chinstrap penguins rely mainly on the krill, *E. superba* and *E. crystallorophias* for their diet (Jansen et al., 1998; Lynnes et al., 2002; Miller and Trivelpiece, 2008; Miller et al., 2010; Wilson and Peters, 1999). Feeding studies indicate that these birds also predate pelagic fish (Jansen et al., 1998; Miller and Trivelpiece, 2008; Miller et al., 2010), possibly at dusk, as the fish rise towards the surface, but while there is still sufficient light for the penguins to hunt (Jansen et al., 1998), or overnight (Miller and Trivelpiece, 2008). The species that are taken include especially *Electrona antarctica*, but also *Electrona carlsbergi*, *Gymnoscopelus nicholsi*, *Krefftichthys andersonni* and the paralepedid, *Notoscopelus coatsi* (Jansen

Figure 30 Chinstrap penguins, *Pygoscelis antarctica*, porpoising in the Scotia Sea above the East Scotia Ridge, west of the South Sandwich Islands. *Photograph A.D. Rogers, 2009.*

et al., 1998; Miller and Trivelpiece, 2008). However, chinstrap penguins are heavily dependent on krill for their diet and adult condition and breeding performance are correlated to krill abundance (e.g. Croll et al., 2006). In addition, long-term trends in chinstrap population size appear to be correlated with krill abundance (e.g. Trivelpiece et al., 2011). Still, evidence suggests that a response to the presence of small krill can be a switch to foraging for fish at night (Miller and Trivelpiece, 2008). It is possible that the dependence on krill is linked to nesting, when adult chinstrap penguins cannot forage far from their nesting sites, but at other times of the year, fish may form a more important part of the diet (Miller and Trivelpiece, 2008).

Chinstrap foraging patterns vary depending on season, krill availability and size and also vary between night and day. Details of foraging patterns vary between localities, and mean foraging trip durations are on average about 6–8 h during the daytime and longer than 14 h at night (Miller et al., 2010). During the day, birds are generally foraging closer to shore, while at night they have a greater tendency to forage at the shelf break or over the slope, further from shore (Miller et al., 2010). Presumably, this reflects a greater tendency to prey on myctophid fish, which are not available to the penguins during the day when the fish are in deeper water, but migrate to the surface at night (Miller et al., 2010). Foraging depths are generally in the range of 5–30 m (Miller et al., 2010) and tend to be deeper by day than at night (Miller and Trivelpiece, 2008). However, in some years diving can be deeper, with changes in diving behaviour particularly notable at night, possibly reflecting increased predation on fish (Miller and Trivelpiece, 2008). Exceptionally, chinstrap penguins can dive to depths as great as 126 m (Miller and Trivelpiece, 2008). Studies of time-depth profiles, together with recording of opening and closing of the beak, suggest that chinstrap penguins may specifically target prey from below, potentially hunting by looking for silhouettes against the down-welling light (Takahashi et al., 2004). There is also evidence from studies using time-depth recorders that chinstrap penguins also forage for krill, at or near, the seabed (Takahashi et al., 2003). During the breeding season, males and females return to shore to trade incubation duties with their mates or to feed chicks. Foraging tends to be restricted to more local trips over this period (Miller et al., 2010).

As previously mentioned, there are no studies on the foraging ecology of chinstrap penguins in the South Sandwich Islands. Tracking might be a useful first step to determining influence on the surrounding sea given the large numbers. One recent study on chinstrap penguin migration tracked a single

individual from Bouvetøya to Montagu Island, a trip of about 3 weeks and 3600 km, to arrive in time for the moult (Biuw et al., 2010). While Bouvetøya has a population of only about 1100 breeding chinstrap penguins, this points to the potential connectivity of disparate populations. Recent genetic studies have shown weak but significant genetic differentiation between chinstrap penguin populations in the Scotia Sea region with the population at Zavadovski showing significant differentiation to those in the South Orkney Islands, on the Antarctic Peninsula and on King George Islands (Clucas et al., 2014).

Life History Because there is little information regarding chinstrap penguins on the South Sandwich Islands, most of what is presented here relies on studies from other Antarctic regions. Chinstrap penguins nest on beaches or ice-free slopes often where there is a supply of stones for nest building (Croxall and Prince, 1980). The adults arrive at breeding sites in November (Conroy et al., 1975; Croxall and Prince, 1980; Lishman, 1985). Generally two eggs are laid, which are similar in size and weight, 3–4 days apart and take on average about 35–40 days to hatch (Conroy et al., 1975; Lishman, 1985). Occasionally, three eggs may be laid but it is probably rare that all of these are raised (Conroy et al., 1975). There is intense competition for stones for the construction of nests and a high degree of stone theft by adult penguins from other nests (Carrascal et al., 1995; Moreno et al., 1995). Thus, parents alternate egg incubation rarely leaving the nest unattended until the eggs hatch in January. The chicks are fed predominantly on krill and in 3–4 weeks leave the nest for small crèches (3–4 individuals). Chicks fledge when they are 53–54 days old (Lishman, 1985). Chick mortality can be high and can result from nest abandonment, predation of the adults by leopard seals, poor weather, or direct predation by brown skuas, *Stercorarius antarcticus*, and sheathbills, *Chionis alba* (Lishman, 1985). Nest size may be related to reproductive success, providing protection of chicks from adverse weather conditions such as flooding following heavy snow fall (Conroy et al., 1975; Moreno et al., 1995). Chinstrap penguins arrive at breeding sites later than Adélie penguins, and may interact aggressively with them over nests, sometimes displacing guarding Adélies, especially if they are relatively young and inexperienced (Trivelpiece et al., 1984). This can significantly depress the breeding success of Adélie penguins in mixed colonies (Carlini et al., 2005).

Population Trends Relatively small numbers of chinstrap penguins occur on South Georgia, where they are largely unmonitored. These birds

breed primarily at the south-eastern end of the island, in and around Cooper Bay, and on the Pickersgill Islands, off the south coast. In 2005, 500–700 dead chinstrap penguins were found at Cooper's Bay and subsequent veterinary investigations indicated that an outbreak of avian cholera was the likely cause (South Georgia Government, 2005). Avian cholera has been reported as a cause of mortality in penguin colonies and for other seabirds elsewhere in the sub-Antarctic and is a conservation concern (Cooper et al., 2009). In contrast to South Georgia, the chinstrap penguin population in the South Sandwich Islands is probably the largest globally. The chinstrap penguin colony on Zavodovski Island is probably the largest single penguin colony in the world and has been estimated to be over one million pairs of birds (Convey et al., 1999). This colony alone may represent up to 7.5% of the world population, although most of the uncertainty in global chinstrap population comes from the error associated with counts on Zavodovski. More than one half million pairs of chinstrap penguins were estimated to occupy the rest of the South Sandwich Islands (Convey et al., 1999). Observations made on an expedition in January 2011 suggest that this number has increased and more detailed surveys on land would be useful to assess current population numbers (T. Hart, Dept. of Zoology, University of Oxford, personal communication, 18 May, 2015).

Numbers of chinstrap penguins are reported to have declined dramatically at study colonies along the West Antarctic Peninsula, in the South Shetland and South Orkney Islands (Forcada et al., 2006; Lynch et al., 2008; Trivelpiece et al., 2011). A reduction in the reported population size in the South Sandwich Islands from approximately 5,000,000 pairs in the early 1980s (Croxall et al., 1984a,b) to about 1.5 million pairs in the 1990s (Convey et al., 1999; Poncet, 1997) has been cited as evidence of a significant decline in this species (Trivelpiece et al., 2011) both regionally and globally. However, the basis for the original estimates of population size of chinstrap penguins on the South Sandwich Islands is unclear as counts of population size depend on survey effort and so a precipitous decline in this species in this area is uncertain. There is evidence of shifts in the distribution of chinstrap penguins around the South Sandwich Islands, probably as a response to volcanic activity, which emphasizes the value of treating the entire island group as important for conservation of chinstrap penguins in this region (Convey et al., 1999). A number of factors relating to regional warming in the Antarctic have also been associated with the decline in numbers of chinstrap penguins, as well as changes in populations of other species, although the exact causes of these changes have been equivocal. The overall

negative trends in krill abundance in the Scotia Sea are considered to be a driver of decline in this species (e.g. Forcada et al., 2006; Trivelpiece et al., 2011). Trivelpiece et al. (2011) suggested that the extermination of competitors in the Scotia Sea, such as whale, and later, fish species, led to increased supplies of krill, allowing the penguins to maintain or increase their populations (krill surplus hypothesis). However, climate-change induced reductions in krill biomass (e.g. Atkinson et al., 2004) may now be acting to decrease population sizes of krill-feeding penguins (Trathan and Reid, 2009).

4.2.1.1.3 Adélie Penguin (*Pygoscelis adeliae*)

- Location: South Sandwich Islands; occasional breeding pairs in South Georgia and a small colony recently reported from Annenkov Island, South Georgia.
- IUCN Red List Status: Least Concern.
- Population size: ~50,000 pairs (South Sandwich Islands).
- Population trend: Uncertain in the South Sandwich Islands; reports of decline elsewhere in the Scotia Sea region.
- Diet: Mainly krill in the Scotia Sea; also reported to prey on ice krill (*Euphausia crystallorophias*) and Antarctic silverfish, *Pleurogramma antarctica,* around continental Antarctica.
- Foraging range: Information is lacking for South Sandwich Islands. This species generally forages above the shelf and out to the shelf break during the breeding season.
- Breeding: No information for the South Sandwich Islands, but elsewhere individuals come to shore in September-October. Eggs (typically two) are laid in November and hatch in December.

Foraging Ecology Adélie penguins are a circum-Antarctic species closely linked to sea ice and, in winter, the marginal sea ice zone (Forcada et al., 2006). They are distributed along the Scotia Arc and southern islands of the Scotia Arc. Large numbers of Adélies are observed as far as the South Orkney Islands. There is a small breeding population in the South Sandwich Islands, which are generally regarded as the northern limit of their distribution in the Scotia Sea (Convey et al., 1999; Forcada et al., 2006). They are recorded as occasional breeders at South Georgia (Clarke et al., 2012), and a small breeding colony has been reported from Annenkov Island, South Georgia (Convey et al., 1999). It is mainly in the middle and northern sections of the western Antarctic Peninsula and the islands of the Scotia Arc, where Adélie penguins are heavily dependent upon

Antarctic krill, *E. superba*, for their nutrition (Fraser and Hofmann, 2003; Lynnes et al., 2002). Further south, around the Antarctic continent, these penguins rely more on the Antarctic silverfish, and the ice krill, *E. crystallorophias*, in their diet (Ainley, 2002; Clarke et al., 1998). They may also take smaller quantities of amphipods and squid (Ratcliffe and Trathan, 2011). In the Antarctic Peninsula region, foraging trip duration of Adélie penguins has been correlated with the presence of krill (Fraser and Hofmann, 2003). In years following poor ice cover, krill abundance decreases to low levels and foraging trip durations increase (Fraser and Hofmann, 2003). In the years following good ice cover, krill abundance increases and, when it reaches a sufficient threshold, penguin foraging trip durations remain approximately level (Fraser and Hofmann, 2003). During the breeding season, Adélie penguins forage predominantly above the shelf and out to the shelf break. Foraging trip distances in Adélie penguins are generally larger than in chinstrap penguins (56–177 km in Lynnes et al., 2002). There is evidence that in poor krill years chinstrap penguins may competitively exclude Adélie penguins from their feeding grounds, resulting in longer foraging trip durations and reduced reproductive success (Lynnes et al., 2002). Duration of foraging trips can also be increased by the presence of fast ice close to the shore, which can also have a negative impact on the reproductive success of this species.

Life History Information on the life history of Adélie penguins has been documented in areas other than the South Sandwich Islands, particularly on the South Orkney Islands. The adult penguins first arrive on nesting sites in September-October and the first eggs are laid in early November, a month before chinstrap penguins (Lishman, 1985). As is the case for chinstrap penguins, two eggs are usually laid, separated by 3 days, and the first egg usually being larger than the second (Lishman, 1985; Figure 31). Eggs hatch in early December and chicks enter creches when 16–19 days old (Lishman, 1985). Creches in Adélie penguins are larger than in chinstrap penguins, and hold 10–20 chicks (Lishman, 1985). Adélie penguins fledge in February, at least 60 days following hatching (Lishman, 1985). Survival of the first chick is generally higher than that of the second in Adélie penguins, especially when adult access to food is impaired by persistent ice (Lishman, 1985). Sources of mortality among Adélie chicks are similar to those for chinstrap penguins. Competition between Adélie and chinstrap penguins for nest and foraging areas has been documented to decrease breeding success in Adélie penguins (Carlini et al., 2005).

Figure 31 Adélie penguins, *Pygoscelis adeliae*, on nests at rookery. *Photo Penguin Watch/T. Hart and C. Black, 2014.*

Population Trends Adélie penguin populations in the Scotia Sea are in decline (Forcada et al., 2006; Trivelpiece et al., 2011). This appears to be related to a reduced survival of juvenile penguins (Forcada et al., 2006), which is apparently related to poor krill availability resulting from winter sea ice conditions (Trivelpiece et al., 2011). Reduced recruitment to the South Shetland Islands has resulted in a ~50% decrease in colony size since 1987. Similar declines have been reported for the South Orkney Islands and parts of the Antarctic Peninsula (Trivelpiece et al., 2011).

Trends of Adélie penguin populations at the South Sandwich Islands are unclear. Croxall et al. (1984a,b) estimated 30,000 pairs. Poncet (1997) estimated that approximately 10,000 pairs (range of 8000–15,000) were present on four of the South Sandwich Islands. Convey et al. (1999) estimated 50,000 pairs on six islands. Current population estimates are needed for this species on the South Sandwich Islands.

4.2.1.1.4 Gentoo Penguin (*Pygoscelis papua*)

- Location: South Georgia and South Sandwich Islands.
- IUCN Red List Status: Near Threatened.
- Population size: ~105,000 pairs (South Georgia); ~1500 pairs (South Sandwich Islands).
- Population trend: possibly increasing in South Georgia although numbers known to fluctuate. Unknown in South Sandwich Islands.
- Diet: krill, pelagic and benthic fish and cephalopods.

- Foraging range: forage close to shore during breeding season (rarely >10 km) around South Georgia.
- Breeding: Usually two eggs are laid in October; eggs hatch in early December and chicks fledging late February.

Foraging Ecology Gentoo penguins (Figure 32) differ markedly in their foraging ecology when compared to other pygoscelid penguins. During the day, they usually forage much closer to shore than other species. At South Georgia, gentoos rarely forage more than 10 km from rookeries (Croxall et al., 1988); at other locations, they typically forage less than 20 km from rookeries (e.g. Miller et al., 2010; Trivelpiece et al., 1987) and generally do not move beyond the shelf edge (Miller et al., 2010). Their primary prey varies and includes varying proportions of fish, cephalopods and krill (mainly *E. superba* but also small amounts of *E. frigida*; Ratcliffe and Trathan, 2011). Evidence suggests that when krill are in short supply, gentoo penguins may switch from feeding primarily on krill to feeding on fish. This coincides with a switch from shallow foraging to deeper dives of up to 150 m depth (Croxall et al., 1988; Miller et al., 2009; Williams, 1991). Unlike other pygoscelids, gentoos sometimes prey upon benthic fish

Figure 32 Gentoo penguin, *Pygoscelis papua*, at Grytviken, South Georgia, austral summer 2009. *Photograph A.D. Rogers, 2009.*

species (Croxall et al., 1988; Miller et al., 2009; Williams, 1991). Gentoos have also been observed to consume a relatively large proportion of pelagic fish in their diet, particularly *E. carlsbergi* (Miller et al., 2009; Williams, 1991). At South Georgia, gentoo penguins feed primarily on krill (Croxall et al., 1988; Williams, 1991), with fish forming a variable proportion of the diet, depending on availability of krill. In the summer, the main fish species that occur in their diet are Antarctic cods, *Notothenia rossii* or *Notothenia neglecta* or mackerel icefish (Croxall et al., 1988), although myctophids can also make up a small part of the diet. In winter, the fish *Nototheniops larseni* can be an important component of the diet as well as mackerel icefish, with a smaller component being formed by *E. carlsbergi* (Williams, 1991). Other invertebrates, such as the amphipod crustacean, *Themisto gaudichaudii,* can also appear in the diet, although their contribution is usually minor (Williams, 1991).

Life History Gentoo reproduction and behaviour during the nesting and brooding period varies depending on locality (Otley et al., 2005). In South Georgia, gentoo penguins breed in small-to-medium-sized colonies (usually <1000 pairs but up to 5000 pairs) and lay two eggs, 3–4 days apart, in October. Adult incubation shifts change approximately daily, and the eggs hatch in early December, frequently with both chicks surviving. At first, one adult will forage while the other guards the chicks. When the chicks join creches at the end of December, both adults will forage. Chicks fledge in late February and adults forage at sea for the next 10 days before coming ashore and moulting mid-March to early April (Davis et al., 1989). Annual adult breeding numbers vary as a function of environmental conditions, which may play a role in the degree of mate fidelity (Williams and Rodwell, 1992). Timing of breeding and rate of growth of chicks can also vary substantially from year to year (Lescroel et al., 2009; Williams, 1991). Food availability can affect the number of young birds that will breed the following year, and therefore has an indirect impact on reproductive output of populations (Williams, 1991).

Population Trends Trends in population size of gentoo penguins vary depending on locality. Numbers of breeding gentoo penguins increased significantly at the South Orkney Islands between 1979 and 2004 (5.5% annual increase; Forcada et al., 2006). At the South Shetland Islands, populations have remained relatively stable since the 1970s, compared to chinstrap and Adélie penguins that have shown a decline in numbers. Approximately 1500 breeding pairs were reported for the South Sandwich Islands (Convey et al., 1999). At South Georgia, the most recent published estimate of

population size for gentoo penguins is approximately 105,000 pairs. It has been suggested that numbers have decreased at Bird Island in South Georgia by ~20% since the 1970s (Woehler and Croxall, 1997). This is a serious concern because South Georgia may be the second largest population for the species globally (Pistorius et al., 2010).

4.2.1.1.5 Macaroni Penguin (*Eudyptes chrysolophus*)

- Location: South Georgia and South Sandwich Islands.
- IUCN Red List Status: Vulnerable.
- Population size: ~1,000,000 pairs (South Georgia); ~55,000 pairs (South Sandwich Islands).
- Population trend: Major decreases in South Georgia. Unknown in South Sandwich Islands.
- Diet: Mainly krill; also pelagic and benthic fish.
- Foraging range: At South Georgia depending on the stage of reproduction as far north as the Maurice Ewing Bank and Polar Frontal Zone, or over the shelf or slope of South Georgia.
- Breeding: Adults arrive in October with egg laying in November to December. Two eggs are laid. The first egg is usually lost as a result of rejection from the nest. Eggs hatch late December. Fledging occurs in March.

Foraging Ecology Krill are the predominant prey of macaroni penguins (e.g. Croxall et al., 1999; Croxall and Prince, 1980; Figure 33) within most regions of their distribution and include *E. superba*, *Thysanoessa macrura*, *Euphausia vallentini* and *E. frigida* depending on locality (e.g. Croxall and

Figure 33 Macaroni penguin, *Eudyptes chrysolophus*. *Photograph T. Hart, Dept. of Zoology, University of Oxford.*

Prince, 1980; Croxall et al., 1999; Deagle et al., 2007). However, fish may comprise a small proportion of their diet (e.g. Croxall et al., 1999). A shift from a predominance of krill to fish during the breeding cycle is also known to occur in macaroni penguins, as has been observed at Heard Island (Green et al., 1998). The most important species of fish, in such cases, is the rhombic lanternfish, *Krefftichthys anderssoni*, although other species, such as *Electrona* sp., *Protomyctophum* sp. and notothenioids, may also be taken (Deagle et al., 2007; Green et al., 1998). Macaroni penguins have a considerable impact on prey population sizes. However, estimates that macaroni penguins consume more than eight million tonnes of krill annually (Boyd, 2002) were based on estimates of penguin population size from the 1970s (>5 million breeding birds), which is much larger than the current population. Regardless, this species likely has a significant impact on the structure of the marine ecosystem around South Georgia with consequences for ecosystem function (Barlow and Croxall, 2002; Trathan et al., 2006).

Foraging patterns of macaroni penguins vary depending on season, sex of the individuals, stage of the breeding cycle and krill abundance. Around South Georgia, tagging studies have indicated a variety of foraging patterns. During the egg incubation period, male macaroni penguins were observed to have a trip duration of up to 26 days and females up to 15 days, with males travelling up to 643 km, and females up to 486 km, from South Georgia, and a maximum distance of more than 2000 km (Barlow and Croxall, 2002). Tagged birds travelled to the Maurice Ewing Bank, to the northwest of South Georgia, with some males travelling to the Polar Frontal Zone and beyond (Barlow and Croxall, 2002; Figure 34). Long foraging trips also coincide with the premoult period (February-March; Green et al., 2009). During the chick-rearing period, foraging trips lasted a much shorter period of time, with the majority (~80%) being less than 48 h duration, although trips could last as long as 358 h (Barlow and Croxall, 2002). During this period, most of the foraging trips were located over the shelf/slope of South Georgia within the 2000 m depth contour, although most were within the 200 m depth contour (note the low sample sizes; Barlow and Croxall, 2002; see Figure 34). Subsequent research tracking penguins from several colonies on the northern coast of South Georgia during the brood guarding period confirmed the tendency for birds to forage northwards towards the shelf edge, with the majority of foraging taking place over the shelf (Trathan et al., 2006). The region to the north of South Georgia is known for high krill abundances with the retention of krill related to the occurrence of mesoscale eddies in this region (Trathan et al., 2006 and references therein).

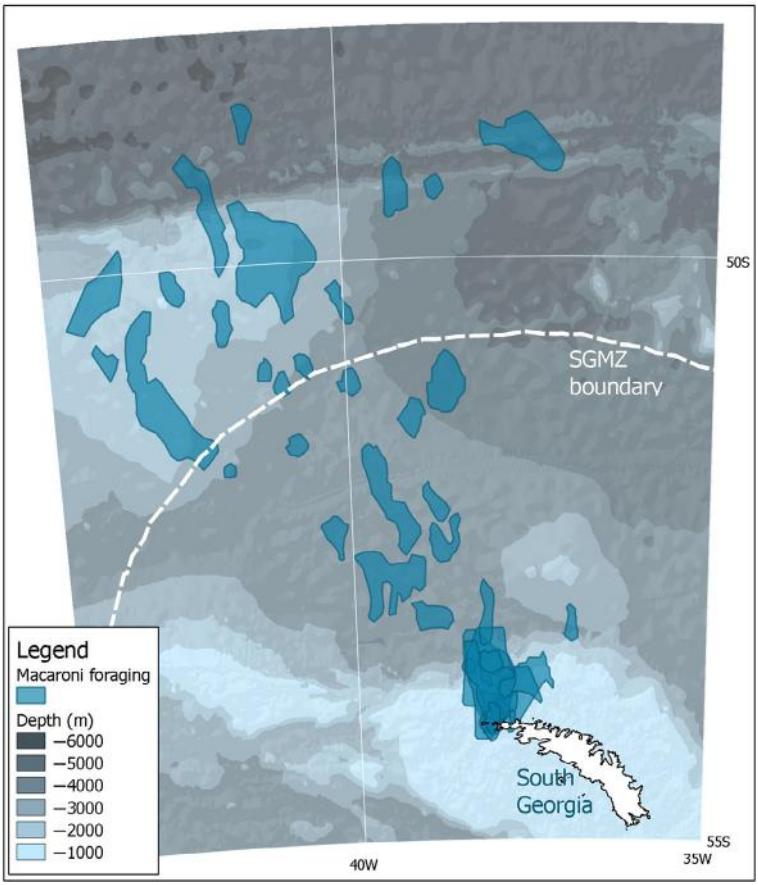

Figure 34 Macaroni penguin, *Eudyptes chrysolophus*, foraging areas through the breeding period. Macaroni foraging areas (presence of various tagged individuals) indicated by blue (grey in the print version) shading. *Data from Barlow and Croxall (2002); see also Trathan et al. (2006).*

It is thought that foraging success probably determined the distance the birds travelled offshore and whether or not they ended up foraging over the shelf break (Trathan et al., 2006). An exception to this behaviour was shown by birds from Willis Island that foraged to the south of South Georgia, and also foraged over the shelf (Trathan et al., 2006).

During the brood period, most foraging trips of macaroni penguins are during the day, starting at sunrise and returning in the afternoon, although some trips are also overnight (Green et al., 2002; Hart et al., 2010). Dive depth during the brooding period is affected, among other factors by whether it is day or night. Deeper dives typically occur during the day, when

krill are at depth, and shallower dives occur at night, when krill are nearer the surface (Hart et al., 2010). During the winter, macaroni penguins migrate away from land, and foraging dives are at greater depths (maximum of 50–60 m depth compared to 40–50 m during the brood period) and for longer durations (Green et al., 2002).

Life History The dispersal of juvenile macaroni penguins is poorly understood, but they recruit to adult breeding colonies at an age of 5 or 6 years. This species has a high level of both nesting site fidelity and pair-fidelity and breeding within colonies is highly synchronous while timing differs between colonies (Williams and Rodwell, 1992). Males arrive at the colony several days before females in mid- to late-October and egg laying is also synchronous within a colony from November to December (Williams, 1995; Williams and Croxall, 1991). Macaroni penguins lay two eggs, an "A" egg and a "B" egg, the latter being up to 80% larger than the former. The "A" egg is usually rejected before the "B" egg is laid (Williams, 1995; Williams and Croxall, 1991). It is not understood why an egg is laid that is generally rejected (St Clair, 1992, 1996). It has been suggested that variation in the levels of rejection and its timing are possibly adaptive to different environments (Massaro and Davis, 2004; Poisbleau et al., 2008). However, more recent work based on measuring the concentrations of vitellogenin, the yolk precursor protein, in blood plasma suggest that this phenomenon may be a result of constraints on macaroni penguin life histories exerted by migration prior to breeding and is therefore not adaptive (Crossin et al., 2010). The reversed egg size and reversed hatching asynchrony are unique in birds and has only been found in crested penguins (Crossin et al., 2010; Warham, 1975). Hatching takes place in late December with chicks moving into creches in mid-January and fledging in March (Williams and Croxall, 1991). Prior to moulting, the adult penguins undertake a long foraging trip during the premoult period to build up body reserves.

Population Trends Macaroni penguin populations have apparently declined dramatically at South Georgia since the 1970s (Trathan et al., 2012) and continued to decline more than 50% in the period between 1980 and 2000 (Barlow et al., 2002). The latest estimate of population size, calculated from aerial survey photographs of breeding colonies in 2000 and 2003, place numbers of macaroni penguins at approximately 1 million pairs compared to estimated population of 5,440,000 pairs in the late 1970s (Croxall and Prince, 1979). This decrease is globally significant. South Georgia was the most important breeding site for this species in the late

1970s, and comprised approximately 45.6% of the global population. The South Georgia population is currently estimated to be only 12.3% of the global population (Trathan et al., 2012).

Macaroni penguins have an estimated world population of 6.3 million breeding pairs (BirdLife International, 2013), a decrease on previous estimates (Brooke, 2004; Woehler, 1995). The largest colonies are found on the islands of Crozet, Kerguelen, Heard and McDonald Islands. Patterns among individual colonies suggest that some of the larger colonies which have undergone major declines are close to fur seal colonies, while some of the smaller colonies that are distant from fur seal colonies have actually increased (Trathan et al., 2012). Thus, competition from fur seals is thought to be a major contributory factor in the decline of the South Georgia populations of macaroni penguins, although declining trends in krill abundance within the region may also be having an impact (Barlow et al., 2002; Clarke et al., 2012; Cresswell et al., 2008; Trathan et al., 2012). Around South Georgia, the largest colonies are now thought to occur at Willis Island, Cooper Island and Natriss Head (Trathan et al., 2012).

4.2.1.1.6 Southern Rockhopper Penguin (*Eudyptes chrysocome chrysochome*)

- Location: South Georgia.
- IUCN Red List Status: Vulnerable.
- Population size: Occasional visitors.
- Population trend: Decrease in the South Atlantic region from 1930s to 1990s, currently stable.
- Diet: Fish, crustaceans and cephalopods.
- Foraging range: No data for South Georgia.
- Breeding: Adults return to breeding colonies in October. Eggs are incubated in November-December, and chicks fledge in February.

This species only occurs in small numbers on South Georgia where it may be found nesting in macaroni penguin colonies (Clarke et al., 2012). Populations in the Falkland Islands declined by more than 80% from the 1930s to 1995s, but have stabilized more recently (Putz et al., 2003). The Falkland Islands population of southern rockhopper penguins remains the most important (BirdLife International, 2010).

4.2.1.2 Albatrosses

4.2.1.2.1 Black-Browed Albatross (*Thalassarche melanophris*)

- Location: South Georgia (breeding) and South Sandwich Islands (foraging).

- IUCN Red List Status: Endangered.
- Population size: 74,296 pairs (South Georgia).
- Population trend: 25% decrease in South Georgia in last 20 years.
- Diet: Krill, cephalopods, fish.
- Foraging range: Variable; early in breeding season north of South Georgia to the Antarctic Polar Front; during brooding Shag Rocks; post brooding, South Orkney Islands and Antarctic Peninsula; winter, Benguela current, Patagonian Shelf, off south coast of Australia.
- Breeding: Adults arrive in September. A single egg is laid in November to December. Eggs hatch late December to early January and chicks fledge April/May.

Foraging Ecology Black-browed albatross (Figure 35) usually seize prey at the surface, but are also capable of diving to a maximum of 4.5 m depth (Prince et al., 1994a). They often associate in large numbers with fishing vessels (ACAP, 2010a), and sometimes also with large ocean predators, such as killer whales (Sakamoto et al., 2009). The diet of the black-browed albatross varies depending on location and inter-annually within a single location/region (ACAP, 2010a; Xavier et al., 2003). At South Georgia, between the years of 1996 and 2000, krill (*E. superba*) formed the majority of the diet of black-browed albatross (38% by mass), followed by squid (31%) and fish (27%; Xavier et al., 2003). However, in some years, fish were the most important component of the diet (1998, 1999; mainly *C. gunnari* and southern barracudina, *Magnisudis prionosa*) or cephalopods (1996, 1997; mainly *Galiteuthis glacialis*, *Kondakovia longimana*, *Martialia*

Figure 35 Black-browed albatross, *Thalassarche melanophrys*, Scotia Sea. *Photograph A.D. Rogers, 2010.*

hyadesi, *Moroteuthis knipovitchi*; Xavier et al., 2003). Breeding success in black-browed albatross appears to be positively correlated with the quantities of the notothenioid fish *C. gunnari* in the diet (Xavier et al., 2003). In previous years, such as 1986, other fish, *P. guntheri* (51% of estimated fish biomass, probably obtained from a commercial fishery) and *Icichthys australis* (40%), were the main prey species (ACAP, 2010a).

As is true of other seabird species, foraging distance varies depending on the time of year for black-browed albatross. At South Georgia, observations have indicated that during egg incubation, adults forage to the north of the islands in sub-Antarctic waters north of the Antarctic Polar Front (Phillips et al., 2008; Figure 36). During brooding, they forage mainly in areas around Shag Rocks, while at the post-brooding stage they forage mainly to the south at the South Orkney Islands and the Antarctic Peninsula (Phillips et al., 2008; 2009; see Figure 35). Over winter, black-browed albatross migrate mainly to the Benguela shelf region, although a small number of birds migrate to the Patagonian Shelf or to areas off the coast of Southern Australia (Phillips et al., 2005a; Figure 36).

Life History Black-browed albatross nest in colonies. The entire breeding cycle lasts about 8 months. Birds begin to return to colonies in South Georgia in late September and egg-laying begins in late October to early November. A single egg is laid and is incubated for about 68 days before hatching in late December to early January. Chicks fledge April to May. Juveniles do not return to land until they are at least 2 years of age to 6 years of age. Birds begin to breed at a median age of 10 (range 8–13 years). Mortality of black-browed albatross chicks mainly arises from the abandonment of the nest following the failure of one of the adults to return from a foraging trip, or predation of chicks by brown skuas and giant petrels (nests on the periphery of colonies are particularly vulnerable; Forster and Phillips, 2009).

Population Trends Breeding populations of the black-browed albatross have declined in both South Georgia and the Falkland Islands, the latter being the most important breeding area for the species. In South Georgia, comparisons between 1985/1986 and 2003/2004 show a decrease of 17.5% in the number of pairs (1.1% per annum) in single species colonies, and of 32.8% (2.2% per annum), in mixed colonies, with larger decreases indicated for individual colonies over a similar time period (e.g. Bird Island, 44%; Poncet et al., 2006). Overall, population size in South Georgia has declined from approximately 101,488 pairs in the late 1980s/early 1990s (Prince et al., 1994b), to 74,296 pairs in the 2003/2004 breeding season

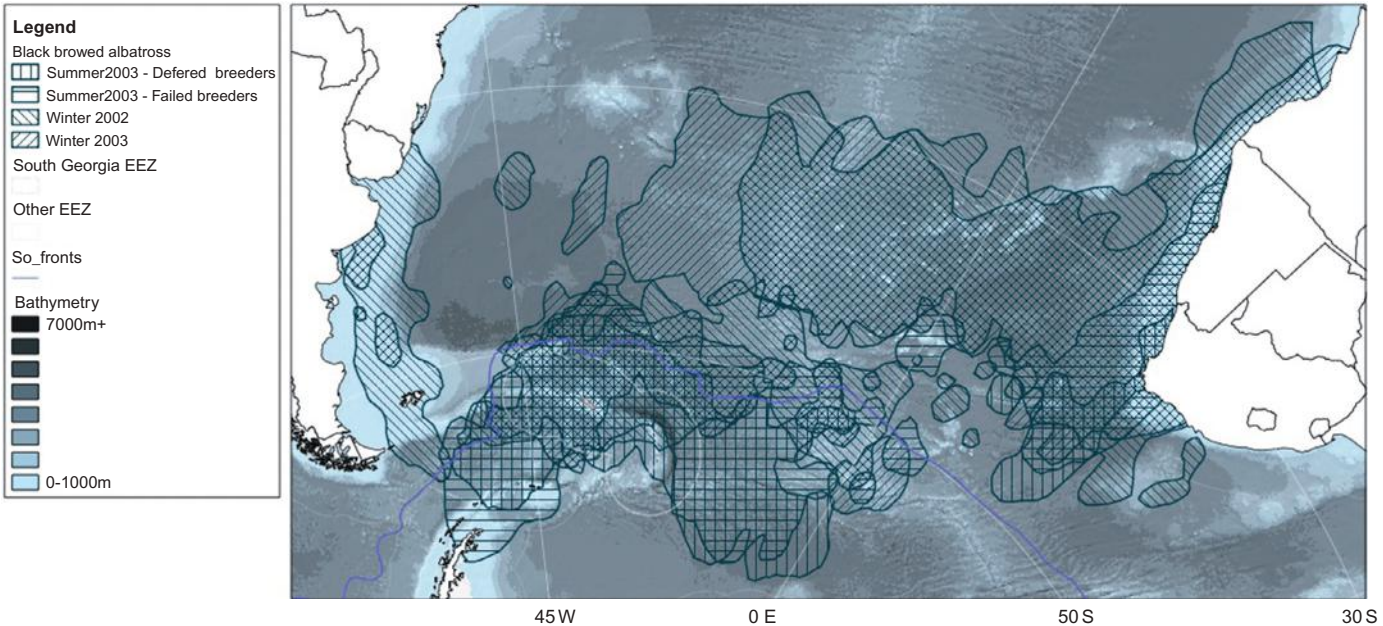

Figure 36 Foraging areas of black-browed albatross, *Thalassarche melanophrys*, from South Georgia throughout the annual cycle of breeding and non-breeding. *Data from Phillips et al. (2005a, 2008, 2009)*.

(Poncet et al., 2006). This decline (about 25% of the population size) is similar in order to the decline of black-browed albatross in the Falkland Islands (Arnold et al., 2006).

It is likely that declines in population sizes of black-browed albatross are occurring for a number of reasons, but accidental mortality from fisheries in the southern hemisphere is probably the most important factor. The distribution of black-browed albatross coincides with the major pelagic and demersal longline and trawl fisheries that are known sources of mortality for the species (see Figure 36). Longlines are recognized as a significant source of mortality for black-browed albatrosses that dive on the baited hooks and are caught or entangled and drowned. Off South Africa, longline fisheries for tuna and swordfish between 1998 and 2000 were estimated as killing between 19,000 and 30,000 seabirds per year, including black-browed albatross (Ryan et al., 2002). Pelagic longline fisheries managed by the International Commission for the Conservation of Atlantic Tuna (ICCAT) overlap substantially with the distribution of black-browed albatrosses in the South Atlantic. Estimates between 2003 and 2006 suggest up to 3900 individual black-browed albatrosses per annum were killed in ICCAT-managed longline fisheries during this period, and that the species made up the highest proportion of identified seabird by-catch (Tuck et al., 2011). Other longline fisheries with a by-catch of black-browed albatross include the swordfish, *Xiphias gladius*, fishery off Chile, the Argentine longline fisheries targeting toothfish and kingclip, *Genypterus blacodes*, the Uruguayan pelagic longline fishery and artisanal fisheries in Brazil targeting tuna (ACAP, 2010a; Azocar et al., 2011; Goya et al., 2011; Jimenez et al., 2009). Historically, longline fisheries off Australia, the Falkland Islands and South Georgia were also sources of mortality for black-browed albatross.

Trawl fisheries are also a source of mortality for black-browed albatross, including aerial collisions with trawl warps, drowning in nets as they are deployed, or, more commonly, becoming entangled in trawl warps and subsequently drowning during trawling operations (Sullivan et al., 2006; Watkins et al., 2008). Such impacts have been identified in finfish fisheries in the Falkland Islands where 1411 birds (predominantly black-browed albatross) were killed in 2002–2003 (Sullivan et al., 2006). In the deep-water hake fishery off South Africa where, based on observations in 2004 and 2005, an estimated 18,000 birds (range of 8000–31,000) were killed annually in 2004 and 2005, of which an estimated 39% were black-browed albatrosses (Watkins et al., 2008). Significant mortality of black-browed albatross also occurs in the trawl fishery in Golfo San Jorge off Argentina (ACAP, 2010a).

Mortality of seabirds from fishing operations can be dramatically decreased with the implementation of technical measures within a fishery, or other mitigation measures such as seasonal closures. For longline fisheries, such measures include changes in the timing of fishing operations, technical measures such as deployment of streamer lines over longlines during deployment to deter birds from diving on baited hooks, and the deployment of longlines through shoots (ACAP, 2010a, 2011a,b; Phillips et al., 2010). Such measures have been successful, and in South Georgia by-catch of albatross in the toothfish longline fishery fell from 5755 individuals in 1997 to zero by 2006 (Croxall, 2008). An identification scheme allowing hooks to be attributed to specific vessels has also been introduced by the Government of South Georgia and the South Sandwich Islands. Effective measures have also been developed to reduce bird mortality in trawl fisheries and include banning the discharge of offal during net deployments, binding nets to allow them to sink rapidly with minimal risk of entanglement of birds, and the employment of streamers on the trawl warps, bird scaring lines over nets (e.g. Tori lines) or booms around the stern of the vessel with streamers to deter birds (e.g. Brady Bafflers; ACAP, 2011c; Brickle et al., 2011; Bull, 2009; Sullivan et al., 2006). In the Falkland Islands, mitigation measures reduced seabird mortality in trawling operations from more than 1400 seabirds killed per annum in 2009 to an estimated 110 in 2010 (Brickle et al., 2011).

A review of longline fisheries identified by-catch reduction in many, including those taking black-browed albatross and other seabird species off South Georgia (Anderson et al., 2011). Technical mitigation measures, management measures reducing the amount of Illegal, Unreported, and Unregulated (IUU) fishing in some regions (e.g. the CCAMLR region), the end of bilateral fisheries agreements shifting fleets with high bird catch elsewhere (e.g. South African waters) the collapse of some fisheries, and other factors that lead to a reduction in fishing effort, played various roles in reducing seabird by-catch (Anderson et al., 2011; Petersen et al., 2008a). International efforts such as BirdLife International's Albatross Task Force, a team of by-catch mitigation instructors, have been successful in reducing by-catch in fisheries based in Chile and South Africa (Croxall et al., 2012). However, reductions in by-catch may also reflect the actual decline in populations of threatened species such as black-browed albatross (Petersen et al., 2008a). It is still estimated that 160,000 seabirds are killed each year in longline fisheries globally (Anderson et al., 2011), and fisheries by-catch is regarded as the most significant and pervasive threat to albatrosses and petrels both in coastal waters and on the high seas (Croxall et al., 2012).

In this context, it is interesting to note that globally, albatrosses, petrels and penguins are the most threatened seabird families (Croxall et al., 2012). By-catch of black-browed albatross and other albatross species in fisheries outside of the SGSSI MZ and outside the CCAMLR regulatory area remains a significant problem (e.g. Phillips et al., 2010). It is clear that although there have been improvements in both the reports of seabird by-catch and introduction of measures to reduce it by Regional Fisheries Management Organisations (RFMOs), implementation of effective measures remains far from adequate (Croxall et al., 2012).

While black-browed albatross in South Georgia are dependent on krill during the breeding period, and years of poor breeding success have been associated with low krill availability (Arnold et al., 2006; Reid and Croxall, 2001; Xavier et al., 2003; but see Reid et al., 2005), modelling has indicated that the main reason for the decline of black-browed albatross in recent years is adult mortality, resulting mainly from fisheries by-catch (Arnold et al., 2006). The decline is likely to have been in progress since the 1970s and has accelerated since the 1990s (Arnold et al., 2006). Of note, juveniles feed predominantly in the Benguela current region, and are likely to be highly dependent on conditions in the region, including interactions with the fishery there (Arnold et al., 2006; Petersen et al., 2008a; Watkins et al., 2008). If the current mortality continues, the population is likely to be reduced to less than 25 pairs in the next 70–80 years (Arnold et al., 2006). Although black-browed albatross forage around the South Sandwich Islands, there are no breeding colonies there (Convey et al., 1999).

4.2.1.2.2 Grey-Headed Albatross (*Thalassarche chrysostoma*)

- Location: South Georgia.
- IUCN Red List Status: Vulnerable.
- Population size: 47,674 pairs (South Georgia)
- Population trend: Estimated >58% decrease in breeding population census size South Georgia in last 20 years.
- Diet: Cephalopods, fish, krill.
- Foraging range: Varies; often in the Antarctic Polar Frontal Zone but can shift south of South Georgia to off the Antarctic Peninsula.
- Breeding: Adults arrive in September. A single egg is laid in October and hatching occurs in December. Chicks fledge April/May. Biannual breeder.

Foraging Ecology Grey-headed albatross generally seize their prey on the surface of the ocean although they are capable of diving to about 6 m

(Prince et al., 1994a). They mostly feed during the day, although evidence suggests that some prey are taken at night while the birds are sitting on the ocean surface. Diet varies with time and locality, and like black-browed albatross, grey-headed albatross feed on a combination of squid, fish and crustaceans (Xavier et al., 2003). However, squid predominate in the diet of grey-headed albatross (in South Georgia, *Galliteuthis glacialis*, *Kondakovia longimana*, *Martialia hyadesi*, *P. glacialis*). Fish species are generally the second most important dietary component (in South Georgia these include the southern lamprey, *Geotria australis*, *C. gunnari* and the barracudina, *Magnisudis prionosa*) and crustaceans (*E. superba*; Xavier et al., 2003, 2007). In some years, the relative importance of these prey categories may shift, and in years where the proportion of the squid *M. hyadesi* is at low levels in the diet, the breeding success of grey-headed albatross decreases (Xavier et al., 2003, 2007). It is notable that the key prey for grey-headed albatross at South Georgia, *M. hyadesi* and *G. australis*, are associated with the Antarctic Polar Frontal Zone where the species forages, in contrast to black-browed albatross which forage more over the South Georgia Shelf (Xavier et al., 2003; Figure 37).

When cephalopod availability is poor, grey-headed albatross tend to forage in Antarctic waters and concentrate on Antarctic prey species such as krill. This may involve a shift in foraging area from the Antarctic Polar Frontal Zone to the shelf/slope of the Antarctic Peninsula (Catry et al., 2004a; Phillips et al., 2009). What is perhaps the fastest sustained tracked flight known for any bird species was recorded for a grey-headed albatross that flew from the Antarctic Peninsula to Bird Island at a speed of at least 110 km h^{-1} for 9 h (taking into account the sinuosity of albatross flight this was probably in excess of 127 km h^{-1}; Catry et al., 2004b).

Life History Grey-headed albatross generally breed biannually, although a small number of pairs may attempt to breed in consecutive years (ACAP, 2010b). Birds return to colonies from early September to early October and egg laying begins in late October (ACAP, 2010b). Incubation averages 72–74 days, and hatching occurs in December. Chicks fledge from April to May, after 116–145 days (ACAP, 2010b). Immature birds return to land at a minimum of 3 years of age, but mostly at 6–7 years. On South Georgia, the modal age at first breeding is 12 years (ACAP, 2010b). South Georgia is the most important breeding locality for grey-headed albatross as the islands host 40% of the global breeding population (Poncet et al., 2006).

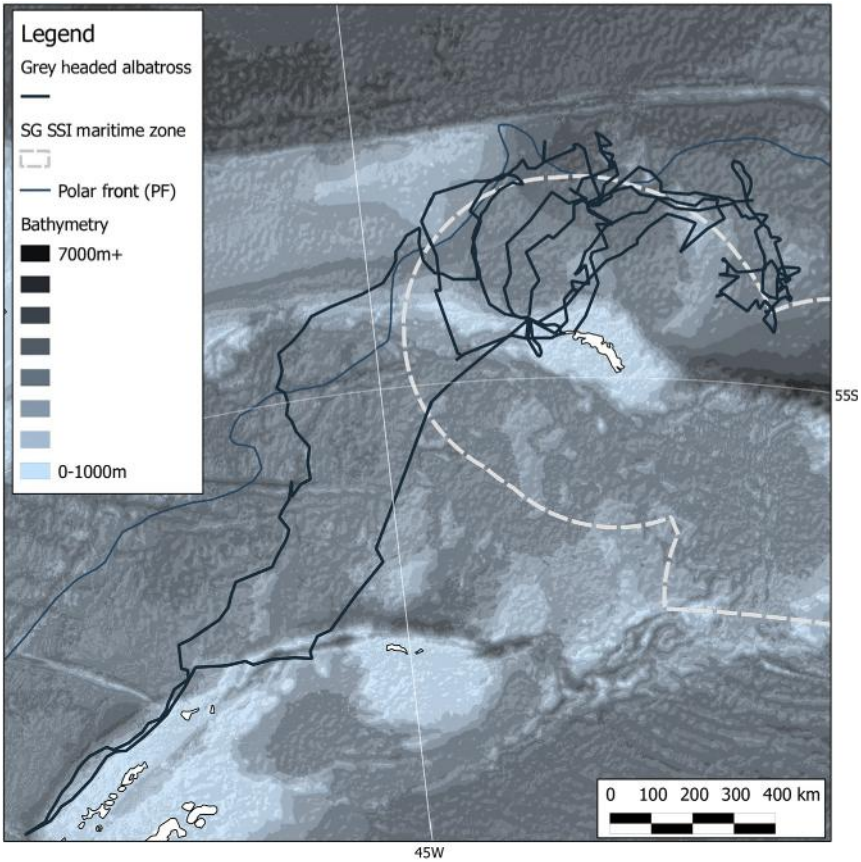

Figure 37 Foraging tracks of four grey-headed albatross, *Thalassarche chrysostoma*, from South Georgia over five foraging trips in March 2003. *Data from Catry et al. (2004a)*.

Population Trends At South Georgia, grey-headed albatross numbers have declined by about 1.1% per year in single species colonies and 2.2% per year in mixed colonies between 1985 and 2004, with individual colonies showing an even greater rate of decline (Poncet et al., 2006). Population estimates for grey-headed albatross in South Georgia during the late 1980s and early 1990 suggested a total breeding population size of 80,904 pairs (Prince et al., 1994b). The most recent population estimate is 47,674 pairs (Poncet et al., 2006). While there may be differences in methodology and effort between these studies, this represents a decrease of more than 58% in the most important breeding location, globally, for this species. The decline is thought to result mainly from by-catch in fisheries, particularly of juveniles (ACAP, 2010b). Evidence suggests that grey-headed

albatrosses are taken in longline fisheries outside of the CCAMLR area (e.g. the Chilean longline fishery for swordfish, and ICCAT-managed longline fisheries in the South Atlantic; Azocar et al., 2011; Tuck et al., 2011).

4.2.1.2.3 Wandering Albatross (*Diomedea exulans*)

- Location: South Georgia.
- IUCN Red List Status: Vulnerable.
- Population size: 1533 pairs (South Georgia).
- Population trend: Estimated >30% decrease in breeding population census size South Georgia in last 20 years.
- Diet: Cephalopods and fish.
- Foraging range: Varies; during the breeding season to the north west of South Georgia on the shelf of the islands or Shag Rocks, in the Antarctic Polar Frontal Zone or on the Patagonian shelf or slope; over winter Antarctic, sub-Antarctic and sub-tropical waters.
- Breeding: Adults arrive in November with single egg laid in December to January. Eggs hatch in March.

Foraging Ecology Wandering albatross (Figure 38) take most of their prey by surface seizing. While breeding at South Georgia, wandering albatross feed mainly on cephalopods (over 50 species; mainly cranchiid and onychoteuthid squid) and fish (roughly 10 species, particularly the Patagonian toothfish, *D. eleginoides* and blue antimora, *Antimora rostrata,* during chick rearing at South Georgia; Xavier et al., 2004; Ceia et al., 2012). They also feed voraciously on carrion, including offal and discharges from fishing vessels (Xavier et al., 2004). During the breeding season, wandering albatross

Figure 38 Wandering albatross, *Diomedea exulans*. *Photograph A.D. Rogers, 2009.*

undertake foraging trips of between 1 and 37 days that range from 28°S (off the Brazilian Shelf) to 63°S (off the Antarctic Peninsula Shelf), and from 19°W (off Tristan da Cunha) to 68°W (Patagonian Shelf; Xavier et al., 2004). Most foraging occurs to the northwest of South Georgia, on the shelf of the islands and Shag Rocks, in the Antarctic Polar Frontal Zone or on the Patagonian shelf/slope (Xavier et al., 2004; Figure 39). However, the amount of time spent foraging in these different water masses varies from year to year depending on food availability (Xavier et al., 2004). Over winter, wandering albatross feed in these same waters, although most time is spent feeding in Antarctic waters, followed by sub-Antarctic and then sub-tropical waters (Xavier et al., 2006). Overall, the foraging ranges for

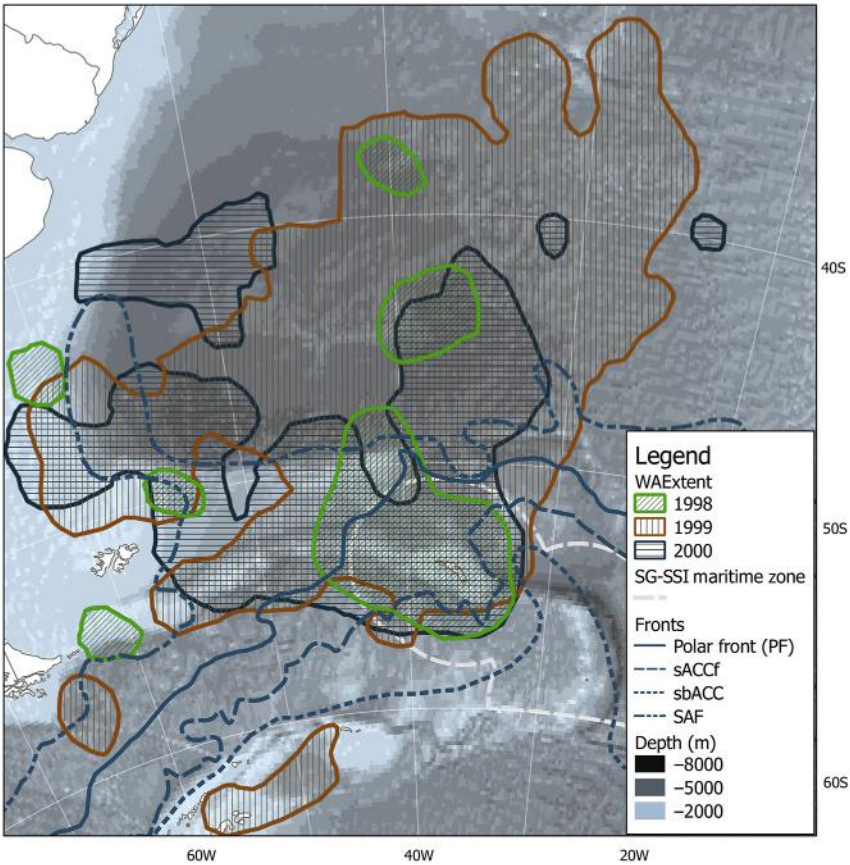

Figure 39 Wandering albatross, *Diomedea exulans*. Areas where tracked birds were present during foraging from 1998 to 2000. *Data from Xavier et al. (2004).*

wandering albatross are very large, up to 4000 km from breeding colonies (ACAP, 2010c). Tracking of birds from South Georgia indicates that they probably interact with several fisheries, including the South Georgia Patagonian toothfish fishery, the Argentinian longline fishery for toothfish and kingclip on the Patagonian Shelf, and longline fisheries further north (Xavier et al., 2004). It is likely that the high level of occurrence of Patagonian toothfish in the diet of birds from South Georgia results from scavenging at fishing vessels (Xavier et al., 2004).

Life History Wandering albatross are biennial breeders, with about a third of breeding birds deferring breeding for a year beyond the expected breeding date (ACAP, 2010c). Adults return to colonies in November, about a month before laying eggs. Eggs are laid during about 5 weeks from December to January, and hatching occurs mainly in March after an incubation period of 78–79 days (ACAP, 2010c). Most chicks fledge in December after 278 days on the nest. Thus, the breeding cycle takes more than a year (ACAP, 2010c). Birds begin to return to colonies on South Georgia at a minimum of 3 years of age, but usually at 5–7 years, and breeding commences at age eight, with a mean of between 10 and 11 years.

Population Trends Population estimates have indicated that all breeding populations of wandering albatross have shown a decrease at some stage between 1985 and 2010 (ACAP, 2010c). Recently, populations in the Indian Ocean have increased in numbers, whereas the South Georgia wandering albatross populations have continually declined (probably since the 1960s and certainly since the 1970s; ACAP, 2010c; Croxall et al., 1990; Poncet et al., 2006). Monitoring of breeding wandering albatross at Bird Island from 1961 to 1989 indicated a mean annual decrease in the population of 1% per annum and 22% overall during this period (Croxall et al., 1990). Comparison of a census of breeding wandering albatross on South Georgia undertaken in 1984, which gave an estimate of 2230 pairs to that of 2004 with 1553 pairs, indicates a decrease in breeding population size of 30.4% in 20 years (Poncet et al., 2006). The demographics of the Bird Island wandering albatross population indicated that increased adult mortality was responsible for the decline in population size (Croxall et al., 1990), as was also found for black-browed albatross (Arnold et al., 2006). Rings recovered from dead wandering albatross were predominantly from longline fishing vessels, indicating that the most likely cause of adult mortality was fisheries interactions (Croxall et al., 1990). As is true for black-browed and grey-headed albatross, the main cause of increased adult mortality is

interaction with longline fisheries beyond South Georgia waters (ACAP, 2010c). These include ICCAT-managed longline fisheries in the South Atlantic Ocean (Tuck et al., 2011), which are regarded as particularly important in the context of wandering albatross mortality (Small, 2005), the pelagic longline fishery off South Africa (Petersen et al., 2008a) and the Chilean swordfish longline fishery (Azocar et al., 2011). Monitoring of the amount of fishing gear found associated with wandering albatrosses nesting on South Georgia showed that an order of magnitude more gear occurs in association with this species than for black-browed or grey-headed albatross (Phillips et al., 2010). About 85% of the fishing gear found associated with wandering albatross was from longlines. Much of this gear probably originates in longline fisheries off Chile, Argentina and Brazil where discarding of longline hooks has not been prohibited (Phillips et al., 2010). As with black-browed albatross, the life history of wandering albatross, which involves a low natural adult mortality and a biennual breeding cycle, renders populations highly vulnerable to increased mortality from fishing (Croxall et al., 1990; Tuck et al., 2011).

4.2.1.2.4 Light-Mantled Sooty Albatross (*Phoebetria palpebrata*)

- Location: South Georgia (breeding), South Sandwich Islands (present).
- IUCN Red List Status: Near Threatened.
- Population size: 5000 pairs (South Georgia but no census since 1976).
- Population trend: Possibly stable.
- Diet: Cephalopods, krill and fish.
- Foraging range: Mainly to the south of South Georgia and to the Antarctic Peninsula.
- Breeding: Adults return in October, eggs are laid late October/early November. Eggs hatch late December to January. Chicks fledge after 139 days. Biannual breeder.

Foraging Ecology Light-mantled sooty albatross (Figure 40) feed by surface seizing or by diving and the species is able to reach about 12.4 m depth (Prince et al., 1994a). Birds located at South Georgia feed predominantly on squid (mainly *G. glacialis* and *P.s glacialis*), krill (*E. superba*) and fish (mainly myctophids but also some notothenioids; Thomas, 1982). The birds forage mainly to the south of South Georgia on the shelf/slope of the Antarctic Peninsula (Phillips et al., 2005b; Figure 41). Foraging trips are long and follow a roughly clockwise direction to and from the Antarctic Peninsula to take advantage of the prevailing winds. Passages to foraging areas are fairly rapid (Phillips et al.,

Figure 40 Light-mantled sooty albatross, *Phoebetria palpebrata*. *Photograph A.D. Rogers, 2010.*

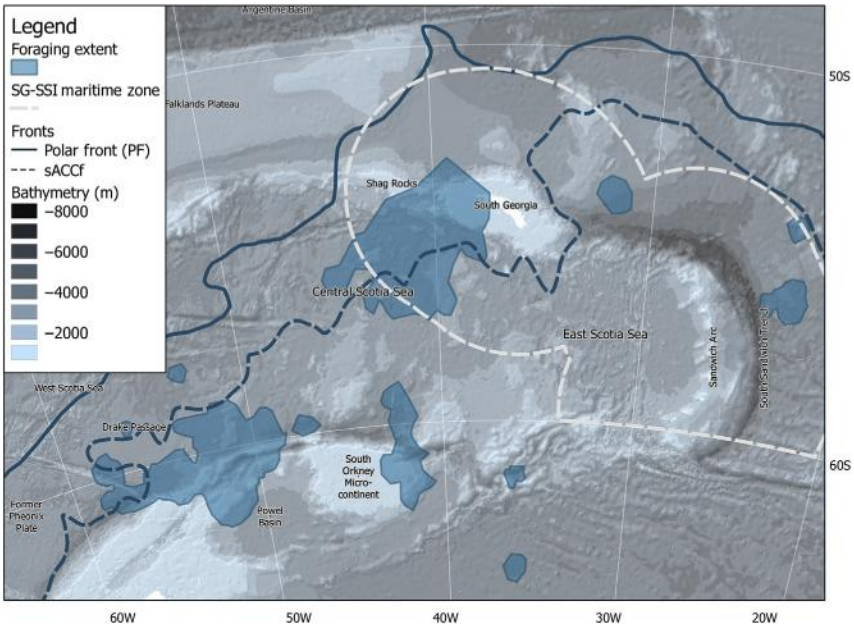

Figure 41 Light-mantled sooty albatross, *Phoebetria palpebrata*. Presence within foraging areas derived from tracking data indicated by (grey in the print version) shading. *Data from Phillips et al. (2005b).*

2005b). Light-mantled sooty albatross spend most of the day and approximately half of the night in flight, and are thus active in the dark for a greater proportion of time than are other albatross species (Phillips et al., 2005b). Foraging trips during the breeding season last on average nearly 4 days, and chicks are fed less frequently than is documented for

other medium to large albatrosses, but are given relatively larger meals (Phillips et al., 2005b).

Life History Light-mantled sooty albatross breed at solitary nests or in small colonies on sheltered cliffs (ACAP, 2010d). They breed every 2 years, although unsuccessful breeders will often attempt to breed again the following year (ACAP, 2010d). Adults return to colonies in October and eggs are laid late October to early November. Eggs hatch late December to January after an incubation period of 70 days at South Georgia (ACAP, 2010d). Chicks fledge after 139 days and young birds return to their natal colony after 7–12 years.

Population Trends Clarke et al. (2012) estimated 5000 pairs at South Georgia, but the population has not been subject to census since 1976. There is little information on population trends of light-mantled sooty albatross globally, including at South Georgia (ACAP, 2010d), although monitoring of a small study population suggests that numbers are stable (Clarke et al., 2012). The main threat to the species is longline fishing, especially because the diving abilities of this species give it greater access to baited hooks as they are deployed or retrieved (ACAP, 2010d). However, the foraging distribution of light-mantled sooty albatross from South Georgia probably renders them less vulnerable to this longline mortality than are black-browed albatross, grey-headed albatross and wandering albatross.

4.2.1.3 Petrels

4.2.1.3.1 White-Chinned Petrel (*Procellaria aequinoctialis*)

- Location: South Georgia (breeding); some foraging around South Sandwich Islands.
- IUCN Red List Status: Vulnerable.
- Population size: 900,000 pairs.
- Population trend: Significant decline from ~2 million pairs in 1980s to 900,000 pairs in late 2000s.
- Diet: Krill, cephalopods and fish.
- Foraging range: Varies depending on breeding stage; during egg incubation, Patagonian Shelf, Falkland Islands; during chick rearing, South Georgia, Shag Rocks and south as far as the South Orkney Islands; in winter, Patagonian Shelf from Tierra del Fuego to SE Brazil and along Pacific coast of Chile.

- Breeding: Adults return September, eggs are laid mid-late November. Eggs hatch mid/late January. Chicks fledge after 139 days in mid/late April.

Foraging Ecology White-chinned petrels (Figure 42) feed by seizing food on the ocean surface, but are also known to dive to 13 m depths around South Georgia (Huin, 1994). Around South Georgia, white-chinned petrels have been estimated to consume approximately 770,000 t of prey per annum (Croxall et al., 1984a,b, 1995a; Martin et al., 2009). This is partitioned between fish (especially myctophids such as *Electrona* spp. and notothenids such as *Lepidonothen larseni* and *P. guntheri*), squid (e.g. *Mastigoteuthis psychrophila*, *P. glacialis*, *Kondakovia longimana*, *Histioteuthis* sp., *Brachioteuthis* sp., *G. glacialis*, *Illex argentinus*; Croxall et al., 1995a; Berrow and Croxall, 1999; Berrow et al., 2000) and krill. Other crustaceans taken include *Themisto gaudichaudii* and *Notocrangon antarcticus* (Berrow and Croxall, 1999). The proportions of these groups in the diet vary over time, so reports from Croxall et al. (1984a,b) of 366,000 t of squid, 210,000 t of krill, and 187,000 t of fish differ from those of Croxall et al. (1995a) of 142,543 t of squid, 365,000 t of krill, and 255,036 t of fish. Irrespective of variation in diet, these estimates suggest that white-chinned petrel are the third most important predator of krill and the most important predator of fish at South Georgia (Croxall et al., 1995a). Despite a reduction in white-chinned petrel population size (see below), taking into account both breeding and pre-breeding birds, these figures remain a realistic estimate of the impact of white-chinned petrels on prey populations at South Georgia (Martin et al., 2009).

Figure 42 White-chinned petrel, *Procellaria aequinoctialis*. *Photograph A.D. Rogers, 2009.*

During egg incubation, white-chinned petrels undertake long foraging trips of up to 15 days duration (mean of 13 days) and travelling up to more than 8000 km (Berrow et al., 2000). During this period, birds forage preferentially along the Patagonian Shelf, off Argentina, and off the shelf/slope of the Falkland Islands (Berrow et al., 2000; Figure 43). During the chick-rearing period, foraging trips are of much shorter duration (5 days mean duration) and are focused on the shelf/slope of South Georgia/Shag Rocks

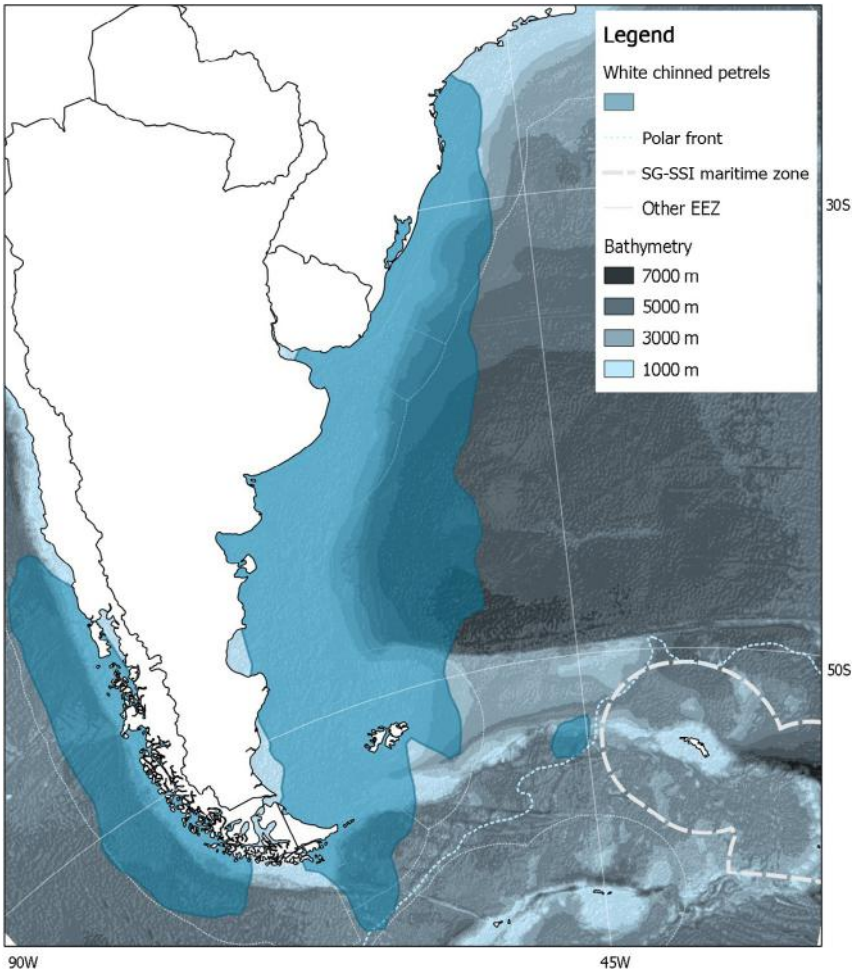

Figure 43 Distribution of non-feeding white-chinned petrels, *Procellaria aequinoctialis*, over winter (2003), demonstrating how the range of birds from South Georgia overlap with areas of the Patagonian Shelf and off the Pacific coast of Chile where significant longline fisheries occur. *Based on Philipps et al. (2006).*

and south of South Georgia as far as the South Orkney Islands (Berrow et al., 2000; Figure 43). The occurrence of significant numbers of myctophids in the diet suggests that white-chinned petrels forage at night as well as by day (Croxall et al., 1995a). During winter, this species disperses to the Patagonian Shelf where it forages from Tierra del Fuego to south-eastern Brazil, and also to more restricted areas off the Pacific coast of Chile (Phillips et al., 2006; Figure 43). It is interesting that, unlike other aquatic predators that have an important component of krill in the diet around South Georgia, white-chinned petrels show more resilience in breeding success during bad krill years (Berrow and Croxall, 1999). This may be related to the ability of white-chinned petrels to switch prey species. In addition, in comparison to albatross species for example, it could also result from the ability of white-chinned petrels to forage over a wider geographic area, as well as from their ability to take prey at greater depths and at night (Berrow and Croxall, 1999).

Life History The white-chinned petrel is the largest petrel to nest in burrows and breeds annually in colonies of 50–200 burrows (ACAP, 2010e; Martin et al., 2009). The nesting habitat of white-chinned petrels is typically pure tussac grass, or in areas where tussac is the dominant vegetation, and there is a preference for headlands or ridges as landscape features (Martin et al., 2009). Birds first arrive at their nesting sites in early to late September, but do not lay eggs for about 49 days (Hall, 1987). At South Georgia, the mean laying date is mid/late November, and incubation takes 59 days. Birds fledge after 98 days (Hall, 1987). Following fledging, the birds do not breed until about 6 years of age (range of 4–9 years).

Population Trends Population size of the white-chinned petrel on South Georgia was once estimated at approximately two million pairs (Prince and Croxall, 1983), but by the late 1990s had shown a decline of an estimated 30% at Bird Island (Berrow et al., 2000). More recent estimates suggest a population size of approximately 900,000 breeding pairs, some 40–50% of its former estimate (Martin et al., 2009). It is known that the species is very vulnerable to longline fisheries, particularly because of its ability to dive and intercept bait on deployment or retrieval of longlines. The distribution of South Georgia birds during incubation, and outside of the breeding season, indicates that they are likely to encounter such fisheries (Phillips et al., 2006; see Figure 43). For example, off Brazil in the 1990s, Brazilian demersal and pelagic longliners killed an estimated 378–1070 (mean 724) and 2165–4004 (mean 3084) white-chinned petrels per year (Olmos et al., 2000). Further south, from 1999 to 2001, Argentinian

demersal longliners killed a mean of 230 (maximum 1400) white-chinned petrels per year (Favero et al., 2003). In addition, artisanal fisheries for austral hake, *Merluccius australis*, and Patagonian toothfish in Chilean waters are thought to have killed an average of 1269 ± 783 white-chinned petrels per year (Moreno et al., 2006). Substantial numbers of white-chinned petrel are also thought to be killed in fisheries off Uruguayan waters by Uruguayan and Taiwanese vessels (Phillips et al., 2006). Substantial numbers of white-chinned petrels are also killed in pelagic and demersal longline fisheries and trawl fisheries from off South Africa and Namibia (Petersen et al., 2008a,b; Watkins et al., 2008). However, tracking studies indicate it is likely that the majority of the white-chinned petrels in this latter area originate from other breeding areas such as Crozet (Weimerskirch et al., 1999) and thus, Indian Ocean populations of the species are under greater pressure from this regional source of mortality (Ryan et al., 2012).

Data indicate a decrease in nest occupancy between 1981 and 1998 suggesting a population decrease of 1.9% per annum at South Georgia (Martin et al., 2009). Estimates indicate that a minimum of 70,000 birds are taken annually in fishing operations. It has been suggested that as many as 276,000 per annum are lost (Martin et al., 2009), but this figure is probably not realistic given an overall estimate of mortality for all seabirds from longlines of 160,000 per annum (Anderson et al., 2011). Phillips et al. (2006) estimated that at least 10,000 white-chinned petrels are killed per annum off the coast of South America as a result of the impacts of longline fisheries. This is a minimum figure given that the vessels of some States are not reporting bird by-catch, and the estimate also does not include the activities of IUU vessels (Phillips et al., 2006).

Brown rats, *Rattus norvegicus*, are an invasive species that are thought to exert a significant impact on white-chinned petrel populations (Clarke et al., 2012). Trampling of the habitat of white-chinned petrels by Antarctic fur seals and habitat alteration by reindeer, *Rangifer tarandus*, may be other sources of local population decline (Clarke et al., 2012).

4.2.1.3.2 Southern Giant Petrel (*Macronectes giganteus*)

- Location: South Georgia and South Sandwich Islands (breeding).
- IUCN Red List Status: Least concern.
- Population size: 8700 pairs (South Georgia), 1541 pairs (South Sandwich Islands).
- Population trend: increase South Georgia, not known for South Sandwich Islands.

- Diet: Seal and penguin carrion, also squid, krill and fish.
- Foraging range: Continental shelf off Argentina (mainly winter); southern Atlantic, Antarctic Polar Frontal Zone; coast, shelf and shelf break, South Georgia.
- Breeding: Single egg is laid mid-November. Approximately 60 days incubation. Hatching occurs in January, and chicks fledge in May.

Foraging Ecology Southern giant petrels (Figure 44), along with their sister species, the northern giant petrel, are dominant scavengers in the Antarctic and sub-Antarctic regions feeding predominantly on seal and penguin carrion (Gonzalez-Solis et al., 2002). Female giant petrels have also been observed to feed chicks on squid, krill and fish (Gonzalez-Solis et al., 2002).

At South Georgia, two types of foraging trips have been identified. Long-range pelagic foraging trips in which the petrels feed mainly at sea, although they occasionally visit the coastline of other archipelagos, range from 6 to 30 days and cover distances greater than 12,000 km (median distance ~7000 km; Gonzalez-Solis et al., 2002; Figures 45 and 46). These foraging trips extend as far north as the continental shelf off the coast of Argentina, although in general they are located further south than in northern giant petrels (Gonzalez-Solis et al., 2008). Such trips are more typical during the incubation period, when male and female birds alternate in incubating the egg. A second type of foraging trip undertaken by giant petrels in South Georgia are shorter duration trips, mainly confined to the coastal areas around the islands, scavenging penguin and seal colonies or foraging on the

Figure 44 Southern giant petrel, *Macronectes giganteus*, white morph. *Photograph A.D. Rogers, 2009.*

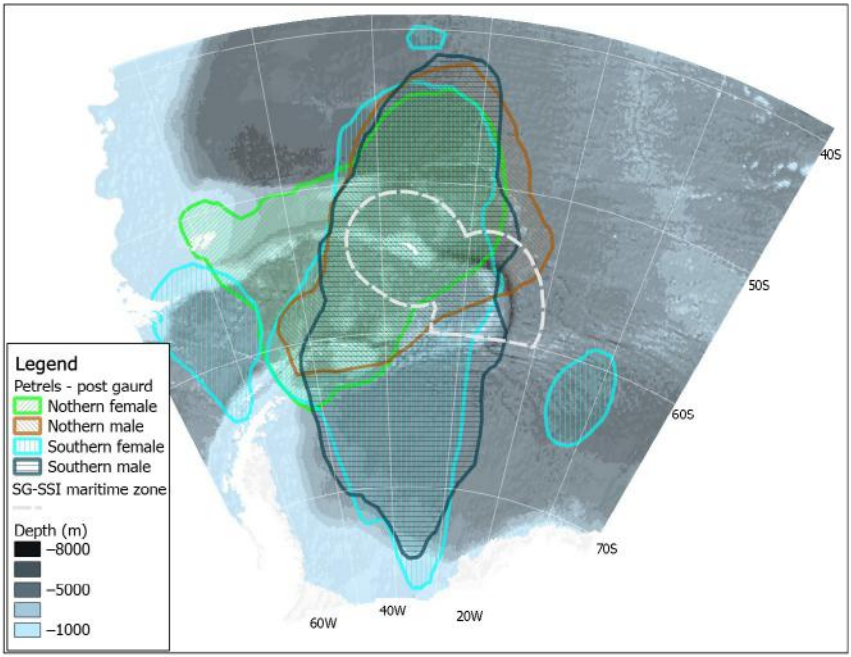

Figure 45 Southern, *Macronectes giganteus*, and northern, *Macronectes halli*, giant petrels. Presence in foraging areas during the breeding period derived from tracking data. *Data from Gonzalez-Solis et al. (2002, 2008)*.

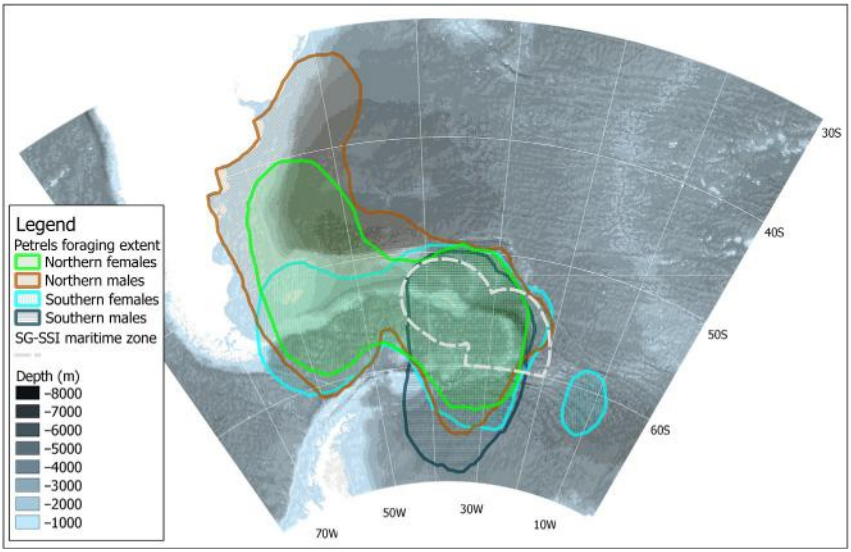

Figure 46 Southern, *Macronectes giganteus*, and northern, *Macronectes halli*, giant petrels. Presence in foraging areas during winter derived from tracking data. *Data from Gonzalez-Solis et al. (2002, 2008)*.

shelf and shelf break (Gonzalez-Solis et al., 2002). These trips last from 4 to 13 days and range more than 2300 km, with a median range of approximately 1700 km (Gonzalez-Solis et al., 2002; see Figure 45). Both types of foraging trips begin and end with a period of time on the sea, which is probably related to feather cleaning and preening (Gonzalez-Solis et al., 2002). Male birds are more likely to undertake short duration foraging trips than female birds, and have been observed feeding at seal carcasses more often than have female birds (Gonzalez-Solis et al., 2008). There is marked sexual dimorphism in this species, with males being significantly larger than females (Gonzalez-Solis et al., 2008). There is also separation in the foraging zones of northern and southern giant petrels with the northern species foraging much further north, especially during winter (Gonzalez-Solis et al., 2008).

Life History Southern giant petrels breed in small colonies that are loose and widely scattered. The birds are faithful to their breeding island, although actual nesting sites may vary from year to year (ACAP, 2010f; Clarke et al., 2012). Nests are large (up to 1.5 m across) and made of tussac grass, *Deschampsia antarctica* and *Acaena* sp. (Hunter, 1984). The birds nest in *Deschampsia* meadows, and sometimes in open areas, or up near the scree level on South Georgia (Hunter, 1984). They lay a single egg in mid-November and incubation takes about 60 days. Chick rearing takes place in South Georgia from January to May (ACAP, 2010f; Gonzalez-Solis et al., 2008; Hunter, 1984). Chicks fledge 105–132 days after hatching, with male chicks fledging later and with a higher body mass than females (ACAP, 2010f; Hunter, 1984). Age of first breeding is around 6 years with a peak at 7–8 years on South Georgia (Hunter, 1984). As with other medium-to-large procellariforms, most birds breed annually, but some do not, and southern giant petrels may have "sabbatical" periods from breeding of about 1.4 years (ACAP, 2010f). This means that up to 30% of a breeding population may not breed in any 1 year (Patterson et al., 2008).

Population Trends South Georgia is home to up to approximately 8700 breeding pairs of southern giant petrel, and there are about 1541 on the South Sandwich Islands, representing approximately 15% and 3.1%, respectively, of the total global population (Clarke et al., 2012; Convey et al., 1999). On the South Sandwich Islands, breeding has been observed on Zavodovski and Candlemas islands, although the latter has been considered to be the most important location for this species in the archipelago (Convey et al., 1999). Numbers of southern giant petrel have apparently

increased from the 1970s to 1990s (4650 pairs; Patterson et al., 2008) to the present estimate of 8700 pairs (Clarke et al., 2012). Overall, information on population trends for southern giant petrels is sparse, and in some regions around the Antarctic there apparently are population decreases, while in others, such as South Georgia, populations may be increasing (Patterson et al., 2008; Woehler et al., 2001). Overall data suggest the global population of this species may have declined by more than 20% since the 1980s (Patterson et al., 2008; SCAR, 2006). Reasons for population decline are unclear, although mortality from fisheries (particularly by IUU vessels) is likely in at least some localities (ACAP, 2010f). It is also notable that southern giant petrels appear to be especially vulnerable to human disturbance and populations of this species around some research stations in the Antarctic have shown a marked decrease as a result (Patterson et al., 2008).

4.2.1.3.3 Northern Giant Petrel (*Macronectes halli*)

- Location: South Georgia (breeding), occasional foraging bird South Sandwich Islands.
- IUCN Red List Status: Least Concern.
- Population size: 17,200 pairs at South Georgia.
- Population trend: Increasing.
- Diet: Seal and penguin carrion, also squid, krill and birds.
- Foraging range: Continental shelf off Argentina (mainly winter), southern Atlantic, Antarctic Polar Frontal Zone; coast, shelf and shelf break, South Georgia.
- Breeding: Single egg is laid late September to early October, approximately 60 days incubation. Hatching occurs November to December, chicks fledge in a mean of 110 days (males), 114 days (females).

Foraging Ecology Northern giant petrels take prey by surface seizing and may dive to 2 m depth in pursuit of prey (ACAP, 2010g). Their foraging ecology is similar to that of the southern giant petrel except that individuals that nest in South Georgia forage further north beyond 35°S, along the continental shelf off northern Argentina and Uruguay, especially during winter (Gonzalez-Solis et al., 2008; see Figures 45 and 46). The eggs of the northern giant petrel (Figure 47) are laid about 6 weeks earlier than those of the southern giant petrel potentially avoiding some competition in foraging areas during the breeding cycle (ACAP, 2010g; Hunter, 1984). On Bird Island, in South Georgia, chicks are fed on fur seal and penguin carrion (mainly from macaroni penguins), krill, squid and other birds such as small diving petrels (ACAP, 2010g).

Figure 47 Northern giant petrel, *Macronectes halli*, grey morph. *Photograph A.D. Rogers, 2009.*

Breeding Ecology Northern giant petrels nest in colonies or as solitary pairs and exhibit strong philopatry to the islands of their birth. Pairs usually mate for life. As stated, where both southern and northern giant petrels co-exist, northern giant petrels breed about 6 weeks earlier (Hunter, 1984). Northern giant petrel eggs are laid in late September to early October, and incubation lasts up to 60 days on South Georgia. Female chicks fledge at a mean of approximately 114 days and males at a mean of about 110 days (Hunter, 1984). Age at first breeding is 4–11 years, and individuals take "sabbaticals" from breeding as is true for southern giant petrels (ACAP, 2010g).

Population Trends A recent population census suggests that globally, populations of the northern giant petrel have increased by approximately 30% since the 1980s (Patterson et al., 2008). South Georgia holds the largest breeding population of the species with about 17,200 pairs, which represents about 45% of the global breeding population (Clarke et al., 2012). Population increases were reported to be as high as 60% in South Georgia from 1978 to 1996, probably resulting from an increase in the number of fur seals, and therefore available carrion, on the islands. Threats to this species include by-catch in longline fisheries and incidental mortality from cable strikes in trawl fisheries. This species is reported to be less prone to follow fishing vessels than the southern giant petrel (Patterson et al., 2008). Marine debris and pollutants may also be a threat to northern giant petrels (ACAP, 2010g).

4.2.2 Other Bird Species

4.2.2.1 South Georgia

In addition to penguins, albatross and petrels, many other seabird species occur on South Georgia. In fact, a total of 29 breeding and 58 non-breeding species of birds are reported to occur on South Georgia (Clarke et al., 2012; Prince and Croxall, 1983). Perhaps the most important of these in terms of numbers is the Antarctic prion, *Pachyptila desolata* (Figure 48). An estimated 22,000,000 breeding pairs populated South Georgia in the mid-1980s (Clarke et al., 2012; Prince and Croxall, 1983; Chart 1). Given that the global population of this species has been estimated at 50,000,000 mature birds (BirdLife International, 2012d), South Georgia represents the most important summer breeding area. It nests on slopes under grass tussocks, in crevices on scree or on cliffs and feeds on crustaceans (especially krill, copepods and amphipods), fish and squid.

During the breeding season, Antarctic prions forage in the vicinity of South Georgia, moving to the south and southwest of the island immediately post breeding (Quillfeldt et al., 2013). During April, this species moves northward to the Argentine Basin, east of the Patagonian Shelf (Quillfeldt et al., 2013). It is likely that the species has been in decline as a result of nest predation by rats. Fairy prions, *Pachyptila turtur*, also breed on South Georgia under large boulders and in deep crevices under cliffs, although in small numbers (Prince and Croxall, 1983).

Blue petrels, *Halobaena caerulea*, breed at several sites on South Georgia, including Bird Island (Prince and Croxall, 1983). In the 1980s, numbers of breeding pairs on South Georgia were estimated as at least 70,000 breeding

Figure 48 Antarctic prion, *Pachyptila desolata*. *Photograph A.D. Rogers, 2010.*

pairs, out of a total global population of about 3,000,000 birds (Clarke et al., 2012). The species feeds primarily on krill, but also on fish, squid and insects. Numbers of breeding Wilson's storm petrel, *Oceanites oceanicus* (Figure 49), have been estimated to be in the range of 600,000 on South Georgia out of a global population of 4,000,000–10,000,000 breeding pairs (Clarke et al., 2012; Prince and Croxall, 1983). Black-bellied storm petrels, *F. tropica*, also breed at South Georgia, and have been estimated at around 10,000 pairs (40% of the global breeding population; Clarke et al., 2012; Prince and Croxall, 1983). The South Georgia diving petrel, *P. georgicus*, nests around South Georgia with a total breeding population estimated at two million pairs in the 1980s (Clarke et al., 2012; Prince and Croxall, 1983). Given that the global population was estimated at 15 million mature birds (Brooke, 2004), South Georgia is likely to be a globally significant breeding locality. The South Georgia diving petrel feeds mainly on krill, but also small fish and cephalopods, which are captured by surface seizing or pursuit dives. On South Georgia it nests in burrows on south-facing high scree slopes or moss-covered fringes of scree slopes (Croxall and Hunter, 1982). The breeding population of common diving petrels, *P. urinatrix*, is also the largest globally and was estimated at approximately 3.8 million pairs in the 1980s (Clarke et al., 2012; Prince and Croxall, 1983), out of a global estimated population of 16 million mature adults (Brooke, 2004). This species nests in burrows on very steep tussock slopes on South Georgia and feeds mainly on planktonic crustaceans (krill). It is likely that this species remains in close proximity to South Georgia even outside of the breeding season.

Figure 49 Wilson's storm petrel, *Oceanites oceanicus*. *Photograph A.D. Rogers, 2009.*

Cape petrels, *Daption capense* (Figure 50), are also common around South Georgia but the breeding population is probably only about 10,000 pairs (Clarke et al., 2012).

Snow petrels, *Pagodroma nivea* (Figure 51), occur around South Georgia and nest in the mountains in relatively small numbers (Croxall et al., 1995b). The total breeding population has been estimated at around 3000 pairs (Prince and Croxall, 1983). However, getting accurate estimates of snow petrel population size is extremely difficult because they tend to breed on exposed rock on cliffs or steep slopes (Croxall et al., 1995b).

Brown skuas (*Stercorarius antarcticus lonnbergi*) have increased on South Georgia, probably as a result of increased opportunity for feeding on carrion.

Figure 50 Cape petrel, *Daption capense*. *Photograph A.D. Rogers, 2009.*

Figure 51 Snow petrel, *Pagodroma nivea*. *Photograph A.D. Rogers, 2009.*

In the 1980s, numbers were estimated at 400 breeding pairs (Prince and Croxall, 1983), but the population has recently been estimated at 2000 pairs (Clarke et al., 2012).

The South Georgia pintail, *Anas georgica georgica,* is an endemic taxon, variously accorded the rank of species or subspecies of the yellow-billed pintail, *A. g. spinicauda*, of South America. These birds are widespread throughout much of coastal South Georgia where they feed on freshwater and marine invertebrates (Weller, 1975), as well as algae and carrion from seal colonies. South Georgia pintails have been observed being preyed on by leopard seals (Edwards et al., 2010), and these ground-nesting birds are also vulnerable to rats (Cook et al., 2010).

Several other species are notable inshore feeders at South Georgia, including kelp gull, *Larus dominicanus*, Imperial shag, *Phalacrocorax atriceps* (Figure 52), and Antarctic tern, *Sterna viata* (Headland, 1984). These species feed on shoreline and inshore invertebrates (mainly limpets) and benthic or near-surface fish (Headland, 1984). Kelp gulls are widespread around the islands, but breeding areas are concentrated in larger fjords where there are abundant kelp beds (Prince and Croxall, 1983).

Blue-eyed shags breed in small colonies around South Georgia and the total population has been estimated as less than 5000 pairs (Prince and Croxall, 1983).

Little detailed information exists for the Antarctic terns, *Sterna vittata*, but the breeding population was estimated at around 2500 pairs in the 1980s (Prince and Croxall, 1983).

Figure 52 Imperial shag. *Photo T. Hart, Dept. of Zoology, University of Oxford.*

4.2.2.2 South Sandwich Islands

Antarctic fulmars, *Fulmarus glacialoides* (Figure 53), nest on the cliffs and boulder slopes of Visokoi, Montagu and Bristol Islands, and breeding populations have estimated at 14,000–26,000 pairs (Convey et al., 1999). Lower numbers are thought to be present on Zavodovski and Saunders Islands, probably because of a lack of suitable nesting habitat. Cape petrels nest around all the South Sandwich Islands and have been estimated to number around 10,000 breeding pairs (Convey et al., 1999). Snow petrels breed on the cliffs of all the islands and have been estimated to number around 3000 breeding pairs (Convey et al., 1999). Wilson's storm petrel also breeds around all the South Sandwich Islands and numbers may be in excess of 10,000 breeding pairs. Several hundred pairs of black-bellied storm petrels have been observed nesting on Candlemas Island (Convey et al., 1999). Brown skuas occur on most of the South Sandwich Islands, and more than 300 breeding pairs were once counted on Candlemas Island (Convey et al., 1999). Small breeding populations of kelp gulls and Antarctic terns also occur on the islands (Convey et al., 1999).

4.2.2.3 Other Conservation Threats to Seabirds on South Georgia and the South Sandwich Islands

All these birds face a number of threats at South Georgia. Brown rats, pose a threat to ground-nesting birds, particularly common and South Georgia diving petrels, Antarctic prions, blue petrels and the South Georgia pintail (Clarke et al., 2012). This invasive species is thought to have been introduced to the islands in the 1700s, and has been responsible for the loss of millions of seabirds on the islands (SGHT, 2010). It has been suggested that

Figure 53 Antarctic fulmar, *Fulmarus glacialoides*. *Photograph A.D. Rogers, 2009.*

prior to the introduction of rats, the numbers of petrels may have been an order of magnitude higher than current estimates (Clarke et al., 2012). Rats infested the entire north coast of South Georgia and the northern part of the south coast (Clarke et al., 2012). There was also evidence that rats had spread to at least one offshore island, Saddle Island, off the south-western region of South Georgia (SGHT, 2010). In rat-infested areas, the entire population of small burrowing petrels and the terrestrial South Georgia pipit, *Anthus antarcticus*, were decimated while white-chinned petrels and the South Georgia pintail have been significantly impacted (Clarke et al., 2012). The invasive rat population was spreading on the islands, and there was concern that climate change, and the concomitant decrease of physical barriers such as glaciers, snow and ice, would enable the species to move beyond the areas in which it has hitherto been confined (SGHT, 2010). Without human intervention, it was likely that rats would continue to remain a significant source of mortality for seabirds. The South Georgia Heritage Trust, SGHT (2010) considered that rats had the potential to drive at least one species, the South Georgia pipit, to extinction, although this is not a view shared by the entire scientific community. The South Georgia pipit had already become confined to offshore islands around South Georgia and a narrow strip of coastline (SGHT, 2010). In addition to rats, mice were also present on the entire Nunez Peninsula and on the coast from Shallop Cove to Cape Rosa and to the south coast of King Haakon Bay (Bonner and Leader-Williams, 1977; Clarke et al., 2012). Areas where mice were present also showed a significant reduction in the occurrence of the South Georgia pipit (Clarke et al., 2012). As a result of these concerns, the SGHT, and the Government of South Georgia and the South Sandwich Islands, GSGSSI, embarked upon a major programme of rodent eradication. The programme commenced with trials to test the likelihood of eliminating rodent populations with poisoned bait (SGHT, 2010).

Rat eradication occurred in three phases and involved the aerial distribution of cereal treated with rat poison, brodifacoum (pellets supplied by Bell Laboratories, Wisconsin, USA), by helicopter. Initial trials of the poison were undertaken in several areas on the north of South Georgia and to the southwest on Saddle Island (Black and Rexer-Huber, 2012; SGHT, 2010). A second phase of deployment of the poison was carried out on the western part of the island in 2013 including around King Edward Point, Grytviken, Mercer Bay and Saddle Island (GSGSSI, 2014a; SGHT, 2015). A final, third phase of eradication was completed in March 2015 covering the remaining areas of South Georgia, thought to be infested with rats.

Brodifacoum is an anticoagulant poison similar in action to warfarin but which has a higher potency and a long half-life (20–130 days). It is highly toxic to mammals and fish. The main target areas in the initial trials in the north were the Thatcher, Greene and Mercer Peninsulas, areas abutting the coast, but isolated from the rest of South Georgia by glaciers or ice-covered mountains (SGHT, 2010). Bait was spread from helicopters at approximately 2 kg per hectare (ha^{-1}) or 0.2 t km^{-2} with a further drop of 4.5 kg ha^{-1} along the coastal strip of these areas (SGHT, 2010). A second drop was aimed at eliminating any mice that may also be in these areas. Monitoring of rat eradication in the treated areas appears to indicate a successful eradication of rats and mice, although monitoring will need to continue for several years to establish whether rats have been totally eradicated and have not re-colonised this area (Black and Rexer-Huber, 2012; GSGSSI, 2014a). Unfortunately, several bird species also suffered mortality either from feeding on Brodifacoum pellets directly or from secondary or tertiary poisoning from feeding on carcasses of animals killed by the poison (Lee et al., 2013). Affected species included the brown skua, South Georgia pintail, snowy sheathbills, *Chionis albus,* possibly the South Georgia pipit, and small numbers of kelp gulls (Lee et al., 2013). It has been concluded that these species will recover their numbers rapidly in the absence of rats and that such incidental mortality is within acceptable limits (Lee et al., 2013).

The other invasive species that also has a potentially negative impact on seabirds around South Georgia is the reindeer, *Rangifer tarandus* (Leader-Williams et al., 1989). The reindeer were introduced by Norwegian whalers and form two populations, one distributed from the Barff Peninsula to Royal Bay and the other inhabiting most of the Busen Peninsula (Leader-Williams et al., 1989). There were about 3000 animals and their grazing activities have had a marked impact on the landscape, in particular reducing the availability of native tussac grass and other plants such as macrolichens, and the dwarf shrub, *Acaena magellanica* (Leader-Williams et al., 1987, 1989). Reindeer grazing also encourages the integration of the introduced grass, *Poa annua,* into South Georgia plant communities, which may have had a positive effect in reducing rat populations (Leader-Williams et al., 1987, 1989). Following consideration of options for managing the reindeer on South Georgia (ranging from doing nothing to population control through culling and chemical sterilization to eradication; Christie, 2010), a decision was made to eradicate all individuals (GSGSSI, 2011a). In 2013, 1900 reindeer from the Busen area and 1555 from the Barff Peninsula were shot, followed by a further 3140 in the latter area in 2014 (GSGSSI, 2014a). Eradication should be complete in 2015.

Fishing, research, and cruise vessels also pose a risk to some of these seabird species. Light-induced vessel collision is a potential problem for smaller species. These include Antarctic prion, blue petrel, common diving petrel, South Georgia diving petrel, Wilson's storm petrel, black-bellied storm petrel, grey-backed storm petrel, *Garrodia nereis*, fairy prion and soft-plumaged petrel *Pterodroma mollis* (Black, 2005a). Collisions have been observed from onboard other vessels in the sub-Antarctic (Black, 2005a). Such incidents often coincide with fog, drizzle or rain, where visibility is impaired and birds are disorientated by vessel lights (Black, 2005a). In one incident, the fisheries protection vessel, *Dorada*, was conducting trawl survey work for the GSGSSI, and after a single night, 899 birds, of which 215 were dead, were found on the deck of the vessel (Black, 2005a). Another incident involved the collision of 1000 storm petrels, prions and diving petrels with a cruise ship in Drygalski fjord (South Georgia Government, 2005). CCAMLR regulations stipulate that during fishing operations, deck lighting should be kept to a minimum and should be directed inboard and downward (CCAMLR, 2005, 2011 measures 25-02 and 25-03). Following the Drygalski Fjord incident, the South Georgia Government also asked the cruise industry to minimise lighting on vessels as far as possible given safety requirements, and to avoid anchoring near to colonies of breeding burrowing petrels (South Georgia Government, 2005). The use of searchlights for detecting ice, particularly low-lying icebergs (growlers), is often demanded as a safety measure for vessels operating in Antarctic waters; so, this problem remains one that is largely unquantified and also difficult to solve.

An anthropogenic disturbance of a very different kind has been a concern for penguins on the South Sandwich Islands. This disturbance is the establishment in 1976, and subsequent destruction in 1983, of the Corbeta Uruguay Argentine station on Thule Island. The destruction of this base by explosive demolition by the Royal Navy resulted in a large debris field around the base, including within a penguin-breeding colony and is a source of environmental concern. It is now the subject of a feasibility study by the Government of South Georgia and the South Sandwich Islands (GSGSSI) and the Foreign and Commonwealth Office (FCO) in order to remediate the site.

4.2.3 Pinnipeds

4.2.3.1 Antarctic Fur Seal (*Arctocephalus gazella*)

The Antarctic fur seal, *Arctocephalus gazella* (IUCN Red List Status: Least Concern; Figure 54), was almost hunted to extinction in the late eighteenth

Figure 54 A group of juvenile and subadult Antarctic fur seals, *Arctocephalus gazella*, on the margins of the shore at Grytviken, South Georgia. *Photograph A.D. Rogers, 2009.*

and nineteenth centuries for its fur (Martin, 1946; Payne, 1977). Male Antarctic fur seals reach a maximum size of approximately 200 kg, and females reach a maximum of about 50 kg. This species pups in localities that are free of ice, typically rock or shingle beaches with easy access to the sea (Payne, 1977). Antarctic fur seals are highly polygynous. Males haul out onto beaches in October, and defend territories extremely aggressively. Females appear on breeding beaches November to December and pups are born 1–2 days later (Jefferson et al., 2008; Payne, 1977). Mating takes place about 7 days after pupping. Thereafter, females make frequent foraging trips to sea, and pups are weaned at about 4 months. Soon after mating, males abandon the beaches, however, subadult, and some adult males can be seen at rookeries on South Georgia throughout the year (Payne, 1977).

The first indication of recovery of Antarctic fur seal populations was in the 1930s, following a cessation of hunting (see below), when the *Discovery* expedition discovered adults and pups at Bird Island. In 1956, Bonner (1958a) found thriving fur seal colonies on Bird Island and Main Island in the Willis Island group (Payne, 1977). Colonies continued to expand through the 1950s to the 1960s, and most suitable breeding sites on Bird Island were occupied by the 1970s (Payne, 1977). By the late 2000s, 95% of the world population of Antarctic fur seals (4.5–6.2 million individuals) were located at South Georgia (Aurioles and Trillmich, 2008; SCAR EGS, 2008), although a lower estimate of approximately 4 million individuals may be more accurate (Trathan et al., 2012), given an annual estimated pup production of 269,000 (early 1990s; Staniland et al., 2010). However, one study

suggests that since the early 1990s, there has been a significant decline in annual pup production, which may be related to availability of krill, for monitored fur seal populations around Bird Island (Hill et al., 2010),

Antarctic fur seals at South Georgia prey mainly on krill but also take some fish (approximately 10% of diet; Boyd et al., 2002) and cephalopods (Payne, 1977). This is in contrast with seals at Heard Island, which feed predominantly on fish (Staniland et al., 2010). An adequate supply of food is essential for lactation and successful rearing of the pups (Payne, 1977). It has been estimated that Antarctic fur seals consume about 3.84 million tonnes of food per annum (Boyd, 2002), although this figure may now be as high as 6.8 million tonnes per annum (Trathan et al., 2012). Together with macaroni penguins, which are estimated to consume several million tonnes of food per annum, Antarctic fur seals exert a significant impact on the food webs around South Georgia (Boyd, 2002).

These predators likely have a notable impact on the standing stock of krill, which has been estimated at up to 60.3 million tonnes in the Scotia Sea, and at lower levels around South Georgia (Trathan et al., 1995). It has been suggested that in order to sustain macaroni penguin and Antarctic fur seal populations in South Georgia, there must either be a high influx of krill into the area or the growth rates of krill around South Georgia are high (Boyd, 2002). Patterns of food consumption change throughout the Antarctic fur seal breeding season, with food demands lowest in the first half of the breeding season and considerably higher in the second part of the season (the most critical time in terms of pup rearing; Boyd, 2002). During winter, fur seals are likely to disperse to some degree. The reliance of Antarctic fur seals on krill during the breeding season means that in years in which krill availability is reduced, usually associated with positive sea surface temperature anomalies, breeding success at South Georgia is negatively impacted (Forcada et al., 2005). Sea surface temperature anomalies are usually preceded by El Niño events approximately 2.5 years earlier, showing significant teleconnections in climatic and ecosystem state across large areas of the ocean (Forcada et al., 2005; Trathan and Murphy, 2002).

At Bird Island, Antarctic fur seals undertake either relatively short foraging trips and forage over the shelf (mean water depth ~360 m) or longer duration trips out over the slope of South Georgia (mean water depth nearly 3000 m; Staniland et al., 2004; Figure 55). Foraging occurs predominantly out to the northwest of South Georgia, and seals dive to a maximum depth of approximately 150 m, with durations of greater than 3 min (Staniland et al., 2004, 2010; Figure 55). Tracking studies indicate that during winter,

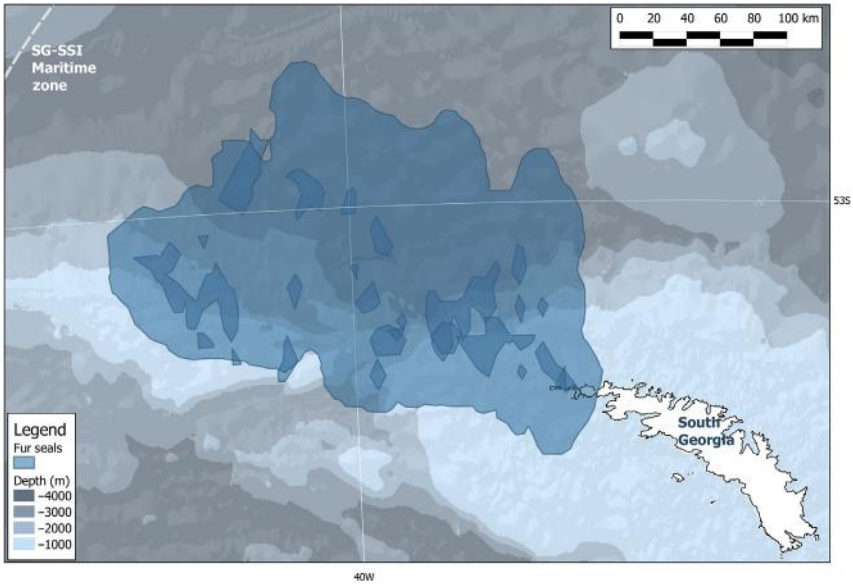

Figure 55 Antarctic fur seal, *Arctocephalus gazella*, presence in foraging areas derived from tracking data for animals located at Bird Island. *Data from Staniland et al. (2004)*.

a substantial proportion (~50%) of female Antarctic fur seals remain in the vicinity of South Georgia (Staniland et al., 2012). Some individuals migrate to the north and northwest, as far as the Patagonian Shelf, and a lesser number move south to feed off the ice edge (Staniland et al., 2012). It is likely that the increased population size of Antarctic fur seals and the overlap in foraging area with macaroni penguins has led to competition for food resources between these species, and to the resultant decline and redistribution of macaroni penguin populations in South Georgia (Trathan et al., 2012).

Relative to South Georgia, there are very few Antarctic fur seals at the South Sandwich Islands, both in terms of absolute numbers and breeding aggregations. It is likely that this is because of a lack of suitable beaches. There are very few beaches that are predictably stable each year, and many of the beaches are subject to large swells causing boulders and gravel to move rapidly. Antarctic fur seals are present on Zavodovski, Visokoi, Vindication, Candlemas and Saunders Islands. Numbers have been estimated in the hundreds of individuals (Convey et al., 1999).

4.2.3.2 Southern Elephant Seals (*Mirounga leonina*)

The southern elephant seal, *Mirounga leonina* (IUCN Red List Status: Least Concern), global population was estimated at ~664,000 in 1990 with

approximately 357,000 residing in South Georgia (Laws, 1994). Male southern elephant seals may reach lengths of 5.8 m and may weigh up to 3700 kg, and females (Figure 56) reach more than 3.5 m and weigh up to 600 kg (Jefferson et al., 2008; Laws, 1953, based on data from South Georgia and Signy Islands). The seals breed on open beaches, short or long beaches backed by tussac grass, and short or long narrow beaches backed by rock or scree (Boyd et al., 1996). Males haul out in August, followed in September or October by pregnant females (McCann, 1980). Male "beachmasters" can hold harems of up to 100 females (Laws, 1956), although as many as 230 have been reported (McCann, 1980). Males with harems aggressively defend them against "bachelor" males although fights generally only occur between males that are evenly matched in size (Laws, 1956). Pups are born at a mean of 5 days after females haul out, and weigh approximately 44 kg (Laws, 1956). Causes of pup mortality include inclement weather, especially when pups become trapped in pools of mud (which may freeze), drown in such pools, or cannot reach or find their mothers (Laws, 1953). Pups may also be crushed by adult seals, particularly males rushing to defend their harems (Laws, 1953). However, pup mortality may be relatively small compared to the mortality of juvenile seals during their first year at sea (Laws, 1953). Lactation is completed in 21 days, during which the pups may grow to 180 kg (Laws, 1956). Females come into oestrus 18 days after pupping (Laws, 1956).

Southern elephant seals are long ranging and deep-diving predators, and although it has been thought that they prey mainly on squid and octopus, they may also, at least seasonally, take significant amounts of fish, potentially

Figure 56 Female southern elephant seals, *Mirounga leonina*, hauled out in wallows around Grytviken. *Photograph A.D. Rogers, 2009.*

including Patagonian toothfish (Biuw et al., 2007; Reid and Nevitt, 1998). Elephant seals from South Georgia have been tracked using conductivity temperature-depth satellite relay data loggers (Biuw et al., 2007; Figure 57). Tracking studies have indicated that the seals do not cross the Weddell-Scotia Confluence into Antarctic waters, but remain in the Antarctic Circumpolar Current, sometimes ranging north of the Sub-Antarctic Front across much of the Atlantic Sector of the Antarctic Circum-polar Front and as far west as off the western side of the Antarctic Peninsula and the Bellingshausen Sea (Biuw et al., 2007; Muelbert et al., 2013). Elephant seals appear to be associated with upwelling circum-polar deep water, probably associated with nutrient enrichment of surface waters and enhanced primary productivity (Biuw et al., 2007). They also appear to forage at specific bathymetric features including seamounts (e.g. the Der Guerlache Seamounts), canyons, banks and troughs (Muelbert et al., 2013). The seals undertake lengthy dives, which typically last for 30–45 min but can last longer than 2 h, with less than 5 min between dives (Biuw et al., 2007). Dives can be more than 2000 m in depth (Biuw et al., 2007).

4.2.3.3 Leopard Seals (*Hydrurga leptonyx*)

Leopard seals, *Hydrurga leptonyx* (IUCN Red List Status: Least Concern), are powerful predators feeding mainly on seabirds and other seals (Walker et al., 1998), but also on krill and, off the Antarctic continent, silverfish (Forcada

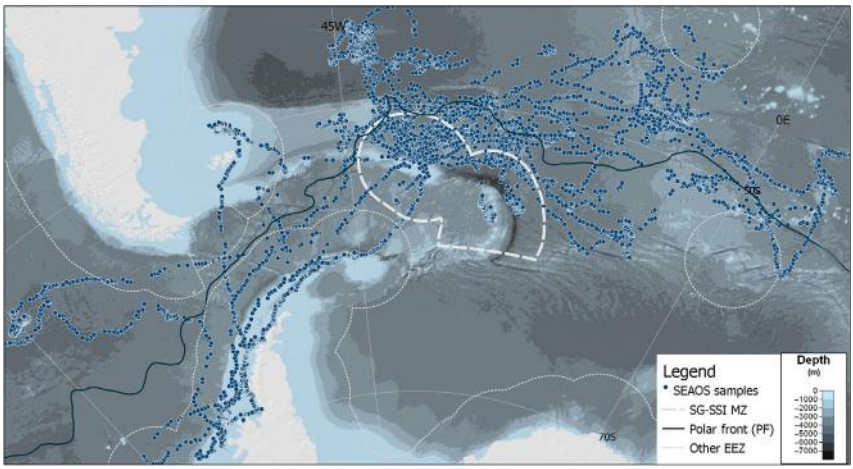

Figure 57 Southern elephant seal, *Mirounga leonina*, tracking data for individuals from South Georgia. *From the Southern Elephant Seals as Oceanographic Samplers (SEAOS) project, University of St Andrews, the United Kingdom.*

et al., 2009; Hall-Aspland et al., 2005; Lowry et al., 1988). These seals breed on pack ice during the Antarctic summer (November to December), but disperse further northward towards the sub-Antarctic Islands in winter. At South Georgia, these seals are observed from April to November, with individuals remaining around the islands for up to 130 days (Forcada and Robinson, 2006; Walker et al., 1998). However, there are also reports of seals present in summer (P. Trathan, British Antarctic Survey, personal communication, 2012). Around South Georgia, leopard seals feed mainly on fur seals, although they take penguins and fish as well, with smaller proportions of other animals, including seabirds, southern elephant seals and also krill (Walker et al., 1998). Krill are particularly important components of the diet of leopard seal pups but also comprise a significant element of the diet of other life-history stages around South Georgia (Forcada et al., 2009). Several hundred individuals are probably present around South Georgia each year with the majority being juveniles (Walker et al., 1998). Leopard seals are also present around the South Sandwich Islands.

4.2.3.4 Other Seals

The Weddell seal, *Leptonychotes weddellii*, is at the northern limit of its range in South Georgia. There is a breeding colony in Larsen Harbour at the southern end of the island; but this probably numbers less than 100 individuals (Headland, 1984). The Weddell seal has also been observed in small numbers on several of the South Sandwich Islands, and may breed there in small numbers (Convey et al., 1999). Crabeater seals, *Lobodon carcinophaga*, have also been observed around the South Sandwich Islands (Convey et al., 1999) and occasionally visit South Georgia (J. Croxall, Birdlife International, personal communication, 2012).

4.2.4 Cetaceans

Large whales were once abundant in the waters around South Georgia, as well as within the fjords of the island. These include humpback whales, *Megaptera novaeangliae* (IUCN Red List Status: Least Concern; Figure 58), southern right whales, *Eubalaena australis* (IUCN Red List Status: Least Concern), blue whales, *Balaenoptera musculus* (IUCN Red List Status: Endangered), sei whales, *Balaenoptera borealis* (IUCN Red List Status: Endangered), fin whales, *Balaenoptera physalis* (IUCN Red List Status: Endangered), and Antarctic minke whales, *Balaenoptera bonaerensis* (Figure 59; IUCN Red List Status: Data Deficient). All of these species are mysticete whales, or baleen whales, and feed on krill. Many of these whale species

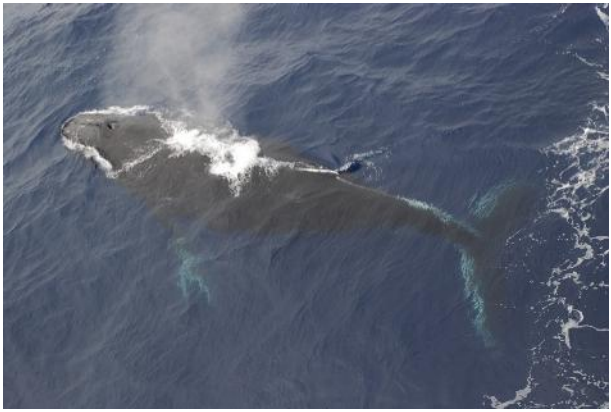

Figure 58 Humpback whale, *Megaptera novaeangliae*, off the South Sandwich Islands. *Photograph A.D. Rogers, 2010.*

Figure 59 Antarctic Minke whales, *Balaenoptera bonaerensis*, lunge feeding off the South Sandwich Islands. *Photograph A.D. Rogers, 2010.*

migrate from northern breeding grounds to feed in the Southern Ocean in the austral summer. The biology and conservation status of these species have been reviewed in greater detail by Jefferson et al. (2008).

More than 175,000 whales were harvested from around South Georgia over a period of about 60 years from the early twentieth century (Moore et al., 1999). Of these species, populations of Antarctic blue whales appear to have been particularly severely depleted. Morphological investigations indicated that blue whales, which occurred off south-western Africa (Saldanha Bay), were very similar to those which fed off South Georgia during the austral summer (Branch et al., 2007). It was estimated that whaling depleted this population to approximately 0.07–0.29% of the

pre-exploitation biomass (Branch et al., 2007). Status of Antarctic blue whale populations are uncertain (Clapham et al., 1999), and although it is thought that they may be increasing by 7.3% per annum, although overall numbers remain low (Branch et al., 2004, 2007). Sperm whales (see below) were estimated to have been reduced by between 85% and 95% of the pre-exploitation population size in the Antarctic (Baker and Clapham, 2002).

Surveys have indicated that cetacean numbers have increased in the region of South Georgia over the past 20 years. Sightings at Bird Island, from vessels transiting South Georgia waters and from surveys conducted between 1979 and 1998, recorded southern right whales, sei whales, fin whales, humpback whales, minke whales and low numbers of blue whales in two main areas off South Georgia, one area on the northern slopes of Shag Rocks and the second on the northern shelf and slopes of South Georgia (Moore et al., 1999). Throughout this period, large concentrations of baleen whales were generally absent, although in 1998 substantial numbers of humpback, fin and sei whales were observed over the shelf break to the north of South Georgia (Moore et al., 1999). In 2000, CCAMLR surveys of whales in the Scotia Sea and Antarctic Peninsula region indicate overall abundances of 18,125 minke whales (10,730 in the Scotia Sea), 9482 humpback whales (2493 in the Scotia Sea), 4672 fin whales (3180 in the Scotia Sea) and 1755 southern right whales (1712 in the Scotia Sea; Reilly et al., 2004). Sightings of southern right whales, humpback whales and minke whales occurred on the northern shelf and slope of South Georgia and Shag Rocks and of southern right whales and minke whales to the west of the South Sandwich Islands (Reilly et al., 2004). Large numbers of humpback whales, fin whales and Antarctic minke whales have also been seen to the west of the South Sandwich Islands (e.g. A.D. Rogers, personal communication, Jan./Feb., 2010), and humpback whales from off the coast of Brazil have been tracked to the South Sandwich Islands (Zerbini et al., 2006). For southern right whales in particular, South Georgia and Shag Rocks appear to be important feeding grounds of the species in the Atlantic sector of the Southern Ocean with animals migrating to areas including off South America, Southern Africa, Australia, and New Zealand to calve (Curry and Brownell 2014; Leaper et al., 2006; Moore et al., 1999; Reilly et al., 2004). The population at the Peninsula Valdes, Argentina, calving grounds has been growing at a rate of about 6.8% per annum with population estimates of 2577 individuals in 1997, 3346 individuals in 2000 and 6100 individuals in 2009 (IWC, 2010). However, observations at Peninsula Valdes have revealed unexplained mass mortalities among southern right whales from 2003 to 2011 having high levels of deaths. Of the 482 mortalities recorded during these events, 89% have been calves

(Rowntree et al., 2013). Suspected causes of these mortalities include poor nutritional condition of breeding females, possibly a result of poor krill availability around South Georgia and in the North Scotia Sea, the occurrence of harmful algal blooms or outbreaks of disease within this population, and attacks (perhaps particularly affecting calves) by kelp gulls (Rowntree et al., 2013; IWC, 2010). There is evidence that poor krill years around South Georgia negatively impact on the breeding success of this species (Leaper et al., 2006).

Smaller odontocete cetaceans that occur around South Georgia include killer whales, *Orcinus orca* (IUCN Red List Status: Data deficient; Moore et al., 1999), Sperm whales, *Physeter macrocephalus* (IUCN Red List Status: Vulnerable; Ashford et al., 1996; Moore et al., 1999), long-finned pilot whales, *Globicephala melas* (IUCN Red List Status: Data Deficient; Moore et al., 1999), southern bottlenose whale *Hyperoodon planifrons* (Moore et al., 1999), Commerson's dolphin, *Cephalorhynchus commersonii* (IUCN Red List Status: Data Deficient; no recent records; Shirihai, 2007), Peale's dolphin, *Lagenorhynchus australis* (IUCN Red List Status: Data Deficient; no recent records; Shirihai, 2007), hourglass dolphins, *Lagenorhynchus cruciger* (IUCN Red List Status: Least Concern; Moore et al., 1999), spectacled porpoise, *Phocoena dioptrica* (IUCN Red List Status: Data Deficient; few records; Shirihai, 2007) and possibly strap-toothed, *Mesoplodon layardii,*(IUCN Red List Status: Data Deficient) and Arnoux's beaked whales, *Berardius arnuxii* (IUCN Red List Status: Data Deficient; e.g. Otley et al., 2012). Both sperm whales and killer whales raid toothfish from longlines in the Patagonian toothfish fisheries around the islands, and the interaction occurs frequently enough to discourage fishing in certain areas (Ashford et al., 1996). Overall losses of toothfish can range between 1% and 8% of the declared catches in the fishery, with CPUE being reduced by 50% for some longline deployments (Moir-Clark and Agnew, 2010).

5. EXPLOITATION OF SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS

5.1 Historical Exploitation of Whales and Seals

5.1.1 South Georgia

5.1.1.1 Sealing

Prior to their discovery, South Georgia and the South Sandwich Islands can be considered to have been pristine. They lie south of the Antarctic Convergence, which had rarely, if ever, been crossed prior to the seventeenth

century. On 17 January 1775, Captain James Cook, sailing on HMS *Resolution,* took possession of South Georgia. Cook is reported to have referred to the island as "savage", "horrible" and "inhospitable", but that it hosted large numbers of seals (Headland, 1984). This resulted in the first sealing foray to South Georgia in 1786 by the vessel *Lord Hawkesbury,* commanded by Thomas Delano. The vessel appears to have targeted fur seals for their skins. Levels of hunting increased, and seal pelts were traded for goods such as spices, silk, nankeen, chinaware and tea in Canton, China (Martin, 1946). As early as 1788, John Leard, a commander in the Royal Navy, in correspondence to Lord Hawkesbury, President of the Council of Trade and Foreign Plantations in London, discussed the management of sealing operations in South Georgia and other locations (Falkland Islands, Patagonia, Tierra del Fuego) to prevent depletions of populations seen elsewhere. The number of vessels visiting South Georgia, however, continued to increase and by the early 1790s elephant seals were also being hunted for their oil. Throughout the next 120–130 years, sealing took place on the islands of South Georgia with several peaks of exploitation taking place around 1800, 1820 and 1870 (Figure 60). The first peak was mainly concentrated on fur seals and the subsequent peaks on elephant seals, although fur seals were taken whenever they were found because of the high value of the skins (Headland, 1984). For example, the U.S. ship *Aspasia*, arrived in South Georgia in 1800 and then became ice bound so no rival sealers arrived until later in the season (Martin, 1946). The *Aspasia* departed for Canton with 57,000 fur seal pelts on board. Later that same season, 17 other hunting parties took 65,000 more pelts (Martin, 1946).

Sealing ships would anchor in the bays of South Georgia and sealers would generally come ashore in small cutters (shallops) and operate from camps. Sealing resulted in major impacts not only on seals, but also is likely

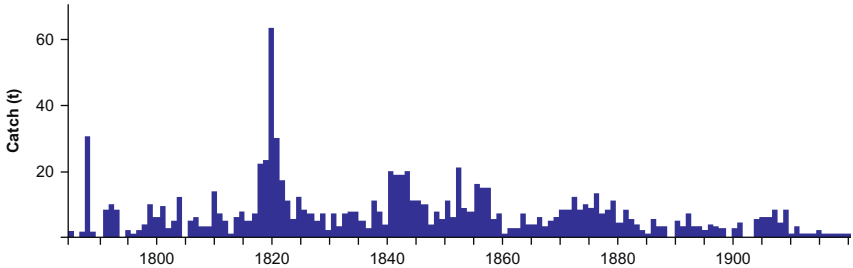

Figure 60 Total numbers of sealing vessels operating in Antarctica from sealing from just before 1790 to just after 1920 (Basberg and Headland, 2008).

to have impacted on seabirds such as penguins, which were used as fuel, and possibly other fauna and flora of the islands because the sealers generally lived off the land (Headland, 1984; Martin, 1946). Use of seals for food and fuel are also well documented. These sealing activities led to the local extermination of Antarctic fur seals around South Georgia and breeding animals were not documented again until the 1930s at Bird Island (Bonner, 1968). Fur seals were protected from 1909 under the Seal Fisheries Ordinance which was extended from the Falkland Islands to the Dependencies (Headland, 1984). There is a suggestion in the literature that there was some recovery in fur seal populations in South Georgia on remote beaches, but that these were hunted "to the last baby seal" by clandestine sealing vessels operating without permission (Martin, 1946). Elephant seals were also harvested in great numbers around South Georgia, particularly close to the whaling stations, although small vessels patrolled and harvested all around the island.

A second period of sealing began in 1904 and lasted until 1965, rising and falling with the whaling industry in South Georgia. This sealing operation was regulated by the Falkland Islands Government who granted a license to the Compañia Argentina de Pesca established by C.A. Larsen primarily for whaling (Bonner, 1958b). Government licensing commenced in 1909 and male elephant seals were harvested from four geographic divisions around South Georgia with one division rested from harvesting each year in rotation (Laws, 1994). Details of sealing operations are given in Bonner (1958b). Because dominant male elephant seals were considered to have the majority of mating success, it was estimated that a large surplus of males could be harvested without affecting recruitment to the population (Laws, 1994). For many years the quota of elephant seals, which were harvested for oil, was maintained at 6000 individuals. In 1948, the quota was raised to 7500 individuals, and in 1949–1950, it was raised to 9000 individuals before dropping again to 8000 individuals in 1951 (Laws, 1994). Even as early as the 1930s, however, data indicated that the South Georgia elephant seal population was in decline, with decreasing catch per unit effort and also a decrease in the yield of oil per individual seal (Laws, 1994). In 1951, population models were constructed for the elephant seals of South Georgia, which could allow for divisional quotas (Laws, 1960). The work showed that the number of males that could be harvested was in the order of 5842 individuals, close to the original 6000 quota. However, taking into account the numbers of individuals, it was apparent that Divisions 1 and 2 were over-harvested and Divisions 3 and 4 under-harvested (Laws, 1994). From

1952 to 1956, a trial of Divisional quotas was undertaken and found to be successful. During this trial, the catch per unit effort increased by 26% and from the 1950s to the 1960s the mean age of seals sampled from kills rose, indicating a sustainable catch (Laws, 1994). Licenses for elephant seal hunting were not taken up in the 1962/1963 season with the collapse of shore-based whaling in South Georgia and in 1963/1964 and 1964/1965, licences were awarded to Japanese companies, however, sealing ceased thereafter (Laws, 1994). During this second epoch of sealing (1904–1965), at least 260,950 mainly elephant seals were killed yielding 84,000 t of oil or about 498,870 barrels of oil (Headland, 1984). Originally, the terms of sealing licences included the killing of leopard seals and Weddell seals (Bonner, 1958b). However, Weddell seals were fully protected from 1916 (Bonner, 1958b), by which time 97 had been harvested (Headland, 1984). Leopard seals, regarded as "ferocious pests," were not protected, and there are no records of them being hunted after 1927 (Bonner, 1958b) by which time 755 had been killed (Headland, 1984).

5.1.1.2 Whaling

Captain Carl Anton Larsen, a Norwegian expedition leader, visited South Georgia in 1894 and 1902. During a reception in Buenos Aires, following the rescue of the Swedish South Polar Expedition of 1901–1903, he made a speech in the capital in which he encouraged the establishment of a local whaling industry in the Atlantic sector of the Southern Ocean. His speech attracted the attention of three entrepreneurs, P. Christopherson, the Norwegian Consul, H. H. Schlieper, an American, and E. Tornquist, a Swedish national. These four figures formed the Compañia Argentina de Pesca, and by the 16 November, 1904, three ships, the sailing vessels *Louise* and *Rolf*, and a steam whale catcher, the *Fortuna*, arrived at Grytviken. Within a month, buildings, a slipway and a factory were erected and the first whale, a humpback, was killed and oil produced by late December (Headland, 1984).

The appearance of Norwegian whalers at South Georgia was no coincidence. The whaling industry of the United States had declined in the later part of the nineteenth century as a result of competition with the petroleum industry for oil-based products (Davis et al., 1997). The Norwegian whaling industry, on the other hand, had flourished along the northern coast of Norway (Finnmark), where the main target species were rorquals (blue, sei and fin whales; Davis et al., 1997). These whales are all fast swimming, large and powerful species and were almost impossible to hunt from small boats using hand-cast harpoons. Early attempts with cannon-propelled

harpoons met with limited success because the cannons, which were liable to exploding, caused whales to scatter and had limited accuracy (Davis et al., 1997). Also, rorquals sank when they were killed (Davis et al., 1997). These problems were solved by the Norwegian, Svend Foyn, who, in the 1860s, developed a cannon-propelled harpoon with an explosive head, mounted in the bows of a small steam schooner or whale catcher. Subsequently, whale catching vessels required relatively few crew and could spend the day hunting whales and towing the catch back to shore for processing. Alongside technical developments in whaling was the development of methods for processing of the whale carcasses for maximum extraction of oil and production of fertilizer and animal feed (Davis et al., 1997). In addition, in the later part of the nineteenth century, the process of hydrogenation was developed whereby whale oil could be converted to a solid fat (Davis et al., 1997). This was suitable for use in the production of soap and margarine, both of which were in increasing demand in the markets of Europe, providing a major economic incentive for the whaling industry. It was upon the production of hydrogenated whale oil that a large industry was developed, and led to the growth of large companies or corporations. The most famous of these companies, Unilever, established dominance over the whale oil market during the twentieth century and is still in existence as a consumer products company today (Basberg, 2011; Sandvik and Storli, 2010). Eventually, the Norwegian whaling industry faced significant problems in Norway stemming from protests related to an unfounded fear that whaling could also impact fishing, and to environmental pollution caused by shore-based whale processing facilities (Davis et al., 1997).

Within 10 years of commencement of operations by the Compañia Argentina de Pesca, a full scale whaling industry had developed in South Georgia. However, the uncontrolled expansion of whaling was not permitted in the waters of South Georgia, then forming part of the Falkland Islands Dependencies (Davis et al., 1997). In the 1906/1907 season, an Ordinance to Regulate the Whale Fishery, which prohibited whaling without a licence and limited the number of whale catchers to two per factory ship, effectively limiting effort on the fishery was introduced by William L. Allardyce, the then Governor of the Falkland Islands (Heyburn, 1980). Whaling vessels also had to take on board a customs officer and a royalty was charged on each whale. Seals, penguins and birds also benefited from protective legislation introduced by Allardyce at this time. A new Ordinance to Regulate the Whale Industry was established by Allardyce in 1908 to simplify administration whereby the royalty on each whale was replaced by a £100 licence fee with a further £100 payable if a third whale catcher accompanied a factory

ship (Heyburn, 1980). Over the next few years, Allardyce also tried to further regulate the whaling industry by maintaining strict limits on the number of whale catchers and establishing a prohibition on the killing of whale calves or females with calves (Heyburn, 1980). There was also a continued problem with the overkilling of whales, leaving carcasses left unprocessed or partially processed in the bays in which factories or factory ships were located. Allardyce attempted to deal with this problem by forcing whaling companies to utilize all parts of the whale for processing into product. Finally, in 1914, he recommended granting no further licences for whaling, only renewing existing licences (Heyburn, 1980). Throughout his sojourn as Governor, Allardyce's actions were apparently propelled by a desire to preserve whale stocks and maintain the industry over the long term (Heyburn, 1980).

Thus, whaling established the first permanent human presence on South Georgia, which brought with it well-documented invasive species and disturbance to wildlife. Whaling stations around South Georgia included:

- Grytviken (1904–1964)
- Stromness (factory ship 1907–1913, shore station 1913–1931, repair yard 1960–1961)
- Husvik (from 1907 factory ship, land-based station 1910–1960, not in operation 1930–1945)
- Leith Harbour (1909–1965)
- Godthul (1908–1929, only a rudimentary land base, main operations on factory ship)
- Ocean Harbour (1909–1920)
- Prince Olav Harbour (factory ship 1911–1916 land station 1917–1931)

These localities processed whales captured around South Georgia using both shore-based facilities and floating factory ships (Davis et al., 1997; Headland, 1984). Flensing of the whales was carried out by different methods, with circular flensing used by ships versus longitudinal flensing used by shore-based facilities (Headland, 1984). Processing of whales by the onshore facilities was more efficient than by factory ships because of the much greater space available for deployment of equipment and stores and for processing of the whale carcasses. South Georgia whaling dominated catches in Antarctica between 1904 to about 1925. Regulation of whaling activities by the government of the Falkland Islands Dependencies was a cause of continual friction with the whaling industry, largely Norwegian and British (Davis et al., 1997; Heyburn, 1980; Figures 61–65).

To escape regulation, factory vessels began to operate outside of waters under British control. In 1924, factory vessels entered the Ross Sea and

Figure 61 The whale catcher *Petrel* stranded in Grytviken Harbour, South Georgia. *Photograph A.D. Rogers, 2009.*

Figure 62 Wreck of the *Petrel* showing the cannon used for shooting explosive harpoons for killing whales. Explosive harpoons resulted in contamination of the whale carcass with metal fragments and bacteria from the guts of the whales leading to rapid decomposition of the whale flesh. Various means were tried to slow down this process including the treatment of the carcasses with antibiotics (Headland, 1984). Efforts were also made to increase the lethality of harpoons using gas, poisons or electricity but these were unsuccessful. *Photograph A.D. Rogers, 2009.*

Figure 63 Whale and seal oil processing facilities at Grytviken, South Georgia, 2009. *Photograph A.D. Rogers, 2009.*

Figure 64 Boilers and other whale/seal processing facilities at Grytviken, South Georgia, 2009. *Photograph A.D. Rogers, 2009.*

Figure 65 The church of the whaling and sealing community at Grytviken, South Georgia. *Photograph A.D. Rogers, 2009.*

killed many "fat" blue whales, although conditions were very harsh and the limitations of processing at sea meant a lower yield of oil per whale (Davis et al., 1997). Another technical innovation revolutionized pelagic whaling, the development of a stern slipway on the factory ships to drag carcasses on board for processing (Davis et al., 1997). The first stern slipway vessel, the *Lancing*, reached the Antarctic in 1925 (Davis et al., 1997). This freed whalers from regulation and a slaughter of whales of unprecedented scale commenced. Within 5 years, the number of whales killed rose from 14,219 (1925/1926 season) to 40,201 (1930–1931), and the number of factory ships rose from 15 to 41, and catchers from 47 to 200 (Heyburn, 1980). In addition, new nations began to become involved in whaling, notably Japan, Germany and the Netherlands (Sommers, 1967). In the 1930/1931 season, over-supply coupled with the economic repercussions of the Great Depression led to a collapse in prices of whale oil. The Norwegian Government declared a moratorium on whaling observed by its nationals but not the British whalers (Davis et al., 1997). These moves were stimulated to reduce the over-supply of whale products, but there was also concern about the overexploitation of whale stocks. In 1931, The League of Nations proposed a prohibition on the hunting of right whales as well as on lactating cows and calves of all species (Davis et al., 1997). These regulations paralleled Allardyce's regulations for the Falkland Islands Dependencies, but although efforts to establish quotas and closed seasons were taken on Norwegian and British whaling fleets, they were voluntary and largely ignored by those of the new whaling nations (Davis et al., 1997; Sommers, 1967). In 1937, The International Whaling Convention was signed in London by nine States (McLaughlin, 1962). The Convention agreed on opening and closing dates for Antarctic whaling and a limitation on the size of whales to be killed as well as the complete protection of smaller species McLaughlin, 1962). However, the new rules were largely ignored by some states, including Japan and South Africa (McLaughlin, 1962). In the 1937/1938 season, 46,039 whales were killed in the Antarctic, the highest count yet (Davis et al., 1997). In the following season, the catch dropped significantly and the proportion of species making up the catch also changed with blue whales declining sharply (Davis et al., 1997). These were clear signs of overexploitation. In 1938 and 1939, efforts were made to improve the whaling regulations, but were interrupted by the Second World War (McLaughlin, 1962).

Whaling decreased to almost nil during the Second World War. After World War II, the U.S. organized a meeting in December 1946 that established the International Convention for the Regulation of Whaling,

and this led to the creation of the International Whaling Commission, IWC, in 1949 (see McLaughlin, 1962). The IWC was established "to preserve the stocks of undepleted species and permit the increase in numbers of those already depleted" (Davis et al., 1997). Measures included closed seasons for whaling, minimum size requirements, quotas and a limit on the overall catch of whales. However, the IWC regulations and subsequent operation of the Commission were limited in two important ways. First quotas were established in blue whale units (BWUs), meaning that they were not based on individual species. This meant that whaling fleets preferentially targeted the most valuable (generally the largest) species with a result that a serial depletion of species occurred (Davis et al., 1997; Sommers, 1967). This depletion occurred despite the maintenance of catches at or below the total quota of BWUs from 1947 to 1959, although even the total BWU quota was exceeded in 1959–1960 (Sommers, 1967) following a breakdown in the catch limit agreement over disagreements on national quotas (McLaughlin, 1962). The second problem under IWC regulations was the voting system, whereby a single State could raise objections to any new regulation (Davis et al., 1997). Antarctic whales were seriously depleted by the 1960s and despite a series of measures attempting to limit the levels of exploitation of affected species, this decline continued. Declines were probably exacerbated by the introduction of improved technology in whaling, such as the use of helicopters for spotting and tracking whales (McLaughlin, 1962). In the 1970s and 1980s, mounting pressure from Non-Governmental Organizations (NGOs), and the public against whaling, combined with diminishing catches led to a succession of States withdrawing from the whaling industry and also closing their markets to whale products (Davis et al., 1997). In 1975, there was an attempt to bring the effort in whale harvesting to a level where populations could recover sufficiently to produce maximum sustainable yields. Disagreements on the science around the setting of appropriate levels of harvesting lead to the IWC agreeing to a global moratorium on whaling which came in force in 1986 (Agnew, 2004). Japan objected to the moratorium on whaling, but withdrew its objection in 1986 (ICJ, 2014). The following season, it issued special permits under Article VIII, Paragraph 1 of the IWC. This article included exceptional conditions under which whaling can take place for scientific purposes:

> *Notwithstanding anything in this Convention any Contracting Government may grant to any of its nationals a special permit authorizing that national to kill, take and treat whales for the purposes of scientific research subject to such restrictions as to the number and subject to such other conditions as the Contracting*

> *Government thinks fit, and the killing, taking and treating of whales in accordance with the provisions of this Article shall be exempt from the operation of this Convention.*
>
> ***ICJ (2014)***

Under this exemption, Japanese whalers killed approximately 6700 minke whales over the course of 18 years, "for the purposes of scientific research". Whale meat from these operations was sold to support the research (ICJ, 2014). In March 2005, Japan proposed the JARPA II scientific programme proposing to sample minke whales, fin whales and humpback whales within the Southern Ocean Sanctuary (ICJ, 2014). In May 2010, Australia filed proceedings against Japan disputing its continued large-scale programme of whaling in the Southern Ocean to the International Court of Justice (ICJ). The objections centred around whether or not the whaling programme could be viewed as "for the purposes of scientific research" and also whether it violated three provisions of the Schedule of the International Convention for the Regulation of Whaling (paragraphs 228–233; ICRW, 1946), setting zero catch limits for the killing for commercial purposes of whales, the moratorium on factory ships beyond 40°S and the prohibition of whaling in the Southern Ocean Sanctuary. The ICJ judged that the JARPAII programme was not consistent with scientific research and that Japan was not compliant with provisions in the ICRW (ICJ, 2014). As a result, the scientific whaling programme of Japan in the Southern Ocean has been stopped, at least for the time being.

The rise of pelagic whaling ensured the demise of the shore-based whaling operations (Agnew, 2004; Headland, 1984), although Grytviken and Leith Harbour remained open for longer because of the sealing industry at Grytviken and the use of Leith Harbour as a forward base for pelagic whaling (Headland, 1984). Overall, about 175,250 whales were known to have been taken at South Georgia, from 1904 to 1965, compared to a known 1,432,862 from Antarctica as a whole, between 1904 and 1978 (Headland, 1984). Approximately 9,360,084 barrels of whale oil were produced at South Georgia during this period (Headland, 1984).

The international community discovered in the early 1990s that Soviet Union pelagic whaling operations had conducted a "vast" illegal whaling campaign from the late 1940s to the early 1970s, but mainly in the 1960s (Ivashchenko et al., 2011). During this period, the U.S.S.R. reported 185,778 whales taken from the Antarctic, but at least 338,336 were actually killed (Ivashchenko et al., 2011). This figure not only increases the total number of whales known to have been taken in the Antarctic during the

period from late the 1940s to the early 1970s but it may also add to the number of whales killed around South Georgia during this time.

5.1.2 South Sandwich Islands

The South Sandwich Islands were discovered on 30 January, 1775 by Captain Cook on the *HMS Resolution*. Bristol Island was the first discovered, and over the next few days, Cook identified Montagu, Southern Thule, Candlemas and Vindication Islands. Cook was unable to get close to the islands because they had rough lee shores, and presumably ice prevented identification of deeper water channels between the islands. On 2 February 1775, he resumed a westerly course. There have been relatively few attempts to explore and exploit the South Sandwich Islands for natural resources, primarily because of the lack of a natural harbour, rough seas and volcanism. Early explorers to the region described it as depauperate in seals (e.g. Morrell, 1832) and extremely hard to work. The lack of seals and good landing sites probably saved the South Sandwich Islands from exploitation pre-1900, and the lack of a suitable harbour prevented the development of a coastal whaling station in the 1900s. Carl Larson investigated the islands as whaling grounds in 1908, even anchoring in Gorgon Pool, Candlemas Island, but failed to find anywhere suitable for development and became ill from fumes on Zavodovski Island (Hart, 2006). With large, well-established coastal stations on South Georgia, the development of faster catcher boats and larger factory ships made subsequent development of the South Sandwich Islands less profitable (see Table 4). The islands also had a bad reputation for ice and weather, so were largely avoided.

Table 4 Total Amounts of Whale Oil Harvested from the South Sandwich Islands in the Early 1900s

Season	Whale Oil (Barrels)
1911–1912	1000
1927–1928	44,055
1928–1929	65,700
1929–1930	82,317
1930–1931	102,600
Total	295,672

From Hart (2006).

Hence, there were a few attempts to develop the South Sandwich Islands region as a whaling ground. There was some renewed interest in the region in 1910 when the government announced that no new licences were to be issued in South Georgia or the Falkland Islands. Eight permits were issued for 1911 to 1912, but only one company took up the permit. The A/S Kosmos Company built a combined catcher and factory ship, the *Tulla* and *Havfruen*, of which the *Tulla* was so badly damaged by ice that she sank near Southern Thule (Hart, 2006). Whaling appears to have focused along the ice-edge lying to the south of the South Sandwich Islands in this region (McLaughlin, 1962).

5.2 Fishing

5.2.1 The History of Fishing in the South Atlantic/South Georgia

As the whaling industry was declining, the Soviet Union distant water fishing fleet was exploring the world's oceans in search of new fisheries resources. The Soviet fleet initially started exploring the Patagonian Shelf, fishing for hake and southern blue whiting, but as it began to deplete these stocks, the fleet began exploratory fishing in the Scotia Sea and around South Georgia in 1962 (Agnew, 2004). Anecdotal evidence and Food and Agriculture Organization (FAO) fisheries statistics suggest that some of this fleet moved to South Georgia in 1968/1969 and a large fleet comprising probably in the region of 30–40 bottom trawl vessels, as well as tankers and cargo vessels, arrived in 1969/1970. This fleet reported catching about 400,000 t of marbled rockcod, *Notothenia rossii*, in 1969/1970, but also probably took large quantities of icefish (Agnew, 2004). Rockcod was rapidly depleted around South Georgia and the Soviet fleet moved into the Indian Ocean, particularly around Kerguelen where it also took large quantities of rockcod, but also significant quantities of mackerel icefish and bumphead rockcod, *Lepidonotothen squamifrons* (Agnew, 2004). In 1972/1973, a catch of 128,194 t of icefish was declared. After depleting these stocks, the Soviet fleet moved back into the Scotia Sea/South Georgia, targeting mainly mackerel icefish and yellowfin notothen around South Georgia before moving to the South Orkney Islands (1977/1978) and the South Shetland Islands (1978/1979). The fishing fleet now also included vessels from Germany, Poland and Bulgaria (Agnew, 2004). Increased interest in fishing in the Southern Ocean was probably stimulated by the declaration of exclusive economic zones (EEZs) by many nations in 1975 (Agnew, 2004). From about 1981/1982, pelagic trawls were also deployed to catch yellowfin notothen and mackerel icefish and large catches of the latter species as well

as blackfin icefish, *Chaenocephalus aceratus,* and spiny icefish, *Chaenodraco wilsoni,* were taken, although these stocks were also rapidly depleted. In the late 1980s and early 1990s, the Soviet fleet even commenced fishing for lantern fish (Myctophidae), taking 200,000 t for fish meal (Agnew, 2004). The collapse of the Soviet Union led to the withdrawal of the large Soviet finfish fleet from Antarctic waters soon after. The stocks of most of the fish species targeted by Soviet trawl fisheries have not recovered around South Georgia and only mackerel icefish are subject to a commercial fishery today (Agnew, 2004).

Patagonian toothfish were declared in bottom trawl catches from 1976/1977 and a targeted longline fishery for them was begun in 1988/1989 by the Soviet fleet (Agnew, 2004). Catches rose rapidly to 8311 t in 1989/1990 and Chilean vessels arrived at South Georgia, which had built up experience in deep-water longline fishing elsewhere. The fishery became a Chilean/Russian/Bulgarian/Ukrainian fishery but in 1993/1994 CCAMLR designated the South Georgia fishery a special area for protection and scientific study, and undertook assessments of toothfish stock size. This study aimed to deploy fishing vessels in specific areas to fish until the catch per unit effort (CPUE) decreased, and then to assess toothfish population size. The experiment did not work but fisheries observers identified a significant problem of seabird by-catch in the longline fishery. From 1997/1998, fishing shifted to winter, targeting deep waters around South Georgia and Shag Rocks. During the 1990s, there was a significant problem with IUU catches in the South Georgia area, which subsequently have receded following the high-profile arrests of three vessels in South Georgia waters. Illegal, unreported and unregulated fishing then shifted to the Indian Ocean sector of the Southern Ocean (Agnew, 2004).

In 1972, targeted fishing of Antarctic krill commenced, and catches rapidly increased. Vessels from Poland, Chile and Korea joined the fishery. Catches peaked in 1981/1982 at around 528,201 t and have since declined, partially as a result of the collapse of the Soviet Union and loss of fishing subsidies but also as a result of the Falklands conflict, which disrupted the fishery in 1982 (Agnew, 2004). Technical issues were also found with krill processing, including high levels of fluoride which were found in the carapace exoskeleton of the animals. Catches of krill remained at around 120,000, about 30,000 t of which have been taken around South Georgia since this time, although technological developments in this fishery mean that interest is rapidly increasing.

5.2.2 CCAMLR and Fisheries Management

The complete failure of the Antarctic Treaty to protect Antarctic fisheries resources in the 1960s and 1970s, and the prospect of an increasing krill fishery, with potentially severe consequences for Antarctic ecosystems, prompted negotiations in the late 1970s to establish the first international fisheries management organisation with the protection of ecosystems as one of its primary objectives, CCAMLR. Negotiations for CCAMLR were initiated by the Antarctic Treaty Consultative Parties in 1977, and concluded in 1980. The convention came into force in 1982 (Agnew, 2004).

CCAMLR was established with the primary objective of the conservation of Antarctica's marine living resources. Achievement of this objective was established on the basis of several principles including the following, as documented by Miller (2009):

- prevention of decrease in the size of any harvested population to levels below those which ensure its stable recruitment;
- maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources; and
- prevention of changes or minimisation of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades.

The convention also incorporated principles of precautionary and ecosystem-based management. These principles can be traced back to the Declaration of the United Nations Conference on the Human Environment (http://www.unep.org/Documents.Multilingual/Default.asp?documentid=97&articleid=1503), the United Nations Convention on Law of the Sea (1982), and subsequently its' implementing agreements, particularly the United Nations Fish Stocks Agreement (1995). The underlying principles of CCAMLR in allowing the exploitation of marine biotic resources whilst maintaining the viability of such populations over the long term and preserving the structure and function of the Antarctic ecosystem has led to some innovative approaches in the holistic, scientific and ecosystem-based management of fishing. Thus, requirements of reporting and observation of fishing activities, management of harvesting levels, and the initiation of technical measures to prevent ecosystem-wide impacts of fishing activities, such as prevention of seabird by-catch from longlines and monitoring of encounters with vulnerable marine ecosystems, have meant that CCAMLR has met many of its conservation objectives (CCAMLR Review Panel, 2008).

It is important to note that within the boundaries of CCAMLR are a number of sovereign sub-Antarctic islands, including South Georgia and the South Sandwich Islands. According to the statement by the Chairman

on the Conference of the Conservation of Antarctic Living Resources Paragraphs 1–5 (CCAMLR, 1980), the CCAMLR convention gives coastal states the rights to:

- Include or exclude from their waters the application of any Conservation Measure or system of international observation or inspection;
- Promulgate national measures that are more strict than the Commission's measures or which deal with other matters; and
- In the absence of consensus within the Commission, to promulgate any measures that the coastal state deems appropriate.

Unlike other states with sub-Antarctic islands within CCAMLR (Australia, France, South Africa), the United Kingdom has not exempted its waters from the application of CCAMLR Conservation Measures. There have also been cases when the United Kingdom has imposed additional Government regulations, which are more stringent than the CCAMLR regulations or measures. For example, the Government of South Georgia and the South Sandwich Islands has imposed Restricted Impact Areas (RIAs) located around South Georgia in areas of previous high coral by-catch in the toothfish fishery. Entry to the South Georgia and South Sandwich Islands fisheries also requires that fishing vessels have a licence, the conditions of which include that such vessels demonstrate they have not been involved in illegal or unregulated fishing. The GSGSSI also manage their fisheries through the allocation of the CCAMLR Total Allowable Catch (TAC) to individual fishing vessels.

5.2.3 Current Fisheries

5.2.3.1 Toothfish (*Dissostichus* spp.)

Toothfish are from the Suborder Notothenioidei, a group that dominates the fish fauna of the Antarctic in terms of diversity, abundance and biomass. The Patagonian toothfish is found on the Patagonian and Chilean continental shelves and around sub-Antarctic islands and seamounts between latitudes 45°S and 62°S (Collins et al., 2010). Patagonian toothfish occur around South Georgia and around the northern South Sandwich Islands (Agnew, 2004; Collins et al., 2010). The distribution of Patagonian toothfish overlaps with Antarctic toothfish, *Dissostichus mawsoni*, around Saunders and Montagu Island in the South Sandwich Islands, with the latter species occurring around the islands further south (Figure 66; CCAMLR Appendix N, 2010). Antarctic toothfish are predominantly found around the margins of the Antarctic continent and, in the Atlantic sector of the Southern Ocean, around the South Shetland Islands and Elephant Island (Agnew, 2004).

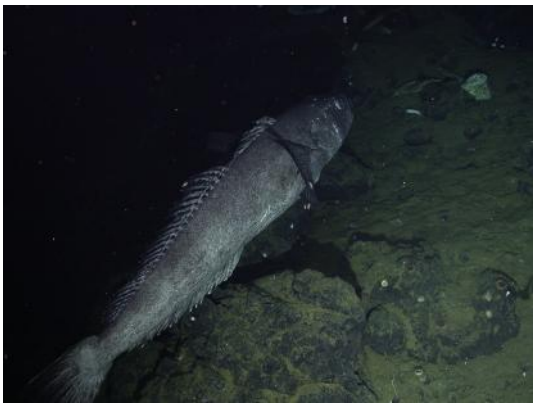

Figure 66 Antarctic toothfish, *Dissostichus mawsoni*, in the caldera adjacent to Kemp Seamount to the north west of Thule Island, approximately 1300 m depth (NERC CHESSO Consortium).

Although not fully understood, the life history of Patagonian toothfish around South Georgia can be outlined. The fish spawn in winter (June-September) in deep water (1000 m) and the eggs are pelagic, being found in the upper 500 m of the water column, over deep water (Collins et al., 2010). As with other deep-water fish species (e.g. orange roughy, *Hoplostethus atlanticus*), a significant proportion of mature females do not spawn each year (Collins et al., 2010). The eggs are thought to hatch in October to December, after 3 to 4 months, at approximately 15 mm standard length, and then at a threshold size, to become benthopelagic. Around Shag Rocks individuals appear in research trawls at an initial length of about 150–250 mm, when they are about a year old (Agnew, 2004; Collins et al., 2010). At this size, the animals are mostly concentrated around Shag Rocks, although they also occur around South Georgia (Agnew, 2004). As they grow, juvenile toothfish begin to migrate into deep waters at a length of about 500–700 mm in length (Collins et al., 2010). They become vulnerable to longline fishing at a length of 60–70 cm, when they are 6–7 years of age (Agnew, 2004). Male toothfish mature at an age of 6–7 years (mean length at which 50% of the population is mature [L_m50] is 78.5 cm) and females at 10–12 years (L_m50 is 98.2 cm; Everson and Murray, 1999; Agnew, 2004). As with other fish species, fecundity of females is dependent on size and varies from approximately 57,000 eggs to about 570,000 over a size range of 90–170 cm (Agnew, 2004). Patagonian toothfish show a bigger, deeper trend as they undergo their ontogenetic migration, as is observed

for other scavenging deep-water fish species. Around South Georgia, this species has been observed in baited camera traps as deep as 1600 m. A characteristic of a number of commercially fished deep-sea species is high longevity, and maximum age of Patagonian toothfish from around South Georgia has been determined to be approximately 50 years (Belchier, 2004).

Recruitment to the South Georgia toothfish stock is punctuated and highly variable. The abundance of juvenile toothfish in research trawls have revealed a negative correlation between spawning success and sea surface temperature around South Georgia a year earlier when adults spawn. The mechanism through which this operates is unclear. Krill abundance is also negatively correlated with sea surface temperatures with cold periods being associated with the influx of swarms from the Peninsula (see above). It is possible that there is an indirect relationship between the reproduction of toothfish and krill availability. Toothfish are mainly piscivorous as juveniles (although small juveniles may have a higher proportion of crustaceans in the diet) and feed mainly on demersal and pelagic fish, as well as crustaceans and cephalopods. Krill form a small part of the diet of juveniles, but the prey species of toothfish may benefit from high krill abundances via benthic food webs (Belchier and Collins, 2008).

5.2.3.2 Fishing Technology

Several methods are used to catch toothfish in the Antarctic and Sub-Antarctic regions. These include primarily longlines, which are of three main types: autolines, the Spanish longline system and the cachalotera system. Autolines comprise a main "backbone," a rope to which hooks and snoods are attached by a swivel and rotor (Fenaughty, 2008; Figures 67 and 68). The hooks are arranged in groups, called magazines, with each magazine holding 1000–1200 hooks, spaced at approximately 1.4 m intervals along the backbone (Fenaughty, 2008; see Figure 68). Most autoliners carry 20–30 magazines of hooks, although a typical line will comprise seven magazines and will be in the order of 10.5 km in length (Fenaughty, 2008). The line may carry integral weight in the form of a lead core weighing up to 50 g per metre of line. This description is based on a New Zealand fishing vessel so it is likely that exact configuration will depend on the vessel operating at South Georgia. During deployment, the line is drawn off the magazine and goes through an automated baiting machine and is then deployed over the stern of the vessel. As one magazine runs out, a new one is attached to the line and deployment continues. Deployment typically takes 1 to 1 h 30 min, but hauling takes 6–8 h depending on the depth of the line (Fenaughty, 2008).

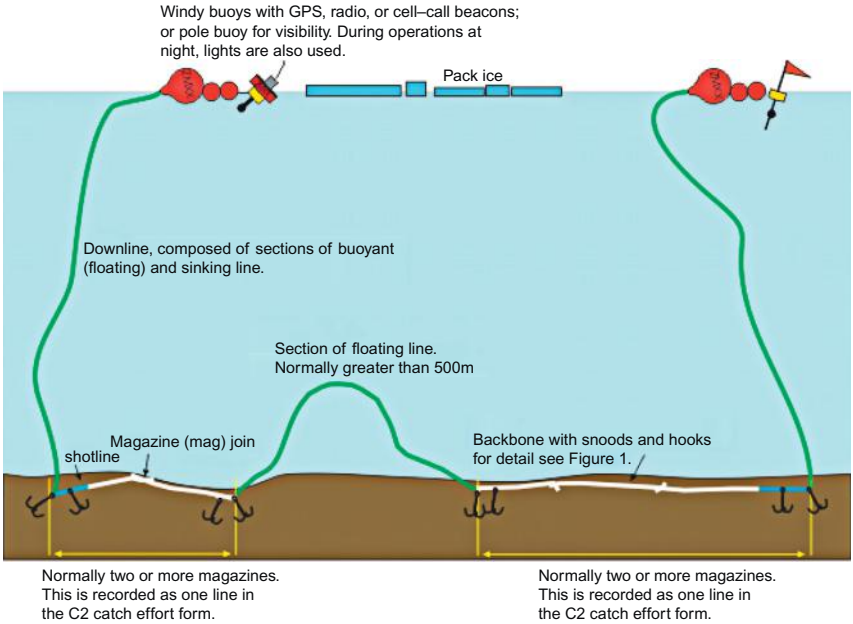

Figure 67 Diagram of a deployed autoline showing the configuration of the buoys, down line, magazines and grapnels or chain used to weigh the line down (Fenaughty, 2008).

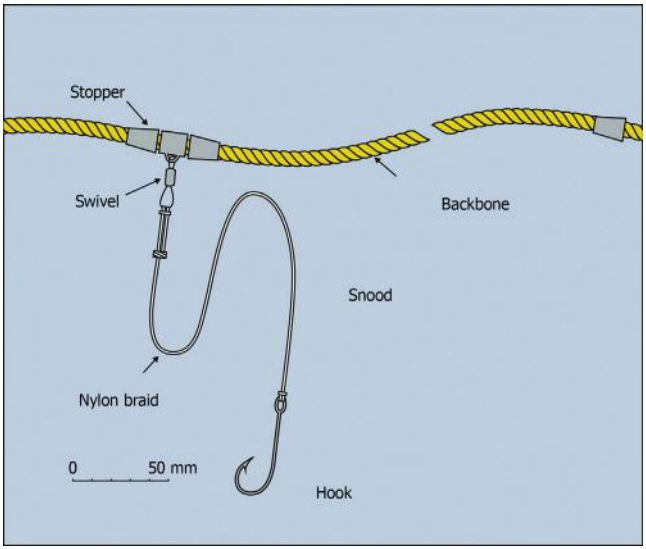

Figure 68 Diagram of a hook and snood attached to the backbone rope by swivel and rotor (Fenaughty, 2008).

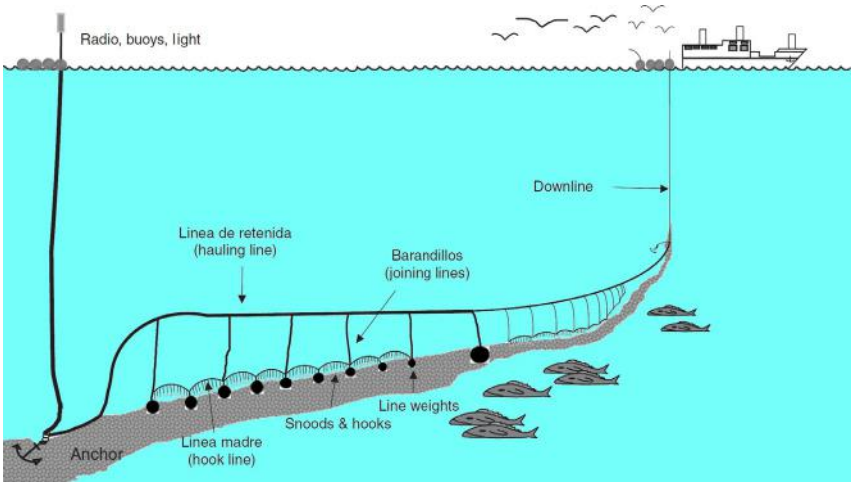

Figure 69 Schematic diagram of Spanish longline system used for catching toothfish (Robertson et al., 2008).

The Spanish longline system is more complicated than the autoline system in that two lines are actually deployed, the heavy hauling line (*línea de retenida*) and a light hook-bearing line (*línea madre*; Robertson et al., 2008; Figure 69). The hauling line is stored on the vessel as a continuous line, and the hook-bearing lines are in separate baskets (*cajones*). The baskets have separate compartments for the coiled up hook line and for the baited hooks (Robertson et al., 2008). During setting, the hauling line and the hook line are deployed from opposite sides of the setting window in the vessel. The hauling line is paid out continuously, whereas the hook lines are paid out from consecutive baskets and joined manually so that the hook line becomes continuous (Robertson et al., 2008). Line weights are attached to the hook line at the end of each hook line and one at the middle. Joining lines attached to the hauling line are attached to the hook line at every second weight although this may vary (Robertson et al., 2008).

There is also currently some fishing using pots for catching toothfish around South Georgia. Elsewhere, these are typically deployed at about 150 pots per tow (Guerro and Arana, 2009; Figure 70). Pots are generally less efficient at catching toothfish than longlines, although the average size of fish can be greater (Guerro and Arana, 2009).

5.2.3.3 Technical Modifications of Gear

Longlines have been modified as a result of significant seabird by-catch, particularly albatross, around South Georgia and elsewhere. This problem was

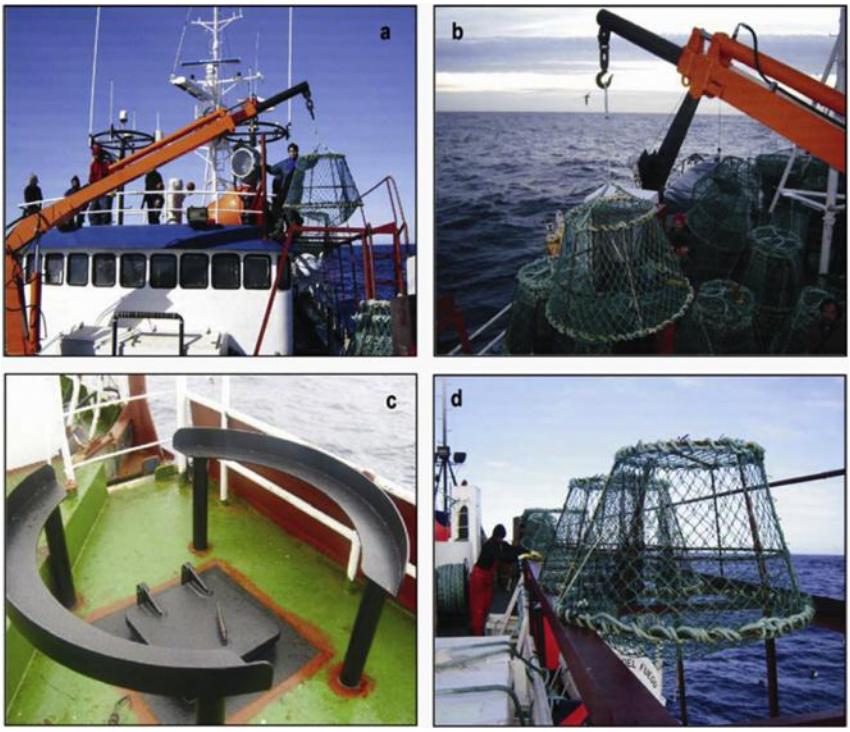

Figure 70 Pots used for fishing in the Antarctic (Guerro and Arana, 2009).

identified initially through time-series observations of colonies of albatross and other seabirds at South Georgia and at other breeding sites that demonstrated that populations were in decline and that this was mainly a function of reduced survival of adults and juveniles (Croxall, 2008; Croxall et al., 1990). Subsequently, ringing of birds identified that many of the ring recoveries were associated with dead birds recovered by fishing vessels (Croxall et al., 1990) and this was confirmed by direct observations of fisheries that demonstrated that albatross and other birds were diving on baited hooks and being caught and drowned as longlines were deployed (Brothers, 1991; Croxall, 2008). Following further observations, and the realisation that around South Georgia the annual by-catch of albatrosses and petrels had reached an estimated 5755 birds by 1997, CCAMLR initiated compulsory measures for by-catch mitigation including (Croxall, 2008):

- The prohibition of offal discharge from fishing vessels.
- The use of streamer (tori) lines to scare birds away from longlines during setting.

- The use of heavier weights or weight lines to sink longlines from the surface faster.
- To avoid setting lines during daylight hours.
- To fish in winter where possible.

Streamer lines (Figure 71) were initially required under CCAMLR CM25-02 (2005), and then modified as CM25-03 (2011) as further data became available on the effectiveness of different designs of streamer (Melvin et al., 2004). Essentially, these comprise one or more lines deployed above the baited longlines with arrays of plastic tape in various configurations that act to scare the seabirds away and prevent them from diving on bait. At South Georgia, seabird by-catch was reduced by an order of magnitude within a year, and this figure has been reduced further so that since 2005/2006 almost zero seabird by-catch has been recorded (CCAMLR Appendix M, 2010; Croxall, 2008; though a fine was imposed on one vessel in 2010 for failing to report seabird catches and for the discarding of baited hooks). Seabird by-catch remains a major source of mortality for seabirds from South Georgia and elsewhere. The problem is now occurring outside of the SGSSI MZ and mainly outside of the CCAMLR Convention area.

A further problem encountered with toothfish fishing has been the depredation of captured fish by cetaceans, particularly killer whales and sperm whales (Ashford et al., 1996; Moir-Clark and Agnew, 2010; Purves et al., 2004). The latest study on depredation around South Georgia suggests that

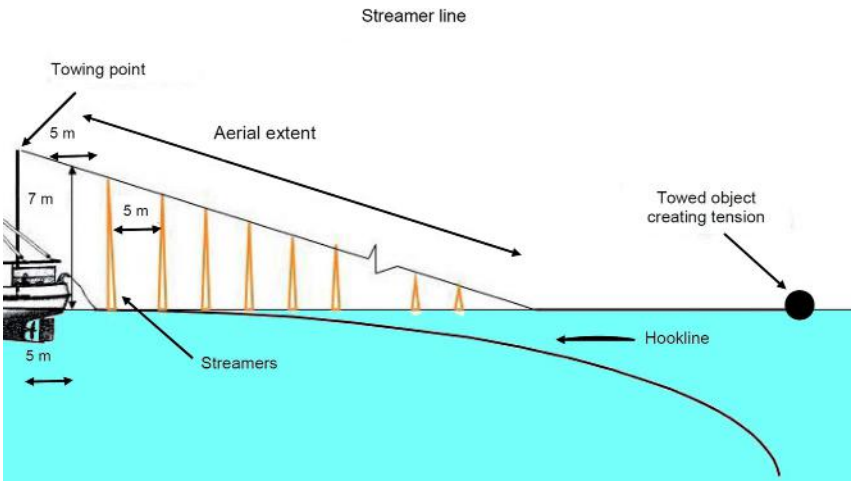

Figure 71 General design of streamer line as recommended under CCAMLR CM 25-02 (2005) as detailed in Melvin et al. (2004).

sperm whales are most frequently encountered (17.7% of longlines), with killer whales being the second most commonly encountered species interacting with longlines (Moir-Clark and Agnew, 2010). When interactions occur, CPUEs are reduced by up to 20% with depredation by sperm whales and 50% with killer whales (Moir-Clark and Agnew, 2010). Density of these whales around South Georgia appears to vary throughout the year as they undergo movements around the islands although these are more seasonal in sperm whales (Moir-Clark and Agnew, 2010). Overall, despite the increased costs of fishing as a result of having to move fishing location or tie off longlines during hauling operations, the overall effects on the fishery are relatively small with losses of 1–8% of catches estimated between 2003 and 2009 (Moir-Clark and Agnew, 2010).

Partially not only as a response to cetacean depredation, but also as a response to seabird mortality, a new development of the longline system has been employed in recent years. This system, known as an umbrella longline, is an adaptation of the Spanish longline system that retains the hauling line, from which, every 40 m, a branching line is suspended (Figures 72 and 73). These branch lines are weighted at one end and have clusters of snoods and hooks attached to them, above which is suspended a net sleeve known as

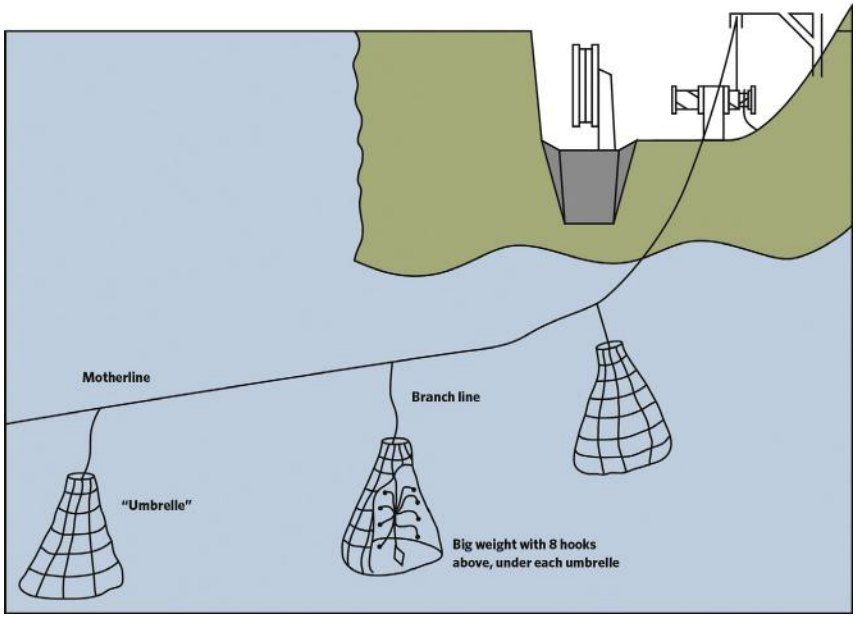

Figure 72 Umbrella or cachalotera longline system being set (Brown et al., 2010).

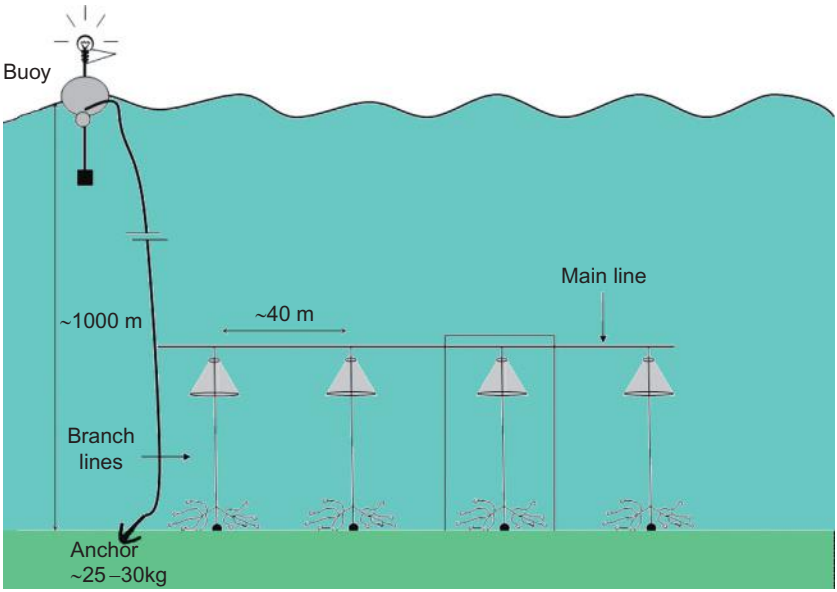

Figure 73 Umbrella longline system deployed (Moreno et al., 2008).

a *cachalotera* (from the Spanish for sperm whale; Moreno et al., 2008). The system significantly reduces seabird mortality as well as depredation from cetaceans (Brown et al., 2010; Moreno et al., 2008), and is also more efficient than the Spanish longline system at catching toothfish from areas where they occur at lower densities (Brown et al., 2010). However, because of the bait plume characteristics, by-catch of grenadiers (Family Macrouridae) is increased and the baits are more heavily scavenged by amphipods (Brown et al., 2010).

5.2.3.4 Current State of the Toothfish Fisheries Around South Georgia and the South Sandwich Islands

Because toothfish are generally caught by baited longlines, assessment of stock size based on CPUE as a measure of population abundance alone has not been appropriate for management (Agnew, 2004). This is because many of the assumptions made in the use of CPUE as an index of population abundance are problematic. For example, changes in the efficiency of a fishing fleet, caused by changes in the vessels fishing, can alter the relationship between apparent fishing effort (e.g. number of hooks deployed) and catch (Maunder et al., 2006). Other factors may alter the catchability of fish, such as changes in the environment, changes in the spatial distribution or depths in which fishing is taking place, changes in current strength and direction

where lines are deployed, changes in fishing gear, changes in depredation of fish, gear saturation, gear interference, soaking time of baits, or the selectivity of the gear with respect to age and size of the fish (Haimovici and Avila-da-Silva, 2007; Maunder et al., 2006). As with other fisheries, an integrated approach is used to estimate population abundance of toothfish around South Georgia, Shag Rocks and the South Sandwich Islands (Agnew, 2004). This includes analysis of a time series of catch and effort data, a programme of fish tagging (mark-recapture surveys), biological measurements taken from catch by observers (length at maturity, growth rate of fish, natural mortality and age at which fish enter the fishery), and the use of an annual research trawl survey of juvenile fish to estimate the size of recruitment to the toothfish population. These parameters form the input to an age-based stochastic simulation model of the state of the stock and the progress of the fishery, initially a General Yield Model (Agnew, 2004) and more lately CASAL models (C++ Algorithmic Stock Assessment Laboratory; Bull et al., 2012). This software is used to run models that estimate the size of the toothfish population over approximately 50 years, incorporating historical data on the fishery and projecting forward about 35 years in the future. The aim is to set a constant catch level that, over 35 year periods, does not allow the stock to become overexploited (Agnew, 2004). Decision rules are set on the basis of CCAMLR objectives and include two main provisions. First, the stock size should only have a 10% chance of decreasing below 20% of the virgin stock biomass to prevent a serious decrease in recruitment (Agnew, 2004). Second, that after 35 years the median final stock size should be no less than 50% of the initial stock size. This second decision criterion is aimed at protecting the supply of toothfish for its natural predators (Agnew, 2004).

The GSGSSI set Total Allowable Catches (TACs) based on the scientific assessment of the biomass of the fish stock and progression of the fishery (Agnew, 2004). TACs are presented to CCAMLR and (if there is agreement) a quota is set for each CCAMLR sub-area. The GSGSSI then allocates catches to individual fishing vessels, which are licensed to fish in the waters of South Georgia/Shag Rocks or the South Sandwich Islands (Figures 74 and 75). Vessels are required to collect their licences at King Edward Point in South Georgia where they are inspected prior to being allowed to fish (Agnew, 2004). Transhipment of fish is also only allowed in Cumberland Bay, South Georgia. All vessels are required to carry a Vessel Monitoring System, VMS, and an observer (Agnew, 2004). Observers monitor the operation and catches of fishing vessels as well as take part in special scientific projects for GSGSSI. During fishing operations, vessels

Figure 74 Chilean longline vessel *Cisne Verde*, one of the vessels that has fished off South Georgia. *Photographed in Punta Arenas, by A.D. Rogers, 2010.*

Figure 75 Toothfish longlining vessel *Argos Georgia*, which has fished around South Georgia, photographed at Port Stanley, Falkland Islands, 2009. *Photograph A.D. Rogers, 2009.*

are required to submit data to CCAMLR including catch reports every 5–10 days, haul-by-haul data and biological data relating to the targeted species or for other fisheries-related projects (Agnew, 2004). A fisheries patrol vessel, the *Pharos SG*, also operates in the waters of South Georgia and Shag Rocks, and surveillance is supplemented by occasional Royal Navy vessels and aircraft operating from the Falkland Islands.

5.2.3.5 The Current Performance of the South Georgia/Shag Rocks Toothfish Fishery

Around South Georgia and Shag Rocks estimates of juvenile toothfish abundance in recent years have shown a single dominant year class of fish, which has been observed in research trawls starting from about 2001, at 30 cm length (Figure 76). Such sporadic recruitment is obviously a cause for concern in the management of the fishery.

It should also be noted that CPUE has been declining in the fishery since 2002 (Figure 77) and that quotas and catches have reduced considerably since the targeted longline fishery began (CCAMLR Appendix L, 2009; Figure 78), although over the past 2 years these have levelled off and most recently showed an increase (CCAMLR, 2013a, 2014c). Part of this is simply a reduction in fishing in order to meet the targets of fisheries management. However, reduction of the toothfish quota from the CCAMLR recommendation of 3000–1800 t in January 2011 under advice of fisheries managers (GSGSSI, 2011b) reflected the lack of a recent recruitment event. In 2012 and 2013, the quota rose again to 2600 t (CCAMLR, 2013a). Reductions in quota and revenue are obviously an issue of concern for the GSGSSI. Currently the licence fee for fishing toothfish in the waters of South Georgia is £12,875 per month access fee, and an additional quota fee of £1648 per tonne (additional quota fee for South Sandwich Islands is £1203 per tonne; GSGSSI, 2014b). This is set to rise to an access fee of £13, 261 per month and a quota fee of 1697 per tonne in 2015 (GSGSSI, 2014b). Overall, the income from the toothfish fishery has recently represented about 80% of the entire fisheries income for South Georgia/South Sandwich Islands. Therefore, the income generated by licences for toothfish fishing has a considerable bearing on the overall balance of income and expenditure for the GSGSSI (see below).

5.2.3.6 The South Sandwich Islands Toothfish Fishery

Toothfish fishing in the South Sandwich Islands began in 1992/1993 when a precautionary catch limit of 240 t was set. A single Chilean longliner fished the waters but abandoned fishing after a week of poor catches (CCAMLR Appendix Q, 2008). A Bulgarian longliner also fished during the season and reported a catch of 39 t. In 2004/2005, the United Kingdom conducted experimental fishing with a mark recapture programme; 27 t of Patagonian toothfish were caught and 42 individuals were tagged and

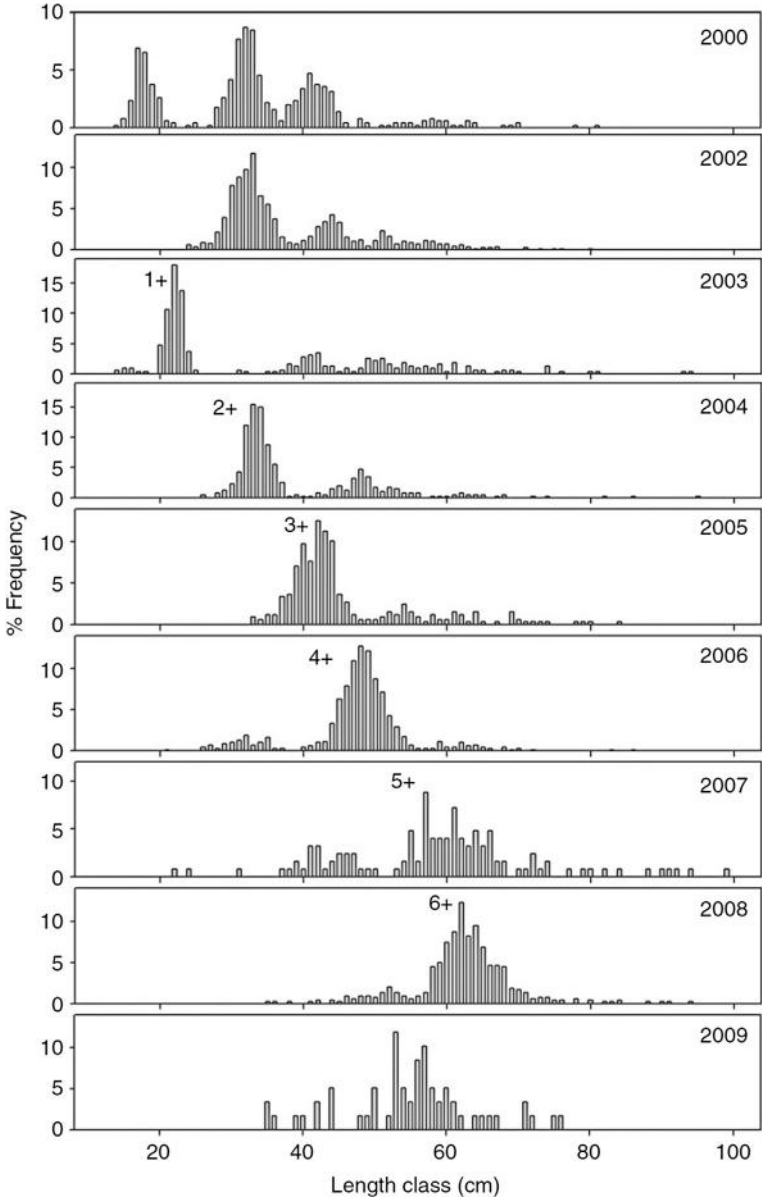

Figure 76 Length frequencies of Patagonian toothfish, *Dissostichus eleginoides*, from trawl surveys at 100–350 m depth from South Georgia and Shag Rocks Shelf (Collins et al., 2010).

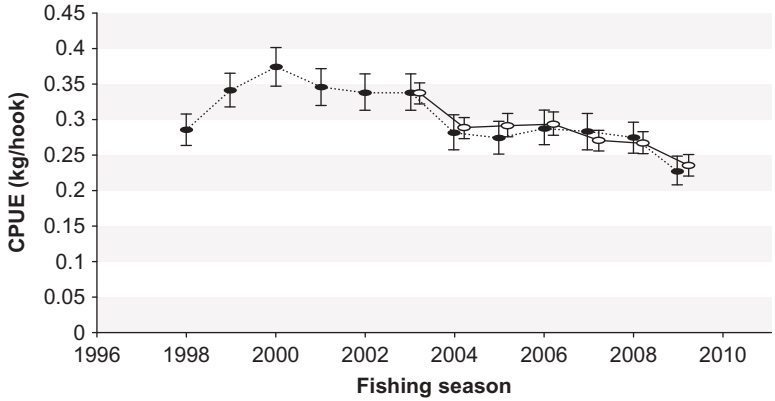

Figure 77 CPUE for longline catches of Patagonian toothfish, *Dissostichus eleginoides*, around South Georgia and Shag Rocks fitted using GLM for data during the second part of the fishery (CCAMLR Appendix L, 2009).

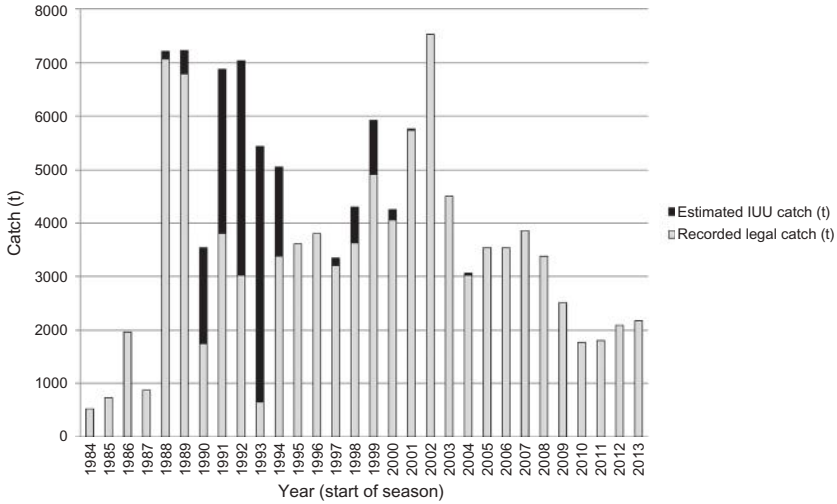

Figure 78 Patagonian toothfish, *Dissostichus eleginoides*, catches for CCAMLR Sub-area 48.3 (South Georgia/Shag Rocks) since 1984/1985 including both officially reported catches and estimates of IUU catches (CCAMLR, 2014c).

released (CCAMLR Appendix Q, 2008; Figure 79). Following this, a more extensive mark-recapture programme was initiated in 2005/2006. Since this time, approximately 2945 Patagonian toothfish and 815 Antarctic toothfish have been tagged, with 212 and 37 returns, respectively (CCAMLR, 2013b).

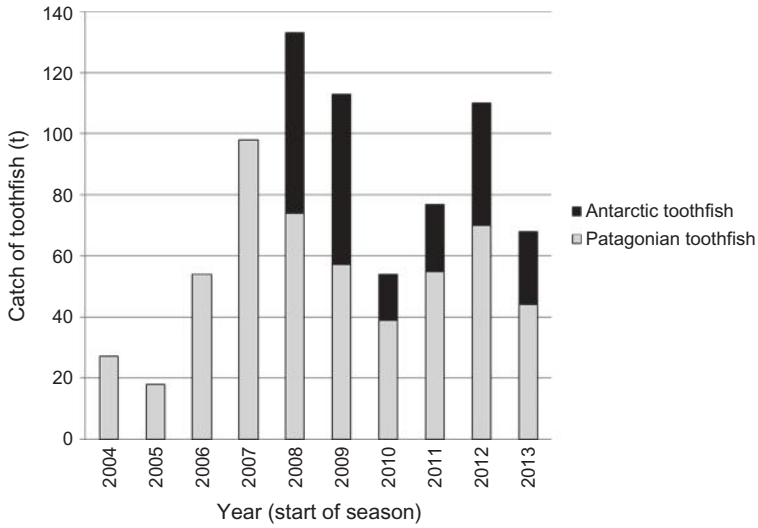

Figure 79 Total recorded catch of toothfish at the South Sandwich Islands in the recent experimental fishery. *CCAMLR (2014d)*.

Over the past several seasons, experimental fishing has continued and longliners have also targeted Antarctic toothfish from the southern half of the South Sandwich Islands. Fishers have caught fish particularly around Protector Shoal, the slopes of Visokoi, Vindication and Candlemas Islands in the northern area, and Saunders Island and associated banks around Montagu Island and a bank/slope to the east of Montagu Island. Smaller catches have occurred around Bristol Island, Cook Island and Thule Island, and the seamounts associated with Vysokaya Bank to the southwest of Thule (see Figure 80; CCAMLR, 2013b).

The length frequency of fish captured in the South Sandwich Islands suggest the progression of fish from a single year class until 2009, when data suggest the recruitment of a new year class into the fishery (see Figure 81). This represents a situation that is similar to South Georgia/Shag Rocks where, again, recruitment to the fishery in South Sandwich Islands may be sporadic, complicating the management of fisheries for this stock. Another factor increasing the complexity of management (and reducing sustainable catches) is evidence of male-biased migration of Patagonian toothfish from the South Sandwich Islands to South Georgia (Roberts, 2012).

Data for Antarctic toothfish have been reported since 2008/2009. Modelling of the catch data, biological characteristics of the stock and mark-recapture data (as in South Georgia) for the northern part of the South

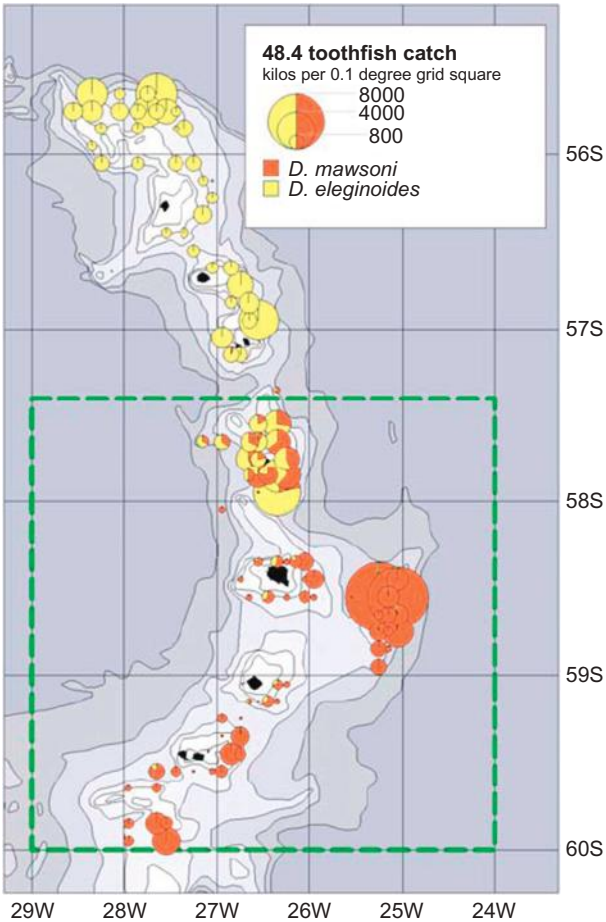

Figure 80 Toothfish catches for the South Sandwich Islands exploratory fishery (from 2008/2009 catch statistics are for both Patagonian, *Dissostichus eleginoides*, and Antarctic, *Dissostichus mawsoni*, toothfish; it is likely that prior to this date, figures for Patagonian toothfish include Antarctic toothfish; CCAMLR, 2013b).

Sandwich Islands have led to a general decrease in quota from ~100 in 2004/2005 to 40 t in 2010/2011, but with an increase to 63 t for 2012/2013 (CCAMLR Appendix O, 2012). We note, however, that reported historical catch limits appear to have changed with the most recent fisheries report (CCAMLR, 2013b), and the limit was recorded as 115 t in 2012/2013 for *Dissostichus* spp but dropped to 69 t in 2013/2014 (CCAMLR, 2014d). For the southern part of the South Sandwich Islands, where Antarctic toothfish are the main target of the fishery, the quota was reduced to 30 t for the 2010/2011 season. This catch level was thought to be

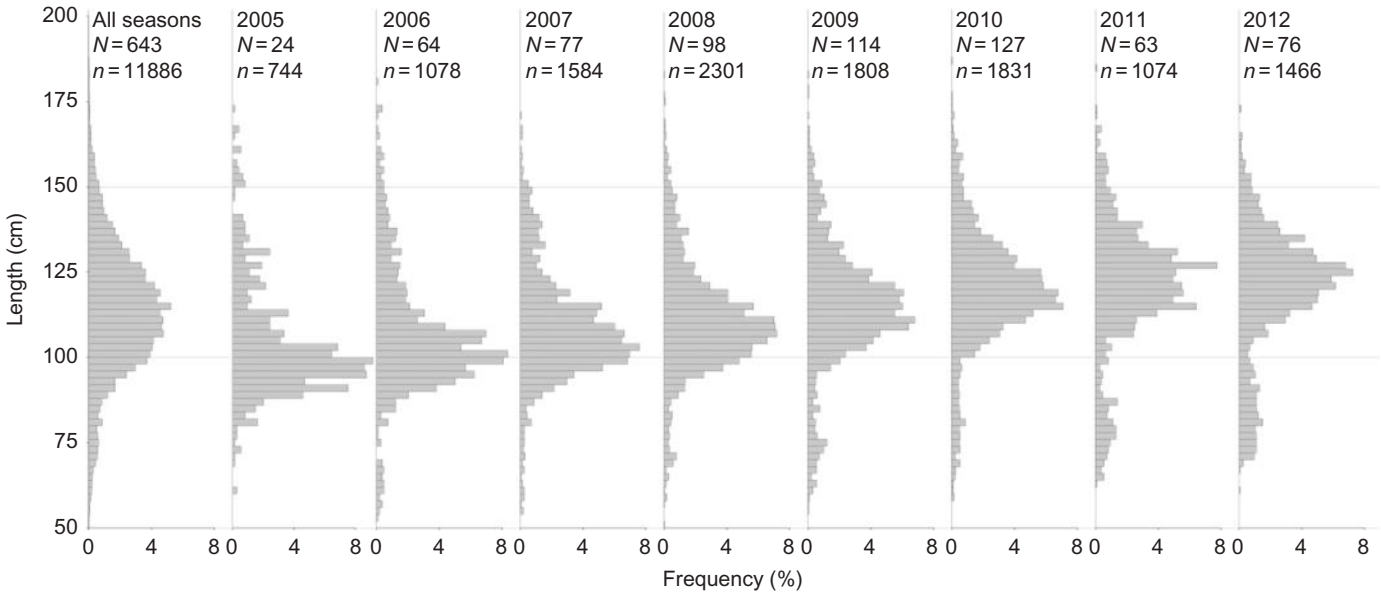

Figure 81 Catch length frequencies for Patagonian toothfish, *Dissostichus eleginoides*, for South Sandwich Islands (CCAMLR Appendix O, 2012).

sufficiently conservative as not to overexploit the stock (CCAMLR Appendix N, 2010), was even raised to 52 t in 2012/2013 (CCAMLR Appendix O, 2012). Catches seem broadly to be within catch limits and the most recent catch limits for 2014 are reported at 45 t for Patagonian toothfish and 24 t for Antarctic toothfish (CCAMLR, 2013b).

5.2.3.7 By-Catch Issues with the Toothfish Fishery in South Georgia/Shag Rocks

5.2.3.7.1 Seabirds Following the discovery of seabird by-catch on longlines, technical and operational measures have apparently been successful in near elimination of by-catch of albatrosses and petrels by longline gear around South Georgia with the exception the 2013/2014 season where more than 70 white chinned petrels were killed on a single long line (CCAMLR, 2014c; Figure 82). In recent experimental fisheries around the South Sandwich Islands, there have been no recorded incidents of seabird mortality associated with longlining (CCAMLR Appendix O, 2012). The incidence of light-induced collisions with fishing (and other) vessels in the vicinity of South Georgia and the South Sandwich Islands remains a concern. Regulations and guidelines have been introduced to avoid light-induced bird collisions with vessels (CCAMLR, 2005, 2011, measures 25-02 and 25-03; South Georgia Government, 2005), but at present the extent of this problem is unknown.

5.2.3.7.2 Fish Species Many species of fish are caught as by-catch in Southern Ocean toothfish fisheries (Rogers and Gianni, 2010). However, macrourids and rays are among the most significant by-catch species in terms of biomass, and they are vulnerable to overfishing because of their conservative life histories. Figure 83 shows the by-catch for macrourids from the South Georgia/Shag Rocks longline fisheries.

Macrourid by-catch in the Southern Ocean comprises several species, originally thought to be *Macrourus carinatus*, *Macrourus holotrachys*, *Macrourus whitsoni*, *Coryphaenoides armatus*, *Coelorhinchus fasciatus* and *Coelorhinchus marinii*. There has been a long-standing concern about the systematics of the species that commonly turn up as by-catch in the toothfish fisheries and generally they are referred to in fisheries statistics simply as macrourids. Genetic investigations indicate that around South Georgia the macrourid by-catch is of *Macrourus carinatus*, *Macrourus holotrachys* and *Macrourus* c.f. *whitsoni* (Fitzcharles, 2014). However, DNA sequence data from the mitochondrial 16S ribosomal RNA and cytochrome oxidase 1 genes (16S rRNA, COI) show no differences between *Macrourus holotrachys* and *Macruorus berglax*, a species previously thought to only occur in the North Atlantic

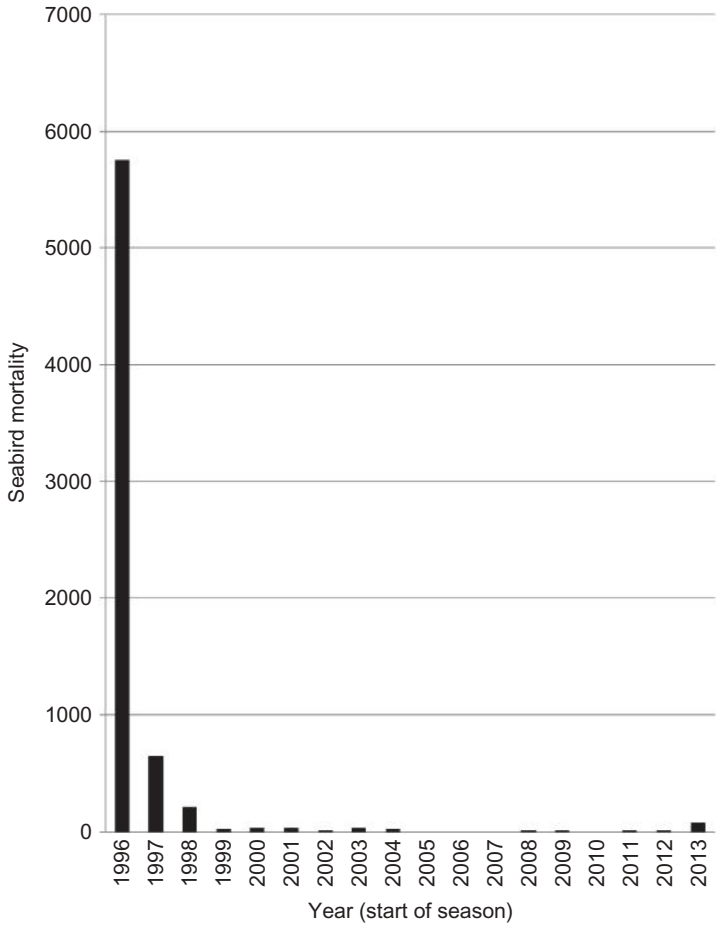

Figure 82 Total estimated mortality of seabirds from being caught on lines in the South Georgia toothfish fishery to 2013. After this period, the way of reporting seabird by-catch changed, reducing the figures, although exactly how it reduced the numbers is unclear (possibly actual recorded mortality rather than estimated for the whole fishery; CCAMLR, 2013a). *Data from CCAMLR Appendix I, 2012; CCAMLR, 2014c.*

(Fitzcharles, 2014). It would also appear that *Macrourus whitsoni* in the Scotia Sea comprises a dark morph and a pale morph. Around South Georgia, only *Macrourus* c.f. *whitsoni*, dark morph, has been identified while in the South Sandwich Islands, both dark morph and pale morph are found (Fitzcharles, 2014). The *Macrourus* c.f. *whitsoni* pale morph is mainly confined to the southern part of the South Sandwich Islands chain (Fitzcharles, 2014). McMillan et al. (2012) described a new species of grenadier, *Macrourus caml*, and combined molecular and genetic studies, again based on 16S rDNA and

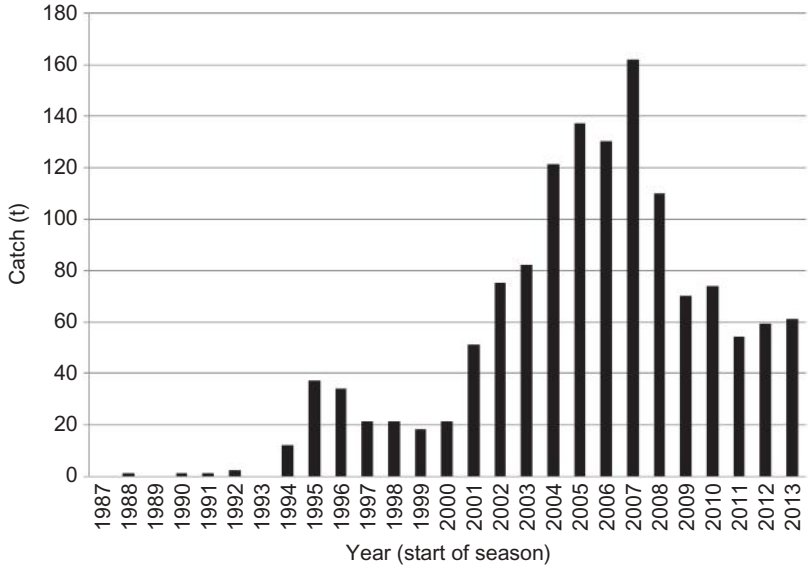

Figure 83 By-catch of macrourids (t) in the South Georgia longline fishery from 1987/1988 to 2013/2014. *Data from CCAMLR Appendix I (2012) and CCAMLR (2013a, 2014c).*

COI data, have identified that this is likely to be the "dark morph" (Fitzcharles, 2014). Thus, the "pale morph," which only occurs in the southern part of the South Sandwich Islands (Fitzcharles, 2014; Figure 84), in a similar distribution to *Dissostichus mawsoni*, is *Macruorus whitsoni*. At South Georgia, catches of macrourids have increased over recent years and then declined since 2008, although these have remained below the catch limits set for this group of species (see Figure 83). However, there is apparently no assessment of the effects of fishing mortality on macrourid populations. Measures have been taken to discourage macrourid by-catch, including a move-on rule whereby if more than 1 t of fish is caught in a single haul, the vessel must move 5 nm away from the path which the gear was laid/retrieved. This is the line between the first and last anchors deployed on a longline, known as the path. Vessels may not approach within 5 nm of this line for 5 days following the by-catch incident (the reporting period for the fishery; Conservation Measure 42.01 in CCAMLR, 2014b).

As is true for macrourids, skates and rays in Southern Ocean toothfish fisheries are represented by a number of species of *Bathyraja* and *Raja*, including *Bathyraja eatonii*, *Bathyraja irrasa*, *Bathyraja maccaini*, *Bathyraja meridionalis*, *Bathyraja murrayi, Raja georgiana* and *Raja taaf*. However, it is apparent from genetic studies that the systematics of ray species in the sub-Antarctic are poorly understood with a number of undescribed and

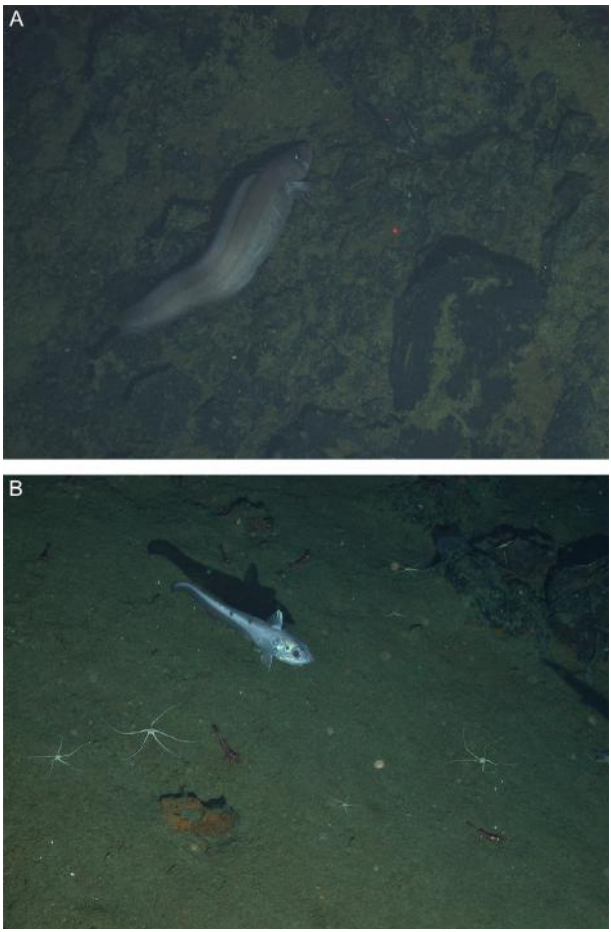

Figure 84 *Muraenolepis* sp. (left) and a macrourid (right; possibly *Macrourus whitsoni*), both by-catch species in the South Georgia/South Sandwich Islands toothfish fisheries. Photographs taken from the caldera adjacent to Kemp Seamount, approximately 1300 m depth (NERC CHESSO Consortium).

cryptic species present in different regions (Smith et al., 2008). Quantities of rays caught as by-catch in the South Georgia fishery are shown in Figure 85 (see CCAMLR Appendix I, 2012; CCAMLR, 2013a).

Quantities of rays caught as by-catch remain below the catch limits set for this group of species (130 t for 2012; CCAMLR Appendix I, 2012) and have been declining since 2008. Around South Georgia, these appear to be mainly *Raja georgiana*, *Bathyraja meridionalis* and an unidentified *Raja* species (Endicott and Agnew, 2004). Preliminary analyses of ray populations around South Georgia and the South Sandwich Islands indicate that present catches

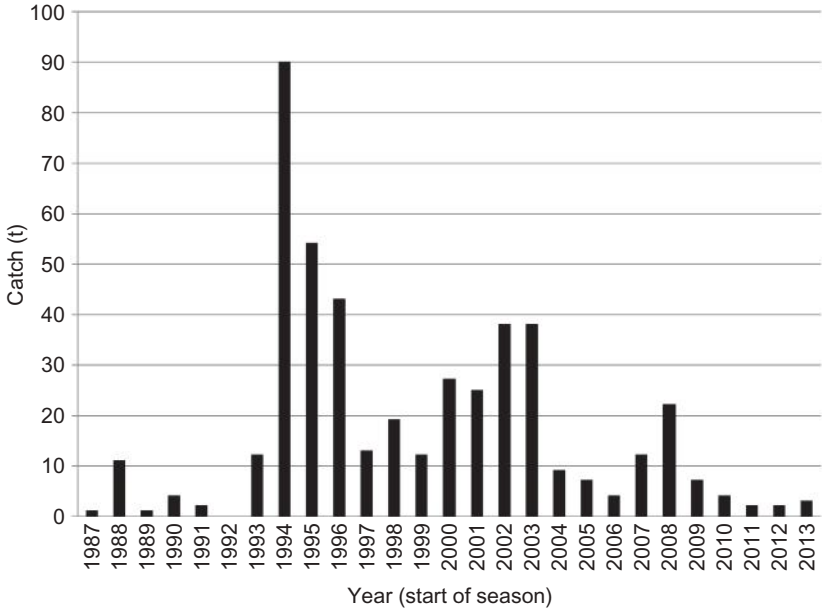

Figure 85 By-catch of skates and rays (t) in the South Georgia longline fishery from 1987/1988 to 2011/2012. *Data from CCAMLR Appendix I (2012) and CCAMLR (2013a, 2014c).*

are sustainable, although no age-structured population analyses are available for any species. As a result of concerns regarding skate and ray by-catch in CCAMLR, a tag and release programme has been initiated, and up to 23,709 rays have been released in a single year (CCAMLR Appendix I, 2012; Figure 86). The numbers of rays released per annum approximately reflect the by-catch during the period 2005/2006–2013/2014. Ray survival upon release from longlines appears to be related to the depth of the longline, but weather conditions and the sex of the individuals may also be a factor (Endicott and Agnew, 2004). A discard experiment conducted on skates (*Raja* sp.; $n = 95$) in the waters of South Georgia indicated survival of 75% in waters shallower than 1300 m, 46% in waters between 1300 and 1500 m and 24% in waters between 1500 and 2000 m depth (Endicott and Agnew, 2004). Ray by-catch remains an issue of concern in this fishery because of the lack of clarity regarding the effects of fishing mortality on particular species, although catches are monitored and the release scheme is in place (CCAMLR Appendix I, 2012).

5.2.3.7.3 Sessile Organisms By-catch of soft corals, sea fans, crustaceans and brachiopods on longlines around South Georgia was reported

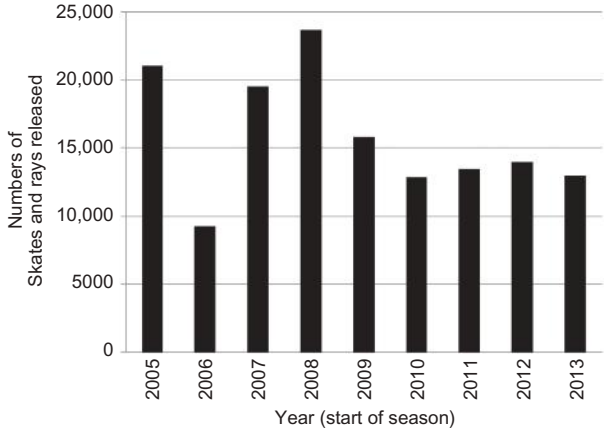

Figure 86 Number of rays released by year in the South Georgia toothfish fishery (CCAMLR Appendix I, 2012; CCAMLR, 2014c).

in 2004 (Agnew, 2004). In 2005, the Marine Stewardship Council, as a condition of certification of the toothfish fishery, requested that observers recorded the by-catch of benthic fauna to identify areas associated with complex biological communities and for consideration of protective measures if such areas were identified. This coincided with increasing concern among the international community regarding the impacts of bottom fisheries on vulnerable marine ecosystems, culminating in UN General Assembly Resolutions 61/105 (UNGA, 2007) and 64/72 (UNGA, 2009). A study by the Marine Resources Assessment Group, based on observers identifying benthic by-catch to taxonomic group on individual segments of longlines, identified that corals formed the majority of by-catch (~65% in 2005; Wakeford et al., 2006; see Figure 87), but echinoderms, crustaceans, polychaete worms, sponges, ascidians and molluscs were also observed (Wakeford et al., 2006). Over a 2-year period, more than 25,000 individual organisms were observed in the by-catch programme (Agnew et al., 2007). The majority of corals were octocorals (~85%) but scleractinians, stylasterids and black corals were also taken (in order of numerical importance). Observations in both 2005 and 2006 indicated that highest coral by-catch was between 1000 and 1400 m depth and was concentrated in several particular areas including West Shag Rocks, North Shag Rocks, South Shag Rocks, West Gully (western side of channel between Shag Rocks and South Georgia), East Gully, north-west South Georgia, north-east South Georgia and south South Georgia, a situation that remained the same in 2010 and 2011 (Figure 88).

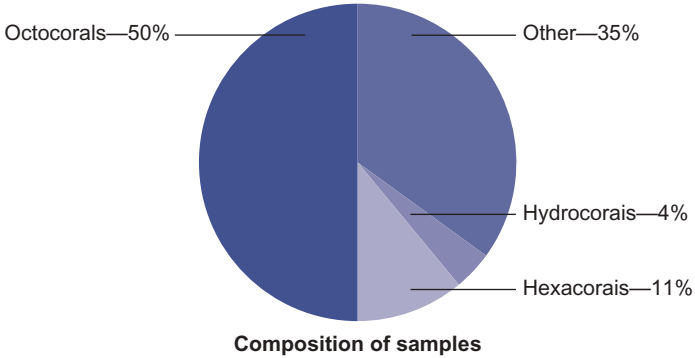

Figure 87 Composition of by-catch of benthic species recorded by observers in 2005 and 2006 (Agnew et al., 2007).

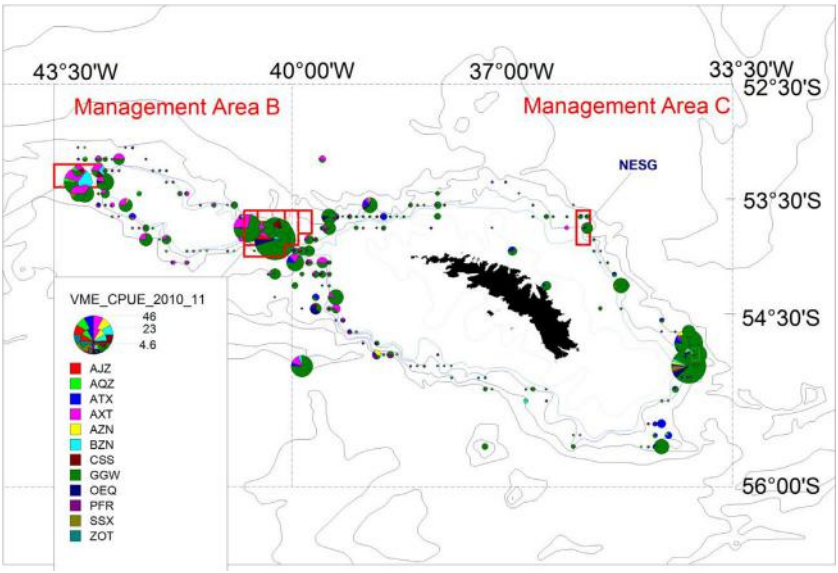

Figure 88 Catch per unit effort, CPUE, and relative proportion of different coral taxa from different areas around South Georgia and Shag Rocks in 2010 and 2011 (Martin et al., 2012).

These six areas were analysed based on the 2005 and 2006 data as candidate RIAs where commercial fishing was prohibited apart from for fisheries assessment purposes. RIAs were analysed to identify the proportion of coral population protected, to assess the impacts on toothfish catch, and to analyse the performance of the area with respect to conservation of rays and macrourids (Agnew et al., 2007). Following this study, three RIAs were selected for protection: the West Shag Rocks area, the West

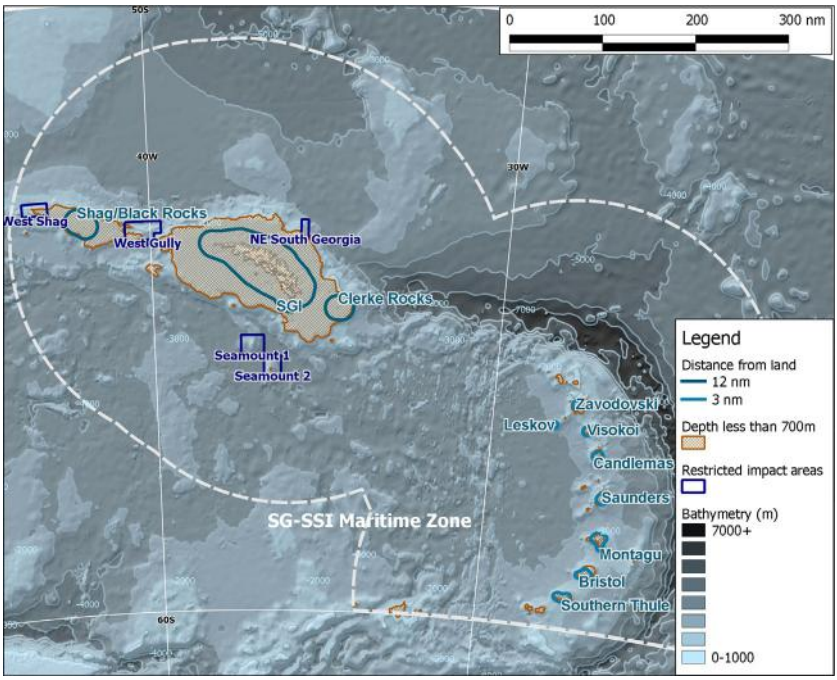

Figure 89 Map of South Georgia, Shag Rocks and South Sandwich Islands showing protected zones, and Restricted Impact Areas (GSGSSI, 2011b) and seamounts added to areas closed for fishing in 2012/2013 (GSGSSI, 2012).

Gully area and the Northeast South Georgia area (Figure 89). The West Gully area was subsequently extended to protect potential spawning grounds for Patagonian toothfish. In addition, there already existed a ban on bottom fishing shallower than 500 m depth. This was extended to 700 m depth recently, exceeding the 500 m depth limit of fishing for other CCAMLR areas. In the season 2012/2013, two new adjacent closed areas have been established to the south of South Georgia protecting two seamounts (GSGSSI, 2012). These were closed because fishing on them revealed particularly large toothfish and accordingly closing them was a measure to conserve the stocks around South Georgia.

While there is likely to have been a benefit in the establishment of the Restricted Impact Areas (RIAs) to the conservation of cold-water corals and other benthic species off Shag Rocks and South Georgia, the level of significance is still unknown. It is clear that the RIAs do not include all of the area associated with high levels of by-catch of benthic species, and that hotspots of by-catch occur just outside the West Shag Rocks, and West Gully protected areas. This reflects the tension between keeping areas of

high toothfish catch open, and protecting benthic communities. The present RIAs do not cover more than a small area of the depth zones fished for toothfish. Furthermore, the significance of the impacts of longline fishing on deep-water coral communities is still unclear because of the lack of baseline information on the species diversity and abundance of organisms living on the seabed around South Georgia and Shag Rocks, the lack of information on gear retention of by-catch (see Auster et al., 2010), the lack of detailed benthic surveys in deep waters of this region, and the lack of any information on the population biology of these animals. The South Georgia area has high octocoral species richness, which appears to follow patterns in other benthic taxa. Molecular phylogenetic and taxonomic investigations of octocorals taken as by-catch in the observer programme have revealed at least 34 species from 21 genera, of which nine represent new species, and two represent new genera (Taylor, 2011).

5.2.3.7.4 By-Catch Issues with the Toothfish Fishery in the South Sandwich Islands As mentioned previously, there have been no observed bird mortalities in the South Sandwich Islands. Macrourid by-catch is reported to have been relatively high at the start of this experimental fishery in proportion to the toothfish catch (Figure 90). This has subsequently been decreased through the initiation of a move-on rule for macrourids wherein a catch of 16% of the weight of toothfish (minimum 150 kg weight of macrourids) triggers the move on (CCAMLR Appendix N, 2010).

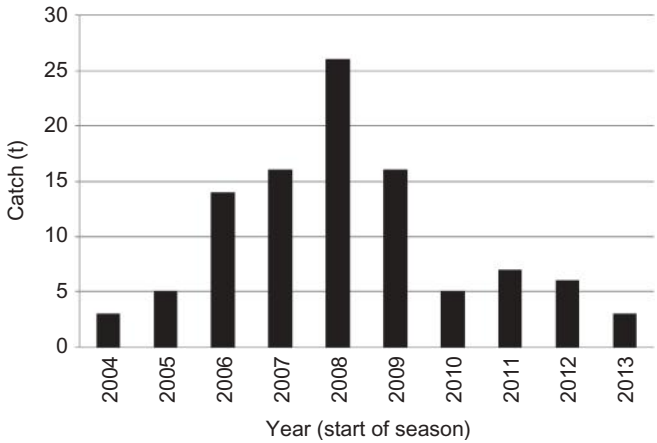

Figure 90 Macrourid by-catch (t) in the South Sandwich Islands experimental fishery in the northern and southern sectors of the island chain from the season 2004/2005 to 2013/2014. Note that from 2007/2008 the fishery was divided into a northern and southern sub-area for the purposes of management (hence the reporting of southern and northern by-catch from this time). *Data from CCAMLR, 2014d.*

Macrourus caml in the north and *Macrourus whitsoni* ("pale morph") in the south likely comprise the main macrourid catch at South Sandwich Islands (see *Fish species*, above). Ray by-catch in the South Sandwich Islands experimental fisheries for toothfish is low by weight (1–4 t; CCAMLR Appendix N, 2010). However, the number of released rays is extremely high given the toothfish catch (Figure 91), and, at worst, is close to 50% of the highest release number for South Georgia. This indicates a relatively high by-catch of rays, probably of a small size in the South Sandwich Islands area despite the report that ray by-catch is highest in the east compared to the distribution of toothfish which are mainly to the west (CCAMLR Appendix N, 2010).

There is currently no published information on benthic by-catch associated with longline fisheries in the South Sandwich Islands where fishing is concentrated on several topographic features that may harbour vulnerable species such as cold-water corals. Video observations of Kemp Seamount to the southwest of Thule Island in 2009 indicated a dense benthic community comprising ophiuroids, pennatulids and large anemones on the upper parts of the seamount and areas dominated visually by other octocorals and brachiopods elsewhere (A.D. Rogers unpubl. data).

5.2.3.8 Mackerel Icefish

Mackerel icefish, *Champsocephalus gunnari*, are mid-water predators, as adults, where they feed primarily on krill (Agnew, 2004), but also on other crustaceans such as *Themisto gaudichaudii* (Main et al., 2009). They remain close to the seabed by day, but rise into the water column at night, to within

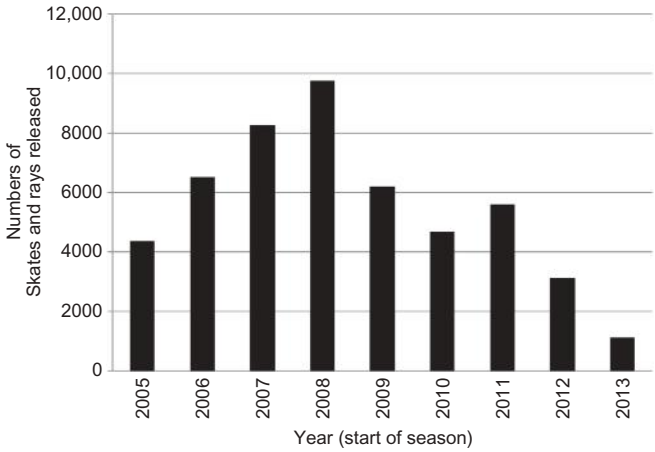

Figure 91 Release numbers of rays for the northern and southern sectors of the South Sandwich Islands. *(CCAMLR, 2014d).*

50 m of the surface (Agnew, 2004). They are preyed upon by other fish, Antarctic fur seals, and birds (see Section 4; Agnew, 2004). Around South Georgia mackerel icefish can live for up to 10 years and grow to 55 cm in length, although in recent years they have only been caught up to ~40 cm length and 8 years of age. This is probably a result of the impact of fishing on the population structure of this species. They are fished using pelagic trawls, which may be towed close to the seabed (Agnew, 2004). Hauls of 10–20 t are taken with up to 100 t day^{-1} caught, with the best catches during periods of full moon when the fish form dense shoals (Agnew, 2004). Mackerel icefish spawn over 2-to-4 weeks from April to May although spawning may occur as early as March and as late as June (Agnew, 2004). Spawning tends to take place in deep fjords, bays and inshore waters in the northeast coast of South Georgia, particularly around Cumberland Bay, with another spawning area around Shag Rocks, but limited spawning also occurs elsewhere (Agnew, 2004). Fecundity is 13,000–31,000 eggs, depending on the size of the fish (Agnew, 2004). The eggs are probably demersal and hatch after about 4 months in August and September (Agnew, 2004). They remain inshore until the following January to February before moving out on to the shelf when they are 1 year of age, and they recruit to the fishery at age two. The fish mature at an age of 3 years (Agnew, 2004).

Catches of mackerel icefish have shown a large variability with periods of a build-up of stocks followed by a sudden decline in catches (see Figure 92). However, since the late 1990s, catches have remained low compared to historic catches and in 2009/2010 catches dropped to 12 t. The reason for this is not completely clear but may be partially related to the supply of krill in the waters of South Georgia. During years of poor krill availability, icefish cannot find enough food, and they may also be targeted by predators, such as Antarctic fur seals and gentoo penguins, that switch prey from krill to fish (Agnew, 2004; Reid et al., 2005). Increase in the abundance of fur seals may have been a factor in the longer-term decline of mackerel icefish in recent years (Reid et al., 2005). Icefish catches improved in 2012/2013 with a reported catch of 999 t, and again in 2013/2014 with a catch of 1354 t (CCAMLR, 2013c).

5.2.3.8.1 By-Catch in the Mackerel Icefish Fishery In the earlier phase of fishing for mackerel icefish, a mixture of pelagic and bottom trawls were used, and so a variety of other species were also taken in the fishery including *Notothenia gibberifrons*, *Chaenocephalus aceratus*, *Pseudochaenichthys*

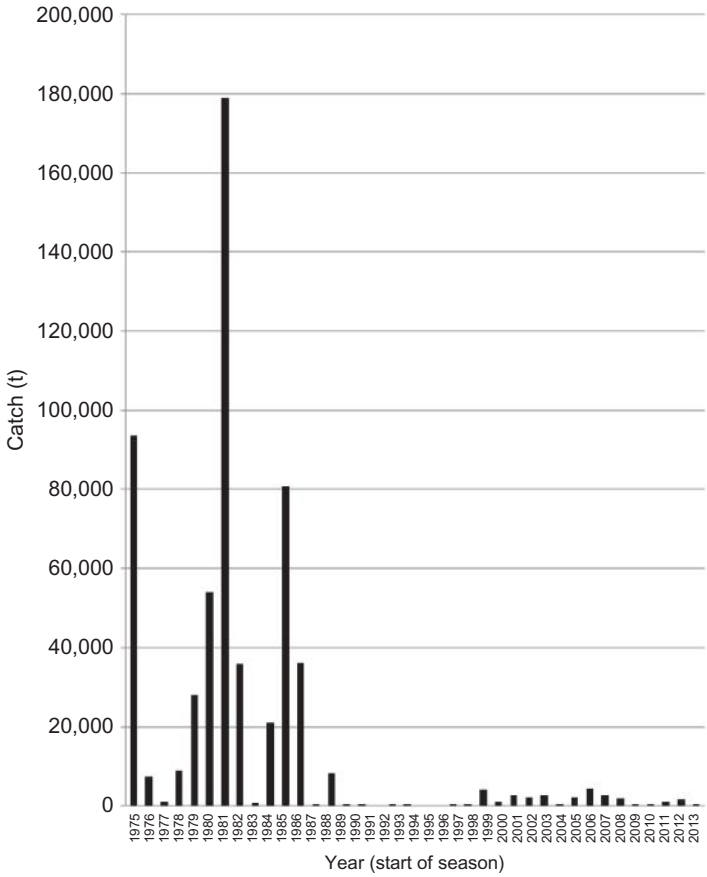

Figure 92 Catches of icefish around South Georgia/Shag rocks over time (tonnes). *(CCAMLR, 2014e).*

georgianus, *Notothenia rossii* and *Lepidonotothen squamifrons* (Agnew, 2004). By-catch was dramatically reduced with the prohibition of bottom trawling and over the past 20 years relatively small catches, or zero catches, of these species have been taken (CCAMLR Appendix S, 2010). The use of mid-water trawls has resulted in a by-catch of birds around South Georgia and Shag Rocks in the mackerel icefish fishery (Figure 93). Birds dive on the nets as they are being hauled in as pelagic trawls float on the surface of the sea for longer than heavier bottom trawls. The main species affected have been grey-headed albatross, black-browed albatross and white-chinned petrel (see Section 4). Mortality has been as high as more than 90 birds, in some years, on the observed trawls, although in recent years mortality

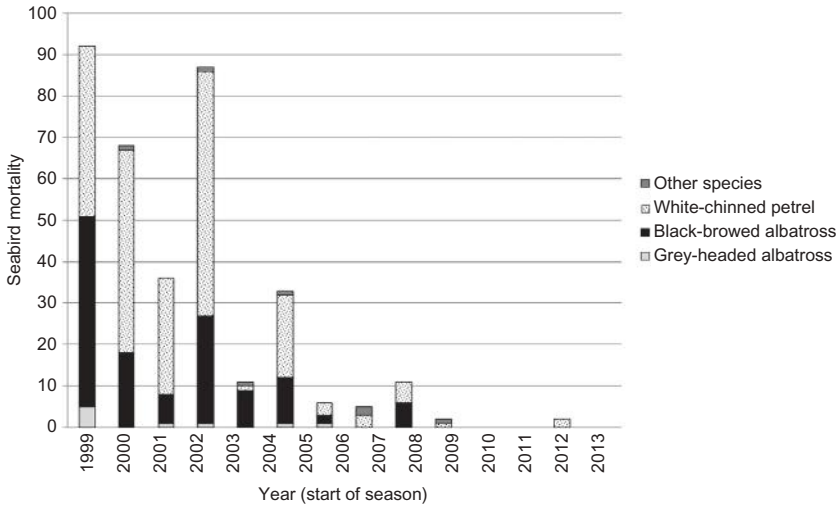

Figure 93 Bird mortality as a result of by-catch in the South Georgia mackerel icefish fishery. *Data from CCAMLR Appendix G (2012) and CCAMLR (2014e).*

has been less than 40 birds, and mortality dropped to two birds in 2009/2010 and zero birds in the past two seasons (in 2009/2010 and 2010/2011 relatively few trawls were taken; CCAMLR Appendix G, 2012). Despite a recent increase in catches of mackerel icefish, the by-catch of birds has remained low (2 birds in 2013/2014; CCAMLR, 2013c). Measures have also been taken to reduce bird by-catch, such as binding of nets prior to deployment (see Section 4). Such mitigation measures are important as bird mortality from the trawl fishery has exceeded that in the longline fishery for the waters of South Georgia.

5.2.3.9 Stone Crabs

South Georgia and Shag Rocks host populations of at least five species of stone or king crabs. The most common of these are *Paralomis spinosissima* and *Paralomis formosa*, with fewer observations of *Paralomis anamerae* and a few observations of *Neolithodes diomedeae* and *Lithodes murrayi* (Purves et al., 2003). There are doubts over the identification of the rarer of the species and their taxonomic identification is yet to be confirmed by morphological and genetic analyses (Belchier et al., 2012). Experimental fisheries have been undertaken for stone crabs in South Georgia since 1992 and the species are also captured in pots deployed for taking toothfish (Belchier et al., 2012). *Paralomis spinosissima* inhabits waters < 800 m depth

with peaks in abundance around 400 m. *Paralomis formosa* occurs at depths >300 m with peaks in abundance at 800–1400 m depth (Belchier et al., 2012; Purves et al., 2003). *Paralomis anamerae* occurs at depths between 600 and 1200 m (Belchier et al., 2012; Purves et al., 2003). *Paralomis spinosissima* occurs across shelf and shelf break regions around South Georgia and Shag Rocks, but highest abundances appear to be located around the northwestern shelf and slope of South Georgia (Belchier et al., 2012). The density of *Paralomis formosa* appears to be highest on the northern slope of South Georgia (Belchier et al., 2012). Further information on the biology and ecology of these crabs are available in Purves et al. (2003) and Belchier et al. (2012), but relatively little is known about their ecology, especially for the rarer species.

Experimental fisheries for stone crabs in South Georgia have yielded a maximum catch of 497 t in one season (Belchier et al., 2012). For some time, the maximum catch limit for the species has been set at 1600 t per annum, although this catch may not be sustainable in the longer term (Peatman, 2007). To date, a commercial fishery has not developed for stone crabs and it is thought that such a development is very unlikely in the future (Belchier et al., 2012). This is partially because at present catch is limited to male crabs only above a carapace width of 94 mm for *P. spinosissima* and 90 mm for *P. formosa,* rendering the fishery uneconomic (Belchier et al., 2012). In addition, crabs are often rejected if they have missing limbs or other forms of damage that render them unsaleable (Belchier et al., 2012). Lifting some of these restrictions may make this fishery more attractive, but at present it is likely it will remain commercially unviable.

5.2.3.10 Krill

Antarctic krill are regarded as the world's last major underexploited fishery with precautionary catch limits for the CCAMLR area of 8.6 million tonnes per annum (5.61 million tonnes in the Atlantic Sector including the Scotia Sea and the Antarctic Peninsula), nearly 40 × more than the latest catch figure of ~285,000 t, the highest figure since 1991 (CCAMLR Scientific Committee, 2014; Nicol et al., 2011). Previously, krill fishing has been limited by the costs of fishing in the Southern Ocean and problems associated with processing and marketing krill as a product (Nicol et al., 2011). However, the number of vessels fishing krill has nearly doubled over the past 5 years, from seven vessels licensed by CCAMLR in 2006/2007 to thirteen licensed for fishing in 2010/2011 and there are notifications for 21 in the 2014/2015 season (CCAMLR Scientific Committee, 2012; CCAMLR

WGEMM, 2014). Catches of krill have also increased significantly over the past few years with the notified catch for the 2012/2013 season projected to reach 611,000 t (CCAMLR Scientific Committee, 2014). The projected catch figure exceeds the catches at the previous peak of krill fishing in the 1980s (Nicol et al., 2011; Figure 94). It is also several times higher than the mean annual catch of krill, 108,863 t, from 1994 to 2009 (Nicol et al., 2011).

Of importance to understanding the potential impacts of projected krill catch in the Southern Ocean, catches for krill may be significantly under-reported. One reason for this is that much of the catch is rendered to fish meal on vessels, and conversion factors used to convert the weight of fish meal to biomass of krill vary from vessel to vessel (Pramod et al., 2008). Attempts to obtain accurate estimates of "green weight" of krill catches are problematic, especially on vessels where no observers are present to advise crews (it is the state's responsibility to ensure accurate data collection; CCAMLR WGEMM, 2014). In general, the lack of mandatory observers on board krill fishing vessels has led to a lack of consistency in data collection by krill fleets (Nicol et al., 2011). The CCAMLR Scientific Committee (2014) has expressed the desire for 100% observer coverage for krill fishing vessels. Although this has been contested, the level of observer coverage has been raised to 50% for the 2014/2015 season (Conservation Measure CM 51-06 see CCAMLR, 2014b).

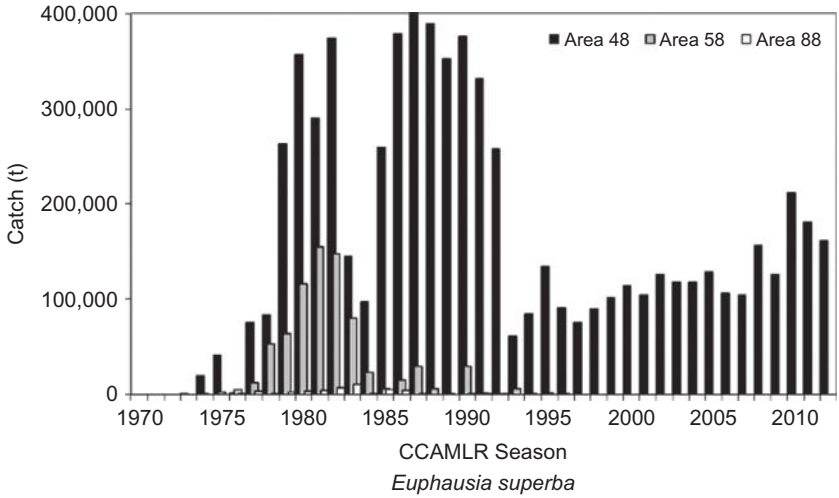

Figure 94 Annual estimated catches of Antarctic krill, *Euphausia superba*, from 1972 to 2012 in tonnes (Available from CCAMLR at: https://www.ccamlr.org/en/fisheries/krill-fisheries).

It is apparent that krill fishing is undergoing a major change with a dramatic increase in catches, changes in fishing technology and an increase in the number of krill products for sale (Nicol et al., 2011). Norwegian vessels have recently employed a pumping system for the harvesting of krill. This involves pumping air into the cod-end of the net with the air bubbles lifting krill into a hose that deliver the animals to the processing facility on the vessel. This method not only increases daily catches to up to 800 t day^{-1} (compared to catches using standard trawls of 100–400 t day^{-1}), but also delivers the krill to the vessel processing facility in a very good condition avoiding problems of spoilage using conventional fishing (Nicol et al., 2011).

During the 1980s, krill fishing was mainly undertaken by Soviet bloc vessels and focused in the Atlantic Sector of the Antarctic and East Antarctica. Recently, fishing has concentrated in the Atlantic Sector, focusing mainly around the Antarctic Peninsula (Sub-area 48.1), the South Orkney Islands (sub-area 48.2) and South Georgia (sub-area 48.3). These sub-areas were all associated with the highest concentrations of fishing/catches in fisheries between 1974 and 2000 (Figure 95), and during this period the general pattern of fishing was to fish around South Georgia during winter and to move

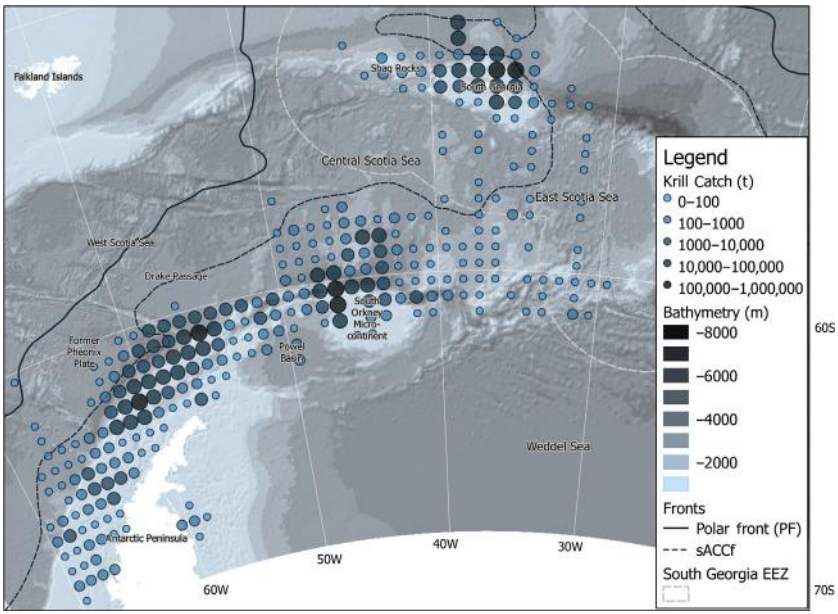

Figure 95 Commercial catches of krill (t) between 1974 and 2000 in Sub-areas 48.1, 48.2, 48.3, 48.4 and 48.5 aggregated by fine-scale rectangles (0.5° latitude, 1.0° longitude). *Data from Jones and Ramm (2004); see also Kawaguchi et al. (2009).*

southwards as the sea ice retreated (Everson and Goss, 1991; Jones and Ramm, 2004). This pattern of fishing has changed with changing patterns of sea ice distribution caused by climate change. The krill fishing season has now extended and mainly takes place in late summer to midwinter, with vessels fishing further south in winter than in the past (Kawaguchi et al., 2009; Nicol et al., 2011). Most of the krill fishing that has taken place historically around South Georgia has concentrated over the shelf/slope to the north of the islands (see Figure 95; Murphy et al., 1997). This pattern coincides with the main foraging areas for many of the predators on South Georgia (e.g. birds, Figure 96), although most fishing is concentrated during the austral winter outside of the time when birds and other predators are feeding young. The targeting of krill aggregations during winter by such

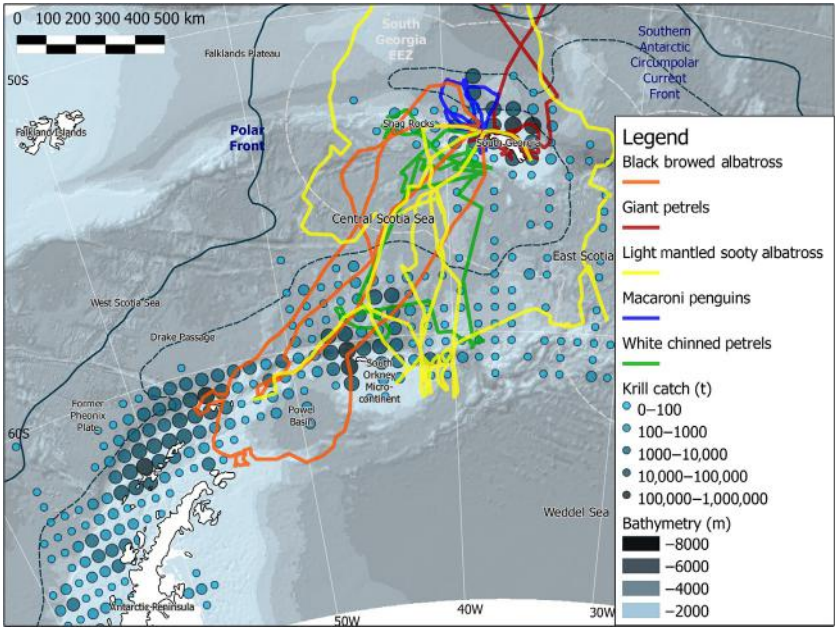

Figure 96 Commercial catches of krill, *Euphausia superba*, (t) between 1974 and 2000 in Sub-areas 48.1, 48.2, 48.3, 48.4 and 48.5 aggregated by fine-scale rectangles (0.5° latitude, 1.0° longitude). Superimposed on the krill catch are the tagging tracks from a variety of studies on marine predators (birds) from South Georgia (see references and species-specific tracks under Section 4). Areas of intense predator foraging are particularly notable on the north-western and western margins of South Georgia. Note that the foraging of monitored predators is generally temporally separated from krill fishing around South Georgia. However, the winter movements of many predators around South Georgia, especially less-studied species such as diving petrels are unstudied. *Data from Jones and Ramm (2004); see also Kawaguchi et al. (2009).*

predators may be critical to breeding success in the following season (Murphy et al., 1997). In general, there is still a lack of knowledge on the winter foraging patterns of many of predator species, especially smaller seabirds, such as Antarctic fulmars, blue petrels and Cape petrels, which are reported to occur consistently where the krill fishery takes place and to feed on krill in the wakes of the vessels (Black, 2005b; Varty et al., 2008). The GSGSSI are reported to be undertaking research on winter distribution of predator species (e.g. see Staniland et al., 2012).

Most of the krill stocks around Antarctica are located in the Atlantic Sector of the Southern Ocean (Atkinson et al., 2008, 2009). It is therefore likely that the projected increased effort in krill fishing will focus on this region. In the 2013/2014 season, about 283,000 t of krill were caught in CCAMLR Area 48, of which about 66,000 t was taken in the waters of South Georgia (CCAMLR Scientific Committee, 2014). This is currently worth about 10% of the total fisheries revenue in South Georgia (see Section 6). The CCAMLR has set an overall limit for 279,000 t of krill from South Georgia waters, with an overall "trigger" level of 620,000 t for Area 48 (CCAMLR CM51-01, 2010). This level, which was supposed to represent the summed maximum annual krill catch in any year for all sub-areas, is the point at which fishing must be broken down into individual Small-Scale Management Units (SSMUs) for fisheries management purposes before it is allowed to continue (Gascon Gonzalez and Werner Kinkelin, 2009). At the trigger level, the entire area would have to be assessed for its potential yield in krill, along with harvest control rules, and the resultant potential yield would then be divided among the SSMUs based on ecosystem model simulations that take predator demand into account (Gascon Gonzalez and Werner Kinkelin, 2009). This strategy is, as yet, untested (Gascon Gonzalez and Werner Kinkelin, 2009). Nonetheless, SSMUs are widely considered to be the best way to manage the krill fishery from a conservation perspective. On an area-by-area basis, the trigger level of 620,000 t has been divided into: Sub-area 48.1–25%, Sub-area 48.2–45%, Sub-area 48.3–45%, Sub-area 48.4–15% (CCAMLR CM51-07, 2009). The overall precautionary catch limit for Area 48 has been determined at 5.61 million tonnes but this cannot be fished until quotas for SSMUs for the fishery have been determined (Nicol et al., 2011). In 2010/2011, the krill fishery in Sub-area 48.1 was closed as catch, for the first time in any sub-area, approached the trigger level for an individual sub-area (155,000 t; Nicol et al., 2011). It is notable that in this season the two Norwegian vessels, *Saga Sea* and *Antarctic Sea*, using new fishing technology for krill, took 49% of the entire krill catch

for the CCAMLR area (CCAMLR Scientific Committee, 2012). By May of the 2011/2012 Season, 78,468 t of krill had been caught, mainly in Sub-area 48.1, of which the Norwegian vessel *Saga Sea* had taken 60% (CCAMLR Scientific Committee, 2012). The MSC approved the krill fishery in Area 48 by the Aker Marine vessel *Saga Sea* in 2010 and in the same year the establishment of a krill fishing industry association was announced to help provide scientific data to CCAMLR (Nicol et al., 2011). In June 2013, Sub-area 48.1 was then closed again because the trigger level was approached and again a closure occurred in May 2014, earlier than the previous closures (CCAMLR Scientific Committee, 2014).

5.2.3.10.1 By-Catch from the Krill Fishery Predator by-catch associated with older methods of krill trawling were not systematically investigated because of a lack of observers on krill vessels. However, around South Georgia there have been no reports of bird strikes associated with krill trawling from observers present on vessels (Varty et al., 2008). By-catch and mortality of Antarctic fur seals were reported to be a problem in the South Georgia krill fishery as the animals foraged in nets during fishing, became entangled and drowned (Hooper et al., 2005). However, trials with various types of seal excluders fitted to krill trawls were found to be successful at preventing seal mortality (Hooper et al., 2005) and all vessels must now have these devices fitted to their nets in the South Georgia fishery (Trathan et al., 2014). Because of the inclusion of fine mesh excluders in modern krill nets and the short distance that trawl warps extend from vessel to water, as well as the greatly reduced need to haul nets using the krill pumping technology, by-catch of marine predators such as birds and seals has not been identified as a current problem in this fishery.

The main by-catch reported currently from krill fisheries is of larval and juvenile fish. Occasionally, large by-catches of mackerel icefish, and lower numbers of other species, were reported during krill fishing operations on the South Georgia shelf in the 1980s (Everson et al., 1992). Catches comprised mainly 0- to 2-year-old fish and were spatially patchy (Everson et al., 1992). Subsequent observations of by-catch from krill fisheries around South Georgia also identify by-catch of fish larvae. A figure of up to 58 individual mackerel icefish per tonne of krill caught is given in the recent report on krill fishing for Sub-area 48.3 in the years 2006–2008 (Marine Resources Assessment Group, 2009). More recently, Aker Biomarine has conducted an assessment of larval fish catches in Sub-area 48.2 as a condition of their MSC certification. However, a summary of some of the findings indicates that the main fish larvae caught as by-catch in the Aker Biomarine krill fishing

operations are Myctophidae (lantern fish), Channichthyidae (icefish) with lower levels of Nototheniidae (Hough and Medley, 2012). The catches of myctophids were likely to be insignificant. Issues of identification of the larvae meant that the by-catch was not attributed to a specific species, but for fisheries purposes they were assumed to be mackerel icefish and marbled rockcod, *Notothenia rossi*, two commercial species that have been fished in the region. Only for marbled rockcod was the by-catch estimated (adjusted for impacts on adult stock) to represent >0.25% of the lower 95% confidence limits of the stock biomass. This species has not been found as by-catch in Sub-area 48.2, instead humped rockcod, *Gobionotothen gibberifrons,* makes up 40% of the notothen records in the area. It was concluded that by-catch levels are unlikely to be significant for this species (Hough and Medley, 2012). A wider study examining fish by-catch in 9303 hauls on 60 cruises and 18 different vessels from 2010 to 2014 has been undertaken. The frequency of occurrence of fish was between 10% and 98%, and 14 species occurred at a greater than 1% frequency, 10 of which were channicthids (CCAMLR WGEMM, 2014). Given the lack of details available on these studies, and the very limited number of observations on by-catch from krill fishing, especially using the new methods involving pumping of krill, it is premature to take a view on the significance of this activity in the vicinity of South Georgia. Coupled with this, knowledge of the pelagic ecosystem in terms of populations of larval/juvenile populations of commercial species and of small fish species inhabiting the epipelagic and mesopelagic zone around South Georgia is relatively poor. There is a requirement for more research regarding the catch of larval fish by krill fishing in all sub-areas, and for all fishing methods, in order to ascertain the significance of this source of mortality for commercial and non-commercial fish species (ASOC, 2010a; CCAMLR WGEMM, 2014).

5.2.3.10.2 Ecosystem Concerns Krill are the keystone species in the Antarctic marine food web. The majority of predators at South Georgia are dependent on krill originating from the Antarctic Peninsula, especially during the breeding season. Recent estimates for the standing stock of krill in the CCAMLR area of management range from 117 to 379 million tonnes, depending on the method used to calculate biomass from net-based sampling (Atkinson et al., 2009). Acoustic estimates based on the CCAMLR 2000 survey gave a figure of approximately 133 million t for the whole of the Antarctic with an annual production of 342–536 million t per annum (Atkinson et al., 2009). These estimates are large, but given total predator

consumption estimates of 128–470 million t per annum, they are consistent with other information about the Antarctic marine ecosystem (Atkinson et al., 2009). However, despite the large biomass and production of krill, the key to understanding the potential impacts of krill fishing at the ecosystem level around South Georgia is gaining an understanding of local spatial patterns of fishing and how this coincides with spatial and temporal patterns of foraging by predators (e.g. see Figure 96). This has to be considered alongside evidence of declining levels of krill abundance in the Atlantic sector of the Southern Ocean (Atkinson et al., 2004; Flores et al., 2012), and the observations that years of poor krill abundance in this region may impact recruitment of fished species, such as toothfish and mackerel icefish, and effect the breeding success of marine predators including birds and seals. Currently, the krill fishery is operating well below precautionary catch levels at a gross geographic scale and may be regarded as a minor predation loss (Atkinson et al., 2009). However, at smaller scales, such as around South Georgia, there is the potential for competition between locally concentrated fishing and foraging predators. Around South Georgia, predators take considerable quantities of krill, with some estimates suggesting that Antarctic fur seals and macaroni penguins may take nearly 12 million tonnes of krill per annum (Boyd, 2002; but see Hill et al., 2007 and Trathan et al., 2012). It also appears that foraging activities are localised to specific areas around South Georgia (e.g. northern, north-western and western shelf and slope; see Figures 34, 37, 41, 55, 57, and 96). This information should be treated with caution, though as this partially reflects the predators that have been studied and also where the studies have been carried out. Given that fishing effort and catches are rapidly increasing at the present time and demand for krill products will presumably maintain pressure to further expand fisheries in the future, prey requirements of predator species are of significant concern in the context of South Georgia. CCAMLR's ability to maintain a precautionary and ecosystem-based approach to managing such a rapidly expanding krill fishery has not yet been tested (Nicol et al., 2011). Resistance by some States to establish management measures such as a requirement for 100% observer coverage is not encouraging (ASOC, 2007; CCAMLR WGEMM, 2014). There are also concerns regarding methods of estimating the biomass of krill caught by fishing vessels. These concerns arise because differences in the methods used to convert the weight of krill captured/processed to the weight of krill actually captured by the vessel, and because variation in body condition of the krill influences these calculations (CCAMLR Scientific Committee, 2012). Furthermore, there are concerns

that environmental changes associated with CO_2 emissions, such as ocean acidification, will further impact krill, potentially within a timescale of tens of years (Kawaguchi et al., 2010; Nicol et al., 2011; Orr et al., 2005).

5.2.3.10.3 The Future of the South Georgia Krill Fishery The fauna of South Georgia, especially predators, are heavily dependent on krill as a main source of food. There is substantial evidence of a decline in the availability of krill in the Scotia Sea region that is highly likely to be a response to forcing by global climate change (Atkinson et al., 2004; Flores et al., 2012; Quetin and Ross, 2009); this, in turn, is likely to impact populations of krill-dependent predators. However, in some areas, especially around South Georgia, such trends may also reflect increased competition among predators because animals such as seals and whales may be recovering post exploitation (e.g. Trathan et al., 2012, 2014). Such long-term impacts of harvesting, coupled with the relatively short time over which data have been collected and the patchy nature of sampling, means that it is very difficult to discern long-term trends in krill abundance and the dynamics of zooplankton communities in general (Murphy et al., 2013). This may explain why there has been no discernable change in the biomass and availability of krill around South Georgia (Murphy et al., 2013). Observations do indicate that in years of poor krill abundance, populations of seabirds, seals and probably fish are all impacted in terms of their reproductive success and recruitment. If declines in krill abundances are occurring, then consequential impacts on the food webs around South Georgia and the South Sandwich Islands are likely to deteriorate further as the Antarctic Peninsula is one of the three areas of the globe that are currently experiencing rapid regional climate change (Ferrigno et al., 2009; King, 1994; Vaughan et al., 2003). The other two regions experiencing rapid climate change are western North America and an area centred on central Siberia. The three regions are all high latitude areas and each has experienced a mean annual temperature rise of more than 1.5 °C since 1950, compared with a global mean increase of ca 0.6 °C. Added to this, experimental evidence suggests that ocean acidification may also have negative impacts on krill development, raising the potential of further impacts on population size (Kawaguchi et al., 2010). There is already direct observational evidence of the impacts of ocean acidification on other elements of the Southern Ocean zooplankton community (Bednaršek et al., 2012), and these are also likely to increase in geographic extent and severity over the next century. The very same effects of climate change are extending the krill fishing season further south (Kawaguchi et al.,

2009). In a situation wherein krill stocks around the Antarctic Peninsula are becoming more available to fishers, the likelihood that fleets will pay for licences to fish krill within the SGSSI MZ during winter may decrease. Opportunities for charging substantial fees for krill licences around South Georgia may diminish with time as rising temperatures around the Peninsula give greater access to fishing fleets targeting abundant krill stocks in the region. As we have discussed, climate change may also further reduce krill concentrations around South Georgia as bioregions are pushed further south, adding to the economic incentives to fish further south with the additional risk that fishing may impact the supply of krill crossing the Scotia Sea from the Antarctic Peninsula to South Georgia. In other words, we are entering a period of great uncertainty in terms of the effects of climate change on Antarctic krill populations and consequent impacts on krill supply around South Georgia and the South Sandwich Islands. Yet, we know krill to be the keystone species on which much of the unsurpassed marine biological richness of South Georgia and the South Sandwich Islands is based. To promote a strategy to target krill populations by intensive fishing operations within the SGSSI MZ of South Georgia and the South Sandwich Islands at such a time represents a risk to the status of predator populations, and to the structure and productivity of the ecosystem as a whole, at South Georgia and the South Sandwich Islands. The level of this risk will depend on a variety of factors including future trends in krill abundance, other effects of climate change on the marine ecosystems of the Scotia Sea, the response of populations, species and ecosystems to changes in krill abundance and environmental parameters, the spatial and temporal overlap of any future krill fisheries and predator foraging ranges, and other factors such as the human introduction of alien species or range changes of species moving south with increasing ocean temperatures (an example of which has been observed in benthic ecosystems of the western Antarctic Peninsula; Smith et al., 2011). These factors argue for a precautionary approach in the development of krill fishing both around South Georgia and the South Sandwich Islands, and also around the Scotia Sea and Antarctic Peninsula as a whole.

6. AN ECONOMIC REVIEW OF SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS

6.1 Introduction

The aim of this part of our review is to analyse the key economic value drivers of South Georgia and the South Sandwich Islands (SGSSI). The

objective is to provide an understanding of the economic context in which conservation decisions that may impact the area have been taken and will continue to be taken in the future. Such a review seems both worthwhile and timely. The Antarctic continent and the surrounding Southern Ocean have been in many respects the last frontier for human development. These areas have been somewhat protected by their remoteness to human population centres, and by the very challenging physical environment. Yet the world's human population continues to expand and pressure for economic development continues apace.

Growing demand for food, especially animal proteins, may lead to new attempts to harvest the Southern Ocean fisheries. Globally, many important fish stocks have already been severely depleted but the Southern Ocean krill fishery has barely been exploited and is attracting renewed interest, with China being the latest nation to establish an exploratory fishing programme. Because krill represent a critical link in the Antarctic food chain, connecting the microscopic phytoplankton with larger marine fish and mammals, any attempts to harvest this resource must face close scrutiny in terms of understanding its impact on dependent species (see Sections 3 and 4).

Developing economies are also hungry for raw materials. Improving technology and the incentive of the long-term rise in commodity prices are making many mineral deposits around the world that were historically inaccessible or unprofitable, of increasing interest for commercial development. As traditional mineral reserves are exhausted, it is possible that political pressure to develop extractive industries in the Antarctic region will grow. Geologically, Antarctica was part of the same landmass from which Africa, India, South America and Australia originated and at the core of these continents and Antarctica are Precambrian shields which host rich mineral deposits including iron, manganese, gold, uranium, copper, cobalt, lead silver and diamonds (U.S. Congress, Office of Technology Assessment, 1989). To the extent that these territories have rich mineral resources, it seems reasonable to suspect that Antarctica might also have significant mineral reserves.

Remote islands are well known for their role in supporting species of conservation importance. In some cases, physical separation might have created the conditions for new species to evolve. In others, remoteness served to protect populations and habitats against human encroachment, creating a refuge while local extinctions occurred elsewhere. Consistent with this general model, South Georgia and the South Sandwich Islands are home to globally significant populations of a number of important bird and mammal species (Section 4). Some of these—such as the chinstrap and macaroni

penguins—appear to be highly vulnerable to changes in their environment (Section 4). In recent years, a number of the relevant species have displayed worrying trends in their populations (Section 4). For many of these species, declining populations seem to be a function of fishery impacts (e.g. albatrosses) or the more widespread effects of climate change (e.g. macaroni penguins; see Section 4).

The fauna of South Georgia and the South Sandwich Islands can be considered to have an economic value, not only through the contingent value that we humans might place on their continued existence, but also as an exploitable resource through revenue-generating activities such as tourism. In many cases, tourism can be a two-edged sword, bringing environmental impacts as well as an incentive to preserve. However, it seems rational to seek an understanding of the economic potential of habitat-based tourism and to weigh that opportunity, for example, against the economic gains to be had through further exploitation of fisheries or the environmental risks of other forms of development such as extractive industries.

With the possibility that economic activity in and around the SGSSI will increase, whether as a policy objective or through the actions of others, an understanding of the economic forces at work and their potential impacts will be important in order to ensure appropriate conservation planning. The common experience of conservation activity worldwide has been that environmental consequences can be far reaching and that a systematic understanding of the situation is needed to devise effective protections.

In order to develop a better understanding of the overall economic context of SGSSI, we explore some of the main economic themes and drivers of economic value. Where relevant, we touch upon topics not related exclusively to SGSSI, but also more broadly to the Antarctic region, the area governed by the Antarctic Treaty. The main topics covered are:

- A financial overview of the SGSSI.
- The development potential of the krill fishery
- Trends in other fisheries
- Tourism in SGSSI and Antarctica
- Non-marketed goods and services

These topics have been chosen based upon a range of criteria that might apply in varying degrees across each of the different categories. Criteria include current economic activity, environmental and other physical impacts, and future potential. Each of these has relevance to conservation planning in SGSSI and should be of interest to decision makers.

6.2 South Georgia and the South Sandwich Islands: Background in Relation to Socioeconomics

As already outlined, the aim of this part of the review is to investigate the economic value drivers and themes that are likely to shape conservation planning in SGSSI, both in the immediate future and stretching out some decades into the future. This objective naturally includes within its scope all current economic activity within SGSSI. It also requires in some cases, however, a broader understanding of activity across the Antarctic region.

As sub-Antarctic islands, SGSSI are effectively satellites of the southern continent. This is true in a biogeographical sense, given the interconnectedness of ecosystems. It also shares with Antarctica some key components of political governance:

- Within the British Foreign and Commonwealth Office (FCO), Britain's affairs in both SGSSI and Antarctica are commonly managed within a single Polar Unit.
- Although fisheries management around SGSSI is the responsibility of the Government of South Georgia and the South Sandwich Islands (GSGSSI), GSGSSI acts to ensure its management measures are in line with, and reinforce, the provisions of CCAMLR the regional fisheries management organisation (RFMO) which manages the whole region within a common framework (Trathan et al., 2014).

Given the extent of the overlap between SGSSI and wider Antarctica, in a number of the subsequent sections, it is useful to review economic themes primarily at a regional Antarctic level, before offering comments on how those regional trends might impact upon SGSSI.

In common with many other remote territories with conservation significance, somewhat limited economic data are available. The data that do exist are often dated, in some cases might not be immediately relevant to the calculations required to perform an economic valuation and sometimes are not in the public domain.

This review is not, therefore, a typical environmental valuation analysis which seeks to place a quantitative value on each identified component of economic activity. Rather, here we seek to summarise the known data and to highlight, where relevant, the most important factors that are likely to influence economic value. Each section reflects a somewhat different balance between a quantitative and qualitative approach, and between description and prediction.

6.3 Methods

We have conducted a thorough examination of the academic literature in parallel with a search across the grey literature (including government documents and NGO publications) and media sources. Some of the material included in our financial overview of South Georgia and the South Sandwich Islands is based on data to year end 2012—the last year for which accounts have been published at the time of analysis (2005–2013 GSGSSI Financial Statements currently available from http://www.sgisland.gs/index.php/(d)Financial?useskin=edu).

Statistics and other information pertaining to Antarctica and South Georgia and the South Sandwich Islands tourism have been drawn from publicly available material on the GSGSSI website (http://www.sgisland.gs/index.php/Main_Page). Other material include the GSGSSI Annual Reports for 2013 and 2014 (GSGSSI, 2013, 2014a); and reports of the 17th to 27th Annual General International Association of Antarctic Tour Operators (IAATO; 2007–2014), the GSGSSI Presentation to IAATO members May 2012, the GSGSSI briefings to IAATO (GSGSSI, 2006, 2007, 2008, 2009, 2010b, 2011c, 2013, 2014a,b); and the South Georgia and South Sandwich Islands Strategy 2010–2015 (GSGSSI, 2010a).

In addition, between 2011 and 2014 we conducted private interviews with individuals with expertise in their field. These individuals are: J. Rumble (Head of the Polar Regions department, UK Foreign and Commonwealth Office), M. Collins (Chief Executive, GSGSSI), J. Pearce (Principal Consultant, MRAG, 18 Queen Street, London, W1J 5PN), D. Agnew (Standards Director, MSC, Marine House, 1 Snow Hill, London, EC1A 2DH), R. Werner (Pew Charitable Trusts), D. Miller (Director, Antarctic Tasmania and Science Research Development), P. Leat (Science Programme Co-ordinator, British Antarctic Survey), D. Liggett (Scientific Committee on Antarctic Research, SCAR, Social Sciences Action Group), S. Wellemeir (MD, Navilogue; formerly Executive Director, International Association of Antarctic Tour Operators, IAATO) and J. Haase (Administrative Officer, IAATO). Their personal comments are referenced where relevant in the text.

In our section on the non-use values of South Georgia and the South Sandwich Islands, we highlight work that has been done in a Northern Hemisphere ecosystem, particularly an earlier study undertaken to assess a possible value of the ecosystems of Prince William Sound in Alaska (Carson et al., 1992, 2003). That work took place in the context of the court

process that followed the *Exxon Valdez* disaster in 1989 and provides a useful discussion of the possible non-use value of SGSSI.

6.4 Financial Overview of the Government of South Georgia and the South Sandwich Islands

6.4.1 Overview

The Government of South Georgia and the South Sandwich Islands operates on a very small budget of approximately £5 million per annum with revenues broadly matching expenditures. Revenues are derived primarily from fishing licences representing about two thirds to three quarters of all income. The majority of the remainder is derived from visitor fees in the form of landing charges with a small amount from stamps and various other sources. Expenditures primarily relate to fisheries research and protection, fisheries observers, salaries of established staff and environmental management.

Although revenues have covered expenditures on an ongoing basis, the revenue deficit of 2010 and 2011 highlighted the reliance on toothfish licence income as well as the underlying cyclicality in visitor numbers. The strengthened financial performance in 2012 (and expectations for 2013 and 2014) reflects a significant rise in toothfish licence fees as well as the success of the 2010 strategic objective to diversify revenues. Krill licence fees in 2012 were 8× their 2010 level with nearly half a million pounds of additional funds received from a number of largely heritage-related sources.

6.4.2 Description of Government Activities

Although the UK Government retains overall responsibility for the good governance, defence and foreign policy of the Territory, SGSSI has its own constitution and administration. The administration is currently based on the Falkland Islands. There are three staff members on South Georgia, with inhabited facilities at King Edward Point (KEP) and Grytviken. There is no permanent population on the Islands. In addition to the basic components of governance provided by Government employees, the Government undertakes a number of activities which it fulfils in co-operation with a range of Government bodies, publicly funded providers such as the British Antarctic Survey (BAS), Centre for Environment Fisheries and Aquaculture Science (CEFAS) and the Natural Environment Research Council (NERC), private companies such as Byron Marine and charitable

organisations such as the South Georgia Heritage Trust (SGHT). These activities include environmental management, fisheries management, tourism oversight, scientific research, heritage management and outreach and publications.

6.4.3 Revenues

Tables 5 and 6 show the revenues and expenditure of GSGSSI for 2005–2012. The largest source of revenues is the granting of fisheries licences, which averages between two-thirds and three-quarters of all revenues. Licence revenues have been shown to be fragile. The other main source of revenue is the landing fees from tourists, which over the past few years have run at 13–16% of total income.

6.4.3.1 Fishery License Fees

Table 7 provides a breakdown of the licence fee data by individual fishery. Toothfish has typically provided around 90% of the total, highlighting the lack of diversity in revenues for the GSGSSI as a whole. In 2013, toothfish licences raised approximately £3.86 million, an all-time high. While overall toothfish revenues have been broadly in the £2.5–3.5 million range over the period shown (2004–2010), the underlying economics reflect some significant changes. On a volume basis, catches have declined markedly. Between 2004 and 2013, the total toothfish catch declined from 4210 to 2200 t in line with the fall in the total allowable catch (TAC). Offsetting this fall in volume was a steep rise in the implied quota price per tonne, from £624/tonne in 2004 to £1748/tonne in 2013—equivalent to a compound growth rate of around 12% p.a.

The revenue and catch profile of the krill fishery differs from that of the toothfish fishery. Although the total catch of krill in SGSSI regularly exceeds 10 × the volume of that of toothfish, the license fee yield achieved on this fishery is roughly 2% of that from toothfish—standing at less than £20 per tonne. There are a number of reasons for this difference in licence fee yield. Historically, krill has been a low grade product for which demand has been low, making higher license fees unsupportable. Furthermore, roughly three quarters of the Southern Ocean krill catch come from areas within Antarctica "proper" as opposed to sovereign waters (e.g. Sub-area 48.1). This makes it available to catch without a licence fee. The krill fleet only travels north to SGSSI where licence fees must be paid only in the austral winter months when sea conditions and/or krill stocks necessitate the move. Krill licences in the SGSSI MZ currently cost in the region of £100 per day of fishing.

Table 5 Revenues of GSGSSI (£)

Revenue	2005	2006	2007	2008	2009	2010	2011	2012
Fishing licenses	2,779,161	3,762,474	3,761,048	4,118,514	4,071,000	3,179,000	2,906,000	3,680,000
Fisheries landings (toothfish)						2,917,000	2,436,000	3,043,000
Fisheries landings (icefish)						155,000	179,000	217,000
Fisheries landings (krill)						55,000	291,000	420,000
Fisheries landings (crab)						52,000		
Sub-charter of vessels	305,455			332,000	59,000	5000	9000	163,000
Landing fees	218,278	435,220	526,118	954,919	846,000	687,000	644,000	697,000
Sale of stamps	140,414	73,761	109,879	130,786	162,000	152,000	189,000	201,000
KEP post office non-philatelic revenue							22,000	13,000
Recovery staff benefits/costs							1000	
Sale of water						2000		1000
Investment income	135,257	130,273	158,352	103,857	6000	4000	8000	49,000
Miscellaneous revenue						2000	618,000	1000
Court fees and fines		107,871		2000	0	25,000		
Customs/harbour dues	75,195	63,787	94,314	203,624	95,000	68,000	98,000	84,000
Media/film fees						7000	20,000	

Continued

Table 5 Revenues of GSGSSI (£)—cont'd

Revenue	2005	2006	2007	2008	2009	2010	2011	2012
Grants received	51,067	106,193	29,277	25,594	5000	37,000	62,000	20,000
Income tax	32,722	37,063	31,275	37,856	44,000	36,000	35,000	35,000
Other	28,980	69,990	2003	17,036	61,000			
Transhipment fees	15,600	6500	14,300	32,500	3000	1000	16,000	17,000
Expedition applications	3447	476	3000	3500	2000	3000	4000	6000
Sale of publications	3038	7241	7082	1593	2000			
Seignorage on coins	1697	46,196	10,586	10,576	9000	4000	6000	9000
OTEP revenue							42,000	90,000
Darwin house								72,000
Heritage fund revenue						1000		150,000
Norwegian heritage funding								101,000
Sponsorship; Ph.D. student						8000	24,000	30,000
Accommodation fees							15,000	15,000
Donations								1000
Total	3,790,311	4,847,045	4,747,234	5,974,355	5,365,000	4,221,000	4,719,000	5,435,000

Source: GSGSSI Accounts.

Table 6 Expenditures of GSGSSI (£)

	2006	2007	2008	2009	2010	2011	2012
Salaries	179,727	176,342	263,367	335,000	355,000	383,000	416,000
Administrative costs	90,690	74,930	76,566				
Passages				51,000	55,000	45,000	66,000
Telecommunications				5000	6000	6000	4000
Maintenance (buildings and equipment)				9000	3000	1000	4000
Incidental expenses				1000	3000	8000	11,000
Exchange rates						9000	−1000
Stationary and printing					1000	1000	1000
Insurance				26,000	27,000	26,000	27,000
Vehicle operational costs						4000	1000
Office administration				17,000	5000	2000	8000
Mail service and stamps	63,262	62,899	88,977	75,000	121,000	98,000	89,000
Overseas agency commission				16,000	18,000	20,000	21,000
Official entertainment				3000	1000	1000	3000
Auditors fees and charges				6000	5000	5000	6000
Bank charges				2000	1000	1000	1000

Continued

Table 6 Expenditures of GSGSSI (£)—cont'd

	2006	2007	2008	2009	2010	2011	2012
Bad debt expense				43,000	2000	5000	−3000
Profit/loss on sale of fixed assets				6000	5000	−10,000	8000
Pensions				5000	5000	5000	5000
Contribution to FIG administration				40,000	40,000	40,000	40,000
Medical services	133,202	133,721	171,009	139,000	142,000	145,000	148,000
Fisheries management	3,221,051	2,826,974	2,905,681				
Fishing license administration				9000	11,000	7000	9000
Fisheries research and protection				2,525,000	197,000		
Fisheries patrol costs					2,268,000	2,596,000	2,814,000
Fisheries research					189,000	200,000	80,000
Catch verification					18,000	9000	9000
Judicial review						8000	85,000
Observer fees				439,000	1000		
Toothfish observer fees					263,000	120,000	209,000
Icefish observer fees					28,000	8000	24,000
Krill observer fees					13,000		
Crab observer fees					15,000		

Project Atlantis				20,000	37,000	26,000	28,000
Stock consumption				−132,000	104,000	23,000	11,000
Fuel write-off							56,000
Provision for obsolete stock						72,000	−1000
Major incident and ancillary equipment						39,000	3000
Publications	22,030	11,828	21,704	22,000	15,000	2000	20,000
OTEPI					6000	2000	
OTEPI (rats)						5000	38,000
Darwin house							11,000
Groundfish survey				18,000	9000	88,000	2000
Environmental programme	132,766	174,218	148,296	71,000	95,000	50,000	42,000
Data management							11,000
Invasive species							19,000
Habitat restoration/monitoring							8000
KEP running costs	500,075	501,422	509,372	550,000	550,000	500,000	500,000
Museum	25,642	80,722	197,519	34,000	49,000	52,000	28,000
Domestic equipment				1000			
Specialist consultancy			3500	4000	5000	9000	1000

Continued

Table 6 Expenditures of GSGSSI (£)—cont'd

	2006	2007	2008	2009	2010	2011	2012
Other expenditure	109,567	108,277	79,550				
Depreciation costs			221,175	220,000	214,000	191,000	257,000
Heritage programme	28,121		950				
Heritage fund							91,000
Norwegian heritage fund							51,000
Expedition consultancy				2000	2000	1000	5000
MSC consultancy				31,000	5000	7000	8000
Funding Ph.D. student					6000	21,000	27,000
Total	4,506,133	4,151,333	4,687,666	4,593,000	4,895,000	4,831,000	5,301,000

Source: GSGSSI Accounts.

Table 7 The GSGSSI License Fees by Fishery, for Toothfish, Krill and Icefish Fisheries (£)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Toothfish	2,625,480	2,217,253	3,224,245	3,200,485	3,561,281	3,487,111	2,917,000	2,436,000	3,043,000	3,862,000
Krill	255,697	324,552	82,674	220,921	364,744	142,222	55,000	291,000	420,000	611,000
Icefish	115,219	367,554	218,560	296,364	226,766	369,314	155,000	179,000	217,000	269,000
Total	2,996,396	2,909,359	3,525,479	3,717,770	4,152,791	3,998,647	3,127,000	2,906,000	3,680,000	4,742,000

Source: UK Foreign and Commonwealth Office.

Like krill, the icefish fishery generates a relatively low licence fee yield in comparison to toothfish—which is highly variable, but of the order of £200/tonne—and with a similar inconsistency in total revenues. In the case of icefish, volatility in revenues reflects significant variability in the allowable catch. In the case of both icefish and krill, licences are issued at short notice (within 1 month of commencing fishing) and for short periods of activity.

6.4.3.2 Landing Charges

Landing charges are the fees levied by GSGSSI on yachts and individual visitors visiting the Islands. Their three-fold increase over the period 2005–2012 reflects a combination of an increase in landing charges and the growth in visitor numbers (see Figure 97). In 2014, the tariff for a "standard" visit was £120, an increase from £110 in 2013. As is true of fishery revenues, landing charges have started to recover from their 2011 trough. The overall tourism revenue has been meaningfully augmented in recent years by other sources of tourism income—most notably from the sale of stamps.

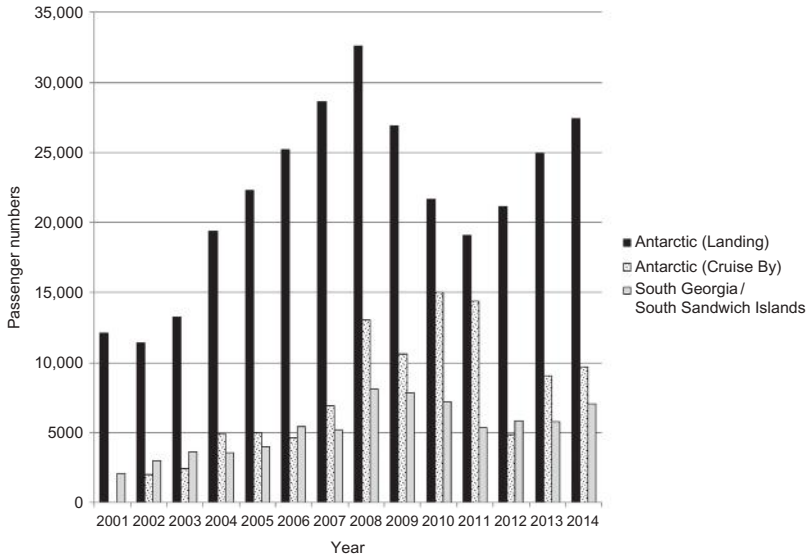

Figure 97 Trend in passenger numbers in the Antarctic and in SGSSI. Source: *IAATO (2014)*.

6.4.3.3 Other Sources of Revenues

The dependency of GSGSSI revenues on fishing license fees, particularly toothfish licence fees, gave rise to the 2010 strategic objective to find alternative sources of income (especially in the face of a declining Total Allowable Catch for toothfish). Although not explicitly stated, it has been tacitly assumed that the growing krill market would bring in extra income—as indeed it has done. Additional short- to medium-term funds have been raised for heritage-related projects from the South Georgia Heritage Trust (SGHT) and the Norwegian Government. This is part of an ongoing drive by GSGSSI to find external sources of funding for discretionary projects. The recent refurbishment of Discovery House which now has a residential capacity of about 10 people is also expected to raise funds from visiting scientists. The most significant alternative source of income in recent years, however, has been unspecified or undescribed revenue items. In 2011, a single revenue item of £618,000 appears in the accounts, making a major impact upon the total revenue. This was apparently money transferred from British Antarctic Survey (BAS) to GSGSSI from the jointly funded FCO/GSGSSI KEP (King Edward Point) project.

6.4.4 Expenditures

6.4.4.1 Fisheries Management Expenditures

The greatest expense for GSGSSI is fisheries management. In 2012, fisheries-related expenditures amounted to approximately £3.2 million, roughly 58% of total GSGSSI expenditure and consumed in the region of 75% of fisheries licence revenues. Fisheries management is comprised of a number of functions, the most costly of which are operating the fisheries patrol vessel (FPV), observer fees and the fisheries management contract with MRAG Ltd. Of these, the FPV, the *Pharos IX*, is by far the largest component, accounting for in excess of £2.25 million of total expenditures. The *Pharos IX* is leased by GSGSSI over a 20-year period (originating in 2006) from Byron Marine and operates 300 days per year.

Observer fees made up another £260,000 of the total fisheries management costs in 2012. This cost is directly related to fishing activity in the waters of the SGSSIMZ, as more observers are required the greater the number of fishing vessels that are active in the area. The majority of the remainder of fisheries management costs are accounted for by fisheries research and protection. Included in these costs is a contract with CEFAS which replaced MRAG Ltd. in spring 2012 to provide advice to GSGSSI on fisheries licensing and management and on various science and stock assessment programmes.

The fisheries management budget is not only augmented by the activities of the GSGSSI Fisheries Officer, but also by scientific research undertaken in a range of programmes outside of that specifically ear-marked for fisheries. In 2010 it was estimated by the FCO that a sum in the region of £100,000 of the general budget was directed towards fisheries research—roughly equivalent to 1.5 persons and mostly concentrated in the KEP location.

In addition, there is a relatively small but important contribution made by industry towards the GSGSSI Science Programme via industry participation in the juvenile toothfish survey and through leading the icefish certification programme. It is not possible to estimate with any great precision the additional expenditure on fisheries research—if for no other reason than the fact that, given the marine bias of SGSSI's ecosystems, the vast majority of science undertaken on the territory will have some bearing on the fisheries. An estimate of the value of the incremental additional spending on fisheries research and management might be in the region of £200–300,000 per annum (approximately 7–10% of the reported total). However, it should be noted that industrial contributions to research within Sub-areas 48.2, 48.3 and 48.4 may increase considerably with the construction of a new Norwegian krill-fishing vessel capable of undertaken a wide range of scientific research (Godø et al., 2014).

The second largest expense is the King Edward Point running costs. These costs were maintained at an expense to GSGSSI of roughly £500,000 per annum for 2005–2012. This figure was supplemented by an equivalent amount paid by the FCO bringing the total up to about £1 million a year. Operation of KEP is outsourced to the BAS, which mans and runs the base. The costs of running the base include not only staff costs but also the cost of running the boats and of general provisioning. One of the most important research projects managed by BAS is the regular predator survey, which is undertaken on a biennial basis.

6.4.4.2 Additional Expenditures

The final major category of cash expenditures for GSGSSI is on government salaries. The KEP doctor is accounted for separately. The Environment Programme, which is no longer accounted for as a single item, has included various projects over time such as rat eradication, invasive plant work and various monitoring programmes.

A number of important projects are being undertaken by, or in conjunction with SGHT. SGHT was established in 2005 to raise funds to support two primary purposes. The first one is to support efforts to conserve and

protect the wildlife of SGSSI. The second purpose of SGHT is to preserve the historical heritage of South Georgia, focusing on its history as a former whaling base and its connections with a number of famous polar expeditions. The charity is registered in Scotland with a branch in Norway and representation in the United States. The main project that SGHT has been funding and managing over the past few years is the rat eradication programme.

6.4.4.3 Special Expenditures

Table 8 shows the GSGSSI special expenditures from 2005 to 2012. No itemised breakdown is available for the years 2005–2007 when the outgoing expenditure were significant, but they include expenditure on a hydroelectric scheme, habitat restoration and asbestos removal and other restoration projects at Grytviken. The main component of the special expenditure in 2012 was habitat remediation.

6.5 Looking Ahead

6.5.1 The Strategic Plan for South Georgia and the South Sandwich Islands

GSGSSI is currently developing its next Strategic Review. The starting point for this project is very different to that of 2010 when the previous plan (South Georgia and South Sandwich Islands Strategy 2010–2015, GSGSSI, 2010a) was produced. In 2010, revenue growth and diversification were key priorities for GSGSSI: foremost among the objectives in the plan were to "investigate ways of increasing and diversifying income streams" and "to generate a surplus of £500,000 in each of the next 5 years".

This financial emphasis of the 2010 strategy document was developed in the context of concerns over the future of toothfish license revenue (because of a falling toothfish TAC), and a global economic downturn that resulted in SGSSI tourist numbers to collapse from 8089 at their peak in 2008 to a low of 5354 in 2011. The past few years have seen a hefty rise in the toothfish license fee along with a pronounced bounce back in tourist numbers which now approach past peaks allowing revenues to grow. At the same time as revenues have risen, there has been a concomitant end to a number of major

Table 8 GSGSSI Special Expenditures from 2005 to 2012 (£)

	2005	2006	2007	2008	2009	2010	2011	2012
Special expenditures	852,513	638,637	1,640,555	15,339	17,000	4000	13	227

Source: GSGSSI Accounts.

expenditures—specifically the rat and reindeer eradication programmes which are near completion as well as the refurbishment of Discovery House.

The forthcoming strategic plan is expected to reflect a period of consolidation for GSGSSI. The upturn in tourism and fisheries license fees has relieved the short to medium concerns regarding revenues. In addition, a number of expensive projects (specifically the rodent and reindeer eradication projects) are nearing their end.

A major focus of GSGSSI over at least the next 5-year period will be tourism management. Tourism management has a number of dimensions which primarily revolve around planning and managing all visits to ensure visitor safety and environmental protection. There are a number of factors driving this focus on visitor management. Most obviously, tourism numbers are growing and are forecast to continue to do so. Conservative visitor forecasts for the Antarctic area for 2060 are 120,000. If SGSSI continues to receive about a quarter of the total number of visitors to the Antarctic area, this produces an estimate of about 30,000 visitors to SGSSI for the year 2060. Any strategic plan going forward will have to take account of this greatly enlarged numbers. The death of a visitor undertaking the Shackleton Walk in South Georgia in 2012 has also resulted in an increased emphasis on tourism management for safety reasons. An additional and slightly unexpected driver behind the emphasis on visitor management is the forecast increase in birds to the SGSSI following the rat extermination programme. The removal of the rats is expected to greatly benefit a range of bird species, especially ground nesting ones. Limiting visitor impacts upon the increased numbers of birds is a key management priority.

6.5.2 The Krill Fishery

Krill represents the largest catch by volume but the smallest catch by value of all of the SGSSI fisheries. As Table 9 shows, the total catch and associated licence fees were erratic over the reported period (2004–2013). The average total catch and licences fees (2004–2013) were 32,027 t and £276,781, respectively. Fees from the fishery have averaged 7.4% of total annual SGSSI fishery licence receipts and 77% of the combined fishery catch.

The potential for growth in the Southern Ocean krill fishery generates considerable excitement among some market observers, but as Nicol and Foster (2003) pointed out more than a decade ago, the krill market has hitherto "failed to reach anticipated levels". For current purposes, the question is the extent to which this krill market potential may be fulfilled in the coming years and the implications of this for the SGSSI krill industry.

Table 9 Summary of the SGSSI Krill Fishery, 2004–2013

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Krill catch	32,486	48,460	14,113	18,777	54,277	0	8781	54,832	56,410	32,132
Total license fee (£)	255,697	324,552	82,674	220,921	364,744	142,222	55,000	291,000	420,000	611,000
License fee yield (£)	7.9	6.7	5.9	11.8	6.7	n.m.	6.3	5.3	7.4	19.0

Source: UK Foreign and Commonwealth Limited.

6.5.2.1 History of the Krill Fishery

Following the collapse of the marbled rockcod fishery in the 1970s (see Section 5), krill has become the largest Southern Ocean fishery by volume, if not by monetary value (Shotton, 2005). For over a decade, the krill catch stood at about 500,000 t year^{-1} before falling dramatically to about 100,000 t year^{-1} in the early 1990s. This decline was attributed largely to the collapse of the Soviet Union which heavily subsidised the fishery (Kock, 1994), as well as to the discovery of high levels of fluoride in the shell which raised concerns related to human consumption and health (Croxall and Nicol, 2004). Following the break-up of the Soviet Union, a number of new entrants moved into the market including Poland, Ukraine and Korea. Japan went on to dominate catches until the appearance of Norway, which is now the lead player in the fishery (Kawaguchi and Nicol, 2007; see Section 4). For many of the participants in the fishery, the initial move into the Antarctic krill market was not driven by certainty of end-market demand; rather, it simply offered an opportunity for some distant-water fleets displaced by declining fisheries elsewhere globally and the extension of exclusive economic zones (EEZs) to utilise their capacity (Nicol, 1995; D. Agnew, MSC, personal communication).

Figure 98 illustrates the key Antarctic fishing grounds as designated by CCAMLR. The SGSSIMZ is located between longitudes of 20°W and 50°W, in the upper left of this map. Sub-area 48.3 broadly corresponds to that part of the EEZ in the vicinity of South Georgia. Sub-area 48.4 includes the South Sandwich Islands.

Table 10 and Figure 99 summarise the reported krill catch by sub-area. Many of the krill vessels fishing around the Southern Ocean follow a seasonal pattern, and much of the krill fishing is done adjacent to the Antarctic ice shelf where the boats can find krill in the largest numbers. Historically, the fleet was most active in SGSSI waters in the winter when the shelf was at its northernmost extent, before moving further south with the summer months (Everson and Goss, 1991; Jones and Ramm, 2004). The retreat of the ice shelf in the main fishing areas has meant that the fishery is active throughout the year as accessibility has increased (R. Werner, Pew Charitable Trusts, personal communication; Kawaguchi et al., 2009; Nicol et al., 2011). Although there is some evidence that individual nations have their own preferences in terms of fishing areas (Kawaguchi and Nicol, 2007), the fleet is generally seen as being very mobile throughout the whole area (R. Werner, Pew Charitable Trusts, personal communication). This mobility explains why the overall krill catch across the region has been more stable than has the activity within any given designated area.

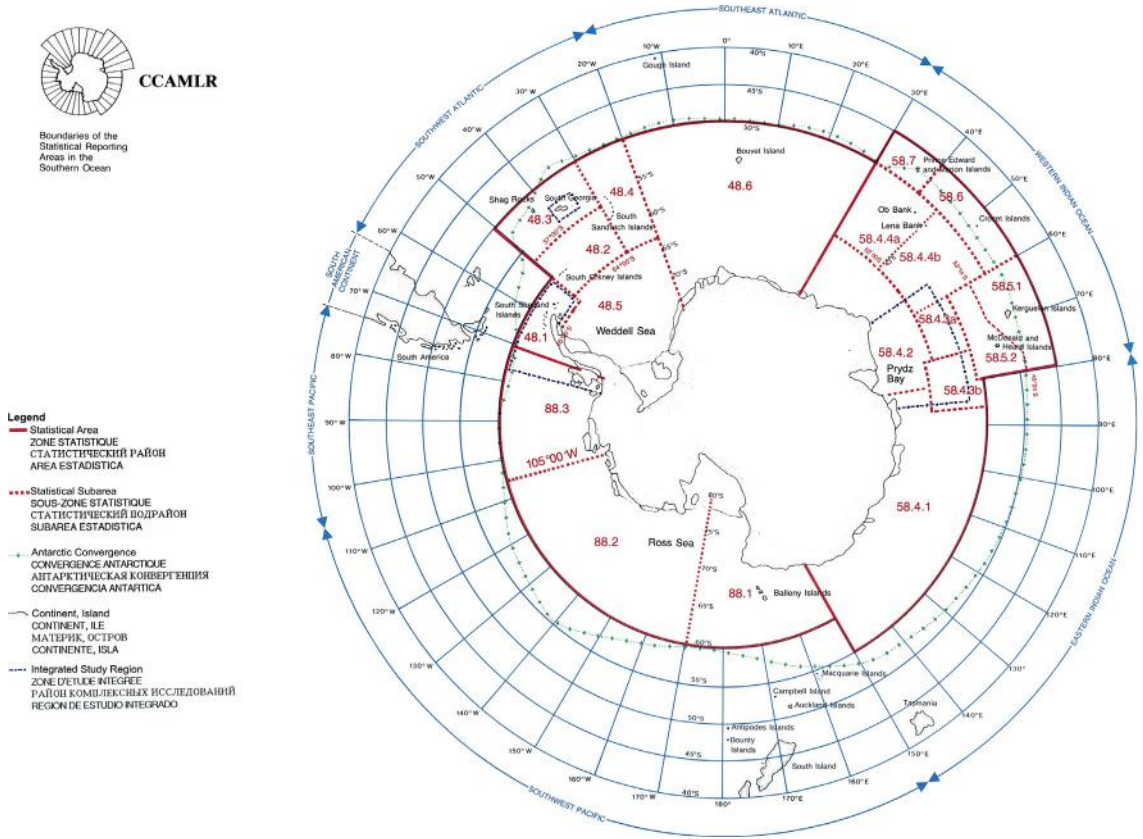

Figure 98 The Southern Ocean fishing area (CCAMLR).

Table 10 CCAMLR Krill Catch by Designated Area (tonne) (CCAMLR, 2014a,b)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
48.1	13,882	7095	88,834	18,419	2884	33,970	154,613	9215	75,630	153,831
48.2	46,456	73,494	3102	65,591	93,384	91,855	49,999	115,995	29,040	31,306
48.3	57,829	48,437	14,613	20,576	60,253	1	8712	55,782	56,415	32,221
	118,167	129,026	106,549	104,586	156,521	125,826	213,324	180,992	161,085	217,358

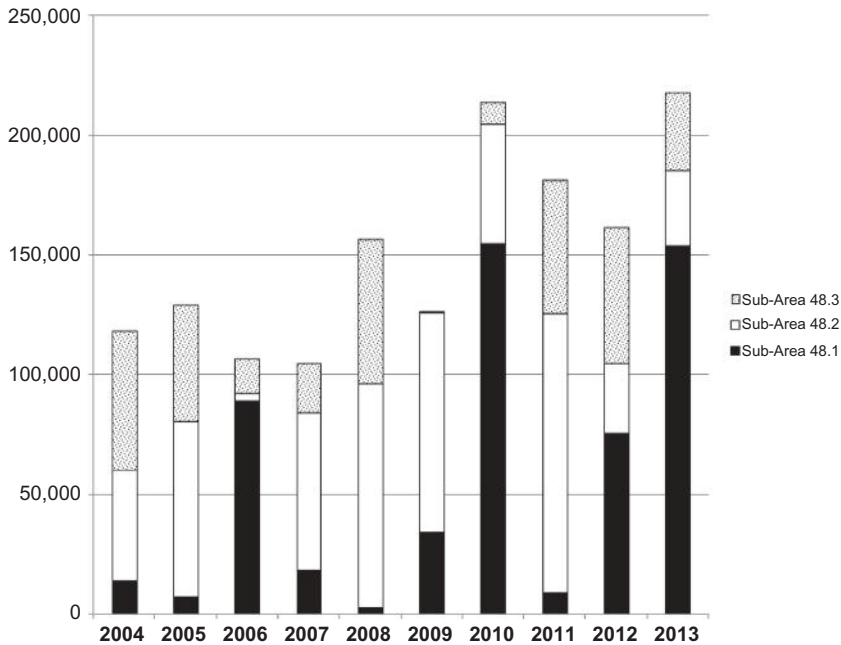

Figure 99 Krill, *Euphausia superba*, catches in Sub-areas 48.1, 48.2 and 48.3 (CCAMLR).

6.5.2.2 The Krill Fishery Today

Total krill catch in 2013 was around 217,000 t (CCAMLR, 2014a,b). Table 11 provides details of krill catch by fleet nationality from 2004 to 2013. The country of origin of the fleet has changed markedly in recent years. Norway is now the major fleet in this fishery accounting for over half the total catch and with Japan no longer fishing. After Norway, the next largest fleets are Korea and China, respectively.

A major study of the krill fisheries of world (Nicol, 1997) provided a comprehensive list of krill-based products. In volume terms, the main categories include food for human consumption, bait for sport fishing, aquarium food and aquaculture feed. Industry experts are of the understanding that each participating country in the fishery has a small, targeted, domestic market for both animal and human products (D. Agnew, MSC, personal communication).

Although it is well known that the majority of the krill catch is used for aquaculture (e.g. Nicol, 1997), the extent to which krill is used in the animal versus the human market is not very well understood. In a comment against a U.S. firm's decision not to sell krill products in 2010, a Director of Azantis,

Table 11 CCAMLR Reported Catch for the Antarctic Krill Fleet from 2004 to 2013 (tonne) (CCAMLR, 2014a,b).

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Chile					2			2436	10,662	7259
China							1956	16,020	4265	31,944
Great Britain	16	0	2		0	0		<1		
Japan	33,583	22,793	32,711	24,301	38,803	21,020	29,919	26,390	16,258	
Korea	24,522	28,910	43,031	33,088	38,033	42,827	45,648	30,642	27,100	43,861
Norway			9228	39,783	63,293	44,174	119,401	102,460	102,800	129,647
New Zealand					0					
Poland	8967	4335	6413	7414	8035	8149	6995	3044		
Russia	775				222	9654	8065			
Ukraine	12,261	22,440	15,206		8133					4646
USA	8550	2159								
Vanuatu	29,491	48,389								
Other	2		48			2	1340			
Total	118,167	129,026	106,639	104,586	156,521	125,826	213,324	180,992	161,085	217,357

a Colorado-based biotechnology company and krill processor, stated that "…about 99% of the krill catch is used in animal feed and only one per cent for human nutrition…" (NutraIngredients, 2010a). Although it has not been possible to substantiate this statement for the purposes of this report, it provides a clear indication from a market insider about the main focus of the fishery. Of note, the krill supplied to the aquaculture industry is generally provided as a high-value additive to regular feeds, rather than as the primary ingredient (Nicol et al., 2011).

With the total biomass currently estimated to be in the region of 133 million tonnes (Atkinson et al., 2009) and a total potential allowable catch recently standing at 8.6 million tonnes (Nicol et al., 2011), the krill fishery's failure to develop over the past 30 years is, superficially at least, extraordinary. The reasons behind this "latency" appear fairly straightforward, although it has been only occasionally documented. As a small, commercially insignificant industry largely under private ownership, there is very little published information about the structure and dynamics of the krill industry. This lack of economic data and information on the krill industry has been noted regularly by commentators (e.g. Croxall and Nicol, 2004). Essentially, fishing in Antarctica is expensive (Nicol et al., 2011); it is a great distance from the majority of global markets and the fishing conditions require highly specialised vessels.

Consistency of supply has also been an issue with the krill fleet having to travel great distances in search of commercially sufficient aggregations (sometimes with minimal success; J. Pearce, MRAG Ltd., personal communication), adding to the catch cost. In addition, krill has also been expensive to process. There have been a number of difficulties associated with processing krill (Nicol, 1995). Thin shells have meant that krill could only be caught and handled in relatively small numbers to avoid spoiling through crushing—a characteristic exacerbated by their propensity to decompose rapidly even at very low temperatures (Nicol et al., 2011). Such is the rate of decomposition that after 8 h on the deck of a boat in the Southern Ocean, krill are unfit for use in animal feed—let alone human feed (Budzinski et al., 1985). Possibly the most important factor implicated in its high processing cost, however, is the need to remove the high level of fluoride from the shell of the dead animal (Budzinski et al., 1985), which is a pre-requisite for human consumption (Nicol, 1995).

Budzinski et al. (1985) estimated that as far back as 1984, krill meal cost in the region of $2000 a tonne to produce—at a time when fishmeal cost in the region of $400 a tonne (FAO, 1986). Meanwhile, the majority of the

ultimate customers for krill-based products were operating in highly competitive markets such as a feedstock for aquaculture, animal feed and low-grade human food. This has meant that where competing substitutes for krill have been cheaper, they have been readily adopted, resulting in a weakening of demand. In short, the market has been unattractive to both fishers and end-customers for a considerable period of time.

6.5.2.3 The Outlook for the Krill Fishery

Looking forward, four factors have emerged that might initiate a renewed period of growth in the market for krill. Three of these factors are shaping demand for the product, and the fourth affects supply. The issue apparently generating the most excitement about the prospects for the krill industry is the growing demand for krill oil as a nutritional ingredient. The use of krill oil in hybrid nutritional/pharmaceutical products, sometimes referred to as nutraceuticals, is recognised as an important driver of investment in the krill industry going forward (Nicol et al., 2011). Krill's characteristics as an important source of Omega 3 phospholipids (Tandy et al., 2009) provide a potential niche in this market. Omega 3 fatty acids have become widely marketed as food supplements with various claims as to their benefits for cardiovascular, brain and joint health (see for example, the Global Organisation for EPA and DHA Omega-3, the international trade body for Omega-3 products). According to the European market leader in krill oil, AkerBiomarine, its Omega 3 product Superba Krill is "more efficiently utilized by the (human) body" than "Omega 3 derived from fish" (e.g. AkerBiomarine, 2013). The validity of these claims remains somewhat contentious, with AkerBiomarine's competitors regularly disputing them. Global spending on Omega-3 products is forecast to grow from $25.4 bn in 2011 to $34.7 bn in 2016 (Packaged Facts, 2013). The Omega-3 EPA-DHA oil ingredients market represented roughly $2 bn of this in 2011 and is expected to grow at almost double the rate of the wider ingredients market over the same period. Although krill oil represents only a fraction of the total market (roughly $20 mn in 2008; NutraIngredients, 2010b), it is widely believed that demand for krill oil is by far the highest growth market segment (e.g. NutraIngredients, 2012). We note that the market data supporting these estimates on the size and prospects for the nutraceuticals industry is almost all proprietary information owned by a number of international market research companies. The common theme running through all of the press reports over the past 2–3 years has been the above market growth of krill oil products (e.g. Natural Products Insider, 2012).

The second demand-side factor shaping the prospects for the krill industry is the continued growth of aquaculture and the strength of fish feed prices. Aquaculture has been the fastest growing food production sector in many countries of the world for the last two decades, while capture fisheries have experienced a declining trend (FAO, 2012). Wild-caught supplies of fish meal and fish oil (Figure 100) have been in the region of 5–6 million and 1 million t year^{-1}, respectively (Bostock et al., 2010). Although the industry no longer appears to be experiencing the very high growth levels it once did, with total aquaculture output expected to reach over half of global food fish consumption by 2021 (FAO, 2012).

Krill has long been ear-marked as an aquaculture feed stock of considerable potential but up until now its presence has barely registered in the industry. Assuming that half of 2012s Southern Ocean krill catch (a total of just over 160,000 t) was converted into meal, and that the vast majority of this was channelled into aquaculture, krill constituted a miniscule 0.015% of the total (based upon the total global fishmeal production of 4775 million tonnes in 2009; Chamberlain, 2011).

Looking forward, there are a number of changes taking place that look set to promote krill's potential in this market. In the first instance, according to Bostock et al. (2010), the spoilage and high fluoride content issues that had once constrained krill's use in aquaculture have now been solved leading the way to what the authors anticipate to be large-scale commercial exploitation. Second, traditional fishmeal markets have started to demonstrate meaningful price increases over the last decade (see Figure 100) and these have the potential to increase the relative attractiveness of krill products as a substitute. Although it is not possible to test this theory in the absence of an open-market price for krill meal, the fact that the traditional fishmeal fisheries are now fully exploited (e.g. Shepherd et al., 2005), allied with the continued growth in their primary feedstock end-markets (FAO, 2014) seems to create strong tailwinds for the development of this market. Others (e.g. Bostock et al., 2010) believe, however, that demand from the human food additive market will ultimately supersede the fishmeal market since achieved prices will be higher for the former.

Looming large behind any continued growth in aquaculture, and indeed behind the prospects for the krill market as a whole, is Chinese demand. China is the largest producer and largest consumer of farmed aquatic products—a position that is expected to continue (Hall et al., 2011). China supplies about two thirds of global aquaculture production and consumes approximately half (World Bank, 2013). Chinese economic output still

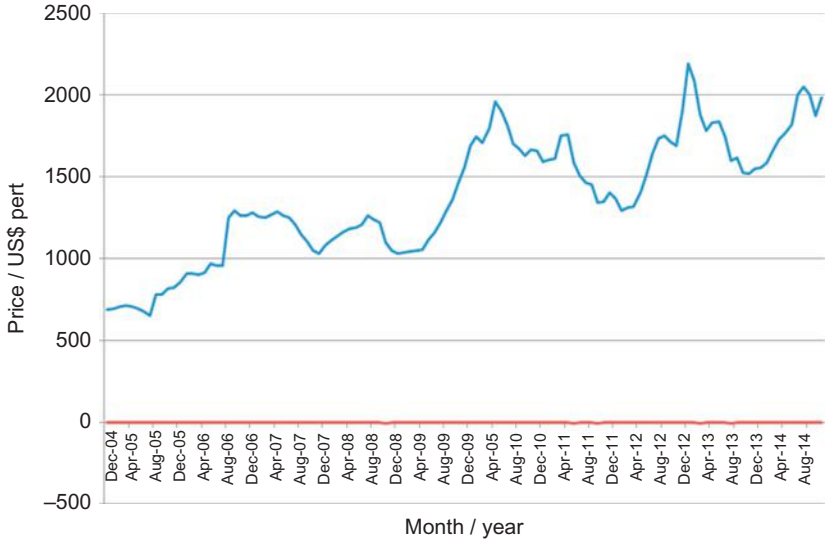

Figure 100 Price of fish meal (U.S. $/t) (indexmundi.com).

remains high, with forecasts for 2015 and 2016 running 6.8% per annum and 6.3% per annum, respectively compared to global output of approximately 3.5% (IMF, 2015), and it does not seem unreasonable to expect that further growth in the Chinese economy will provide support for continued supportive conditions for the aquaculture market.

In this context, it is interesting to note the Chinese presence in the Southern Ocean krill fishery. Having only recently entered the fishery with two notifications in 2010/2011, by 2012/2013 there were four boats fishing (taking 15% of the total krill catch), which made China the third largest player. The Chinese krill initiative is apparently part of a 5-year project that was to begin with an exploratory fishery, and then move to a commercial operation after 2 years assuming the pilot scheme validates assumptions. The scientific project, of which the fishery is a part, is intended to develop krill products for sale in China and for export. The project is being led by the Director General of the Bureau of Fisheries himself (ASOC, 2010b). Not only does this project have commercial potential, but it may be perceived to contribute to food security and provide the Chinese with an economic, and therefore, political presence, in the Southern Ocean.

All global demand for krill, as a supplement, feedstock or foodstuff, must be framed against the anticipated growth in the world's population coupled with economic development in developing regions. Both factors are

creating incremental demand for food, particularly animal-based proteins and their relevant feedstock. A combination of rising income and increased world population size are expected to drive an increase in demand for food of over 70% from current levels by 2050—and there may be additional pressures on agricultural capacity related to biofuels (Bruinsma, 2009). Given the growing challenges in improving agricultural productivity resulting from stresses such as water shortages and environmental degradation (Nellemann et al., 2009), it is almost inevitable that the spotlight will eventually fall on the world's last major unexploited fishery as a key source of nutrition. Industry commentators (D. Agnew, MSC, personal communication; D. Miller, personal communication) are of the view that the demand for krill for direct human consumption will eventually supersede all other krill markets. The sheer weight of demand for krill as a human protein allied to the inherent inefficiencies of converting it into any other foodstuff will, at some point, push the market to unprecedented levels.

The final demand-led element of support for the krill market is the easing ethical environment. Although not readily quantifiable, it will almost certainly be the case that the Marine Stewardship Council's (MSC) certification of Aker Biomarine's Antarctic Krill fishery (see http://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/southern-ocean/aker-biomarine-antarctic-krill) and the reversal of the major U.S. health food company Whole Foods Market's ban on krill products in 2012 may have provided a solid ethical underpinning to end-consumer demand.

Underpinning the market on the supply side are a number of technological developments. Probably the most significant of these are developments in the fishing process itself. Krill fishing has traditionally been undertaken by large pelagic trawls, hauled regularly throughout the day and yielding up to about 100 t (Nicol et al., 2011).The continuous pumping method whereby air is injected into the cod end of the net and the contents pumped back into the ship continuously, Norwegian vessels have been using since 2007 (Nicol et al., 2011), yields significantly greater quantities of krill in one day's fishing (up to 1000 t day^{-1}; Nicol et al., 2011). Also, because the krill are brought on board alive, they are less prone to damage and are therefore available for a wider range of products (Nicol et al., 2011). Additionally, such vessels are now equipped for analysis of krill as they come on board to determine the suitability of catch for processing and storage of different commercial products. The vessels are also being used for marine research mainly supporting management of krill fisheries (Godø et al., 2014). Although the capital costs of equipping a krill vessel with continuous pump technology

are very high, market reports, by the leader AkerBiomarine, are that the improved productivity more than supports the investment.

It is not possible to rank these krill market growth drivers in terms of their likely impact on the demand for krill, but it is clear from the catch figures of recent years that the market has started to move. Although the shape of the growth trajectory cannot be predicted, the market changes and recent demand signals all point towards a krill catch that will be greatly increased from current levels. Miller (2014) suggested that the krill fishery has been firmly on track to a 5 million tonne catch per annum, and a place in the top 10 catches for wild stocks. Miller (2014) also commented on the shape of the krill industry going forward. As the market grows, it is likely to become international, supporting a Northern Hemisphere krill fishery. This globalisation will in turn attract spare mid-water capacity and in all probability an IUU fleet. In other words, the long anticipated growth in the krill market is coming into fruition, but incumbent with all the antecedent problems of any other large-scale international fishery.

6.5.3 Other Fisheries

6.5.3.1 Overview

The Government of South Georgia and the South Sandwich Islands is responsible for fisheries management in the SGSSI MZ. As Table 12 shows, toothfish makes up in the region of 90% of licence fees and typically between 10% and 20% of the catch. Icefish and krill account for sizeable tonnages but are much less valuable catches and generate considerably lower licence yields.

6.5.3.2 Toothfish

Toothfish is white and firm-fleshed and as such is in high demand as a table fish. Its largest markets are in the United States, Europe and Japan with the majority of the SGSSI catch feeding U.S. demand (J. Pearce, MRAG, personal communication). It is marketed in many western countries as "Chilean sea bass".

In 2013, the SGSSI toothfish catch was 2024 t out of a total CCAMLR take of 11,590 t (CCAMLR, 2014a,c,d) and a global catch of 19,057 t (CCAMLR, 2014a). SGSSI thus represents 17% of the CCAMLR catch and 11% of the total global catch. The contemporary fishery in SGSSI is certified by the MSC. Licenses to longline for the toothfish are issued by GSGSSI (Agnew, 2004). Licensing policy is based upon two main criteria (D. Agnew, MSC, personal communication). The first is for prospective

Table 12 Summary of the SGSSI Toothfish, Krill and Mackerel Icefish Fisheries, 2004–2013

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Licence fee (£)										
Toothfish	2,625,480	2,217,253	3,224,245	3,200,485	3,561,281	3,487,111	2,917,000	2,436,000	3,043,000	3,862,000
Krill	255,697	324,552	82,674	220,921	364,744	142,222	55,000	291,000	420,000	611,000
Icefish	115,219	367,554	218,560	296,364	226,766	369,314	155,000	179,000	217,000	269,000
Total licence fees (£)	2,996,396	2,909,359	3,525,479	3,717,770	4,152,791	3,998,647	3,127,000	2,906,000	3,680,000	4,742,000
% Toothfish	88	76	91	86	86	87	93	84	83	81
Catch (tonnes)										
Toothfish SG	4497	3034	3535	3539	3864	3382	2519	1763	1806	2094
Toothfish SSI		27	18	54	98	74	114	54	78	110
Total toothfish	4497	3061	3553	3593	3962	3456	2633	1817	1884	2204
Krill	32,486	48,460	14,113	18,777	54,277	0	8781	54,832	56,410	32,132

Icefish	2683	200	2169	4345	2491	1834	12	12	999	1370
Total catch (tonnes)	39,666	51,721	19,835	26,715	60,730	5290	11,426	56,661	59,293	35,706
% Toothfish	11	6	18	13	7	65	23	3	3	6
Price per tonne (£)										
Toothfish	584	724	907	891	899	1009	1108	1341	1615	1752
Krill	8	7	6	12	7		6	5	7	19
Icefish	43	1838	101	68	91	201	12,917	14,917	217	196

Data on the total licence fees, catch (tonnes) and price per tonne are included. The % of revenue and catch of toothfish from the total is given.
Source: UK Foreign and Commonwealth Office and CCAMLR (2014c,d,e).

licensees to demonstrate their "fitness" to hold the licences, including factors such as compliance with industry standards, etc. The second incorporates UK foreign policy considerations such as the flag state of the applicant (D. Agnew, MSC, personal communication). Until 2012, the GSGSSI was advised by MRAG as to what would be considered an appropriate licence fee (they are currently advised by CEFAS). The procedures for setting licence fees are considered politically and commercially confidential and are not in the public domain. However, both the value of the catch (based on landed price per tonne) and fuel costs are believed to be central to the process of determining licence fees. Since fuel costs have increased significantly since 2004—certainly up to 2013—continuing increases in market prices for fish have been needed to sustain the profitability of and continuing interest in licenses. Indeed, the implied toothfish licence fee yield rose from £584 t^{-1} in 2004 to £1752 t^{-1} in 2013, which is equivalent to a compound growth rate of around 13% per annum compared to an equivalent increase in total toothfish licence fees of 4.4% per annum.

The strength in capture fish prices in recent years is a well-known phenomenon (Figure 101). Demand has been strong—in large part reflecting the growing internationalisation of the market (FAO, 2010)—while on the supply side, high fuel prices have also driven end-price increases

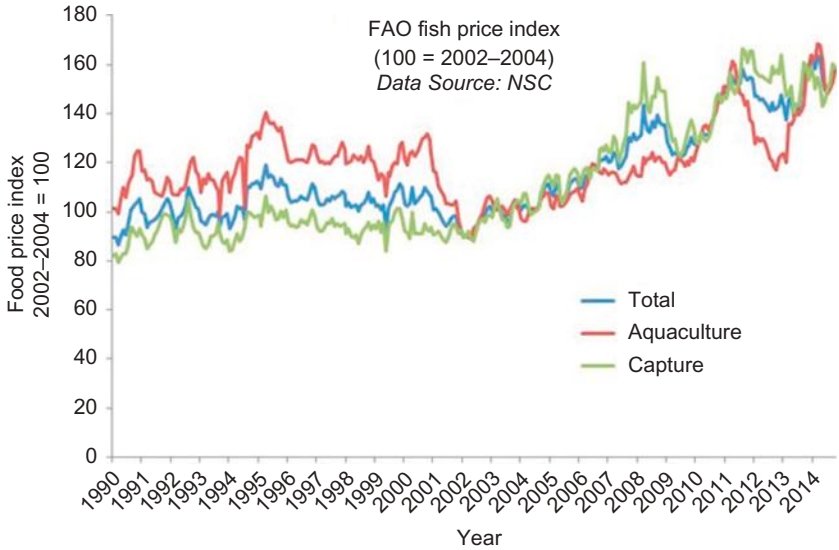

Figure 101 FAO fisheries price index (FAO Globefish, 2015).

(FAO, 2010). Although no market data in a comparable format is available for toothfish, toothfish price history is consistent with the broader trend towards escalating market prices. For example in 2001, headless, gutless and tail-off (HGT) Patagonian toothfish fillets traded at around 7.5 USD kilo^{-1} (Lack, 2001), while by 2013, prices for the same product were fetching over 25 USD kilo^{-1} (COLTO, 2014). In what is currently a low-fuel price environment, it would appear to be primarily strength in demand pushing prices to all time highs. According to the toothfish industry association (COLTO, 2014), the market has shown particular strength recently in relation to the fishery's rebuilt reputation as a sustainably fished resource. The upgrade of most of the major toothfish fisheries to "Best Choice" or "Good Alternative" by the Monterey Bay Aquarium Seafood Watch Program in 2012 is seen a particular catalyst in this development (SeafoodNews.com, 2014).

6.5.3.3 Mackerel Icefish

Mackerel icefish is a slightly fatty whitefish with markets in Russia and the Far East (SeafoodSource, 2010). It was once the most abundant fish found in near shore waters in the Southern Ocean (MSC, 2011), with catches in the early 1980s reaching nearly 200,000 t (Section 5). The fishery suffered a similar fate to that of many others in the region having attracted the attention of the Russian fleet following the collapse of the marble rock cod stocks (Constable et al., 2000; see above). There are currently two Southern Ocean fisheries for icefish. One of these is at South Georgia and the other is at the Heard and McDonald Islands, with occasional strong year classes at Kergeulen Island (MSC, 2011). The total CCAMLR catch in 2013 was 2014 t with the majority coming from South Georgia (CCAMLR, 2014e,f). The South Georgia mackerel icefish stock is highly variable, fluctuating not necessarily on the back of over-exploitation, but as a result of highly variable recruitment (Agnew, 2004). Table 12 shows this variability, along with its relatively low licence take. The fishery offers regional fleets a secondary opportunity to fish during off-season periods from their main target catch (J. Pearce MRAG, personal communication; Skins, 2006).

Although the relatively recent MSC certification of both the South Georgia and Heard and McDonald Islands icefish fisheries may well produce some impetus to the market, the fishery is expected to remain small, constrained by its low total allowable catch, fluctuating output and limited end-market demand.

6.5.4 Tourism in the Antarctic and South Sandwich Islands

6.5.4.1 Overview

During the course of the 2014 austral summer season (November 2013 to March 2014), the SGSSI were visited by 7024 tourists. Nearly all of these tourists visited on a total of 55 small- to medium-sized cruise ships (with capacities of between 30 and 500 passengers). The remainder arrived on 15 yachts making 18 visits. Virtually all of the visits were to South Georgia. Visits to the South Sandwich Islands are rare, with perhaps one cruise visit per year. Land is reached by inflatable boats launched from the mother ship. In the 2012/2013 season, 28 sites were visited on a total of 285 occasions. Other activities undertaken by the cruise ship passengers were extended walks, kayaking and Zodiac cruising. Unlike for the Antarctic Treaty region, larger cruise ships (exceeding 850 passengers and often in excess of 2000 passengers) are not allowed in SGSSI waters.

Per person fees are levied for a visit of up to 72 h to SGSSI. These per person fees, totalling roughly £700,000 in 2012, make up the bulk of the income earned by tourism. A steady 30% of tourism revenues are raised each year from harbour fees and sales of stamps, coins and other gifts and mementos (Table 13). In total, visitor income accounted for roughly one fifth of total revenues for GSGSSI in 2012. From July 2014, the levy has stood at £120 for 3 days and £20 per additional day up to a maximum of £200.

With the exception of a handful of expeditions (four in the 2013/2014 tourist season), there is currently no land-based tourism on the Islands. Tourism on the Islands is very tightly controlled by the Government of SGSSI. Visitor activities, including the timing and location of these activities, are heavily regulated for the benefit of environmental protection (including bio-security concerns) and visitor safety. Tourism is regulated with the co-operation of IAATO, the voluntary body with the self-appointed responsibility for regulating Antarctic tourism.

6.5.4.2 Trends in Antarctic Tourism

To understand the dynamics of tourism in SGSSI, it is helpful to look at tourism in Antarctica as a whole. Although SGSSI is sovereign territory, essentially a sub-Antarctic island group sitting for the most part outside of the scope of the Antarctic Treaty System, its tourist activities share many of the key characteristics and drivers of those undertaken further south. In practical terms, tourism to SGSSI should be considered a subset of Antarctic tourism, with a significant overlap in product offering (predominantly

Table 13 Visitor-Based Revenues for GSGSSI 2005–2012 (£)

	2005	2006	2007	2008	2009	2010	2011	2012
Landing charges	218,278	435,220	526,118	954,919	846,000	687,000	644,000	697,000
Customs/harbour dues	75,195	63,787	94,314	203,624	95,000	68,000	98,000	84,000
Sale of stamps	140,414	73,761	109,879	130,786	162,000	152,000	189,000	201,000
KEP post office non-philatelic revenue						4000	22,000	13,000
Sale of publications	3038	7241	7082	1593	2000			
Seignorage on coins	1697	46,196	10,586	10,576	9000	4000	6000	9000
Tourism-related total	438,622	626,205	747,979	1,301,498	1,114,000	974,000	959,000	995,000
Landing charges % total tourism	50	70	70	73	76	71	67	70
Total GSSSI revenues	3,790,311	4,847,045	4,747,234	5,974,355	5,365,000	4,225,000	4,719,000	4,792,000
Tourism contribution (%)	12	13	16	22	21	23	20	21

Source: GSGSSI Accounts.

expedition cruising), customer base and operators (S. Wellmeier, IAATO, personal communication, Snyder and Shackleton, 2001; Tracey, 2001).

Although no statistics are available (S. Wellmeier, IAATO, personal communication), it is generally recognised that tourism to SGSSI is the highest for all of the sub-Antarctic islands because of its proximity to Antarctica. The Islands offer an additional point of interest on an itinerary and are often scheduled as a stop-over en route to the Antarctic Peninsula (Snyder and Stonehouse, 2007a; Tracey, 2001), albeit creating a lengthy diversion. As a general rule, trips to SGSSI tend to be more expensive and therefore less popular (D. Liggett, SCAR, Social Sciences Action Group, personal communication) than those only visiting the Peninsula. Expert opinion seems to be of the view (D. Liggett, Scientific Committee on Antarctic Research, SCAR, Social Sciences Action Group, personal communication) that the product offering is not fundamentally different, but rather the pricing differential simply reflects the far higher costs of visiting the Islands because of their extreme remoteness. Although expedition-style cruising to Antarctica is the most popular means of visiting the area, a significant number of tourists to Antarctica visit on large ships which "cruise only" i.e. do not make any shore visits. These "cruise only" boats tend to be very large—in excess of 2000 passengers—are generally of U.S. origin and offer a relatively cheap way of visiting the Peninsula (S. Wellmeier, IAATO, personal communication).

6.5.4.3 The History of Antarctic Tourism

Tourism as an activity is one of the "peaceful purposes" permitted to take place within Antarctica under the Antarctic Treaty System (Lamers et al., 2012). Following some early expeditions in the 1950s, Antarctic tourism began in earnest in the 1960s with the first expedition cruise organised by Lindblad in 1966 (Liggett et al., 2011). Tourism is now the largest single human activity in the southern continent (Snyder and Stonehouse, 2007b). Notwithstanding the expense and difficulty of getting to the region, the attractions of Antarctica to tourists are obvious, with visitors enjoying, among other things, its remoteness, wilderness, scenic beauty and a sense of discovery (Snyder, 2007). Market studies note the importance of wildlife (Tisdell and Wilson, 2004) as crucial to the appeal of the area. The growth in the number of visitors to Antarctica has been rapid since records began in 1989, and has been driven by the secular trends in adventure and wildlife tourism (Bastmeijer and Roura, 2004). A significant rise in activity took place in the early 1990s when a number of ice-worthy vessels were made

available to the tourist market following the collapse of the Soviet Union (Liggett et al., 2011). According to IAATO, roughly 37,000 people visited Antarctic waters in the 2013/2014 season (IAATO, 2014; Table 14).

Expedition cruising, whereby visitors reach stop-off points on a large vessel (up to 500 passengers) but disembark between one and three times daily using smaller inflatable vessels, has remained the primary means of visiting the region ever since tourism began (IAATO, 2011a,b). This segment of the market is clearly very cyclical: most probably as a consequence of the weak global economic environment, the number of visitors landing on the Antarctic Continent fell by one third from 2008 to 2011, with expedition cruises bringing less than 20,000 visitors in 2010/2011 down from 32,000 in 2007/2008. There has been a steady rebound over the past few years as the global economy has recovered. Roughly 50 vessels account for the 24,000 passengers who travelled in 2013/2014.

Based on the assumption that many SGSSI visits are part of an Antarctic itinerary (see Table 14) would imply that about one-quarter of expedition cruises to the Antarctic Peninsula currently make a stopover in South Georgia. The fact that this proportion peaked during the global downturn as overall passenger numbers to the region have declined may suggest that there is a somewhat greater resilience in the higher end of the market.

Until 2011, the greatest growth in the cruise market had been seen in the "cruise-by" segment. "Cruise-by" cruises typically take place on very large vessels (sometimes in excess of 2500 passengers) which do not make any landings. Cost per passenger is typically significantly lower than for expedition cruises. In addition, Antarctica is rarely, if ever, the primary destination and these cruise-by ships normally included Antarctica as part of a larger South American cruise, sometimes originating in the Caribbean or even circumnavigating the continent (S. Wellmeier, IAATO, personal communication). In a certain sense, the cruise ship itself is the destination. Although market information suggests this trend is likely to continue in the medium to long term (Liggett et al., 2011), the cruise-by market has been heavily impacted in recent years by the ban on heavy fuel oil (HFO) in Antarctica in August 2011 (J. Haase, IAATO, personal communication).

Over the past 20 years, there has been some diversification in the tourist activities in Antarctica (Bastmeijer, 2003), including kayaking, mountain climbing, SCUBA diving, skiing, snowboarding, camping, running events, helicopter operations and use of an ROV as having taken place (IAATO, 2010). Land-based tourism has failed to develop, however,

Table 14 Tourist Numbers in the Antarctic Region, 2001–2014 (Passengers)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Antarctic (Landing)	12,109	11,429	13,263	19,369	22,297	25,167	28,622	32,637	26,921	21,622	19,065	21,131	24,892	27,374
Antarctic (Cruise-By)	0	2029	2424	4949	5027	4632	6930	13,015	10,652	15,026	14,373	4872	9070	9670
Antarctic total	12,109	13,458	15,687	24,318	27,324	29,799	35,552	45,652	37,573	36,648	33,824	26,003	33,962	37,044
SGSSI	2100	3000	3606	3600	3965	5436	5214	8089	7800	7200	5354	5860	5792	7024
SGSSI as % of Antarctic landing	17	26	27	19	18	22	18	25	29	33	28	28	23	26

Source: IAATO, 2014, GSGSSI

because of its great expense as well as the absence of land-based facilities (Liggett et al., 2011).

Over-flight air tourism (whereby tourists fly over the region with a view to getting a glimpse of the ice sheets) has never recovered from the Air New Zealand disaster in 1979 when a plane carrying 257 passengers crashed into Mount Erebus killing all on board (Liggett et al., 2011). Just over 2000 passengers were carried in over flights of Antarctica in 2005 (slightly fewer passengers than in 1993; Bertram, 2007). Recently, as air-cruise industry has developed in the region, three operators are currently involved in the air-cruise market (IAATO, 2014). In 2013–2014, 1848 passengers participated in 15 air-cruise trips in the Antarctic Peninsula area, flying to/from King George Island (either one-way or round-trip) from/to South America to embark a vessel and cruise for approximately 1 week, making landings (IAATO, 2013). This represents a dramatic increase over the 285 passengers made during the 2008–2009 season (IAATO, 2010).

6.5.4.4 Tourism in SGSSI

The history of tourism in SGSSI mirrors in large part that of tourism to Antarctica "proper"—albeit pre-dating it by the best part of half a century (the first tourist visits to South Georgia took place in 1924; Headland, 1994). SGSSI offers a spectrum of interest points for visitors. These range from spectacular scenery and close encounters with wildlife to a historical legacy of the maritime industries and polar exploration (Snyder and Stonehouse, 2007a). As already discussed, the majority of visits are made by smaller cruise ships, often focussed on the wildlife, including the large breeding colonies of various species of penguin and albatross.

Tourist numbers increased from around 2000 visitors to the SGSSI in 1998 to more than 8000 at the 2007 peak. The slump to just over 5000 visitors by 2011, followed by the recent steady recovery, in SGSSI tourism demonstrates a clear cyclicality in line with global economic fortunes. With tourists measured in the low thousands, the SGSSI remain far from being a mainstream destination and in addition to economic vicissitudes, tourism figures are very sensitive to the cruise schedules and logistics determined by specific operators. Part of the expansion in visitor numbers up to 2007 was a consequence of operators bringing larger ships to the SGSSI.

The Grytviken whaling station on South Georgia is the only whaling station with selected sites open to visitors (see Figures 63–65), and Grytviken also has a small museum (Snyder and Stonehouse, 2007a). Many of the whaling stations are judged to be hazardous to visitors owing to the presence of

asbestos. The liability of GSGSSI towards its visitors is central to the management of the Islands. It is one of the reasons why the GSGSSI banned large boats (>500 passengers) in 2006. Since then, significant progress has been made to improve the disaster response management at King Edward Point and a decision has been made to allow IAATO Cruise-only category passengers with a capacity of up to 850 pax to land passengers at Grytviken. The IAATO regulations prohibit the landing of passengers from ships with a capacity of greater than 500 pax in the Antarctic Treaty area (IAATO, 2013).

Notwithstanding the linkage between tourism in SGSSI and Antarctica, there is one distinguishing factor, namely that GSGSSI, unlike members of the Antarctic Treaty System, is able to levy taxes and other charges as a means of raising revenues (D. Liggett, Scientific Committee on Antarctic Research, SCAR, Social Sciences Action Group, personal communication). To date, the greatest source of tourism revenues has been landing fees. Revenues have also been raised from tourism spending on the Island—specifically the sale of stamps, publications and seignorage on coins. As Table 13 shows, landing fees have risen over threefold between 2005 and 2012, reflecting both the growth in tourist numbers and increased per capita charges over the period. The increased revenue generated per visitor has also been driven by good growth in other revenue generating items, particularly stamps.

6.5.4.5 Outlook for Tourism in the Region

Looking forward, industry commentators expect tourism in the region to be driven primarily by a secular increase in vacation spending with the majority of growth coming from cruises (S. Wellmeier, IAATO, personal communication). The extent to which this growth will come from expedition versus cruise-by cruising is not clear at this stage. A major survey of IAATO members undertaken before the heavy fuel oil ban was announced in April 2010 (Liggett et al., 2011) found that, in their opinion, large "cruise-by" boats were set to provide the growth in cruise tourism—or even supersede that of smaller cruise ships as the smaller boats became increasingly uneconomic in the face of relentlessly rising fuel costs. In the short term, however, the ban on HFO in Antarctic waters has had, and is likely to continue to have, an impact on visitor numbers (IAATO, 2010).

Demand for land-based expeditions is expected to grow at a rate exceeding that of cruising (Liggett et al., 2011), but the numbers involved in such activities are so small that they will fail to make a meaningful impression on

the overall market (S. Wellmeier, IAATO, personal communication). Although the air-cruise market has made impressive strides in recent years, it is not expected to replicate this progress in the immediate future, with IAATO forecasts for the 2013/2014 being in the region of 1500 passengers (IAATO, 2013).

There has been strong growth in Chinese visitors to the region and this trend is expected to continue. China represented 3% of tourists in 2010/2011 (IAATO, 2011a,b) growing to 4.4% in 2011/2012 (IAATO, 2012) and 6.8% in 2012/2013 (IAATO, 2013). IAATO believes that the vast majority of these visitors are coming via domestic tour agencies chartering ships for their domestic clientele (J. Haase, IAATO, personal communication).

Overall, IAATO anticipates that the market for tourism to Antarctica to remain "a specialized and relatively expensive niche destination offered by a limited number of experienced operators focusing on educational voyages to areas of natural and wilderness value" (IAATO, 2011a,b).

6.5.5 Oil and Minerals

There are no known mineral deposits on South Georgia and the South Sandwich Islands themselves, although the extensive hydrothermal activity in SGSSI's waters suggests there may be seabed mineral reserves of a meaningful scale (M. Collins, GSGSSI, personal communication). Methane seeps around South Georgia have been discovered in cross-shelf depressions around the island (Römer et al., 2014). Whether sufficient reserves are present for commercial exploitation or as a local energy source for fuelling activities on South Georgia is unknown. Seepage is thought to be quite weak compared to seep sites elsewhere in the world possibly meaning that methane reserves are small. Recent interest has been expressed in prospecting for manganese nodules within the SGSSI MZ (J. Rumble, FCO, personal communication). This has not been allowed by GSGSSI on the grounds of the likely environmental damage and political implications (J. Rumble, FCO, personal communication). This combination of environmental and political sensitivity seems likely to prevent any mineral exploitation in SGSSI and its EEZ for the foreseeable future.

There are no known oil reserves in SGSSI territorial waters. Oil-related accidents, whether involving tankers or drilling, can cause severe damage to marine life—as the *Exxon Valdez* catastrophe in Alaska and British Petroleum's more recent *Deepwater Horizon* blow-out in the Gulf of Mexico have demonstrated. If some of the world's largest oil companies can become

embroiled in such events, it is hard to argue that such catastrophes can be readily avoided simply through taking proper care. The risks to the SGSSI ecosystems from an oil-related accident could be disastrous given the presence of high concentrations of aquatic predators, especially seabirds, prone to high mortality from spills.

Here, we focus on the potential exploitation of Antarctica as a whole because it is difficult to isolate SGSSI as a specific "exploration and production" opportunity. We further note that, even if there are no exploitable reserves within the EEZ, the marine environment of the SGSSI would likely be profoundly affected by the development of resource-based industries in the Antarctic region.

6.5.5.1 Background

Antarctica (defined as all land and ice shelves south of the 60th parallel) has no human population and is administered by international agreement (Dalal-Clayton and Wilson, 2008). The collection of international agreements, together with the original 1959 Antarctic Treaty and the suite of Measures, Decisions and Resolutions accompanying it, provide the framework governing all activities in Antarctica. Together they are known as the Antarctic Treaty System (ATS) (Thorp, 2009). The original 12 signatories to the Treaty have been supplemented by another 16 members. These 28 countries have decision-making authority under the ATS and are known as Consultative Parties.

Under the ATS, Antarctica has been set aside as a scientific preserve where military activity is banned, sovereignty claims over the territory are frozen and no new claims are recognised (Dalal-Clayton and Wilson, 2008). The issue of how to manage the mineral resources of Antarctica was thrown into focus in the 1970s following the Organization of the Petroleum Exporting Countries (OPEC) oil embargo and the success on a deep-sea drilling exercise in the Ross Sea in 1974 (Thorp, 2009). The subsequent interest in the mineral potential of the area led the main contracting parties to seek a legal process to manage any prospective exploitation. The resulting 1988 Treaty, the Convention on the Regulation of Antarctic Mineral Resources (CRAMRA), which proposed a limited mining approach, was eventually abandoned because of a lack of consensus over the agreement to allow mineral extraction in the region (Grob, 2007). In 1991, the Consultative Partiers negotiated the Protocol to the Antarctic Treaty on Environmental Protection. This treaty, known as the Madrid Protocol, designated the Antarctic Treaty (AT) area as a "natural reserve, devoted to

peace and science". The terms of this agreement include a 50-year moratorium on all mineral exploitation (including mining and drilling in Antarctica), which may be lifted prior to the end date with the agreement of all contracting parties (Grob, 2007). After 50 years (i.e. in 2048), a proposal to lift the ban needs a simple majority of all parties (Grob, 2007).

6.5.5.2 The Mineral Potential of Antarctica

When considering the mineral resources of Antarctica, one needs to keep in mind that very little is known about their true extent (Parsons, 1987). Although this statement was made nearly a quarter of a century ago, it remains as true today as it was then. Research into the potential oil, gas and mineral resources of Antarctica is regarded as being part of the exploitation process and as such is banned in accordance the terms of the Madrid Protocol (British Antarctic Survey, 2015b). Expert opinion is of the view that certainly among the treaty members mentioned, there are no "covert operations" being undertaken in defiance of this official protocol (P. Leat, BAS, personal communication).

At the heart of understanding Antarctica's oil and mineral potential is the Gondwanaland theory (e.g. Beck, 2014; Lohmeier, 1987; Parsons, 1987). In the Gondwanaland theory, Antarctica was at the hub of the Gondwanaland super-continent that began to break up about 180 MYA to form the smaller modern continents of South America, Africa, India, Australia and Antarctica. It follows that just as there are extensive oil and mineral reserves in these other continents so there ought to be in Antarctica. Coal and iron ore are expected to be the most abundant resources, along with deposits of chromium, platinum, gold, silver, nickel and rare earth metals (Australian Antarctic Division, 2012; Parsons, 1987; U.S. Congress, Office of Technology Assessment, 1989). The Dufek Massif in the Pensacola Mountains is often recognised as being of greatest mineral interest (De Wit, 1985; U.S. Congress, Office of Technology Assessment, 1989). It is sometimes compared to the Bushveld Complex in South Africa, which is believed to hold 85% of the world's platinum. The Dufek Massif is estimated at 50,000 km^2, whereas the Bushveld Complex has an area of 67,000 km^2 (Parsons, 1987).

There has only been limited field research regarding oil and mineral reserves, and there is some disagreement over the actual extent of these reserves, although it is interesting to note that much of the debate relates to arguments over the commercial potential of reserves rather than the actual size of the deposits. It is generally, but not universally, accepted (e.g. Parsons, 1987) that there is a very meaningful probability of finding sizeable mineral

deposits on Antarctica, if for no other reason that that they exist on every other continent. In the absence of any real, supporting evidence, the continent remains what Macdonald (2012) called a "Frozen El Dorado", where the anticipation and excitement over the discovery of bountiful hidden resources is growing, but the knowledge and understanding regarding these potential resources has not increased.

6.5.6 Oil

Estimates of hydrocarbon reserves (oil and gas) in Antarctica vary widely. There has been no attempt at commercial drilling, and the only drilling that has been done has been for scientific purposes has been conducted by the Deep Sea Drilling Project (DSDP), the Ocean Drilling Project (ODP) and by specific projects in the Ross Sea (Australian Antarctic Division, 2012). The DSDP activity in the early 1970s did encounter traces of gas in the Ross Sea. No other drilling-based oil or gas shows are known from Antarctica (Australian Antarctic Division, 2012). The U.S. Energy Information Administration has estimated Antarctic oil reserves at 50 billion barrels, which is roughly the same as those of the Arctic (Tray, 2008) and is the ninth largest "country" source in the world (Central Intelligence Agency World Factbook, 2011). Other published (but infrequently referenced) estimates, put the total Antarctic oil reserves at over 200 billion barrels (Ward, 1998).

6.5.7 Exploiting Antarctic Mineral Resources: If and When?

The terms of the Madrid Protocol's international agreement concerning the extraction of Antarctic minerals require a consensus agreement to begin extraction immediately and a majority agreement to start when the Madrid Protocol expires in 2048 (Grob, 2007). How realistic is it to assume that resource exploitation will take place in Antarctica and if so over what time scale?

As discussed in Section 6.5.2.3, global demand for raw materials of all kinds tends to increase over time (Krausmann et al., 2009). Many of the factors, such as population and income growth, that are helping to drive a potential demand for krill, are similarly relevant to the global demand for oil, gas and minerals (Krausmann et al., 2009).

Notably, while oil and mineral resources are by definition finite, proven reserves are not necessarily declining. Global oil reserves have actually increased in recent years. In 1997, global oil reserves stood at 1020 billion barrels (U.S. Energy Information Administration, 2015), while a decade later they had risen to roughly 1656 billion barrels (U.S. Energy Information

Administration, 2015). Oil shale, which has global reserves conservatively estimated at just short of three trillion barrels (Dyni, 2006), is now being touted as an important new source of fossil reserves (Johnson et al., 2004). The problem is that proven reserves can only be maintained by constant new finds to replace extracted volumes. Spurred on by higher end-prices and new extraction techniques (Verrastro et al., 2010), leading producers are in a continual search for new potential sources. The great supply hope for the gas industry, for example, is fracking—a technique that is not lacking controversy with respect to its possible environmental impacts (Howarth et al., 2011). Meanwhile, the oil industry is increasingly turning its attention towards more challenging reserves, such as those expected to be founded in deep-water sites (Verrastro et al., 2010). Moreover, global prices for commodities such as gold and copper point to a significant continuing imbalance between supply and demand, even if there are other dynamics affecting these prices, such as financial activity and stock movements.

Whether the search for new reserves will ultimately result in insurmountable pressure to begin commercial exploitation of Antarctic resources remains to be seen. An important criterion will be the technical challenge involved in operating within this environment and whether mineral reserves, even if they are present, are sufficiently accessible so as to be commercially viable. The economic viability of any reserves targeted will be severely undermined by environmental factors (Beck, 2014). The fact that the continent is 98% covered with ice that extends as much as more than four kilometers deep has proved to be a material impediment to investigation (Ward, 1998), but may provide even more formidable challenges to anyone seeking to exploit reserves that might be discovered.

Most of these challenges apply similarly to minerals and hydrocarbons. These include the extreme temperatures, winds, permanent and seasonal ice cover, typical sea conditions and distance from a major population centre and key markets (Berkowitz and Swanson, 1989; Cullen, 1994). Unlike in the Arctic, where successful oil exploration currently takes place, Antarctica is seen as presenting greater challenges with more severe weather and a far larger concentration of icebergs (Ward, 1998). For oil, although the extraction technology now exists to cope with moving ice (D. Liggett, SCAR, Social Sciences Action Group, personal communication), there are still major issues around accident management. For example, ice-covered waters present significant challenges compared to more temperate waters, especially considering their remoteness, cold temperatures, seasonal darkness and presence of ice (National Research Council, 2014).

A deep-water blow-out, such as the *Deepwater Horizon* incident in the Gulf of Mexico in 2010, could have grave consequences in Antarctica. There is no infrastructure in place to support the management of such an event, and even if the necessary resources were available to manage a disaster of this type, they would be difficult to deploy in the typically extreme weather conditions of the region (Ward, 1998). Moreover, the Antarctic environment is widely recognised as being fragile and easily damaged: low temperatures mean responses to injury are slow, clean-up costs are high and damage in some instances may be irreversible (Cullen, 1994).

6.5.7.1 Political Developments

In 1960, Dr Lawrence M. Gould, the Chair of the Committee on Polar Research, National Academy of Sciences stated that he "would not give a nickel for all the resources of Antarctica" (Ward, 1998). Implied by this statement was an underlying view that technological constraints and the high cost of extraction would never make these reserves commercially viable. More than half a century later, gathering economic and political forces may be challenging this assumption. The international press and web commentary note the increased interest of China, Korea and Russia in the Antarctic Continent's mineral wealth, with even the International Institute for Environment and Development (Dalal-Clayton and Wilson, 2008) writing of the retraction of the polar ice shelf and the countdown to the exploitation of the resources that will become exposed.

The media, especially in the southern hemisphere, has for many years reported on the quiet scramble for resources in Antarctica by a number of nations and China, in particular. Widespread suspicion with respect to China's intentions was justified in the eyes of some in 2010, when the Chinese Land and Resources Minister stated on a visit to an Australian Antarctic base, that they were there because of an interest in the "potential of the resources and how to use these resources" (The Age, 2010). In 2013, the Guardian newspaper reported on a Politburo meeting, during which the Chinese president Xi Jinping emphasised the necessity of polar exploration to "take advantage of ocean and polar resources" (Guardian Online, 2013). The interest in Antarctica may be most overtly expressed by China, but reports of interest in the resources of the Continent are widespread. Countries geographically closer to the Antarctic region have also demonstrated interest. Colombia's first Antarctic expedition was conducted in 2013, and Argentina, Chile and Peru have shown interest in procuring icebreakers (Defense News, 2014). These activities may be driven by

the current push to exploit natural resources in the Arctic, which South American countries reportedly expect to be replicated in Antarctica (Defense News, 2014). However, we note that the Government of Australia has repeated its' intention to negotiate to retain the ban on mining beyond the end of the Madrid Protocol in 2048 several times in the media over recent years (e.g. Sky News, 2015).

6.5.7.2 Sensitivity to Market Prices

For any natural resource, a key gating factor for development of production, is the price that can be secured for the end product. If global shortages push up prices, resources that were once not seen as commercially viable may move closer to development. At the same time, demand for resources also demonstrates some elasticity against price, with consumers more willing to look at alternatives as prices increase. Renewable energy technologies—e.g. solar and wind—offer a different economic proposition with oil at USD 200 per barrel than compared with a lower value of USD 50 per barrel. Substitution effects thus provide some restraint against runaway commodity prices, depending on the specific resource.

Given the political framework and associated "ban" on oil, gas and mineral exploration-related research, there is an absence of commentary in the literature and elsewhere on where commodity prices would have to trade in order for commercial exploitation of Antarctica to become viable. A somewhat apocryphal figure, often talked about but no longer reported, is an oil price of USD 200 at which extraction in Antarctica becomes viable. Mills (2008) suggested that less than USD 100 a barrel is sufficient to allow a very large field (in excess of 1 billion barrels) to be viable. Mills also noted that some large economies, Japan for example, are nearer to Antarctica than they are to the oil reserves of the Middle East.

6.5.8 Implications for SGSSI

From a practical point of view, the United Kingdom must ensure compatibility between the actions it takes narrowly within SGSSI and its broader diplomatic stance in the wider Antarctic region. As a matter of future planning, the overwhelming imperative would seem to be to ensure that any development of extractive activities within the Antarctic region will not threaten the ecosystems of SGSSI. This is supported by the fact that, under the Madrid Protocol, Antarctica has been designated a "natural reserve, devoted to peace and science" with resource-related activities prohibited (Blay, 1992). Any exploitative moves that might threaten Antarctica may also be construed in

a certain sense as increasing the non-use economic value of SGSSI as a wildlife refuge and insurance policy against damage elsewhere in the Antarctic region. Issues such as these form the topic of the next section.

6.6 Non-Use Values of South Georgia and the South Sandwich Islands

6.6.1 Conceptual Framework

We have presented a socioeconomic overview of the marketable goods and services (as they currently exist or have potential for future development) of South Georgia and the South Sandwich Islands, and more broadly, of the Antarctic region. A very significant part of SGSSI's economic value might, however, be the passive, "non-use" value of its natural capital. Underpinning the premise that SGSSI's wild nature can make a contribution to its economy is its identity as a scarce resource. By limiting the exploitation of SGSSI's resources (particularly with respect to land based development), a decision has been made over the allocation of its natural capital giving an economic and not simply inherent value (Barnes, 2003). The concept of a non-use value of nature refers to a value that reflects people's stated preference for preservation as opposed to any actual use of that environment (Turner et al., 1994). According to Weisbrod (1964), one of the first to publish on the subject, many people will attach a value to parts of wild nature that they are aware of but might never visit. The key component of this value, which as a public good is not marketable, is known as the existence value (Krutilla, 1967). A closely related concept includes bequest value (Krutilla, 1967), whereby an individual may attach value to the satisfaction of bequeathing unique environmental resources to future generations. Following this line of reasoning, the question may be raised as to whether part or all of SGSS's nature has a significant existence value, and what that value might be.

The most obvious component of SGSSI's wild nature that is likely to have an existence value is its wildlife. Notwithstanding the great waves of exploitation that have swept through the Islands since the 1700s, SGSSI is still a haven for a stunning array of wildlife. South Georgia hosts one of the largest and most diverse populations of seabirds and marine mammals on Earth (Section 4). The list of species with populations of global significance on SGSSI is listed on Table 15, and includes substantial colonies of many species, some of which would have universal familiarity and affection. The Islands also have the most speciose marine ecosystem in the whole Southern Ocean, with a higher diversity of species than in the ocean around many island archipelagos around the world.

Table 15 Selection of Species of Conservation Importance at SGSSI Including the Proportion of Global Breeding Populations Occurring in the Islands

Species	Number at South Georgia; Birds = Breeding Pairs (Year of Last Census)	% Global (Breeding) Population	Number at South Sandwich Islands; Birds = Breeding Pairs (Year of Last Census)	% of Global (Breeding) Population	IUCN Status	Trend (Confidence)
King penguin	>450,000 (2002)	45	2 (1997)	<1	LC	Increase (high)
Chinstrap penguin	12,000 (1987)	<1	1,500,000 (1997)	18.75	LC	Decreasing (low)
Gentoo penguin	105,000	27	>1500	<1	NT	Increasing (low)
Macaroni penguin	~1,000,000 (2003)	16	54,128 (1997)	<1	Vu	Decreasing (high)
Black-browed albatross	75,500 (2004)	12	N/A	N/A	En	Decreasing (high)
Grey-headed albatross	47,800 (2004)	40	N/A	N/A	Vu	Decreasing (high)
Wandering albatross	1553 (2004)	12	N/A	N/A	Vu	Decreasing (high)
Light-mantled sooty albatross	5000 (1983)	20	N/A	N/A	NT	Stable (low)
White-chinned petrel	900,000 (2008)	50	N/A	N/A	Vu	Decreasing (high)
Southern giant petrel	8700 (2007)	15	1541 (1997)	3.1	LC	Increasing (high)
Northern giant petrel	17,200 (2007)	45	N/A	N/A	LC	Increasing (high)
Antarctic prion	22,000,000 (1983)	>85	N/A	N/A	LC	Unknown
Wilson's storm petrel	600,000 (1983)	5–10	5000 (1997)	<1	LC	Unknown

Continued

Table 15 Selection of Species of Conservation Importance at SGSSI Including the Proportion of Global Breeding Populations Occurring in the Islands—cont'd

Species	Number at South Georgia; Birds = Breeding Pairs (Year of Last Census)	% Global (Breeding) Population	Number at South Sandwich Islands; Birds = Breeding Pairs (Year of Last Census)	% of Global (Breeding) Population	IUCN Status	Trend (Confidence)
Black bellied storm petrel	10,000 (1983)	40	N/A	N/A	LC	Unknown
South Georgia diving petrel	2,000,000 (1983)	30	N/A	N/A	LC	Unknown
Common diving petrel	3,800,000 (1983)	50	N/A	N/A	LC	Unknown
Snowy sheathbill	2000 (1983)	20	N/A	N/A	LC	Unknown
Antarctic tern	2500 (1983)	15	7 (1997)	<1	LC	Unknown
Brown skua	2000 (1983)	10–20	N/A	N/A	LC	Unknown
Southern elephant seal	357,000	54	N/A	N/A	LC	Stable (high)
Antarctic Fur seal	>4 million	95	N/A	N/A	LC	Stable (high)

An additional aspect of SGSSI's wild nature that might have an existence value is its identity as a wilderness. The U.S. Wilderness Act (1964) defines wilderness as "… an area where the earth and its community of life are untrammelled by man, where man himself is a visitor who does not remain" (McCloskey, 1965). Sloan (2002) presented widely varying interpretations of the meaning of wilderness when applied to the sea. These incorporate concepts ranging from refugia to multiple use reserve, but all seem to encompass the concept of minimal extraction. Taken at face value, these definitions of wilderness do not appear to apply to SGSSI, a group of islands with a surface area of less than 4000 km^2 and with a clear human imprint including a number of invasive species (see Section 4 and 5), several industrial sites with hazardous materials and an international fishing fleet. However human impact notwithstanding, there is a case for classifying SGSSI as a wilderness, or at least as a "wild area". In the first instance, the Islands have never been heavily populated and are now only barely so, with a resident population of around eight people. The active economic use of the islands is very light, particularly on land. Both of the land-based economic activities—science and tourism—are not extractive in nature and qualify as legitimate uses within the U.S. Government's definition of wilderness (Loomis and Richardson, 2001).

At sea, although SGSSI waters are actively fished, the catch remains relatively light compared with other more intensive fisheries in other areas. In 2013, for example, the total catch taken within SGSSI was 35,706 t (Table 12) based on a total sea area for the SGSSI MZ of 1,449,532 km^2. This compares with a catch in UK waters of 624,000 t (Marine Management Organisation, 2014) in a sea area half the size (EEZ: 773,676 km^2).

In terms of other commercial interests, the vast SGSSIMZ is currently barely touched by global economic activity. Figure 102 shows the world's principal shipping lanes and highlights the very light density of commercial traffic through the Scotia Sea.

Figure 103 shows the absence of submarine communications cables in the SGSSI MZ region.

All these data point to the special location of SGSSI. Extremely remote, far from any major centre of population and shielded by formidable seas, the Islands exist as magnificent natural oases, home to an abundant and diverse marine biota. Whether or not they can be classified as a true wilderness under conventional definitions, it is clear that they have considerable biogeographical uniqueness and serve as a crucial refuge for many species of conservation concern.

A further possible contributor to SGSSI's existence value is its human heritage. Travellers from all over the world visit South Georgia not only

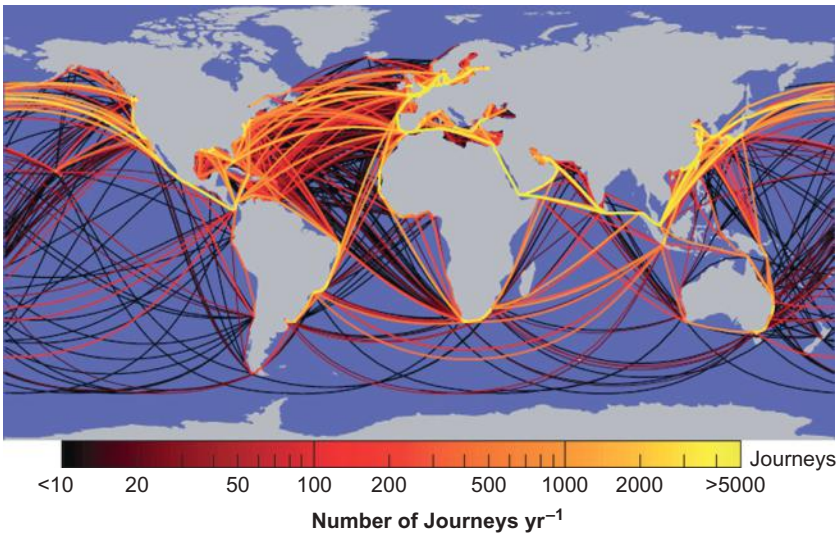

Figure 102 World shipping lanes, journeys per year for 2007 (Kaluza et al., 2010).

because of an interest in its wildlife but also because of its place in the history of Antarctic exploration (Snyder and Stonehouse, 2007b). Sir Ernest Henry Shackleton's connection to the Islands is of particular importance, as is SGSSI's role in the history of the whaling industry and as an example of the global reach of the industrial revolution (Cosier, 2008). It is well beyond the scope of this chapter to investigate the potential economic value of this heritage, but passive values of the man-made environment are often classified and estimated using the same tools as for the natural environment (Pagiola, 1996) and many examples of such studies can be found in the literature (e.g. Navrud and Ready, 2002; The Allen Consulting Group, 2005).

6.6.2 The Challenge of Numerical Estimation

While classifying the main components of SGSSI's non-use value might be straightforward, actually quantifying their value is much less so. Many thousands of case studies conducted over the past 20 years have attempted to establish the non-use value of various aspects of wild nature around the world, yet a review of the EVRI database (https://www.evri.ca/Global/HomeAnonymous.aspx)[1] shows no such valuations for SGSSI. Such studies

[1] The Environmental Valuation Reference Inventory (EVRI) is an internet-based database of over 2000 environmental valuation studies. It is run by the Canadian government and supported by the British, Australian, New Zealand, French, the United States and Canadian governments.

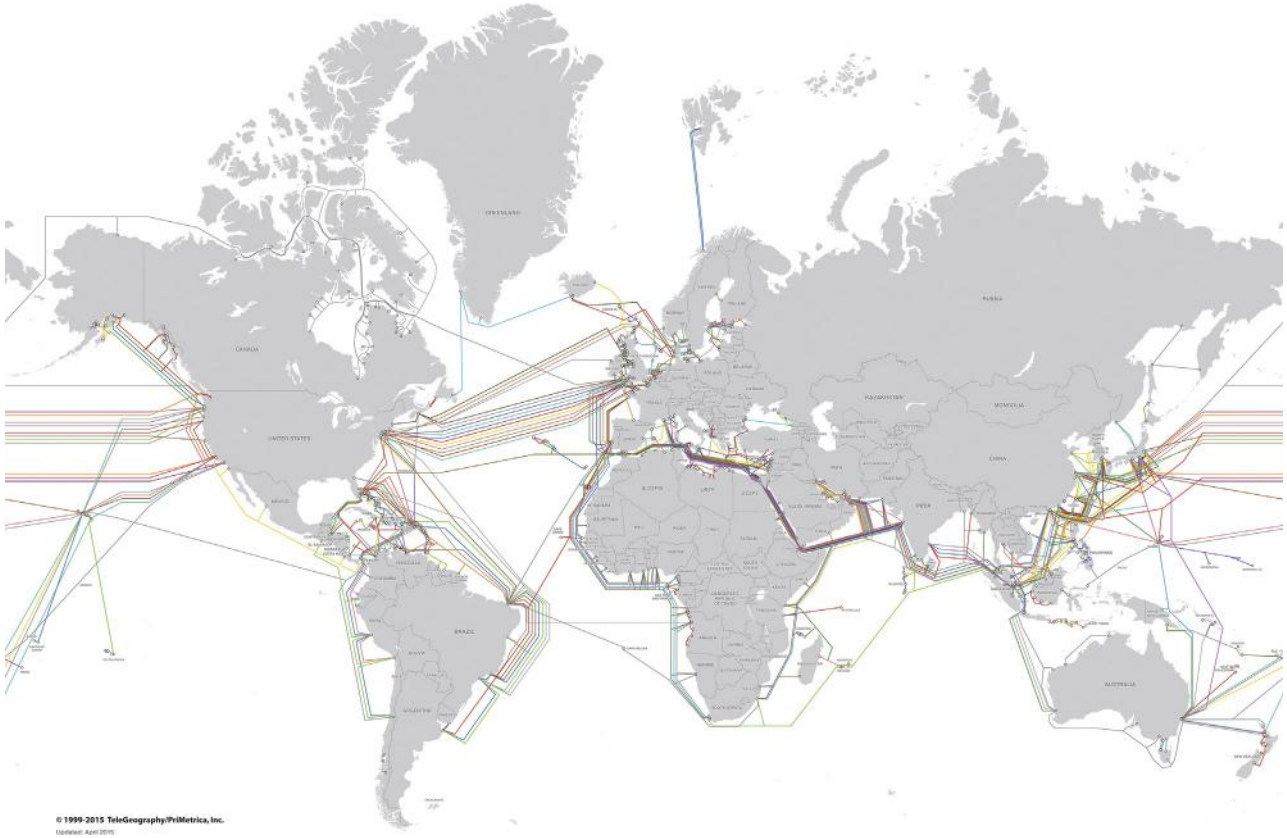

Figure 103 Major submarine cable routes. *(Image courtesy of TeleGeography and submarinecablemap.com).*

are expensive to undertake and are typically performed as part of a cost-benefit analysis and have not been undertaken for SGSSI to date. In addition, marine biodiversity valuations in general remain rare in the literature (Ressurreição et al., 2010) and relevant comparables seem rarer still. SGSSI is clearly unique, even in comparison to the other sub-Antarctic islands.

Notwithstanding all of the above challenges, there is a *prima facie* case that a site-specific study of the non-use values of SGSSI would probably confirm a significant economic value with regard to individual species (and or taxa) and to its broad status as a wilderness cum heritage site.

Richardson and Loomis (2009) referred to "large vertebrates which are appealing to humans…" as "charismatic mega-fauna". The vast majority of SGSSI's biomass, including whales, seals and penguins, might be well described by this label. Richardson and Loomis (2009) also presented the findings of a meta-analysis of a number of studies examining the value of a wide range of vertebrates including several of these "charismatic" species. The study found that many factors determined an individual's willingness to pay to preserve a given species but that marine mammals, fish and birds (especially if charismatic) were among those assigned the greatest value (typically significantly more than land mammals and reptiles).

The existence value of marine flora and fauna (particularly mammals) has been recognised more generally elsewhere with Hall (1996) and Jones (1999) noting the appeal of seabirds, dolphins and turtles, and their influence over NGO and Government marine policies. Campaigns to introduce dolphin-safe tuna are a well-known example of this (Jones, 1999).

Table 16 presents information from Richardson and Loomis (2009) and a number of other studies on the economic value of some threatened, endangered and rare species. These values are presented here to provide some insight into the potential non-use value of the biodiversity of SGSSI without any claim that they could guide towards a rigorous estimate of the SGSSI's existence value. Disparities in the origin of the data in terms of age, methodology and a variety of contextual factors such as the objectives of the original study renders them unreliable for the purposes of site comparisons (see Plummer, 2009; Brouwer, 2001, for a discussion of the limitations of environmental value transfer analysis). In another meta-analysis, Richardson and Loomis (2009) noted the particular importance of the country in which any given study was done in determining the given non-use value of a species. We note that any study commissioned to examine the non-use value of SGSSI would have to be framed carefully to take into account the population to whom the Islands are likely to have value. It can be asserted that the

Table 16 Survey Results Based on Contingent Values for Some Threatened, Endangered and Rare Species Volunteered by Respondents

Species	Objective	Lump Sum	Annual Fee	Reference
Arctic grayling, *Thymallus arcticus*	Improve ⅓ of rivers	$26	N/A	Duffield and Patterson (1992)
Royal albatross, *Diomedea epomophora*	N/A	N/A	$32	Fahy and Kerr (1991)
Steller sea lion, *Eumetopias jubatus*	Avoid loss	N/A	$71	Giraud et al. (2002)
Common Bottlenose dolphin, *Tursiops truncatus*	Avoid loss	N/A	$36	Hageman (1985)
Northern elephant seal, *Mirounga angustirostris*	Avoid loss	N/A	$35	Hageman (1985)
Grey whale, *Eschrichtius robustus*/Blue whale, *Balaenoptera musculus*	Avoid loss	N/A	$46	Hageman (1985)
Sea otter, *Enhydra lutris*	Avoid loss	N/A	$40	Hageman (1985)

Amounts in U.S. dollars and are rounded to the nearest dollar.
From Richardson and Loomis (2009).

SGSSI are relatively little known beyond a small and affluent community with specific interests in their historical, geographical or biological heritage. However, we suggest that because SGSSI are home to many universally well-known species such as king penguins and wandering albatross, they might have considerable non-use value to a much broader audience.

The U.S. Wilderness Act (1964), as mentioned above, provides for the establishment of wilderness areas throughout the United States to protect the natural environment. One of the inevitable by-products of this legislation has been a proliferation of valuation studies intended to support the decision-making process. Loomis and Richardson (2001) identified over 400 such studies over a decade ago, noted that passive, non-use value studies were unusual but increasing in number. Non-use valuation studies can also be found in relation to two other countries with vast wildernesses, Australia and Canada (see Loomis, 2000).

Applying any of these data to SGSSI presents an enormous challenge. Not only are there all of the usual factors hampering a direct value transfer analysis, but also there is the additional complication of the question of scale. The majority of these non-valuation studies are expressed as a function of

area (e.g. acres, hectares or km^2). Loomis and Richardson's (2001) assessment of the annual passive value of wilderness in the lower 48 states of the United States was estimated to be $306 mn per annum for 47.2 million acres. Similarly, another estimate (an average of a number of studies) for the passive use value of the National Wilderness Preservation System of $3.7 bn a year, equates to $34.50 per acre based on around 100 million acres (Bowker et al., 2005). Scaling these findings down to the land area of the SGSSI would be as numerically meaningless as scaling them up to the area of the Exclusive Economic Zone.

In addition, there have been few studies that focused on areas comparable to SGSSI in terms of ecosystem type. One well-known study that may be comparable is the report compiled for the Attorney General of Alaska concerning the *Exxon Valdez* oil spill in Prince William Sound (PWS), Alaska in 1989 (Carson et al., 1992, 2003). The study found that U.S. households were prepared to make a single payment of $31 each to prevent another spill of this type in Prince William Sound. At the time of the study, there were approximately 90 million households in the United States, giving a total of $2.8 billion. This single study may be of particular relevance to SGSSI. The Alaskan site is sub-Arctic, coastal/marine in nature, and is also home to a spectacular array of marine mammals and birds (Okey and Pauly, 1999). These include the mega-charismatic sea otter, *Enhydra lutris*, and less well-known birds known as common murres, *Uria aalgae*, sometimes referred to as the "northern penguin" (Croll et al., 1992).

Table 17 compares some key environmental and other features of Prince William Sound with South Georgia, clearly demonstrating some important similarities. Although no attempt can be made to transfer the value ascribed to PWS, to SGSSI, the Carson study offers a clear exposition of the potential scale of the non-use value of SGSSI. We emphasise here that the contingent valuation study undertaken by Carson et al. (1992, 2003) on PWS did not actually value the ecosystem of PWS, but rather examined the willingness of the study group to avoid an incident of a similar nature. Given the global significance of many of SGSSI's bird and mammal populations, it seems reasonable to suggest that their value might extend beyond that of PWS, both in terms of the population to whom they may have value, and of the absolute dollar value itself. To this end, the $2.8 bn given as the passive value of PWS in 1992 might reasonably be posited as a minimum non-use value of SGSSI today.

A key theme developed throughout our economic review of SGSSI is the economic significance of Antarctica and the implications of this importance to SGSSI. Unfortunately, the literature on the non-use values

Table 17 Comparison of Environmental and Other Characteristics of South Georgia with Prince William Sound, Alaska

Criterion	Prince William Sound	South Georgia
Description	Sub-Arctic ocean inlet on south coast of Alaska, connected with the Gulf of Alaska.	Sub-Antarctic island lying within the Polar Front, 2150 km east of the tip of South America.
Latitude	60°36′N	54°15′S
Characteristics	Almost enclosed bay with sea area of ~1 million ha. Rich marine ecosystem with significant tidal flushing and reduced salinity. Surrounded by Chugach Mountains, with peaks up to 4000 m. 150 glaciers with 17 reaching tidal waters.	Offshore island, 170 km in length and up to 40 km wide. Mostly marine ecosystem covering over 1 million km^2. Two mountain ranges with peaks up to 3000 m. 163 glaciers mostly terminating at the coast.
Wildlife	220 species birds. 30 species of land mammals. 12 species of marine mammals.	29 species breeding +58 occasional breeding or visiting species. ~21 species of marine mammals
Keystone species	Sea otters, *Enhydrus lutris* Killer whales, *Orcinus orca* Bald eagle, *Haliaeetus leucocephalus* Murres, *Uria aalgae*	King penguin, *Aptenodytes patagonicus* Southern elephant seal, *Mirounga leonina* Antarctic fur seal, *Arctocephalus gazella* Wandering albatross, *Diomedea exulans*
Industries	Oil Fisheries Tourism Shipping	Fisheries Tourism
Sources	Okey and Pauly (1999) Alaska Department of Fish and Game	This chapter SGSSI Website

of Antarctica provides very little contribution to developing a quantitative understanding of SGSSI's value. The absence of an imperative to value the Antarctic continent because of its status as a de facto world park coupled with the inherent difficulties and associated expense of retrieving such information, has resulted in a dearth of literature on the subject. In various

papers on the possible value of Antarctica as a world park, Herber, who is an economics advisor to the SCAR Humanities and Social Sciences Expert Group, suggested that the non-use values of Antarctica although unquantified are likely to be "significant" (Herber, 1991, 1992). It was Herber's view that these non-use values along in combination with other "public-goods" of Antarctica were likely to exceed the opportunity costs of foregoing mineral extraction in the continent. Herber also noted that this might not continue to be the case in the event of rising world's mineral prices or the development of a "strategic" demand (Herber, 1991, 1992).

6.7 Other Economic Values

Grant et al. (2013) identified the key ecosystem services of the Southern Ocean including Provisioning Services (fisheries, genetic resources, biochemical, pharmaceuticals and medicines, freshwater), Regulating Services (air quality regulation, climate regulation, waste treatment), Supporting Services (photosynthesis and primary production, nutrient cycling) and Cultural Services (spiritual and religious value, tourism and recreation, aesthetic value). We would add education, science and inspiration (the latter possibly related to aesthetic value) to Cultural Services. It is clear that these services are both vast in scale and of global significance particularly with regard to climate regulation, food supply and the maintenance of biodiversity. With an area of approximately 1.5 million km^2, the SGSSIMZ is not an insignificant part of the Southern Ocean and can be regarded as integral to the provision of the ecosystem services described by Grant et al. (2013). With the exception of the fisheries value of krill (Grant et al., 2013), it would appear none of these services have been fully quantified, let alone values on a regional scale. Two recent studies provide useful examples of the potential economic value of these services. Trueman et al. (2014) showed that the value of deep-water fish in terms of carbon sequestration may be as great, or greater, than their value as fisheries products. Krill is a prime example of an organism that plays an obvious role in the short food chains in Antarctica. However, recent scientific studies are demonstrating that this species affects the Antarctic marine ecosystem via nutrient cycling and by exerting indirect control of the abundance of other organisms including phytoplankton (Flores et al., 2012). Unlike tourism and fisheries, services such as climate regulation and nutrient cycling benefit a much wider part of the global population. In the case of carbon sequestration, these services may possibly have a global effect for all humankind (Grant et al., 2013).

6.8 Summary and Concluding Remarks on Economics

This review covers a broad range of economic topics from highly localised financial issues such as the revenues and expenditures of GSGSSI, to the expanding global market for krill products. What all of these subjects have in common is their significance to the conservation outcomes of SGSSI and the Southern Ocean.

On a local level, the issue of outstanding note is the fact that GSGSSI operates on a minimal budget. With annual revenues of around £5 million, it is in economic terms a "micro-enterprise". With these limited resources, the GSGSSI manages an EEZ with an area of over 1 million km^2 and wildlife populations of immense global significance.

The GSGSSI has a mandate to balance its budget and to generate sufficient income from its activities to cover its costs. The income it generates is in economic terms of very poor quality. Over the past decade, an average of 83% of its income has come from a single source, namely, toothfish licence fees. The growth in GSGSSI revenues over this period has largely been a function of the rising price of toothfish licence fees: if toothfish licence fees had remained at the same implied price per tonne in 2013 as they were in 2004, GSGSSI would have had revenues of £3.59 million (instead of the actual £5.43 million) against expenditures of £5.3 million. Although the majority of fisheries licence fees go towards covering fisheries management expenses, the surplus contributes to the general running expenses of GSGSSI. There is little money readily available to fund significant capital investment. The GSGSSI has been able to focus on specific projects such as asbestos remediation, rat control and infrastructure improvement mostly through one-off grants, help from charitable groups and international collaborations.

Increased revenues from krill were highlighted as a source of future growth in the South Georgia and Sandwich Islands Strategy 2010–2015 (GSGSSI, 2010a). In 2013, krill licence fees were £611,000 compared to £255,000 in 2004. The outlook for krill fisheries in SGSSI cannot be predicted with a great deal of accuracy, given the unlicensed nature of krill fishing in Antarctica outside of the SGSSI MZ. Long-term growth can be almost guaranteed as the global market for krill continues to expand.

In addition to fisheries, tourism is the main source of income. Revenues come mainly from landing fees plus a number of miscellaneous sources such as the sale of stamps and publications. The advancement in tourism numbers 2005–2012 (a Compound Annual Growth Rate, CAGR of 9%) broadly

mirrors trends in tourism to the region. This growth disguises a pronounced cyclicality in visitor numbers and their associated revenues. In the future, the trend in high-end adventure tourism that drives tourism to SGSSI is expected to continue, interspersed by cyclical downturns. The underlying growth in the market is likely to be well supported by the very rapid growth in Chinese tourists to the region. Managing this continued growth in tourism numbers is seen as an important priority for GSGSSI going forward.

The potential for declared interest in the possible mineral resources of Antarctica seems to be accelerating in pace to a level ringing alarms bells within the conservation community. In 2013, the SCAR Antarctic and Southern Ocean Horizon Scan noted that the pressure for exploration and subsequent exploitation of the minerals and hydrocarbons of Antarctica is increasing (Sutherland et al., 2013). It also commented that when, in 2011, Russia stated its intention to conduct "complex investigations of the Antarctic mineral, hydrocarbon and other natural resources" as part of its research on the Antarctic continent and surrounding seas to 2020, in conflict with at least the spirit of the Madrid Protocol, none of the other 48 signatories to this protocol expressed opposition (Sutherland et al., 2013).

Economic valuation studies of biodiversity (particularly in terms of its non-use value) have not yet been done, but may well be the overwhelming component of economic value of the Islands. The likelihood is that a non-use value for SGSSI would be measured in billions of U.S. dollars. In the court process that followed the *Exxon Valdez* disaster in 1989, a valuation of 2.8 bn USD was placed on the non-use value of Prince William Sound (Carson et al., 1992, 2003). Whether this represents a good proxy for the non-use value of SGSSI would require considerable further analysis, but there are a number of striking similarities between the two sites. Such a valuation provides a useful context, certainly in terms of relative magnitude, for £4–5 mn annual budget of the GSGSSI. Any industrialisation of Antarctica may feasibly increase the non-use value of SGSSI, as it acts as a refuge for wildlife populations and as an insurance policy against degradation in other parts of the Southern Ocean.

Although SGSSI continues its long history of exploitation with a number of fisheries, the islands have not been subject to the economic development and population growth that has transpired throughout most of the world. The geographic, political and economic factors that have facilitated isolation of SGSSI appear to be weakening, as *inter alia*, the world's economy grows. The extent to which GSGSSI, with a budget that amounts to no more than a rounding error in modern financial terms, and an administrative capacity of a

similar magnitude, can continue to manage the iconic resources at stake, remains to be seen.

7. THE SOUTH GEORGIA AND SOUTH SANDWICH ISLANDS MARINE-PROTECTED AREAS: WHAT IS NEEDED IN THE FUTURE

7.1 Assessing the SGSSI MZ Spatial Protection Measures

Here, we draw together the information presented in the preceding sections to address the question of whether current spatial conservation measures in the SGSSI MZ achieve the objective of protecting threatened marine species and the marine ecosystems of which they are part. We do this through first examining the spatial conservation measures taken in other overseas territories in Antarctic and sub-Antarctic waters and how they compare to those in the SGSSI MZ. We then examine the measures already undertaken in the SGSSI MZ, how these have come about and implications for protection of the marine biodiversity of the islands in the future. We consider the establishment of no-take MPAs in the SGSSI MZ in the context of CCAMLR and the broader situation in the global ocean where there is a conflict between the exploitation of marine resources and conservation of marine species, ecosystems and the services they provide. We then make a case as to why current spatial conservation measures are inadequate, and why they should be much more ambitious and implemented with greater speed.

7.2 Spatial Management Imposed by the Governments of Other Antarctic Sovereign Territories

7.2.1 Australia

Coinciding with international discussions and negotiations regarding MPAs in the CCAMLR region, individual States other than the United Kingdom have been undertaking their own measures for marine protection in their Antarctic Territories. Australia designated the Macquarie Island Marine Park in 2001 (now the Macquarie Island Commonwealth Marine Reserve) with a management plan covering the period 2001–2008, now superseded by the South East Commonwealth Marine Reserves Network Management Plan 2013–2023 (Director of National Parks, 2013). The island was declared a World Heritage site under Criteria 7 and 8, and the Marine Park comprises a Sanctuary Zone (IUCN Cat. 1A). The Sanctuary Zone covers an area of 5.8 million hectares and extends in a south easterly direction from the coasts of Macquarie Island to the edge of the EEZ, including a portion of the

Macquarie Ridge (Commonwealth of Australia, 2001). The area is flanked by two Habitat Protection Zones (IUCN Cat. IV), covering 7.7 million hectares, although fishing is still allowed within these zones. The waters out to 12 nm are part of the Macquarie Island Nature Reserve.

The strategic objectives of the Macquarie Island Marine Park were to protect the conservation values of the south-eastern portion of the Macquarie Island Region including protecting the migratory, feeding and breeding ranges of marine mammals and seabirds; threatened species that depend on the area; and the unique benthic habitat (Commonwealth of Australia, 2001).

Australia also designated the Heard Island and Macdonald Island Marine Reserve in 2002 (Environment Australia, 2002), which included listing the islands as World Heritage sites under Criteria 8 and 9. This reserve comprises a 12-mile exclusion zone plus a 1 km buffer zone to fishing around the islands as well as three large areas extending out to the edge of the EEZ in which fishing is also prohibited. The reasons for conserving part of the Heard Island and Macdonald Island EEZ were given as follows (Environment Australia, 2002):

- Only sub-Antarctic island group without introduced plants or animals;
- Diverse and distinctive benthic habitats supporting a range of slow growing and vulnerable benthos such as corals and sponges;
- Several endemic fish and benthic species;
- Nursery areas for a range of fish stocks including commercially harvested Patagonian toothfish;
- Highly productive nutrient-rich areas resulting from the confluence of key oceanographic fronts such as the Antarctic Circumpolar Current;
- Prime foraging areas for a number of land-based marine predators, including threatened albatross and seal species.

Protection of corals and benthic species was particularly relevant for the Heard Island and Macdonald Island Marine Reserve because benthic trawl fishing was still being conducted in the Maritime Zone of the islands.

7.2.2 France

France also declared the EEZ of Île Kerguelen, Île Crozet, Île Amsterdam and Île Saint-Paul as Marine Protected Areas under the jurisdiction of France in 2006 (Ardron, 2007). Areas around Îlots Apôtres, Île aux Cochons, Île des Pengouins, Îl de l'Est (Crozet), Kerguelen, Amsterdam and St Paul have been excluded to fishing to a distance of up to approximately 25 km from the coastline (Government of France, 2010). These reserves cover about

15,700 km^2 of the ocean and about 52.5% of the territorial waters around the islands (to the 12 nm limit; Government of France, 2010). The planning document for the reserves indicates that the islands present unique communities of animals and plants with special adaptations to their environments, as well as the presence of endemic species, and the absence of major taxonomic groups (Government of France, 2010).

7.2.3 South Africa

In 2009, the Government of South Africa declared a Marine Protected Area around the Prince Edward Islands comprising a Sanctuary area of 12 nm around the islands and controlled zones extending out to the edge of the EEZ, where fishing is prohibited, as well as Restricted Zones where fishing was capped at average levels of effort from 2002 to 2005 (Department of Environmental Affairs and Tourism, 2009). This MPA was designed through analyses of the distribution of fish diversity around the islands, benthic habitat classification (substrata present), and the foraging patterns of marine predators (Lombard et al., 2007).

7.2.4 New Zealand

New Zealand has been planning for Marine Protected Areas around the Sub-Antarctic Islands (Antipodes Islands, Auckland Islands, Bounty Islands, Campbell Island and Snares Island) since at least 1998 (Department of Conservation, 1998). Initiation of planning coincided with the designation of the islands as World Heritage sites under Criteria 9 and 10, and consistency with the Convention is cited as one of the main reasons for initiating MPAs around these islands (Regulatory Impact Statement, 2010). Bottom trawling and dredging were banned from the territorial waters of the Antipodes Islands Group, the Bounty Islands and Campbell Island in 2007. Following this, a desktop study of the ecology of the islands and stakeholder consultations took place. Marine Reserves were declared around three of the island areas, and a ban on Danish seining in the area of territorial seas of the islands was introduced (Regulatory Impact Statement, 2010), with final ratification in 2014 (Government of New Zealand, 2014). These reserves only constitute portions of the territorial seas around each island, making up 435,163 hectares in total. Fishing interests within these protected areas were limited, and included a small toothfish and ling fishery. Only 58% of Bounty Island Territorial Waters were protected to allow a small long line fishery to continue in the rest of the area (NZMSS, 2014). In the case of Campbell Island, only 39% of the Territorial Waters were closed to fishing

to allow a pot fishery for the giant spider crab, *Jaquinotia edwardsii,* to continue. This is despite risks to the ecosystem from impacting the population of a large predator which is also an important source of prey for the New Zealand sea lion, *Phocarctos hookeri* (IUCN Red List Category Vulnerable) that breeds on the island (NZMSS, 2014).

7.3 South Georgia and the South Sandwich Islands

7.3.1 Adequacy of the Current Spatial Conservation Measures

Current protection measures in place around South Georgia and the South Sandwich Islands are the result of a systematic conservation planning process described in Trathan et al. (2014). The SGSSI measures are similar to protective measures around other sub-Antarctic territories, in that waters in the immediate vicinity of the coast (12 nm for South Georgia, Clerke Rocks, Shag Rocks and Black Rocks; 3 nm for the South Sandwich Islands; 12 nm around the South Sandwich Islands for pelagic fishing) are no-take marine reserves (Trathan et al., 2014; Figure 89). Several of the other sub-Antarctic MPAs include areas of no-take which extend beyond territorial waters (e.g. Macquarie Island, Heard and Macdonald Islands, Prince Edward Islands). In South Georgia, several small-scale closures have been implemented including Restricted Impact Areas around South Georgia (where there were high by-catches of sessile megafauna, especially corals), seamounts which may be important as spawning areas for toothfish around South Georgia, and the Protector Shoals and Kemp Seamount around the South Sandwich Islands (Trathan et al., 2014). In addition, commercial trawling is banned in the Maritime Zone (as is true of the whole of Antarctic, with the exception of Heard Island); there is no bottom fishing shallower than 700 m and deeper than 2250 m. Additional measures related to pelagic fisheries include a closed season for krill fishing (1 November–31 March) and move-on rules for krill and mackerel icefish fisheries, to prevent excessive by-catch of juvenile toothfish and yellowfin notothen (Trathan et al., 2014).

The approach used in the systematic conservation planning exercise for the SGSSI MZ involved gathering information from two projects, one conducted to identify important and vulnerable marine habitats in the SGSSI MZ and the other to gather baseline data on the benthic biodiversity of the South Georgia slope and shelf (Trathan et al., 2014). Resulting data were subject to spatial analyses and evaluated through expert opinion to develop spatial conservation measures that would contribute towards a number of high-level conservation objectives (Trathan et al., 2014). Stakeholder

engagement included a scientific workshop and presentation of scientific results, conservation and policy objectives and MPA proposals to general meetings and fishing industry meetings held by the GSGSSI annually (Trathan et al., 2014). The spatial and temporal protection measures that are currently in place in the SGSSI MZ are reported to largely meet protection (and target) objectives (Trathan et al., 2014). These objectives can be summarised as:

- Protection of representative pelagic environments (bioregions).
- Protection of large-scale ecological processes.
- Protect trophically important pelagic prey species.
- Protect spatially constrained foraging areas of krill-eating predators.
- Protect localised areas of ecological importance.
- Protect representative benthic environments.
- Protect areas important for toothfish life-cycle processes.
- Protect rare or vulnerable benthic habitats.

This exercise essentially resembled a three-way trade-off between maintaining the commercially viable fishery and tourism, maintaining the fished stocks and conservation of the marine ecosystem, with a focus on predators and Vulnerable Marine Ecosystems (VMEs; Trathan et al., 2014). Such a trade-off was viewed as essential as without the income from fisheries, especially the toothfish fishery, protection of the SGSSI MZ from IUU fishing would not be possible under current arrangements because the costs of the fisheries enforcement vessel could not be met (Trathan et al., 2014). The proposed MPA network in the SGSSI MZ has built on spatial conservation measures that have been put in place incrementally over recent years for reasons of protection of breeding predators, benthic biodiversity and for fisheries purposes. An acknowledged weakness of this process has been lack of data (Trathan et al., 2014).

The spatial and temporal protection measures established by the GSGSSI have met the conservation objectives and their targets to some degree, but we disagree with the extent to which they have been met that was outlined in Trathan et al. (2014). For example, measures to protect the pelagic ecosystem all year around, close just 3.4% of the area of the pelagic zone. Even if this protects rare coastal pelagic habitats, it is a small area. Temporal closures are promoted as largely preventing competition between the krill fishery and krill predators. There is certainly overlap in the foraging ranges of tracked predators (mainly from Bird Island) and areas of krill fishing (mainly northwest of South Georgia, including especially macaroni penguins, black-browed albatross and Antarctic fur seals and to the south of South Georgia

for white-chinned petrels; see Section 4 and 5). Temporal closures of the krill fishery during summer, eliminates competition for many of the breeding predators, but some of the avian predators begin breeding before the closed season starts and complete chick development after the closed season has finished (Trathan et al., 2014). Some predators move away from the SGSSI MZ during winter, and these species are unlikely to be effected by the fishery. However, for many of the bird populations around South Georgia, data are limited on winter distribution and for some species (including globally important populations such as common diving petrel), there is a complete lack of data. Thus, the level of success of temporal closures in preventing competition with the krill fishery for all predators is not fully understood.

Closures to bottom fishing are complete between the surface and 700 m and beyond 2250 m, protecting vulnerable marine ecosystems in these zones, including hydrothermal vents on the East Scotia Ridge, and the South Sandwich Trench (the only trench in the whole of the Antarctic; Trathan et al., 2014). However, only about 15% of the zone between 700 and 2250 m is protected. For octocorals, habitat suitability modelling suggests that approximately 58% of highly suitable habitat for these organisms is protected by the current spatial protection measures around South Georgia (Taylor et al., 2013), an encouraging value that meets the conservation targets for benthic protection for these organisms. Other species of conservation concern, or VMEs, may also be protected alongside the octocoral habitats, but whether this protection is representative for all species or communities is unknown given the extremely poor state of knowledge of the deep-sea ecosystems of the SGSSI MZ. For example, around the South Sandwich Islands, which were not considered in the baseline study for the seabed, there are likely to be other hydrothermal vent ecosystems within the depth range of fishing and research dredging and trawling that are currently unresearched. Given the short longevity of such hydrothermal vent ecosystems, and the importance of metapopulation dynamics in vent-endemic species, spatial protection of existing sites would seem essential. Because the Scotia Arc is the only island back-arc in the Antarctic, it forms one of the 23 Antarctic ecoregions, and the associated hydrothermal systems may be unique (Douglass et al., 2014).

The trade-off between fishing and conservation in other sub-Antarctic territories has been one-sided with only a sub-set of the marine ecosystems of the EEZs protected. Heard and MacDonald Islands have strips of the EEZ under complete protection, and perhaps this represents the best existing

situation in terms of spatial conservation measures among French, Australian and New Zealand Territories (although bottom trawling is still permitted in Heard Island). In SGSSI, the justification for the trade-off has largely been an economic one that the islands must be self-sustaining with respect to running fisheries enforcement and other activities.

7.3.2 Prospects for Developing Alternative Means of Fisheries Enforcement

The emphasis on the importance of economic self-sufficiency to maintain fisheries enforcement results from the need to prevent IUU fishing, a direct threat to species of conservation importance on the islands such as albatrosses and petrels. The use of satellite surveillance to assist with fisheries enforcement in SGSSI MZ has been dismissed with the idea that the seas around South Georgia are often cloud obscured (Trathan et al., 2014). This dismissal was based on incorrect interpretation of the current state of satellite sensor technology. Satellite vessel tracking relies on receiving data from Vessel Monitoring Systems (VMS) and Automated Identification System (AIS) carried by most large fishing vessels (Delfour-Samama and Leboeuf, 2014). Both of these systems can be switched off or tampered with, which is likely to be the case with vessels engaged in illegal activity. However, Earth Observation satellites also carry Synthetic Aperture Radar (SAR), which was specifically developed to "see through" clouds. Fusion approaches, where data from VMS, AIS, SAR, and optical sensors, are increasingly capable of tracking larger fishing vessels almost anywhere in the world (Le Roux et al., 2007; Máttyus, 2013; Navigs, 2005; Stastny et al., 2011). SAR imagery has been used in fisheries monitoring, control, and surveillance in Kerguelen for over 10 years, and has been considered effective (Losekoot and Schwab, 2005). SAR data are still expensive to obtain in real time, but with the launching of more satellites carrying these sensors (for example the European Space Agency's Sentinel satellites) and the wider use of satellite data for maritime enforcement and security, the costs and accessibility of these data will decrease. Other technologies are also in development that may be appropriate for deployment in remote areas for fisheries enforcement purposes which include unmanned surface vehicles (USVs), unmanned aerial vehicles (UAVs), autonomous underwater vehicles (AUVs), enforcement platforms or buoys and acoustic sensors (Selbe, 2014). The remaining barrier to use of satellite and other technologies will be the establishment of a legal framework for use of remote surveillance data in the prosecution of illegal fishers (e.g. for satellites; Delfour-Samama and Leboeuf, 2014). Given the benefits

to the global community of eliminating IUU fishing, we anticipate that this framework will be established fairly quickly.

Coupled with broader measures for combating IUU fishing by governments and the private sector globally, including the Port State Measures Agreement (PSMA; Doulman and Swan, 2012), and increased requirements for traceability of catches, there is the prospect of reducing the threat of illegal fishing in coming years. For remote island territories (such as the British Overseas Territories of SGSSI, Pitcairn, Ascension, Chagos) improvements in technology for monitoring, control and enforcement are likely to significantly increase capabilities to protect these far-flung localities from IUU fishing. In such localities, maintaining crewed fisheries protection vessels for enforcement purposes is logistically extremely difficult and expensive. This leads to a situation, as in the South Sandwich Islands where fisheries enforcement relies on occasional visits by fishing vessels or the fisheries vessel *Pharos,* which is inadequate to ensure the prevention of illegal fishing in this area of the SGSSI MZ. The new technologies described may lead to fisheries enforcement solutions that are operational 24 h a day all year round and which are logistically and economically more viable than crewed enforcement vessels or aircraft.

7.3.3 The Ecological Grounds for No-Take Marine Reserves Around South Georgia and the South Sandwich Islands

7.3.3.1 Global Value as a No-Take MPA

South Georgia can be considered the outstanding sub-Antarctic area of islands in the Southern Ocean in terms of the globally significant populations of predators it harbours (see Table 15). Several of the predator species with globally significant populations in the islands are threatened with extinction under IUCN Red List Criteria as a result of past human impacts, or current direct (e.g. by-catch) and indirect impacts (e.g. global climate change), arising outside of the SGSSI MZ. The South Sandwich Islands do not host so many globally important populations of seabirds as does South Georgia, but they do host globally important populations of chinstrap penguins. South Georgia and Shag Rocks are associated with the highest observed diversity of benthic fauna in the Southern Ocean, and form a unique anomaly to the region's pattern of low endemism. The system is highly sensitive to climate change because it lies on a biogeographic boundary between Antarctic and Magellanic faunal provinces. South Georgia is also sensitive to climate change because many of its predators are reliant on a supply of krill from the Antarctic Peninsula and southern Scotia Arc to successfully complete

their life cycles. The South Sandwich Islands are volcanically active, and the biota are Antarctic in character and fairly typical of the southern Scotia Arc. In addition, the islands are associated with potentially unique deep-sea hydrothermal vent ecosystems, seamounts and the South Sandwich Trench. The SGSSI qualify for World Heritage status under Criteria 9 and 10:

> (9) To be outstanding examples representing significant ongoing ecological and biological processes in the evolution and development of terrestrial, freshwater, coastal and marine ecosystems and communities of animals and plants.
>
> (10) To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

SGSSI may also qualify under Criteria 7 and 8:

> (7) To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance.
>
> (8) To be outstanding examples representing major stages of Earth's history, including the record of life, significant ongoing geological processes in the development of land forms, or significant geomorphic or physiographic features.

Qualification as potential World Heritage SItes means that South Georgia and the South Sandwich Islands are not simply important in the context of the United Kingdom or the region of the Antarctic, but that, in the words of English Heritage, they are, "places of outstanding universal value to all humanity and are of great importance for the conservation of mankind's cultural and natural heritage" (https://www.english-heritage.org.uk/professional/advice/advice-by-topic/international-and-world-heritage/world-heritage-sites/). South Georgia and South Sandwich Island sites are of overwhelming conservation importance for the entire world's population, on a par with other globally important parks such as the Virunga National Park in the Democratic Republic of the Congo. Thus, the ecological grounds for the strongest levels of protection for the SGSSI MZ present an outstanding case without justifications based around the establishment of a representative network of marine-protected areas in the Antarctic.

7.3.3.2 Value as a No-Take MPA in the Antarctic Context

CCAMLR itself outlined the criteria for establishing protected areas in Conservation Measure CM91-04 (CCAMLR, 2014b). These objectives include:

(i) Protection of representative examples of marine ecosystems, biodiversity and habitats at an appropriate scale to ensure their long-term viability;
(ii) The protection of key ecosystem processes, habitats and species including populations and life-history stages;
(iii) As scientific reference areas;
(iv) The protection of areas vulnerable to impact by human activities including unique, rare or highly diverse habitats and features;
(v) The protection of features critical to the function of local ecosystems;
(vi) The protection of areas to maintain resilience or the ability to adapt to the effects of climate change.

South Georgia and the South Sandwich Islands fit all of these criteria. Given the unique nature, particularly of the South Georgia marine ecosystem, but also of the South Sandwich Islands, and their clear value in terms of conservation, current trends and threats to the conservation status of the islands must be considered. Relatively few species are increasing in numbers, and even for those, reasons for increases are not always entirely clear (see Table 15). For species in decline, the main reasons are fisheries-induced mortality (either as target or by-catch species) and/or direct or indirect effects of climate change. In many cases, the cause for the negative trend in population abundance is external to the waters of South Georgia (e.g. fisheries by-catch of albatross and petrels). It should be noted that for the majority of species, including birds, such as prions and burrowing petrels and species caught as by-catch in deep-water fisheries (rays, macrourids and benthic fauna such as corals) there are no data because of a lack of monitoring programmes or baseline data on which to base current observations. We also point to the potentially negative impacts of scientific sampling within the SGSSI MZ using benthic trawls, sledges and dredges as being a significant cause for concern.

The SGSSI MZ has already been identified as a prospective marine-protected area, by CCAMLR and NGO exercises to identify representative areas in terms of bioregions, and for the protection of vulnerable and/or rare and threatened species and communities (e.g. Douglass et al., 2014). Establishment of a no-take MPA for the entire SGSSI MZ would ensure the protection of these ecosystems and their natural biological and physical features for all of humankind. Closure would help to overcome the current hiatus in CCAMLR generated by disagreements over MPA designation and rapidly advance spatial marine protection in the Southern Ocean. McCauley et al. (2015) note how late action to close terrestrial ecosystems failed to prevent

major defaunation on land, with many protected areas representing restoration projects or failing to reduce species loss. In the ocean, there is therefore an urgency to enact such reserves before species are lost and major ecosystem changes take place, and to maintain the resilience of these systems to the effects of global climate change. Maintaining the current conservation measures in SGSSI MZ may be an attractive option to the GSGSSI in that it will allow fisheries to continue currently, and to date these fisheries have been the main source of income for South Georgia and the South Sandwich Islands. However, because toothfish are the economically important fishery in the EEZ, there is a considerable risk to revenues should the population decrease. Increasing catches of krill on the South Georgia shelf/shelf slope would appear a financially viable option in the future, but present a risk of competition with predators especially given the evidence for a current downward trend in krill abundance. Such a strategy therefore has a strong potential to negatively impact the conservation status of species already in decline in South Georgia, including those that are threatened with extinction. Furthermore, there is also a possibility that the climate change induced delay in the onset of winter sea ice around the Antarctic Peninsula may reduce economic opportunities to charge significant amounts for licences to fish krill around South Georgia. Technological changes in fisheries surveillance may also decrease the necessity to finance an expensive fisheries patrol vessel in the EEZ.

It is interesting to note that issues related to financing of the SGSSI MZ strongly reflect the actual text from the Convention Concerning the Protection of the World Cultural and Natural Heritage, "that protection of this heritage at the national level often remains incomplete because of the scale of the resources which it requires and of the insufficient economic, scientific, and technological resources of the country where the property to be protected is situated" (http://whc.unesco.org/en/conventiontext/). While the United Kingdom can hardly be described as a state with a low GDP/income, it is such arguments about the islands of South Georgia and the South Sandwich Islands remaining financially independent, emphasised by current global financial instability, that are being used to maintain the current status in terms of exploitation of resources. This is despite the relatively small cost involved in maintaining the relatively limited infrastructure on South Georgia and fisheries enforcement of the SGSSI MZ. Closure of SGSSI MZ would represent a financial loss to fisheries concerns, but the non-use values and the protection of indirect ecosystem services (both within the SGSSI MZ and in the wider Atlantic Sector of the Southern Ocean

and beyond) may be considerable, if difficult to quantify, and also potentially benefit a larger number of people now and in the future. Closure of the SGSSI MZ should be implemented immediately for the South Sandwich Islands Maritime Zone because they are unique, take from fisheries in this area is minor (~100 t), ecosystem damage is unknown, and contributions to fisheries enforcement marginal. For the South Georgia Maritime Zone, a more protracted process to manage closure may be required so that the infrastructure is in place to ensure protection of the marine reserve from IUU fishing in the future.

We also emphasise, as stated by Trathan et al. (2014), that because of the importance of advection of krill into the SGSSI MZ from the Antarctic Peninsula/Drake Passage regions, careful management of fishing activities outside of such reserves are critical for their success. Given the likely decrease in habitat suitability for krill in waters further north as a result of climate change, this would be especially important. Management of other activities including both tourism and science would also be required to maintain the conservation status of the SGSSI MZ. One final point we make here is that there is still a remarkable lack of knowledge on the ecology of SGSSI MZ and wider Southern Ocean, especially with respect to less charismatic bird species, deep-sea benthic and pelagic ecosystems and the functional ecology of keystone species such as krill. It is a priority to improve this baseline scientific data so that knowledge-driven decision making is enabled for ecosystem-based management that fully accounts for the direct and indirect ecosystem services provided by the ecosystem.

7.3.4 Broader Issues with Respect to Spatial Protection of Marine Biodiversity

The picture that arises from current efforts to initiate a network of protected areas in the Antarctic is confused. Text within CCAMLR Conservation Measure CM91-04 has not helped the current situation: "MPAs shall be established on the basis of the best available scientific evidence, and shall contribute, taking full consideration of Article II of the CCAMLR Convention where conservation includes rational use". It has been used time and again to obfuscate efforts to create protected areas. This obfuscation is reflected in the state of compromise of both SGSSI MZ and other sub-Antarctic territories (especially the New Zealand territories) where commercial exploitation is, in our view, jeopardising the conservation objectives of the protected areas themselves, often for limited gain (although potentially significant for the few doing the exploitation). One problem is that rational

use in the context of CCAMLR has never been defined. Preservation of ecosystems providing ecosystem services that indirectly benefit a much wider part of humankind constitute, in our view, rational use, especially given that the Convention Area is effectively a global commons. We further contend that rational use may also include setting aside areas that are unique and of high conservation priority at global and regional level as parts of networks of protected areas, especially given the wishes of the international community to preserve the natural heritage of Earth for present and future generations. This has been expressed in the Heritage Convention, and also through the Convention for Biological Diversity. The situation in Antarctica, like the rest of the high seas, represents a multifaceted conflict. It is ultimately based, at present, around the desire for resources at the level of individuals, industry and some states, manifesting in the claim for rights to fish wherever the stocks exist, or in the future, possibilities in terms of territorial claims and/or speculation on oil, gas or mineral wealth. Against exploitation is the urgent need to protect biodiversity and the ecosystems and the services that South Georgia and the South Sandwich Islands and other parts of the Antarctic provide, which ultimately underpin human civilization now and in the future. This represents a dilemma in the management of a global commons that is currently being played out against a background of insufficient knowledge, a lack of precaution, and poor systems of governance, transparency and decision making, while ignoring the views of the wider global community. At present, the protection of ecologically important overseas territories in the Antarctic (and indeed elsewhere) has begun the process of protection of a significant network of protected areas in our oceans at a time when they are under unprecedented pressure from humankind and the international political system is so paralysed that it is unable to take the urgent actions required to halt the decline of marine biodiversity.

7.4 Summary Remarks and Conclusions

We have outlined the case here that current conservation provisions for the South Georgia South Sandwich Islands Maritime Zone are insufficient, and that stronger measures in terms of wider or complete no-take MPAs (reserves) should be established with urgency. This is because:

- The ecosystems of the SGSSI MZ represent a globally important bioregion with a unique biota and concentrations of threatened marine predators, including for some species, the world's largest breeding

populations. For these reasons and because of other unique natural features of the islands, they qualify as World Heritage Sites.

- Threats to the marine biodiversity of SGSSI MZ and the wider Antarctic are large and are growing. Examples include the impacts of fishing, invasive species, climate change and various anthropogenic activities (even including some scientific research).
- A substantial no-take MPA in the SGSSI MZ would assist the United Kingdom and CCAMLR in reaching internationally agreed targets for spatial conservation in the ocean and help to overcome the current hiatus in CCAMLR with respect to developing a representative network of MPAs.
- The current lack of scientific information on many aspects of the marine ecosystems of the SGSSI MZ means that the incremental approach to establishing spatial conservation measures comes with significant risks of compromising the features that render the islands and their waters so valuable in terms of their wildlife.
- Cessation of extractive activities in the SGSSI MZ would have limited financial impact and possibly a large benefit in terms of protection of ecosystem services.
- The development of new technologies is likely to rapidly assist states in moving away from expensive and logistically demanding monitoring, control and enforcement measures, that for remote territories (and remote MPAs in general) can be of limited effectiveness. New approaches to enforcement will employ fusion of different technologies to achieve effective enforcement of fisheries regulations and spatial conservation measures. Coupled with an improving ocean governance framework, this will reduce the threat posed by IUU fishing in the future.

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