

## Supplementary Material

### Supplementary Methods

#### Estimating seasonal changes in seabird demand north and south of the Polar Front

A simple bioenergetics model incorporating information on colony sizes, at-sea distributions, breeding schedule, adult body mass, field metabolic rate and energy density of prey was developed to estimate the total number and biomass of individuals, time spent (total bird-days), and energy and prey requirements from waters north or south of the Antarctic Polar Front (APF) during the breeding and nonbreeding seasons by the breeding populations of 32 seabird species in the Antarctic region (**Supplementary Table 3**). The model did not include breeding populations of those same species on islands north of the APF (e.g. sub-Antarctic islands in the Indian Ocean). Nor did the model include other species that breed entirely north of the APF, but feed to some extent to its south, including southern royal albatross *Diomedea epomophora* and Arctic tern *Sterna paradisaea*, sooty shearwater *Ardenna griseus*, short-tailed shearwater *Ardenna tenuirostris*, and various other small petrels (Ropert-Coudert *et al.*, 2014; Quillfeldt *et al.*, 2015). This was because the data available on the sizes and at-sea distributions of these populations were generally even more limited than for the species that breed in the Antarctic.

All seabird species were included that breed around the Antarctic continent and adjacent ice shelves, and islands around the Antarctic Peninsula to as far north as the APF, including South Georgia, South Orkneys, South Shetlands, Bouvet, Heard and McDonald islands. We followed well-established taxonomy, but considered Antarctic shag *Leucocarbo bransfieldensis* and South Georgia shag *L. georgianus* to be separate species, following a recent classification of cormorants based on extensive mitochondrial and nuclear DNA sequences (Kennedy and Spencer, 2014). For all species, estimated annual breeding pairs or total individuals (breeders, nonbreeders, immatures and juveniles), both worldwide, and south of the APF (hereafter referred to as the Antarctic region) were collated from the literature, with counts of annual breeding pairs considered to be more accurate (Prince and Croxall, 1983; Higgins and Davies, 1996; Convey *et al.*, 1999; Brooke, 2004; Tree and Klages, 2004; Creuwels *et al.*, 2007; Lynch and Larue, 2014; Borboroglu and Boersma, 2015; Harris *et al.*, 2015; Phillips *et al.*, 2016, 2019; Schrimpf *et al.*, 2018; Poncet *et al.*, 2020). Species that typically breed biennially if successful ( $n = 3$ ) and annually ( $n = 29$ ) were distinguished (Marchant and Higgins, 1990; Higgins and Davies, 1996; Brooke, 2004). Carneiro *et al.* (2020) used an age and stage-structured Leslie-Lefkovich matrix model to calculate total numbers of adult breeders, nonbreeders, immatures and juveniles for populations of albatrosses and large petrels from various island groups using demographic data (mean annual adult and juvenile/immature survival, breeding frequency [proportion of adults breeding each year], breeding success and age at first breeding). This was used to determine ratios of total population sizes, i.e., breeding adults, deferring (sabbatical) adults and pre-breeders (immatures and juveniles), to annual breeding pairs. We used the mean values of these ratios for annual and biennial species (2.71 and 3.40, respectively) to convert our collated totals for annual breeding pairs (if available) to total individuals worldwide, and in the Antarctic region. If data on annual breeding pairs were not available, we used the published values for total individuals, and estimated annual breeding pairs using the inverse of the correction factor. The estimated proportion of the global population of each seabird species that breeds in the Antarctic region was then calculated.

The proportions of time that the Antarctic populations of each species spend north of the APF during the breeding and nonbreeding seasons were then extracted or estimated from studies of at-sea distribution based on tracking data or at-sea observations (Marchant and Higgins, 1990; Brooke, 2004; Phillips *et al.*, 2004, 2005a,b, 2006; Tree and Klages, 2004; González-Solís *et al.*, 2007; Mackley *et al.*, 2010; Ropert-Coudert *et al.*, 2014; Borboroglu and Boersma, 2015; Navarro *et al.*, 2015; Carneiro *et al.*, 2016; Clay *et al.*, 2016; Delord *et al.*, 2016; Granroth-Wilding and Phillips, 2019). The number of days spent north of the APF (corresponding to duration of the nonbreeding season for annual breeders), and mean adult body mass (weighting means equally for each sex and site if data were available) were collated for Antarctic populations (Marchant and Higgins, 1990; Warham, 1990; Higgins and Davies, 1996; Casaux and Baroni, 2000; Phillips *et al.*, 2002, 2004, 2006; Brooke, 2004; Borboroglu and Boersma, 2015). Total numbers of birds that feed north or south of the APF during the breeding and nonbreeding seasons were then calculated. These numbers were then converted to (i) the total biomass of birds, based on mean adult body mass, and (ii) the total number of bird-days. Field metabolic rate ( $\text{kJ}\cdot\text{day}^{-1}$ ) was estimated from body mass using allometric equations for each order of seabirds provided in Shaffer *et al.* (2011), and used to convert from total bird-days for the Antarctic populations of each species, to energy required from food, allowing for a mean assimilation efficiency of 76%, which is in the mid-range of published values for seabirds (Jackson, 1986; Brekke and Gabrielsen, 1994; Hilton *et al.*, 2000). Finally, the tonnages of prey required north or south of the APF in the breeding and nonbreeding seasons by all the Antarctic populations of seabirds were calculated assuming a mean energy density of  $6 \text{ kJ}\cdot\text{g}^{-1}$  wet mass, which is intermediate between values for squid, crustacea and fish (Croxall and Prince, 1982; Lea *et al.*, 2002; Schaafsma *et al.*, 2018).

There are numerous caveats associated with the bioenergetics model, particularly the uncertainties in parameter values, including proportions of at-sea distributions that are north or south of the APF (especially for juveniles, immatures and deferring adults), seasonal variability in mass and field metabolic rate (FMR), typical prey calorific value (depending on diet) etc. - all of which may vary among species, populations, sexes, individuals and years - and the lack of information on breeding and total population sizes. However, the real values for most parameters in a given year - with the exception of some population-size estimates for burrow or crevice-nesting petrels - are unlikely to be more than  $\pm 20\%$  of the value that was used, and many of the errors would cancel out. Hence, although the numbers in **Supplementary Table 3** should be viewed with considerable caution, the totals are, nevertheless, highly likely to be of the correct order of magnitude. As such, large differences between values for the breeding and nonbreeding seasons, or for north and south of the APF, should be biologically meaningful.

### Estimating seasonal changes in baleen whale demand north and south of the Polar Front

Many populations of baleen whales show evidence of increases in population abundance following exploitation (Antarctic blue, southern right and humpback whales, Branch *et al.*, 2004; Jackson *et al.*, 2008; IWC, 2016). For these calculations we have used population estimates from 2015 as a reference year; where abundance estimates were not available for this year, we forward-projected from earlier abundance estimates, using population growth rates available for the species in question. Fin and sei whales are recovering from intense 20<sup>th</sup> century exploitation (Rocha Jr. *et al.*, 2014). Approximate estimates of abundance have been derived for these species in the Southern Hemisphere in earlier decades (Branch and Butterworth, 2001; IWC, 2001), but population growth rates are not available for these species in the Southern

Hemisphere in order to forward-project abundance estimates to 2015. Here, we forward-projected abundance estimates using conservative population growth estimates of 4%, using population demographic models derived for each species (Taylor *et al.*, 2007). It remains uncertain whether Antarctic minke whales are changing in abundance over time, since they were not heavily exploited during the commercial whaling period; for this species, we used the last available abundance estimate, and assumed a stationary population size over time (IWC, 2013). Total Southern Ocean abundance estimates for all cetaceans included three additional cetacean species (killer whales, southern bottlenose and sperm whales), as estimated by (Branch and Butterworth, 2001) and were assumed to be stationary over time (**Supplementary Table 4**).

To estimate the abundance range we used the estimated confidence intervals where available. For fin and sei whales we used  $\pm 1$  standard deviation based on the estimate of CV. Adjusting for the population demographics of each recovering population is beyond the scope of this study. Given the larger uncertainties elsewhere in the calculations we used adult male body mass in the calculations (Reilly *et al.*, 2004; Tamura and Konishi, 2009), assuming that this provides a reasonable estimate of the mean mass of whales in the population (males, females and juveniles).

For most species we used whale summer consumption rates from Reilly *et al.* (2004), selecting low and high case consumption scenarios. The low case was derived from a revised form of the feeding rate model of (Innes *et al.*, 1986) and the high case assumed daily whale consumption rates during the summer feeding period of 2.5% of body mass (**Supplementary Table 4**). For Antarctic minke whale consumption rates we used estimates from (Tamura and Konishi, 2009). In all cases, we assumed a summertime presence in the Southern Ocean spanning 120 days.

To provide an estimate of the range of the potential demand for prey during winter we use two estimates of the total food intake of baleen whales outside of the summer feeding period, as a proportion of the total annual prey demand i. 17% (Lockyer, 1981), ii. 34% (double the estimate of (Lockyer, 1981)). We assume that 10% of animals remain south of the APF in winter. This is based on very limited observational data. We also assume that the animals that remain south in winter feed at the same rate as animals wintering in the northern latitudes. In southern regions this is likely to be a conservative estimate.

## Supplementary Tables

**Supplementary Table 1.** Ocean exchange processes.

| Exchange processes                 | Characteristics                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | References                                                                                                                                                                                                                                                                                                                                                                            |
|------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Antarctic Bottom Water AABW</b> | <p>Major driver of global thermohaline circulation</p> <p>Few regions close to the continent in the Weddell Sea, Ross Sea and East Antarctic that are major areas of formation of deep AABW</p> <p>Recent studies have examined routes of outflow from the Southern Ocean and demonstrated change and marked variability in volume and heat transfers out of the Southern Ocean.</p> <p>Model studies indicate extensive mixing of AABW within the Southern Ocean indicating that regional signals of change in a particular formation region will be integrated within the wider AABW before being transferred into all the ocean basins. ~70% flows in at least one circumpolar loop.</p> <p>There are outflows of AABW in each of the major ocean basins, but flows east of New Zealand and the Kerguelan Plateau are particularly important.</p> <p>Transfers across ACC with either deep western boundary currents or with locations of enhanced cross-jet mixing in the upper ocean.</p> <p>AABW stores carbon (and heat) in the abyss, isolated from surface processes potentially for several centuries.</p> | <p>Orsi <i>et al.</i>, 1999; Turner <i>et al.</i>, 2009; Meijers <i>et al.</i>, 2010; Marshall and Speer, 2012; Pardo <i>et al.</i>, 2012; Talley, 2013; van Sebille <i>et al.</i>, 2013; de Lavergne <i>et al.</i>, 2017; MacGilchrist <i>et al.</i>, 2019; Ferster <i>et al.</i>, 2018; Purkey <i>et al.</i>, 2018; Rintoul, 2018; Abrahamsen <i>et al.</i>, 2019; Gordon, 2019</p> |
| <b>Circumpolar Deep Water CDW</b>  | <p>At intermediate depths (~1000-3000m), southward flows and upwelling of deep water forming upper (UCDW) and lower (LCDW) are also heterogeneous.</p> <p>Deep waters spiral towards the south east as they flow around the continent in the ACC while also moving upwards to shallower depths, upwelling particularly in areas south of 60°S along the west Antarctic Peninsula and Amundsen Sea Shelf.</p> <p>Pacific Deep Water (PDW), Indian Ocean Deep Water (IDW) and North Atlantic Deep Water (NADW) all flow southwards and upwell in the Southern Ocean.</p> <p>There is some mixing of deep waters from the different basins to form CDW, but the different origin deep waters have different characteristics and pathways of flow.</p>                                                                                                                                                                                                                                                                                                                                                                   | <p>Turner <i>et al.</i>, 2009; Garzoli and Matano, 2011; Marshall and Speer, 2012; Talley, 2013; Dufour <i>et al.</i>, 2015; Foppert <i>et al.</i>, 2017; Tamsitt <i>et al.</i>, 2017; Tanhua <i>et al.</i>, 2017; Drake <i>et al.</i>, 2018; Hauck <i>et al.</i>, 2018; Rintoul, 2018; Foppert <i>et al.</i>, 2019</p>                                                               |

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|                                                 | <p>Stronger inflows in the deep western boundary currents of each of the ocean basins (particularly east of South America, South Africa and in the western South Pacific east of New Zealand and in areas of topographic ridges. Southward flows in the eastern regions, particularly in the South Atlantic in the region influenced by the Aghulas Current.</p> <p>The dominant contribution of deep water into the ACC is from the Atlantic through the southward flow of NADW in the Western Boundary Current east of the Patagonian shelf.</p> <p>Upwelling and southward flow of NADW into southern continental regions is the major contributor of circumpolar deep water (LCDW) into the regions of formation of denser bottom water formation including AABW.</p> <p>The Pacific Deep Water and Indian Ocean Deep Water that enters the Southern Ocean is generally lighter and so lies above NADW as UCDW.</p> <p>Deep waters can also contribute to the formation of AABW, but they are also freshened and warmed as they flow northwards into the subduction regions of formation of AAIW and SAMW.</p> <p>There are areas of particularly intense upwelling and mixing associated with major topographic features such as Drake Passage and the Scotia arc, Southwest Indian Ridge, Kerguelen Plateau, Macquarie Ridge and Pacific-Antarctic Ridge, where the current flow interactions with the bathymetry results in increased eddy activity and north-south exchanges.</p> <p>Intense flow-bathymetry interactions result in north-south displacements of the flow and cross frontal exchanges, which in northern regions, will transport surface waters north or south out of or into the Southern Ocean.</p> <p>Some of the LCDW circulating in the ACC may also enter the Indian and Pacific Oceans, mix with lighter waters and re-enter the Southern Ocean as IDW or PDW.</p> |                                                                                                                                                                                                           |
| <b>Subduction</b><br><b>AAIW</b><br><b>SAMW</b> | <p>Formation of mode waters (AAIW and SAMW) is heterogeneous around the Southern Ocean, with the major regions of formation across the Pacific and Indian Ocean sectors.</p> <p>These “subduction hotspots” have different efficiencies in transporting water out of the Southern Ocean. This heterogeneity in formation appears to generate restricted regions of enhanced northward current flow of subducted waters in the Southern Hemisphere.</p> <p>These regions are strongest in the east and west boundary current regions of the Indian and Pacific Oceans, with some northward flow east of South America.</p> <p>The processes of subduction also show interannual variability associated with Southern Hemisphere atmospheric variability (e.g. associated with SAM and ENSO), directly through atmospheric changes or indirectly through advection of freshwater anomalies associated with sea ice melt, generating variations in SAMW formation rates and properties (including nutrient concentrations).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | <p>Turner <i>et al.</i>, 2009; Ayers and Strutton, 2013; Jones <i>et al.</i>, 2016; Tamsitt <i>et al.</i>, 2017; Gao <i>et al.</i>, 2018; Cerovecki <i>et al.</i>, 2019; Meijers <i>et al.</i>, 2019a</p> |

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|                          | <p>This is likely to generate major variations between years in the amount of subducted water and in the strength of northward flowing currents.</p> <p>The time scale of subduction transfers in the opposite direction varies in the different ocean basins, with model estimates indicating more than 50% of the mode water reaches the subtropical thermocline (<math>\sim 25^{\circ}\text{S}</math>) within 50 years.</p> <p>The time scales for exchange of deep waters from the sub-tropical regions to the surface Southern Ocean is decades to a century, with half of the deep water from <math>30^{\circ}\text{S}</math> upwelling to the mixed layer in <math>\sim 60\text{--}90</math> years.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>Eddies</b>            | <p>Mesoscale eddies are a dominant feature of circulation in the Southern Ocean and play a fundamental role in the transport of water along and across the ACC.</p> <p>The sites of large topographic deflections and meanders are generally associated with intense shedding of mesoscale eddies.</p> <p>Formation, direction of rotation, and movement and longevity of the eddies vary in different Southern Ocean regions.</p> <p>Physical properties and influence vary with depth and may penetrate to <math>&gt;2000\text{m}</math>.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | <p>Venables <i>et al.</i>, 2012;<br/> Dufour <i>et al.</i>, 2015;<br/> Frenger <i>et al.</i>, 2015;<br/> Foppert <i>et al.</i>, 2017;<br/> Tamsitt <i>et al.</i>, 2017; Della<br/> Penna <i>et al.</i>, 2018; Frenger<br/> <i>et al.</i>, 2018; Rintoul, 2018;<br/> Tamsitt <i>et al.</i>, 2018;<br/> Foppert <i>et al.</i>, 2019</p>                                                                                                                                                                                                                                                                                                                                                                           |
| <b>Surface exchanges</b> | <p>Transfers of surface waters into and out of the Southern Ocean vary regionally associated with the eastward ACC flow and Ekman transport, Stokes drift and eddy activity and drift associated with sea ice during winter.</p> <p>In some areas, Ekman driven circulation transports surface waters northwards out of the Southern Ocean. These flows are mainly associated with the eastward drift of the main Southern Hemisphere ocean gyres, moving waters eastward and northward in eastern boundary regions.</p> <p>The major exception is in the area around southern Africa, where the Agulhas retroflection plays a major role moving waters to the west from the Indian Ocean into the Atlantic, where they join northward flowing waters in the Benguela Current region.</p> <p>Surface waters can also cross the PFZ southwards to enter the Southern Ocean as a result of storm driven mixing, surface waves (Stokes Drift) and mesoscale eddies. These waters spiral south-eastward as they flow around the continent in the ACC, similar to the deep water currents.</p> <p>These surface water cross-frontal exchange processes will be affected by variations in atmospheric processes, wind stress and eddy activity, particularly in areas of strong topographic-flow interactions. These surface flow patterns will also show seasonal variation associated with changing atmospheric conditions and sea ice distribution and drift.</p> <p>These processes are highly variable and can generate rapid transfers over large distances into or out the Southern Ocean over periods of weeks to months or they may take years or even decades depending on the variation in rates of retention</p> | <p>Ito <i>et al.</i>, 2010; Garzoli<br/> and Matano, 2011;<br/> Holland and Kwok, 2012;<br/> Lumpkin and Johnson,<br/> 2013; Dufour <i>et al.</i>, 2015;<br/> Abernathey <i>et al.</i>, 2016;<br/> Haumann <i>et al.</i>, 2016;<br/> Hobbs <i>et al.</i>, 2016; Kwok<br/> <i>et al.</i>, 2017; Tamsitt <i>et al.</i>,<br/> 2017; Venkatachalam <i>et al.</i>,<br/> 2017; Ferster <i>et al.</i>,<br/> 2018; Fraser <i>et al.</i>, 2018;<br/> Pauthenet <i>et al.</i>, 2018;<br/> Rintoul, 2018; Ceroveck<br/> <i>et al.</i>, 2019; MacGilchrist<br/> <i>et al.</i>, 2019; Meijers <i>et al.</i>,<br/> 2019a; Meijers <i>et al.</i>,<br/> 2019b; Roach and Speer,<br/> 2019; Chapman <i>et al.</i>,<br/> 2020</p> |

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|  | <p>and directions of drift and interaction with winter sea ice. These rates and their temporal and spatial variabilities are poorly quantified.</p> <p>Model studies have examined and attempted to quantify volume transports between ocean basins. Analyses of the ECCO mode 24-yr time-mean depth-integrated residual volume transports across each of the basins suggest that surface and mode water flows (30°S) are similar in the Atlantic and Pacific with southward flows of the same order in the Indian Ocean. Northward flows in the Atlantic are dominated by these upper and mode water flows rather than the bottom water flows which are much greater in the Pacific. In contrast deep water southward flows are much stronger in the Atlantic.</p> <p>Although the PFZ is an important biogeographic boundary, it is variable and dynamic and in some areas there are strong cross frontal exchanges.</p> <p>In a number of areas the location of the Polar Front is strongly constrained by large topographic features, while in other regions its position is more variable. This variability smears the signature of the front over a broad area, which can also separate the surface thermal and salinity signature of the front from the deeper, potentially more constrained position.</p> <p>The dynamic and variable nature of the front and the associated mesoscale eddy activity, along with wind and storm driven processes of Ekman and Stokes drift can enhance cross frontal exchanges of energy, heat and water mass properties.</p> <p>Regional processes are also important in influencing north-south exchanges across, into and out of the Southern Ocean. Localised processes of upwelling and circulation modify waters masses, in areas of the Ross Sea, Weddell Sea and Scotia Sea and around the Antarctic Peninsula and regions of major topographic features such as the Kerguelen Plateau, which in turn affect wider circulation processes across the Southern Ocean.</p> <p>A series of recent studies have highlighted the importance of interactions between sea and surface ocean processes in Southern Ocean circulation, sea ice dynamics and ocean and ice variability. Sea ice forms each winter over an area of between <math>\sim 17</math> and <math>20 \times 10^6 \text{ km}^2</math> at the maximum extent, extending out over a large area of the ACC. The circumpolar distribution is patchy, with major areas of sea ice formation in southern regions, particular in areas of the Weddell, Ross Sea and Prydz Bay associated with the generation of cold dense AABW.</p> <p>Both surface ocean currents and wind stress affect directions and rates of drift of sea ice across the Southern Ocean. The circulation of the Weddell and Ross Sea gyres is important in the northward drift and extensive northern winter ice extent in regions of the Atlantic and Pacific sectors respectively.</p> <p>This northward extension and drift during autumn and winter transports freshwater, elements and material northwards from high latitude regions across the ACC and north-eastwards to lower latitudes and towards the Polar Frontal Zone. Each summer, melting ice inputs freshwater and other ice associated elements and material across the ACC.</p> <p>These processes vary regionally and interannually associated with oceanographic and atmospheric variability.</p> |  |
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**Supplementary Table 2.** Major scales over which Southern Ocean organisms move and the major dispersal processes and interactions which determine distributions.

| <b>Movement</b>                 | <b>Movement scale</b>                  | <b>Dispersal processes</b>                                                                                                                                                                                                                                                                             | <b>Organisms and movement processes</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|---------------------------------|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Passive dispersal</b>        | <b>fine-scale</b><br>< 10s to 100s m   | <p>Dispersal dominated by transport in ocean currents (drift) and modified by horizontal and vertical movements/interactions.</p> <p>Speed and directions of dispersal are dominated by physical flows.</p> <p>Small to large organisms can undertake fine scale behavioural movements (swimming).</p> | <p>Microbial organisms: pico (&lt;2 <math>\mu\text{m}</math>), nano (2–20 <math>\mu\text{m}</math>), and micro (20–200 <math>\mu\text{m}</math>) plankton.</p> <p>Mesoplankton (0.2 – 20 mm) and macro- (.02 - .2 m) and megaplankton (.2 -2 m).</p> <p>Horizontal and vertical movements influenced by morphological adaptations and physiological and behavioural processes (e.g. movement/swimming).</p> <p>Includes bacteria, phytoplankton, zooplankton (including copepods and krill) and nekton from early life cycle stages (fish and cephalopods) to adults (jellyfish)</p> |
| <b>Mixed passive and active</b> | <b>sub-mesoscale</b><br>1 km to 10s km | <p>Ocean current flows (drift) dominate overall dispersal.</p> <p>Dispersal modified by horizontal and vertical movements/interactions.</p> <p>Some directed (sub-mesoscale) movements/interactions occur.</p> <p>These may be restricted to particular stages of the life cycle.</p>                  | <p>Macro- (.02 - .2m) and megaplankton (.2 -2 m) and nekton.</p> <p>Vertical migration patterns of fish and cephalopods - daily and seasonally.</p> <p>Migration movements of fish and cephalopods.</p> <p>Life-cycle development linked migration – e.g. mesopelagic fish movements or movement of Antarctic krill to deep waters for spawning.</p> <p>Foraging activity of some seabirds and marine mammals.</p>                                                                                                                                                                   |
| <b>Active</b>                   | <b>mesoscale</b><br>10s to 200 km      | <p>Dispersal dominated by foraging and migratory movements/interactions.</p> <p>These may involve interactions with local and regional ocean currents or atmospheric circulation patterns.</p>                                                                                                         | <p>Seabirds and marine mammals, e.g. some penguin species and seals during the breeding season.</p> <p>Foraging movements.</p> <p>Movements may be limited to areas close to coastal shelves during summer or in areas adjacent to frontal zones.</p> <p>Dispersal patterns outside of breeding season of some species (e.g. penguins).</p>                                                                                                                                                                                                                                          |
| <b>Active</b>                   | <b>large-scale</b><br>> 200 km         | <p>Dispersal dominated by foraging and migratory movements/interactions.</p> <p>These may involve interactions with local, regional and global ocean currents or atmospheric circulation patterns.</p>                                                                                                 | <p>Seabirds and marine mammals, e.g. foraging trips of some Albatross species and seasonal dispersal and migration patterns of a range of seabirds and marine mammals.</p> <p>Movements over oceanic regions resulting in major seasonal changes in distribution within and in/out of the Southern Ocean.</p>                                                                                                                                                                                                                                                                        |

**Supplementary Table 3.** Proportion of at-sea distributions, biomass (in tonnes) and prey demand (in tonnes) north and south of the Antarctic Polar Front (APF) during the breeding and nonbreeding seasons of Antarctic seabird populations (see **Supplementary Methods** above for further details).

| Species                        | Global pop.<br>(individuals) | Antarctic<br>pop.<br>(individuals) | Prop.<br>distrib. Nth<br>of APF<br>(nonbr.<br>season) | Prop.<br>distrib.<br>Nth of<br>APF (br.<br>season) | Biomass<br>Nth of<br>APF<br>(nonbr.<br>season) | Biomass<br>Nth of<br>APF (br.<br>season) | Biomass<br>Sth of APF<br>(nonbr.<br>season) | Biomass<br>Sth of<br>APF (br.<br>season) | Prey demand<br>Nth of APF<br>(nonbr.<br>season) | Prey<br>demand Nth<br>of APF (br.<br>season) | Prey<br>demand<br>Sth of<br>APF<br>(nonbr.<br>season) | Prey<br>demand<br>Sth of<br>APF<br>(br.<br>season) |
|--------------------------------|------------------------------|------------------------------------|-------------------------------------------------------|----------------------------------------------------|------------------------------------------------|------------------------------------------|---------------------------------------------|------------------------------------------|-------------------------------------------------|----------------------------------------------|-------------------------------------------------------|----------------------------------------------------|
| Antarctic prion                | 50000000                     | 59620000                           | 0.90                                                  | 0.00                                               | 8131.9                                         | 0.0                                      | 903.5                                       | 9035.4                                   | 1235098                                         | 0                                            | 137233                                                | 686165                                             |
| Antarctic petrel               | 15000000                     | 15000000                           | 0.02                                                  | 0.00                                               | 220.5                                          | 0.0                                      | 10804.5                                     | 11025.0                                  | 23109                                           | 0                                            | 1132319                                               | 577714                                             |
| Wilson's storm<br>petrel       | 20000000                     | 10840000                           | 1.00                                                  | 0.00                                               | 376.7                                          | 0.0                                      | 0.0                                         | 376.7                                    | 80873                                           | 0                                            | 0                                                     | 40436                                              |
| Common diving<br>petrel        | 16000000                     | 10298000                           | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 1584.9                                      | 1584.9                                   | 0                                               | 0                                            | 0                                                     | 359769                                             |
| Adélie penguin                 | 10270900                     | 10270900                           | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 46681.2                                     | 46681.2                                  | 0                                               | 0                                            | 0                                                     | 2826921                                            |
| Chinstrap penguin              | 7454858                      | 7454858                            | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 29543.6                                     | 29543.6                                  | 0                                               | 0                                            | 0                                                     | 1867758                                            |
| Macaroni penguin               | 17102263                     | 5611804                            | 0.26                                                  | 0.00                                               | 6516.1                                         | 0.0                                      | 18260.0                                     | 24776.1                                  | 199107                                          | 0                                            | 557955                                                | 757063                                             |
| South Georgia<br>diving petrel | 15000000                     | 5420000                            | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 639.0                                       | 639.0                                    | 0                                               | 0                                            | 0                                                     | 154433                                             |
| Snow petrel                    | 4000000                      | 4000000                            | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 1228.2                                      | 1228.2                                   | 0                                               | 0                                            | 0                                                     | 237032                                             |
| White-chinned<br>petrel        | 3144012                      | 2095237                            | 1.00                                                  | 0.30                                               | 2797.1                                         | 839.1                                    | 0.0                                         | 1958.0                                   | 191086                                          | 57326                                        | 0                                                     | 133760                                             |
| Cape petrel                    | 2000000                      | 1800000                            | 0.20                                                  | 0.05                                               | 166.9                                          | 41.7                                     | 667.4                                       | 792.6                                    | 14616                                           | 3654                                         | 58465                                                 | 69427                                              |
| King penguin                   | 4336000                      | 1436300                            | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 17379.2                                     | 17379.2                                  | 0                                               | 0                                            | 0                                                     | 773878                                             |
| Southern fulmar                | 1084000                      | 1084000                            | 0.20                                                  | 0.05                                               | 173.9                                          | 43.5                                     | 695.5                                       | 825.9                                    | 17852                                           | 2232                                         | 71409                                                 | 42399                                              |
| Emperor penguin                | 644980                       | 644980                             | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 17742.3                                     | 17742.3                                  | 0                                               | 0                                            | 0                                                     | 610458                                             |
| Gentoo penguin                 | 1048770                      | 603040                             | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 3638.1                                      | 3638.1                                   | 0                                               | 0                                            | 0                                                     | 201571                                             |
| Black-browed<br>albatross      | 1872735                      | 202968                             | 0.80                                                  | 0.30                                               | 545.0                                          | 204.4                                    | 136.3                                       | 476.9                                    | 10819                                           | 5680                                         | 2705                                                  | 13254                                              |
| Blue petrel                    | 3000000                      | 189700                             | 0.10                                                  | 0.00                                               | 3.7                                            | 0.0                                      | 33.6                                        | 37.3                                     | 533                                             | 0                                            | 4799                                                  | 2666                                               |
| Grey-headed<br>albatross       | 333486                       | 162092                             | 0.55                                                  | 0.15                                               | 293.3                                          | 80.0                                     | 240.0                                       | 453.4                                    | 7033                                            | 1918                                         | 5754                                                  | 10869                                              |
| Black-bellied storm<br>petrel  | 500000                       | 135500                             | 1.00                                                  | 0.00                                               | 7.6                                            | 0.0                                      | 0.0                                         | 7.6                                      | 1279                                            | 0                                            | 0                                                     | 913                                                |
| Antarctic tern                 | 120473                       | 107723                             | 0.50                                                  | 0.00                                               | 9.0                                            | 0.0                                      | 9.0                                         | 18.1                                     | 1006                                            | 0                                            | 1006                                                  | 2012                                               |
| Southern giant<br>petrel       | 137719                       | 65292                              | 0.10                                                  | 0.10                                               | 29.0                                           | 29.0                                     | 260.9                                       | 260.9                                    | 1244                                            | 1742                                         | 11199                                                 | 15678                                              |
| Northern giant<br>petrel       | 58758                        | 41729                              | 0.35                                                  | 0.10                                               | 63.0                                           | 18.0                                     | 117.0                                       | 162.0                                    | 2722                                            | 1089                                         | 5056                                                  | 9800                                               |
| Antarctic shag                 | 31664                        | 31664                              | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 92.3                                        | 92.3                                     | 0                                               | 0                                            | 0                                                     | 10497                                              |
| Southern<br>rockhopper penguin | 3264325                      | 27100                              | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 80.8                                        | 80.8                                     | 0                                               | 0                                            | 0                                                     | 5584                                               |
| South polar skua               | 25745                        | 25745                              | 1.00                                                  | 0.00                                               | 30.0                                           | 0.0                                      | 0.0                                         | 30.0                                     | 2211                                            | 0                                            | 0                                                     | 1105                                               |

| Species                  | Global pop.<br>(individuals) | Antarctic<br>pop.<br>(individuals) | Prop.<br>distrib. Nth<br>of APF<br>(nonbr.<br>season) | Prop.<br>distrib.<br>Nth of<br>APF (br.<br>season) | Biomass<br>Nth of<br>APF<br>(nonbr.<br>season) | Biomass<br>Nth of<br>APF (br.<br>season) | Biomass<br>Sth of APF<br>(nonbr.<br>season) | Biomass<br>Sth of<br>APF (br.<br>season) | Prey demand<br>Nth of APF<br>(nonbr.<br>season) | Prey<br>demand Nth<br>of APF (br.<br>season) | Prey<br>demand<br>Sth of<br>APF<br>(nonbr.<br>season) | Prey<br>demand<br>Sth of<br>APF<br>(br.<br>season) |
|--------------------------|------------------------------|------------------------------------|-------------------------------------------------------|----------------------------------------------------|------------------------------------------------|------------------------------------------|---------------------------------------------|------------------------------------------|-------------------------------------------------|----------------------------------------------|-------------------------------------------------------|----------------------------------------------------|
| South Georgia shag       | 22626                        | 22626                              | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 60.6                                        | 60.6                                     | 0                                               | 0                                            | 0                                                     | 6452                                               |
| Light-mantled Albatross  | 41079                        | 18190                              | 0.15                                                  | 0.05                                               | 8.4                                            | 2.8                                      | 47.5                                        | 53.1                                     | 205                                             | 68                                           | 1163                                                  | 1300                                               |
| Kelp gull                | 45000                        | 10705                              | 0.10                                                  | 0.00                                               | 1.1                                            | 0.0                                      | 9.9                                         | 11.0                                     | 0                                               | 0                                            | 0                                                     | 1263                                               |
| Brown Skua               | 21680                        | 8130                               | 0.80                                                  | 0.00                                               | 12.2                                           | 0.0                                      | 3.0                                         | 15.2                                     | 783                                             | 0                                            | 196                                                   | 490                                                |
| Wandering albatross      | 28421                        | 4828                               | 0.80                                                  | 0.80                                               | 33.7                                           | 33.7                                     | 8.4                                         | 8.4                                      | 395                                             | 790                                          | 99                                                    | 197                                                |
| Fairy prion              | 5000000                      | 2710                               | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 0.2                                         | 0.2                                      | 0                                               | 0                                            | 0                                                     | 44                                                 |
| Grey-backed storm petrel | 200000                       | 1355                               | 0.00                                                  | 0.00                                               | 0.0                                            | 0.0                                      | 0.0                                         | 0.0                                      | 0                                               | 0                                            | 0                                                     | 15                                                 |
| <b>Total</b>             |                              |                                    |                                                       |                                                    | 19419                                          | 1292                                     | 150867                                      | 168994                                   | 1789971                                         | 74498                                        | 1989357                                               | 9420924                                            |

**Supplementary Table 4.** Estimates of abundance, biomass and prey consumption during summer of populations of six species of whales (see **Supplementary Methods** above for further details).

| Common Name                   | Scientific name                       | Abundance Southern Ocean (CL or CV) Base year           | Body mass adult male (kg) from Reilly <i>et al.</i> , (2004) | Total biomass in Southern Ocean in 2015 (tonnes) | C1 Consumption rates Innes <i>et al.</i> , (2018) revised by Reilly <i>et al.</i> (2004) kg/day | C2 Consumption rates 2.5% of body mass, Reilly <i>et al.</i> (2004) kg/day | consumption summer (120 days at daily rate C1) (10 <sup>6</sup> tonnes) | consumption summer (120 days at daily rate C2) (10 <sup>6</sup> tonnes) | References and notes                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-------------------------------|---------------------------------------|---------------------------------------------------------|--------------------------------------------------------------|--------------------------------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Humpback whale                | <i>Megaptera novaeangliae</i>         | 96675 <sup>1</sup><br>(78041-117527)<br>2015            | 26924                                                        | 2.60                                             | 497.23                                                                                          | 785.96                                                                     | 5.77                                                                    | 9.12                                                                    | <sup>1</sup> Estimates from summary of IWC Comprehensive Assessment of humpback whales (IWC, 2016)                                                                                                                                                                                                                                                                                                                                                                                    |
| Southern right whale          | <i>Eubalaena australis</i>            | 28378 <sup>2</sup><br>(15034-49779)<br>2015             | 55880                                                        | 1.35 <sup>3</sup>                                | 747.87                                                                                          | 1471.63                                                                    | 2.55                                                                    | 5.01                                                                    | <sup>2</sup> Derived from circumglobal population trajectory (IWC, 2001) trajectory;<br><br><sup>3</sup> Assumes 85% of southern right whales are south of APF during summer, since they use high and low-latitude feeding grounds. This proportion is derived from (Valenzuela <i>et al.</i> , 2018) isotope signatures of 196 whales at Peninsula Valdez, of which 29 had a Patagonian Shelf signature and the rest had spent at least part of the season south of the polar front. |
| Antarctic blue whale          | <i>Balaenoptera musculus musculus</i> | 7040 <sup>4</sup><br>(1177-17906)<br>2015               | 84328                                                        | 5.94E+05                                         | 941.3                                                                                           | 2095.63                                                                    | 7.95E+05                                                                | 1.77                                                                    | <sup>4</sup> Estimates from the Antarctic blue whale population assessment trajectory (Branch, 2008).                                                                                                                                                                                                                                                                                                                                                                                 |
| Antarctic minke               | <i>Balaenoptera bonaerensis</i>       | 515500 <sup>5</sup><br>(361000-733000)<br>1992/3-2003/4 | 6800 <sup>6</sup>                                            | 3.51                                             | 102 <sup>6</sup>                                                                                | 476 <sup>6</sup>                                                           | 6.31                                                                    | 2.94E+07                                                                | <sup>5</sup> Circumpolar estimate agreed by IWC (IWC, 2013). Assumed no significant trend in abundance over time.<br><br><sup>6</sup> Body mass and consumption rates from Tamura and Konishi (2006). Stomach contents analysis used to infer daily summer prey consumption as between 4.36-4.95% of body mass. Here we used 1.5% as lower case, 7% as upper case.                                                                                                                    |
| Southern Hemisphere fin whale | <i>Balaenoptera physalus</i>          | 17608 <sup>7</sup><br>(CV = 0.58)<br>2015               | 48768                                                        | 8.59E+05                                         | 693.07                                                                                          | 1309.22                                                                    | 1.46                                                                    | 2.77                                                                    | <sup>7</sup> (Branch and Butterworth, 2001) estimated 8036 (CV=0.58) for the third IDCR-SOWER survey (midpoint 1995), including extrapolation to comparable areas and "like fin whale" species. This estimate does not include a correction for surface availability (g(0)). Very likely to be a                                                                                                                                                                                      |

|                               |                              |                                          |       |                 |        |       |              |              |                                                                                                                                                                                                                                                                                                                                                                      |
|-------------------------------|------------------------------|------------------------------------------|-------|-----------------|--------|-------|--------------|--------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                               |                              |                                          |       |                 |        |       |              |              | significant underestimate. Forward projected to 2015 at 4% per annum, using growth rate derived from demographic models (Taylor <i>et al.</i> , 2007).                                                                                                                                                                                                               |
| Southern Hemisphere sei whale | <i>Balaenoptera borealis</i> | 1972 <sup>8</sup><br>(CV = 0.51)<br>2015 | 17780 | 3.51E+04        | 394.29 | 550.3 | 9.33E+04     | 1.30E+05     | <sup>8</sup> Unpublished abundance estimate from (Branch and Butterworth, 2000), reported in (IWC, 2001) calculates 900 whales (CV=0.51) but estimates not extrapolated to comparable (unsurveyed) areas and data were sparse. Estimate, forward projected to 2015 at 4% per annum, using growth rate derived from demographic models (Taylor <i>et al.</i> , 2007). |
| <b>Totals</b>                 |                              | 667173                                   |       | <b>8.95E+06</b> |        |       | <b>16.98</b> | <b>48.24</b> |                                                                                                                                                                                                                                                                                                                                                                      |

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