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Global Drivers on Southern Ocean Ecosystems: Changing Physical Environments and Anthropogenic Pressures in an Earth System

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The manuscript assesses the current and expected future global drivers of Southern Ocean (SO) ecosystems. Atmospheric ozone depletion over the Antarctic since the 1970s, has been a key driver, resulting in springtime cooling of the stratosphere and intensification of the polar vortex, increasing the frequency of positive phases of the Southern Annular Mode (SAM). This increases warm air-flow over the East Pacific sector (Western Antarctic Peninsula) and cold air flow over the West Pacific sector. SAM as well as El Niño Southern Oscillation events also affect the Amundsen Sea Low leading to either positive or negative sea ice anomalies in the west and east Pacific sectors, respectively. The strengthening of westerly winds is also linked to shoaling of deep warmer water onto the continental shelves, particularly in the East Pacific and Atlantic sectors. Air and ocean warming has led to changes in the cryosphere, with glacial and ice sheet melting in both sectors, opening up new ice free areas to biological productivity, but increasing seafloor disturbance by icebergs. The increased melting is correlated with a salinity decrease particularly in the surface 100 m. Such processes could increase the availability of iron, which is currently limiting primary production over much of the SO. Increasing CO₂ is one of the most important SO anthropogenic drivers and is likely to affect marine ecosystems in the coming decades. While levels of many pollutants are lower than elsewhere, persistent organic pollutants (POPs) and plastics have been detected in the SO, with concentrations likely enhanced by migratory

species. With increased marine traffic and weakening of ocean barriers the risk of the establishment of non-indigenous species is increased. The continued recovery of the ozone hole creates uncertainty over the reversal in sea ice trends, especially in the light of the abrupt transition from record high to record low Antarctic sea ice extent since spring 2016. The current rate of change in physical and anthropogenic drivers is certain to impact the Marine Ecosystem Assessment of the Southern Ocean (MEASO) region in the near future and will have a wide range of impacts across the marine ecosystem.

Keywords: Southern Annular Mode, ozone hole, cryosphere and climate change, biogeochemistry, carbon dioxide, non-indigenous species, warming, freshening

INTRODUCTION

The Southern Ocean (SO) physical environment is shaped by permanent cold and predictable seasonal cycles. However, despite its relative isolation within the Antarctic Circumpolar Current (ACC) inter-annual variation of the SO is strongly influenced through atmospheric and oceanic teleconnections. In an era of rapid climate change it is vital to identify the global drivers of the SO marine ecosystems. It is important to understand the regions within the SO where their effects are greatest, the expected impacts of any changes in these drivers, and crucially their interactions. For the working group, Marine Ecosystem Assessment of the SO (MEASO), global drivers are classified as those that influence the whole of the SO, even though their effects may manifest more strongly in some regions than others. Local drivers are defined as those that influence a particular location or series of locations within the SO (Grant et al., to be published in this research topic). While there is a global demand for protein to feed the ever increasing human population, southern ocean fisheries have regional impacts on stocks and ecosystems. A key difference is that local drivers can be managed with local interventions, e.g., regional regulation of fisheries. Yet, global drivers can only be managed externally to the region, e.g., climate change, ozone and plastic. Global tourism is driven by global drivers such as increasing wealth and demand for wilderness experiences. However, the regional impacts of tourism can also be managed through local regulation. Tourism therefore appears as both a global and local driver.

The manuscript outlines the global phenomena that impact the SO now and are expected to continue to impact it in the future. Atmospheric drivers considered here include changes in ozone, trends in Southern Annular Mode (SAM), variability in El Niño Southern Oscillation (ENSO), elevated air and ocean temperatures and ongoing increases in atmospheric CO₂. Global oceanic connections considered here include the global thermohaline (overturning) circulation as well as changes in the SO, including eddies currents and the exchange of water masses (Figure 1). Other global anthropogenic drivers include pollution and tourism.

These drivers, and their interactions, affect a range of attributes of the SO environment. Those considered here are: the cryosphere including marine ice, ice shelves and glaciers as well as salinity. For the purposes of MEASO the SO is separated into five sectors and three zones (Figure 2)

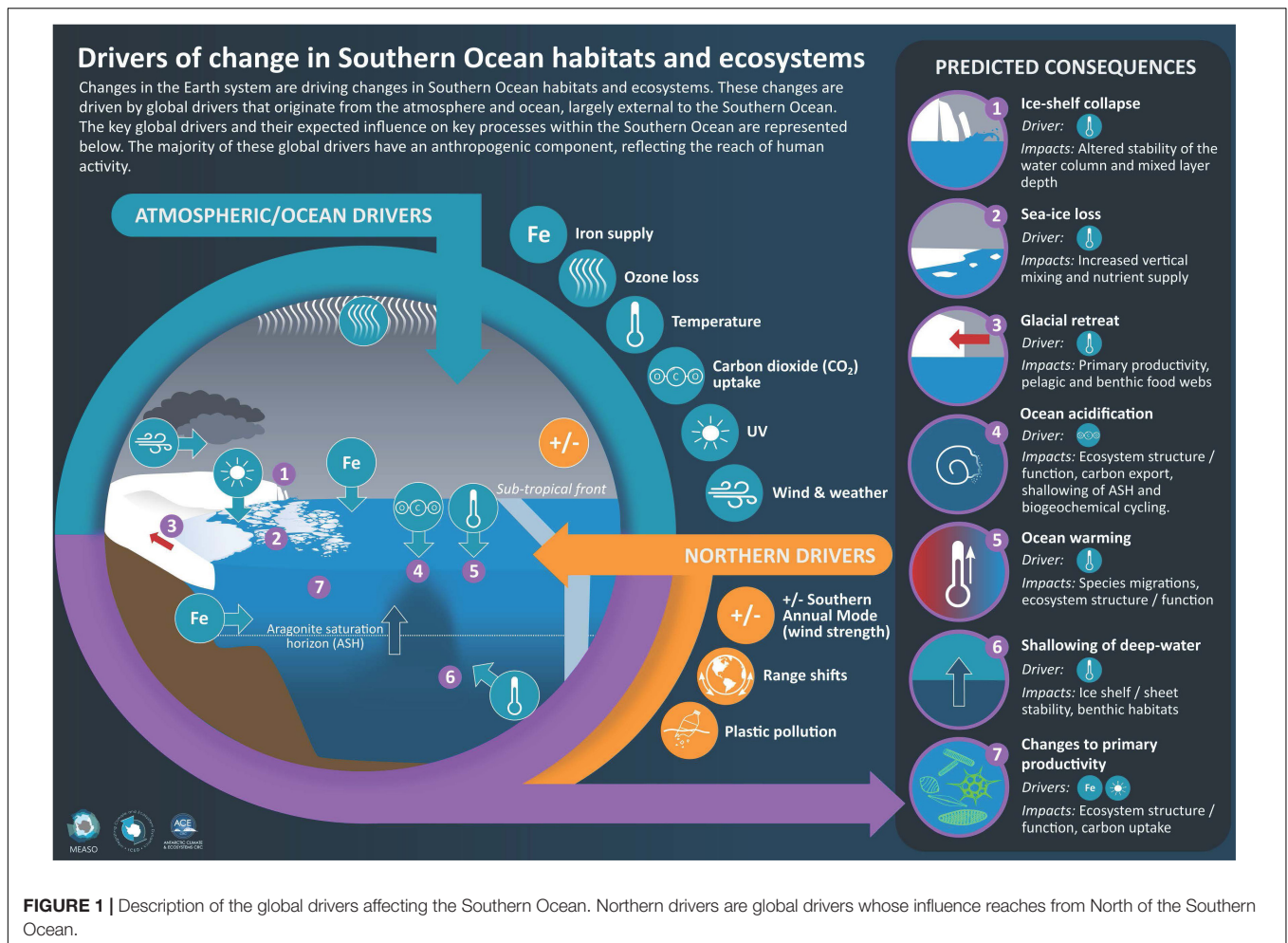
The majority of the biological consequences within pelagic and benthic marine ecosystem are discussed in the specific MEASO biota papers (as described in Constable et al., 2014 to be published in this research topic), but the impact of changes in the biogeochemical cycles, including the impacts of CO₂ and ocean acidification are included. The increased risk of non-indigenous species establishing in the SO (range extensions in Figures 1, 2, 4) and the external influences on species that migrate in and out of the SO are also discussed as external drivers in this manuscript.

There have been several recent attempts to assess the dynamism of stressors impacting the Southern Ocean and its inhabitants (Constable et al., 2014; Gutt et al., 2015; Rogers et al., 2020). Where the current work differs is in taking a detailed look at large scale, global, influences on the physical environment, and to set these into a MEASO context. Where appropriate, the level of confidence in a conclusion is given according to the approach of the IPCC (Mastrandrea et al., 2011). These are given in italics in parentheses, with an appropriate reference where the confidence level has been judged elsewhere. When not accompanied by a reference, we judge confidence from the levels of agreement we observe in the scientific literature and the amount of evidence presented to support the conclusion, including consideration of any contrary evidence. Sometimes, we only report on the scope of the evidence in terms of agreement and amount. The levels of confidence are not to be used as the inverse of confidence for alternative hypotheses, as those alternatives may not be addressed in the literature. The future prognosis of these drivers is assessed and gap analysis is used to define future priorities.

PHYSICAL DRIVERS

SAM/ENSO

Stratospheric ozone concentration in the middle and high latitudes of the southern hemisphere has been decreasing in spring, summer and winter since the 1970s (e.g., WMO, 2011). Termed stratospheric ozone depletion, it is considered the single largest driver of change in summer, tropospheric (atmospheric) circulation in the southern high latitudes (Polvani et al., 2011). Normally, ozone absorbs UV radiation, radiatively warming the stratosphere. Its depletion, caused by chlorofluorocarbon (CFC) emissions, that began in the 1970s, means reduced absorption when sunlight returns to the southern high latitudes in the southern spring, and results in radiative cooling of the

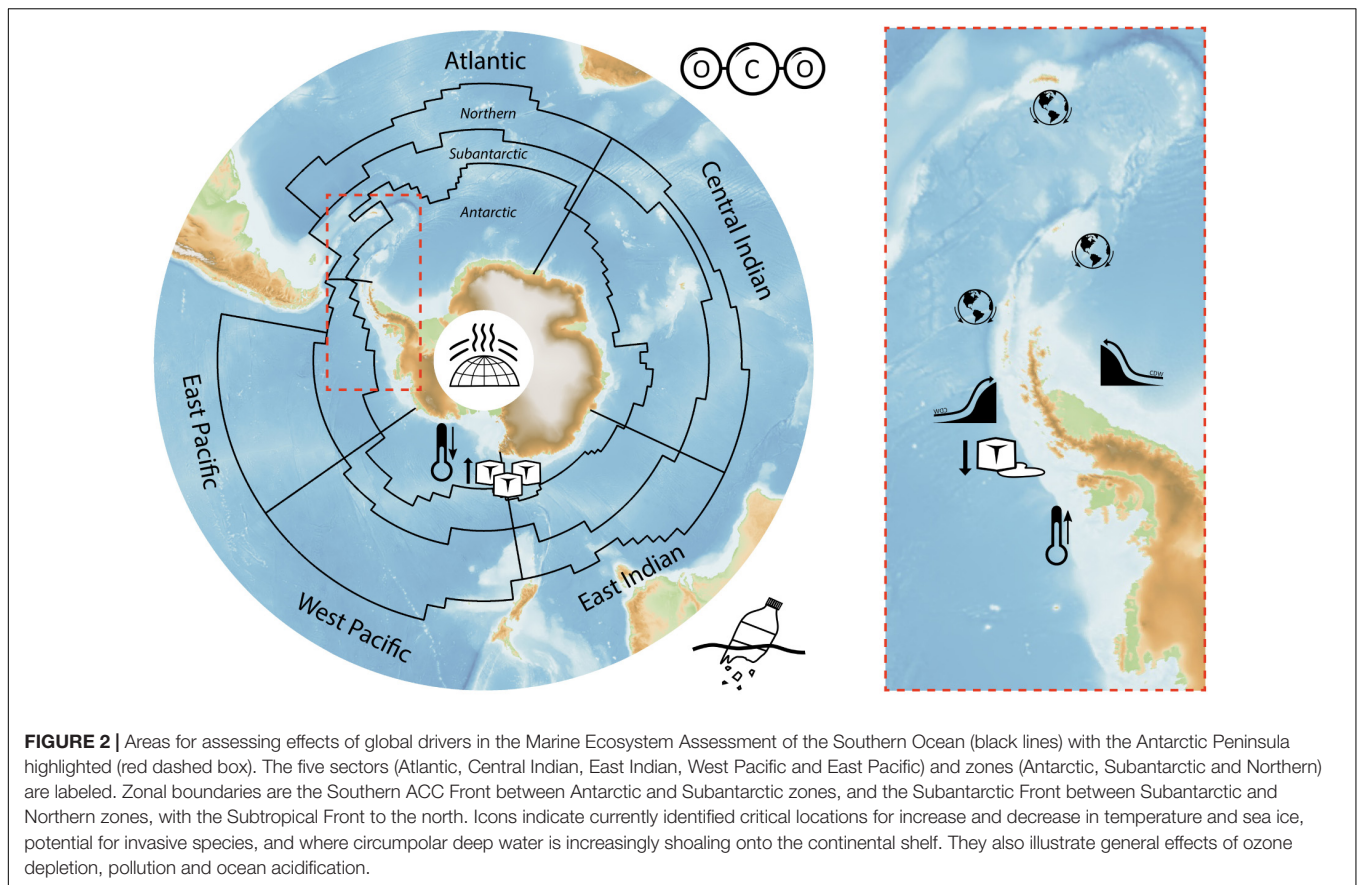


stratosphere over Antarctica. The dynamic response is increased shear in the zonal wind field and a strengthened stratospheric polar vortex as the atmosphere moves to restore the thermal wind balance (Thompson and Solomon, 2002). These changes in the stratosphere propagate to the troposphere, in approximately 2 months. The tropospheric effect is therefore observed in summer and is seen as a poleward shift of the mid-latitude jet and the accompanying storm track (Thompson and Solomon, 2002).

The tropospheric effect is an indication that stratospheric ozone depletion directly influences the leading mode of atmospheric circulation variability in the southern extratropical regions, the Southern Annular Mode (SAM). A measure of the SAM is an index calculated as the pressure gradient between mid-latitudes and Antarctica (Marshall, 2003), which when strongly positive, results in westerlies that are stronger than average and shifted poleward (e.g., Swart et al., 2015). Since 1957 there has been a significant increase in positive SAM in the austral summer and autumn (Marshall, 2003, 2007). The summer trend is thought to be forced primarily by stratospheric polar ozone depletion (Perlwitz et al., 2008). The variability of the SAM has a significant impact on Antarctic surface temperature (Marshall and Thompson, 2016), precipitation (Marshall et al., 2017), and sea ice (e.g., Hobbs et al., 2016; Doddridge and Marshall,

2017). The strong circumpolar westerlies associated with a positive SAM contributes to a cooler, drier, continental plateau (Eastern Antarctica) as they prevent the southward penetration of warmer air. Conversely, the Antarctic Peninsula warms because of warm air advection by the northwesterly flow, which also induces orographic precipitation on the western slopes and a rain shadow on the eastern slopes (Thompson and Solomon, 2002; Marshall and Thompson, 2016; Marshall et al., 2017). The increase in sea ice extent observed in the satellite era is attributed, in part, to increased northward Ekman drift associated with stronger westerlies over the Southern Ocean, facilitating the spread of the ice.

The SAM interacts with ENSO during the austral summer, particularly in the Pacific sector (e.g., Carleton, 2003; L'Heureux et al., 2006; Lim et al., 2019). When a La Niña phase in the tropical Pacific (cooler than average sea surface temperatures in the central and eastern tropical Pacific Ocean) co-occurs with a positive SAM phase at mid-high latitudes, this condition amplifies the effect of stratospheric ozone depletion. SAM and the high latitude ENSO both exert an influence on the Amundsen Sea Low (ASL), a climatological low pressure system centered off the coast of West Antarctica, the central pressure of which has deepened in recent years in response to an increase in the number



of cyclones entering the region. This increase is primarily due to the more positive SAM driven by ozone depletion (Grieger et al., 2018). This effect on the ASL may have far reaching consequences since the ASL plays a role in altering ocean currents, allowing warm Circumpolar Deep Water (CDW) to reach more frequently under the Pine Island and Thwaites glaciers that drain much of West Antarctica (Thoma et al., 2008). This has coincided with a period of thinning of these glaciers (Thoma et al., 2008).

Temperature

Atmospheric Warming

Intensifying warm and moist westerly winds during more frequent positive phases of the summer SAM cause pronounced atmospheric warming of the Northern and central sectors of the West Antarctic Peninsula (WAP). Strong interannual variations of atmospheric warming/cooling patterns are strongly related to climatic modes of SAM and ENSO (Bers et al., 2013). The strengthening of the westerly winds has also resulted in the warm air passing over the mountains of the Antarctic Peninsula, which has contributed to the melting of the east Antarctic Peninsula ice shelves (Cape et al., 2015).

Oceanic Warming

The SO has been a stable cold environment for millions of years, shaping unique ecosystems of cold adapted Antarctic biota. Within this stable regime there have been 100's to 1000's year

time scale variations of 2–4°C on the WAP, which are associated with reconstructions of the SO westerly winds (Shevenell et al., 2011). The increased intensity of positive summer SAM events are correlated with significant changes in seawater temperature that have been recorded in recent decades (*high confidence*; Hellmer et al., 2017; Moffat and Meredith, 2018). Circumpolar deep water (CDW), the temperature maximum layer of Antarctic Continental Shelf Bottom Water (ASBW) is warming ($0.1^{\circ}\text{C decade}^{-1}$) and shoaling (-30 m decade^{-1}) in most regions around the Antarctic (*high confidence*; Schmidtke et al., 2014) and both hydrographic and climatic forcing, modify the atmospheric and ocean heat transport.

Regional Patterns

At the northwestern tip of Bransfield Strait and the South Shetland Islands (East Pacific), ocean temperatures are cooled by water entering from the Weddell Sea, while mean air temperatures increased by 0.4°C per decade between 1991 and 2012 (Schloss et al., 2012). Melt events at the Northern WAP are regional and episodic, and thus amplify environmental and ecological variability in coastal and shelf systems (Meredith et al., 2018). In contrast, the central/south WAP is influenced by atmospheric warming and by upwelling of warm CDW onto the shelf, which has driven thinning of about 75% of the ice shelves of the AP and the Amundsen Sea. Mean atmospheric temperatures increased by 3°C ($0.6^{\circ}\text{C per decade}$) and sea surface temperatures

by 1°C (SST in the upper 100 m) between 1955 and 2004 (Moffat and Meredith, 2018). In spite of a recent superimposed cooling phase recorded since the early 2000s, which appears to be associated with shifts in decadal forcing in this region (Turner et al., 2016), net warming of the WAP atmosphere is still significant and the ocean has continued to warm (Martinson et al., 2008). Similarly, increases in seawater temperature have been reported for the Atlantic Sector, with warming averaging over 2°C in the upper 150 m over the past 81 years (Whitehouse et al., 2008) and 0.3–1.5°C in subsurface temperature (50–400 m) at the Eastern Antarctic Peninsula (Etourneau et al., 2019).

Other regions of the SO either remained stable or cooled in the last two-three decades. These differences originate from varying patterns in the ocean heat transport around the Antarctic (Schmidtke et al., 2014) and shoaling of warm deep water (WDW) up onto the continental shelf. For instance, relatively warm CDW entering the eastern Weddell Sea gyre causes shoaling of WDW (+0.8°) flowing along the continental shelf break in the Southern Weddell Sea. Models project intrusion of WDW into the Filchner-Ronne Ice Shelf cavity as part of a tipping point scenario, which would dramatically increase basal melt rates, threatening the stability of the largest floating ice mass fringing the Antarctic continent (Timmermann and Hellmer, 2013; Hellmer et al., 2017). The warming has been observed in most sectors, but the vertical displacement of the CDW core shows a more complex pattern, with deepening in the Cosmonaut and Northern Weddell Seas and shoaling elsewhere (Schmidtke et al., 2014). It is interesting to note that while the general trend of CDW also persists in the Ross Sea, no shoaling and intrusions of CDW onto the shelf have been observed so far (H. Hellmer, pers. communication). In contrast to the warming of the AP and CDW in the Weddell and Ross Seas/gyres, the Eastern sections of the continental SO have shown a cooling trend (Rogers et al., 2020). With continued warming of the earth's atmosphere, future warming between now and 2100, is expected across the whole of the SO (Rogers et al., 2020).

Many SO marine ectotherms are adapted to a narrow annual thermal range of only 2–4°C, and are therefore vulnerable to the effects of warming (*medium confidence*). Increasing ocean temperature is also correlated with the secondary effects of warming on summer sea ice dynamics and glacial melting in coastal and near-shore regions (*high confidence*). Increasing temperature is therefore projected to shape open ocean ecosystems and affect coastal communities down to the level of species ecological performance and molecular composition (*high confidence*, Ashton et al., 2017; Peck, 2018).

Currents and Eddies

The SO circulation forms a major horizontal connection between ocean basins as well as a vertical link between shallow and deep water masses. The ACC consists of a strong, multi-jet, and turbulent eastward flow around Antarctica, transporting approximately $173.3 \pm 10.7 \times 10^6 \text{ m}^3 \cdot \text{s}^{-1}$ (Donohue et al., 2016). The ACC, driven by westerly winds and surface buoyancy fluxes, is also identified by three main circumpolar fronts, separating distinct water masses, which contribute to the isolation of the SO (Sokolov and Rintoul, 2009).

As indexed by the SAM, a clear trend in strengthening of westerly winds has been observed in recent decades (Swart et al., 2015), yet there is no evidence of a significant increase in the ACC transport (*medium confidence*; Chidichimo et al., 2014). Although the response of the ACC transport and eddy field to wind forcing is still uncertain (*low confidence*), the presence of active ocean eddy dynamics, and its saturation suggested by modeling (Munday et al., 2013), buffers the oceanic response to atmospheric changes. This apparent cascade of energy into small scale eddies is supported by the satellite derived measurements, which indicate an increase in eddy kinetic energy over the last two decades. This is especially significant in the Pacific and Indian Ocean sectors of the SO (*medium confidence*; Hogg et al., 2015).

The use of sea surface temperature (SST) and sea surface height (SSH) contours to track front locations has suggested there has been a latitudinal change in the mean location of the ACC. This could have major impacts on marine ecosystems by modifying the environmental conditions experienced by numerous marine organisms (Bost et al., 2015; Cristofari et al., 2018; Meijers et al., 2019). However, this approach was challenged because these parameters are affected by the large-scale thermal expansion and steric sea-level rise occurring as a result of the warming of this circumpolar region. Recent studies found no significant long-term trend in either the annual mean latitude of zonal wind jets between 1979 and 2009 (Swart et al., 2015) or the zonally averaged latitude of ACC transport, which seem insensitive to changes in the SO's broad-scale structure (Gille, 2014; Chapman et al., 2020). The location of the ACC may be constrained by sea floor and land mass topography, particularly close to narrow gaps between land masses, such as Drake's Passage (*high confidence*; Moore et al., 1999).

The assessments of trends in the overturning circulation is challenging due to the high inter-decadal variability related to wind stress (*low confidence*; Waugh et al., 2013; DeVries et al., 2017; Ting and Holzer, 2017). While the production and export of Antarctic Bottom Water in the global ocean has decreased (*medium confidence*; Purkey and Johnson, 2013; Desbruyeres et al., 2017), this may reflect the same inter-decadal variability (*low confidence*; Abrahamsen et al., 2019).

Future projections for the SO under different warming scenarios from CMIP5 and CMIP6 models suggest that the trends observed over the last few decades will continue in the coming century at a rate that depends on future emission scenarios (Meredith et al., 2019). Projections include the strengthening of the westerly winds for all scenarios, except under stringent mitigation (Bracegirdle et al., 2020), and as a response, increased eddy activity (Downes and Hogg, 2013). Warming of the ACC and the freshening of surface water from increasing precipitation is projected to continue for all emission scenarios (Sallée et al., 2013; Bracegirdle et al., 2020). Due to their inability to explicitly resolve eddy processes (Gent, 2016; Downes et al., 2018) and increased water input from melting ice (Bronselaeer et al., 2018), the projections from CMIP5 or CMIP6 models have low confidence. Evidence from other models suggests that glacial meltwater from ice sheet might continue in the future (*medium confidence*; Levermann et al., 2020; Seroussi et al., 2020), with important impacts on ocean circulation, including cooling of

surface subpolar ocean (Bronse laer et al., 2018; Rye et al., 2020) and warming of subsurface subpolar waters (Sadai et al., 2020).

Seawater Circulation and Exchange

The observed changes in ocean properties and circulation in Antarctica reveals the central role that regional variability plays in understanding the evolution of this system (Thompson and Solomon, 2002). At depth, warm waters around Antarctica supply heat and nutrients to the continental shelf. This supply to the coastal ocean varies greatly around the continent. Circumpolar Deep Water (CDW) has both warmed significantly since the late 70s and its core has shallowed by about 30 m per decade (Schmidtko et al., 2014). The expression of these changes in open ocean properties is not straightforward, however, as strong shelf currents, the Antarctic Slope Front (ASF) in particular, act as a barrier for cross-slope exchange. In the regions where the ASF is weak or absent, i.e., the Bellingshausen and Amundsen Seas, the warming of shelf waters more closely follows the changes in the open ocean (Schmidtko et al., 2014; Thompson et al., 2018).

The rapid warming of the WAP (Meredith and King, 2005) has impacted ocean properties as a result of increased freshwater input to the coast (Meredith and King, 2005; van Wessem et al., 2017) altering the structure of the upper layers of the ocean (Martinson et al., 2008; Welhouse et al., 2016). This region also shows strong impacts from ENSO and its interaction with SAM variability, which has been shown to modulate wind forcing, which in turns modulates the depth of the mixed layer and marine productivity on interannual scales (Venables and Meredith, 2014). Warming of the subsurface layers of the Peninsula is representative of similar trends along the Bellingshausen and Amundsen Seas, where the weak presence or absence of the Antarctic Slope Front, found along the shelf break elsewhere in Antarctica, facilitates the flooding of the shelf by the warming CDW (Thompson et al., 2018). Deep, steep canyons and other topographic features play a key role in the across-shelf exchange of properties along this and other Antarctic shelves (Moffat et al., 2009; Martinson and McKee, 2012). This exchange is strongly modulated by small ocean eddies that play a role on both the supply of heat and nutrients to the shelf (Moffat et al., 2009) as well as the export of shelf-modified waters to the open ocean (Brearley et al., 2019). Eddy-driven exchange is a key modulating factor of ocean properties around the continent, and this process is modulated by wind forcing (Thompson et al., 2014; Stewart and Thompson, 2015). The WAP shelf has experienced a build-up of subsurface heat (Martinson et al., 2008), and while full attribution of this change remains unresolved, both the changes in open ocean water properties and the increase of coastal stratification as a result of increased freshwater discharge from the coast likely play a role in this process.

The combination of strong regional and temporal variability in observed ocean properties, combined with what are still relatively limited datasets, result in significant challenges when trying to attribute the origin of the changes. Elsewhere in Antarctica, teasing out anthropogenic change from natural variability has proven challenging for many variables, suggesting that the observed change is consistent with the pattern expected from natural variability (Jones et al., 2016). This implies that process

studies to understand the underlying mechanisms of variability as well as continued efforts to improve the observational records around Antarctica are critical to understand the nature of change around the continent and the impacts on marine ecosystems.

SOUTHERN OCEAN ATTRIBUTES

Marine Ice

Every year Antarctic seasonal sea ice undergoes a sixfold change in ice-covered area; it is one of the largest seasonal signals on Earth, with consequent effects on air-sea exchanges of heat, momentum and gases (most notably CO₂), water mass properties and finally, on marine ecosystems. Antarctic sea ice is, however, highly variable and frequently exposed to strong storms, high winds and waves. These factors affect Antarctic sea ice growth and melt processes, thickness evolution and drift, and impart high regional and seasonal variability.

Over the past four decades there has been a modest increase in spatially averaged Antarctic sea ice extent. However, this Antarctic-wide average hides important regional and seasonal details, as Antarctic sea ice is not increasing everywhere and shows high seasonal and regional variability (e.g., Parkinson, 2019). The two regions showing the strongest but opposing sea ice trends are the east Pacific, Bellingshausen-Amundsen Sea, sector (where sea ice decreased over 1979–2015) and the west Pacific, Ross Sea Sector (where sea ice increased over 1979–2015). Although the changes in sea ice were opposite, the rates were comparable to those observed in the Arctic (Cavalieri and Parkinson, 2012; Parkinson and Cavalieri, 2012; Stammerjohn et al., 2012).

These contrasting regional sea ice distributions can in part be explained by the SAM and ENSO changes detailed previously. The westerly winds have strengthened mostly in austral summer and autumn, i.e., when SAM shows the strongest positive trends (Marshall, 2003, 2007), thus impacting sea ice distributions mostly in summer and autumn (Stammerjohn et al., 2008; Hobbs et al., 2016). ENSO also effects regional and seasonal sea ice distributions, with the strongest signal being an Antarctic Dipole between the Amundsen/Ross and Bellingshausen/Weddell sea regions, consisting of positive/negative sea ice anomalies during a La Niña, and vice-versa for El Niño (e.g., Yuan, 2004). Together, strong phases in SAM and ENSO can either amplify or dampen the effect on sea ice distributions, along with other atmospheric perturbations, e.g., Pacific Decadal Oscillation, the Atlantic Multi-decadal Oscillation, greenhouse gas increases, not to mention ocean changes in heat and freshwater content and stratification, making attribution quite challenging.

This last decade, 2010–2020, has been most notable for showing the strongest changes in Antarctic-wide sea ice. During 2012–2014 numerous records were broken for Antarctic-wide high sea ice extent (based on satellite observations since 1979) (Turner et al., 2013; Reid and Massom, 2015; Reid et al., 2015). There appeared to be no one dominant factor behind the record maxima, but instead, for each of these 3 years (2012–2014), there were different regions and seasons contributing to the record high sea ice extent (Reid and Massom, 2015). Then, just as abruptly,

Antarctic-wide sea ice extent since spring 2016 has shown numerous record lows, for which several explanations have also been proposed, including anomalies in both the atmosphere and ocean, with a possible deep ocean driver acting on decadal or longer timescales (e.g., Stuecker et al., 2017; Turner et al., 2017; Schlosser et al., 2018; Meehl et al., 2019; Wang et al., 2019). Whether this recent decline in Antarctic sea ice extent will continue or not is still unknown, and once again points to the challenges in attributing and predicting Antarctic sea ice changes.

Previous work has highlighted the effects of changes in sea ice and how they can transform shallow water benthic ecosystems associated with changes in light regimes (Clark et al., 2013) and also by producing longer phytoplankton blooms and increased iceberg disturbance (Barnes et al., 2018a). Importantly for SO foodwebs, biodiversity and nutrient cycling and the abundance of Antarctic krill (*Euphausia superba*) all depend on the extent of winter sea ice, which is varying between sectors within the SO (Atkinson et al., 2019). Sea ice is one of the major drivers of energy flow into the SO and the effects of future sea ice extent on SO productivity are difficult to predict (*low confidence*).

Ice Shelf Disintegration

The floating ice shelves shape unique conditions in the SO for marine life living below them. Ice shelves are floating masses of ice slowly advancing from the glaciers of the interior toward the ocean, at least regionally and temporarily since the late Oligocene (Hochmuth and Gohl, 2019). They range from 100 to 1,400 m thick. The distance between the grounding line, where they lose contact with the land and the edge facing the open ocean, ranges from a very short distance to approximately 600 km. By far the largest two, which are each roughly the size of Spain are the Ross and Filchner-Ronne Ice shelves in the Pacific and Atlantic Ocean, respectively. With a total area of 1.63×10^6 km² ice shelves cover 36% of the continental shelf being equivalent to 11% of the size of the continent (Clarke and Johnston, 2003). Their existence and dynamics demand a replenishment of ice from the hinterland, permanently low air and water temperatures and depend on specific geomorphological structures. Ice shelves also seem to stabilize glacier draining velocity (Miles et al., 2018) and interact with sea-ice and ocean dynamics (Jourdain et al., 2017). The Larsen A ice shelf in the North of the Antarctic Peninsula most likely disintegrated more than once during the Holocene due to natural temperature changes (Domack et al., 2005). Further south the Larsen B on the east coast of the Peninsula (2002) as well as Wordie (2009) ice shelves on the west coast of the Peninsula, collapsed due to recent regional atmospheric and ocean warming, respectively (Massom et al., 2018). Ice shelves shape almost 50% of the coastline and icebergs as large as the size of Jamaica calve from the seaward edges. Despite this dynamism, the long-term mass balance currently seems to remain stable. However, large-scale long-term disintegration and melting is predicted under ongoing climate-change scenarios (*high confidence*; Naughten et al., 2018).

Besides impacts on ocean physics the disintegration of large ice shelves causes one of the most effective changes in marine ecosystems (*medium confidence*). The covering of ice acts as a barrier to energy exchange between the water and

the atmosphere. Once this barrier is gone then there will be increased transfer of wind, heat and light energy, affecting the stability of the water column and the mixed layer depth. When light penetrates into the water it initiates the production of algal biomass (*medium confidence*, Bertolin and Schloss, 2009; Peck et al., 2010), which is the basis for almost all life in the oceans, in a previously totally dark and, thus, food-poor environment (Raes et al., 2010; Gutt et al., 2011). Icebergs calving naturally and more frequently under climate-change scenarios from ice shelves (*high confidence* for the next decades; e.g., Rack and Rott, 2004) drift in the ACC, scour the sea-floor (see e.g., Post et al., 2020) and eventually run aground before they disintegrate. These processes also have local to regional impact on pelagic and benthic systems (*medium confidence*; Gutt and Piepenburg, 2003).

Glacier Retreat

A third, smaller but important area of marine ice loss is glacier retreat. Like sea ice and ice shelves, glaciers are also showing decreases, and in fairly complex geographic patterns. Nearly 90% of glaciers along the WAP are now retreating, and their retreat rates are also increasing (Cook et al., 2016). CDW upwelling has driven frontline retreat of nearly all glaciers South of the Bransfield Strait (Cook et al., 2016; Etourneau et al., 2019). There is also evidence of thinning in southern glaciers around the East Pacific Sector (Hogg et al., 2017 and references therein). Until they reach grounding lines this glacier retreat generates icebergs and therefore coastal ice scouring and is opening up new fjordic habitats and carbon sinks (see Barnes et al., 2020). Although the high sedimentation in such environments can be harsh for new colonists (Sahade et al., 2015), they could be important for a number of reasons. Unlike elsewhere in the world, Antarctica has no other low wave energy-high productivity habitats, e.g., salt marshes, seagrass meadows and mangrove swamps, that provide hotspot potential for fast track from carbon capture to burial and sequestration. However, they also provide a, previously missing, key habitat which may provide opportunity for invasion of these newly exposed areas by non-indigenous species.

Meltwater and Freshening

Seawater salinity in the whole SO has decreased during the last 60–70 years (e.g., Jacobs et al., 2002; Jacobs and Giulivi, 2010; Hellmer et al., 2011; Durack et al., 2012). Surface waters (i.e., above 100 m depth) south of the ACC have shown stronger freshening rates, 0.0011 ± 0.0004 yr⁻¹ (de Lavergne et al., 2014), than intermediate waters, 0.0002 – 0.0008 yr⁻¹ (Skloris et al., 2014), or bottom waters, 0.0004 ± 0.0001 yr⁻¹ (*medium confidence*; Menezes et al., 2017). Higher freshening rates have been recorded over Antarctic continental shelves, although there are large spatial differences with the Ross and Cosmonaut Sea displaying intense freshening, whereas the Bellingshausen and Amundsen Sea (East Pacific sector) are showing the opposite trend, i.e., increasing salinity, (Schmidtke et al., 2014). The latter may be the consequence of more frequent and shallower intrusions of CDW (Schmidtke et al., 2014), a saltier and warmer water mass (*high confidence*; Moffat et al., 2009). Despite the high melting rates of glaciers in west Antarctica (Paolo et al., 2015),

enough CDW intrusions seem to reach the shelf in order to prevent a steady freshening of these shelf waters. This may be the consequence of changes in large scale atmospheric and ocean circulation patterns (e.g., the increasing frequency and strength of SAM), since these drive the intrusions of CDW, rather than shelf hydrographic conditions (Nakayama et al., 2018). Similarly, a relationship between positive SAM and increased freshening has been registered for other areas (e.g., Atlantic sector: eastern Antarctic Peninsula and Weddell Gyre) although atmospheric warming seems to drive this relationship instead of hydrographic conditions (Dickens et al., 2019). Although similar freshening trends have been registered in different Antarctic regions, the drivers and mechanisms involved vary spatially (*high confidence*). For example, except for the WAP, positive SAM has increased northward Ekman drift of sea ice that is formed close to the continent (Holland and Kwok, 2012), increasing the transport of freshwater to the open ocean and promoting the freshening recorded for offshore waters in the SO (Haumann et al., 2016).

Freshening has other effects besides salinity. Stratification has a key controlling influence on phytoplankton blooms as do sources of iron from glacial meltwater and icebergs (De Baar et al., 1995; Loscher et al., 1997; Dierssen et al., 2002; Höfer et al., 2019; Hopwood et al., 2019). These inputs may, however, be more restricted to coastal waters than previously thought (Hopwood et al., 2019). In contrast, there is limited evidence that meltwater inputs can dilute the macronutrient concentrations of seawater (Henley et al., 2017; Höfer et al., 2019). Meltwater may also carry a high amount of inorganic suspended matter (e.g., glacial flour) that may kill, or impair the functions of, pelagic (Pakhomov et al., 2003; Fuentes et al., 2016; Giesecke et al., 2019) and benthic organisms (high agreement, limited evidence; Torre et al., 2014; Sahade et al., 2015). Finally, although there is medium confidence that the volume of Antarctic Bottom Water has decreased (Purkey and Johnson, 2013; Desbruyeres et al., 2017), there is almost no direct record of freshening hindering the formation of Antarctic Bottom Water (Silvano et al., 2018). Besides, recent studies suggest that the formation and northward export of Antarctic Bottom Water depends on several processes varying on multi-annual time scales (Abrahamsen et al., 2019), which need longer time series in order to detect any long term trend.

Biogeochemistry

CO₂ Uptake and Ocean Acidification

One of the most important functions of the SO in the Earth System is its uptake of atmospheric CO₂ by physical and biological processes and its release of oceanic CO₂ to the atmosphere (Sarmiento and Le Quere, 1996; Marinov et al., 2006; Gruber et al., 2009, 2019; Lenton et al., 2013; Henley et al., 2020 this volume). However, this uptake is leading to changes in ocean biogeochemistry, which could have devastating consequences for the ecosystem. Ocean acidification driven by oceanic uptake of atmospheric CO₂ is expected to occur earlier in the SO than most other ocean regions, due to enhanced solubility of CO₂ at low temperature and upwelling of deep waters with high CO₂ concentrations (Orr et al., 2005; McNeil and Matear, 2008; Feely

et al., 2009). Ongoing changes in upper ocean temperature and salinity are very likely to impact the solubility of CO₂ in SO surface waters, and projected increases in the Revelle factor are expected to increase the biologically mediated uptake of CO₂ over the twenty-first century (Hauck and Völker, 2015; Hauck et al., 2015; Henley et al., 2020).

At the global scale, oceans have absorbed ~30% of the anthropogenic atmospheric CO₂ and this has already caused shifts in seawater carbonate chemistry by reducing seawater pH, carbonate ion concentrations and therefore saturation states of the carbonate minerals aragonite and calcite (Ω , where values < 1 indicate undersaturated conditions that result in the dissolution of carbonate structures; Doney et al., 2009; Orr, 2011; McKinley et al., 2017; IPCC, 2019). Prior to the industrial period, atmospheric CO₂ was approximately 280 μatm with global average surface seawater pH of 8.17 and $\Omega_{\text{arag}} \sim 3.5$. Atmospheric $p\text{CO}_2$ has now reached 380–400 ppm, which has reduced surface seawater pH to 8.01–8.05, equivalent to a 100-fold increase in hydrogen ion concentration (Guinotte and Fabry, 2008; Doney et al., 2009; IPCC, 2019). Associated decreases in carbonate saturation have led to a shallowing of the saturation horizon by 30–200 m (Feely et al., 2002, 2004; Sabine et al., 2004). These trends are likely to continue and to accelerate in the coming decades, based on the current RCP 8.5 worst case “business as usual” emissions scenario. Further reductions of 0.3–0.4 pH units and $\Omega_{\text{arag}} \sim 1.2$ are projected (*high confidence*) at atmospheric $p\text{CO}_2$ of 851–1,370 by the year 2100 associated with further shallowing of both aragonite and carbonate saturation horizons (ASH and CSH) (Houghton et al., 2001; Caldeira and Wickett, 2003; IPCC, 2019).

The SO has taken up around 40% of the total oceanic uptake of anthropogenic CO₂ (Orr et al., 2001; Fletcher et al., 2006; Devries, 2014). The Ω_{arag} in SO surface waters is largely below 1.5, with particularly low values in winter (Jones et al., 2017; IPCC, 2019). Trends of ocean acidification have already been observed in many of the MEASO areas, such as the east Pacific Antarctic and Subantarctic zones, Atlantic Antarctic zone, west Pacific Antarctic zone and across the East Indian sector (Hauck et al., 2010; van Heuven et al., 2011; Midorikawa et al., 2012; Takahashi et al., 2014; Munro et al., 2015; Williams et al., 2015; Lencina-Avila et al., 2018). The ASH resides at ~730 m depth southwards of 60°S, cross-cutting the steep Antarctic continental shelf (McNeil and Matear, 2008; IPCC, 2019), whilst the CSH resides at approximately 3,000 m (Sewell and Hofmann, 2011). The ASH is expected to shoal to the surface during winter periods from ~2,030 and across all seasons by 2100 (Orr et al., 2005; McNeil and Matear, 2008; McNeil et al., 2010; IPCC, 2019). This is likely to impact upon phytoplankton abundance, growth rates and species composition as well as zooplankton growth, reproductive success and survival, especially of ecologically important species of pteropods and krill (Tortell et al., 2008; Kawaguchi et al., 2013; Trimborn et al., 2013; Gardner et al., 2018; Henley et al., 2020). Mg-calcites are more soluble than aragonite and Southern Ocean surface waters are already undersaturated for ≥ 12 mol% MgCO₃ and are predicted to become undersaturated for 4–5% mol% MgCO₃ by 2100 (Andersson et al., 2008). Areas of upwelling CDW (from 2 to 3 km depth) can bring seawater with low Ω_{arag}

($\sim 0.9\text{--}1.08$, $\sim 490\text{--}570 \mu\text{atm } p\text{CO}_2$) toward the upper ocean in the ACC, leading to conditions that are corrosive for aragonite-secreting organisms such as pteropods (Bednaršek et al., 2012). Models suggest that upwelling could become stronger in the near future but the severity and timeframe with respect to carbonate undersaturation remain poorly constrained (Constable et al., 2014; Rintoul, 2018). Potential impacts of ocean acidification on microbial communities could lead to faster recycling of organic matter and overall declines in carbon export (Maas et al., 2013; Deppeler et al., 2018; Westwood et al., 2018), with implications for large-scale biogeochemical cycling and potentially climate, but more research is required.

The coastal regions around Antarctica are characterized by highly variable topography, bathymetry, hydrodynamics and carbonate chemistry, which leads to highly variable seawater pH, $p\text{CO}_2$ and Ω . Present day variations include Ross Sea surface $p\text{CO}_2$ values ranging from ~ 100 to $450 \mu\text{atm}$, equivalent to aragonite saturation of 3–4, between the autumn and summer, which then decline > 4 -fold during autumn/winter to near-undersaturation of aragonite at 1.1–1.2, with an associated reduction of pH by 0.6 units (McNeil et al., 2010). Summer periods are characterized by high primary production, whilst entrainment of carbonate-depleted CDW occurs onto the Ross Sea Shelf during winter (Sweeney, 2004; McNeil et al., 2010). Similar seasonal patterns have been observed in surface waters at coastal sites of McMurdo Sound, McMurdo Jetty and Cape Evans with changes in seawater pH of 0.3 units (Kapsenberg et al., 2015) and in Prydz Bay with changes of 0.6 pH units (Gibson and Trull, 1999). Continued ocean acidification is projected to show large and uncertain regional and local variations, particularly in coastal regions (*high confidence*; IPCC, 2019). Nevertheless, model simulations have projected a pronounced increase in aragonite undersaturation around 2030, affecting around 30% of Southern Ocean surface waters by 2060 (Hauri et al., 2016). There is also medium certainty that the current rates of change are the fastest observed for at least 300 million years and high confidence that these changes will continue to rise at an accelerating rate (Canadell et al., 2007; Hönlisch et al., 2012; IPCC, 2019), making ocean acidification likely to become one of the most important drivers of Southern Ocean ecosystem structure and functioning in the near future (Gutt et al., 2015).

Increasing Iron Inputs and Freshwater Flux From Glacial Ice Melting

The Southern Ocean is a large high nutrient low chlorophyll (HNLC) zone where primary production is not limited by the availability of macronutrients, as in other oceans, but of the essential micronutrient, iron (e.g., De Baar et al., 1990; Moore et al., 2013). As such, iron supply to Southern Ocean surface waters has a profound impact on primary production and ecosystem functioning, and is changing in response to changes in Earth's climate, large-scale ocean circulation and regional environmental conditions (Henley et al., 2020 and references therein). Increases in iron supply are expected due to increases in dust flux from lower latitudes (IPCC, 2019), oceanic iron transport to the sub-Antarctic in strengthening western boundary currents (Bowie et al., 2009) and enhanced

release of terrigenous iron sources from glacial ice and the Antarctic continent (Lin et al., 2011; Gerringa et al., 2012; Sherrell et al., 2015; Winton et al., 2016; van Der Merwe et al., 2019). However, these may be offset to an extent by increased stratification of the upper ocean linked to a weakening overturning circulation, which could lead to a reduction in iron delivery from underlying waters (Tagliabue et al., 2009; Rintoul, 2018), and the ongoing declines in sea ice, which can store iron (Lannuzel et al., 2016). Changes in iron speciation, solubility, scavenging, internal cycling and remineralization—as well as phytoplankton dynamics, iron requirements and the impacts of ocean acidification—further complicate the net effect of climate and environmental changes on iron availability to phytoplankton blooms (e.g., Planquette et al., 2013; Blain and Tagliabue, 2016; Hutchins and Boyd, 2016; Andrew et al., 2019). Nevertheless, there is good agreement amongst CMIP5 models that Southern Ocean NPP will increase overall as a result of increased iron supply, changes in mixed layer depth, declining sea ice cover, increasing SST and altered westerly winds (Bopp et al., 2013; Leung et al., 2015; Fu et al., 2016; Moore et al., 2018). Increased iron supply and temperature could also lead to a floristic shift to diatoms and potentially *Phaeocystis antarctica*, with consequences for benthic and pelagic consumers as well as nutrient uptake, carbon export and large-scale biogeochemical cycling (Henley et al., 2020).

Impact of Climate-Induced Physical Changes on Nutrient and Carbon Supply and Distribution

The ongoing and projected increase in wind speeds and storminess over large parts of the Southern Ocean is likely to increase upwelling and upper ocean mixing, thus micro- and macronutrient flux from the CDW source waters into the mixed layer (Moore et al., 2018; Rintoul, 2018). As regional warming continues, anticipated sea ice losses would also increase vertical mixing and nutrient supply by removing the barrier to wind-driven mixing of the surface ocean, as has been observed at the Antarctic Peninsula (Venables et al., 2013; Henley et al., 2017). The increased vertical flux of iron would be more important than that of macronutrients for biological productivity in the iron-limited open Southern Ocean (e.g., Leung et al., 2015). Increasing wind speeds, storminess and ice losses may also increase the outgassing of oceanic CO_2 , as has occurred in the past (Le Quere et al., 2007; Lenton et al., 2013). Shoaling of carbon- and nutrient-rich CDW in most regions around Antarctica (Schmidtke et al., 2014) is also likely to increase the flux of nutrients and carbon toward the ocean surface. In contrast, projected increases in glacial meltwater inputs may increase stratification around Antarctica with the potential to reduce vertical nutrient fluxes and availability to phytoplankton blooms (see section on freshening). This could limit primary production in locations and at times of year when surface macronutrients are drawn down to limiting concentrations (Henley et al., 2017, 2018; Höfer et al., 2019). Ice shelf disintegration could have complex effects on upper ocean mixing and vertical carbon and nutrient fluxes depending on the relative forcing of increased exposure to winds and altered strength and position of the buoyant meltwater plume (e.g., Randall-Goodwin et al., 2015). Projected increases in

eddy activity within the ACC and the anticipated changes in ocean currents and frontal positions will influence the transport and distribution of nutrients and carbon around the Southern Ocean, as well as air-sea exchange of CO₂ (Sallée et al., 2012; Rintoul, 2018; Chapman et al., 2020).

Biogeochemical Consequences of Climate-Driven Changes to Pelagic and Benthic Food Webs

The large-scale climatic and environmental drivers of changes in the abundance and distribution of marine organisms will also have important consequences for Southern Ocean biogeochemistry through export fluxes, carbon storage in pelagic and benthic food webs, and for benthic-pelagic coupling (Henley et al., 2020). For instance, the southward contraction of krill populations in the Atlantic sector and linked increases in salp abundance may reduce carbon transfer through the pelagic food web, with implications for carbon storage and export (Atkinson et al., 2004, 2019; Murphy et al., 2016). Phytoplankton, zooplankton and higher organisms also play an important role in benthic-pelagic coupling and the transport of nutrients and carbon vertically and horizontally (e.g., Lavery et al., 2010; Belcher et al., 2017; Cavan et al., 2019), which could be interrupted by shifts in abundance, distribution or trophic interactions. In contrast, increases in primary production and benthic biomass in response to reduced sea ice duration and longer growing seasons on the Antarctic Peninsula (Peck et al., 2010; Moreau et al., 2015) have the potential to increase carbon storage and invigorate benthic nutrient and carbon cycling as well as benthic-pelagic coupling (Barnes et al., 2018a). Benthic-pelagic coupling and water column transport are key to the (re)distribution of nutrients in the Southern Ocean, such that climate-forced changes in these mechanisms could hold severe consequences for the entire ecosystem. Because the microbial loop plays a decisive role in the fate of organic carbon in pelagic and benthic food webs (Azam et al., 1991; Sailley et al., 2013), climate-driven shifts in microbial communities and processes are very likely to have a strong impact on ecosystem carbon storage, benthic-pelagic coupling and regional biogeochemistry (Henley et al., 2019 and references therein).

ANTHROPOGENIC DRIVERS

Tourism

Antarctic Tourism started over 100 years ago (Headland, 1994) but the modern trend for ecotourism started in 1950's and the first dedicated expedition cruise ship for the Southern Ocean was the Lindblad Explorer launched in 1969¹. There was a steep increase in shipborne tourism in Antarctic from around 100 visitors in the late 1950's to a peak in the 2007–2008 season of 46,000. Visitor demographics are heavily affected by global socio-economic factors and the sharp decline following 2008 is attributed to the world economic crisis and the International Maritime Organization (IMO) ban on the use and carriage of heavy fuel oil in Antarctica. Traditionally Antarctic tourism is

seen as an emerging market due to increasing global wealth. The industry began growing again steadily after 2011, reaching a new peak of 55,000 visitors in 2018–2019, mostly within the East Pacific and subAntarctic zone of the Atlantic MEASO areas, with most passenger landings and traffic concentrated at a few locations (Bender et al., 2016). Expedition cruising is the fastest growing market within the entire cruise industry, with new expedition cruise ships being built at the fastest rate in history, suggesting that, unless disease outbreaks pause the industry in the long term, this trend in visitor numbers is expected to continue (*high confidence*).

The nature of Antarctic ecotourism is also changing with the increased number of itineraries expanding the market to attract more active tourists, with options to kayak, camp on the ice, dive and snorkel with wildlife as well as skiing, including heli-skiing². Additionally, fly cruising options are increasing with passengers flying into King George Island and starting their trip from there (Bastmeijer, 2009), spending more of their trip within the Southern Ocean. New vessels with the latest X-bow design are expected to increase the ability to push into ice and therefore expected to open up the West Pacific MEASO area (Ross Sea) to more tourism (*medium confidence*).

Today the large majority of all tour operators operating in Antarctica are members of the International Association of Antarctic Tour Operators (IAATO), a self-governing body, including all commercial SOLAS passenger ship operators (see footnote). The association's membership comprises 105 companies and organizations from all over the world. The future protection of Antarctica from the impacts of human activity requires collaboration on a global scale. To promote effective visitor management, IAATO annually shares detailed information on its activities with Antarctic Treaty Parties. Without further regulation the geographic spread of visits is virtually certain to increase.

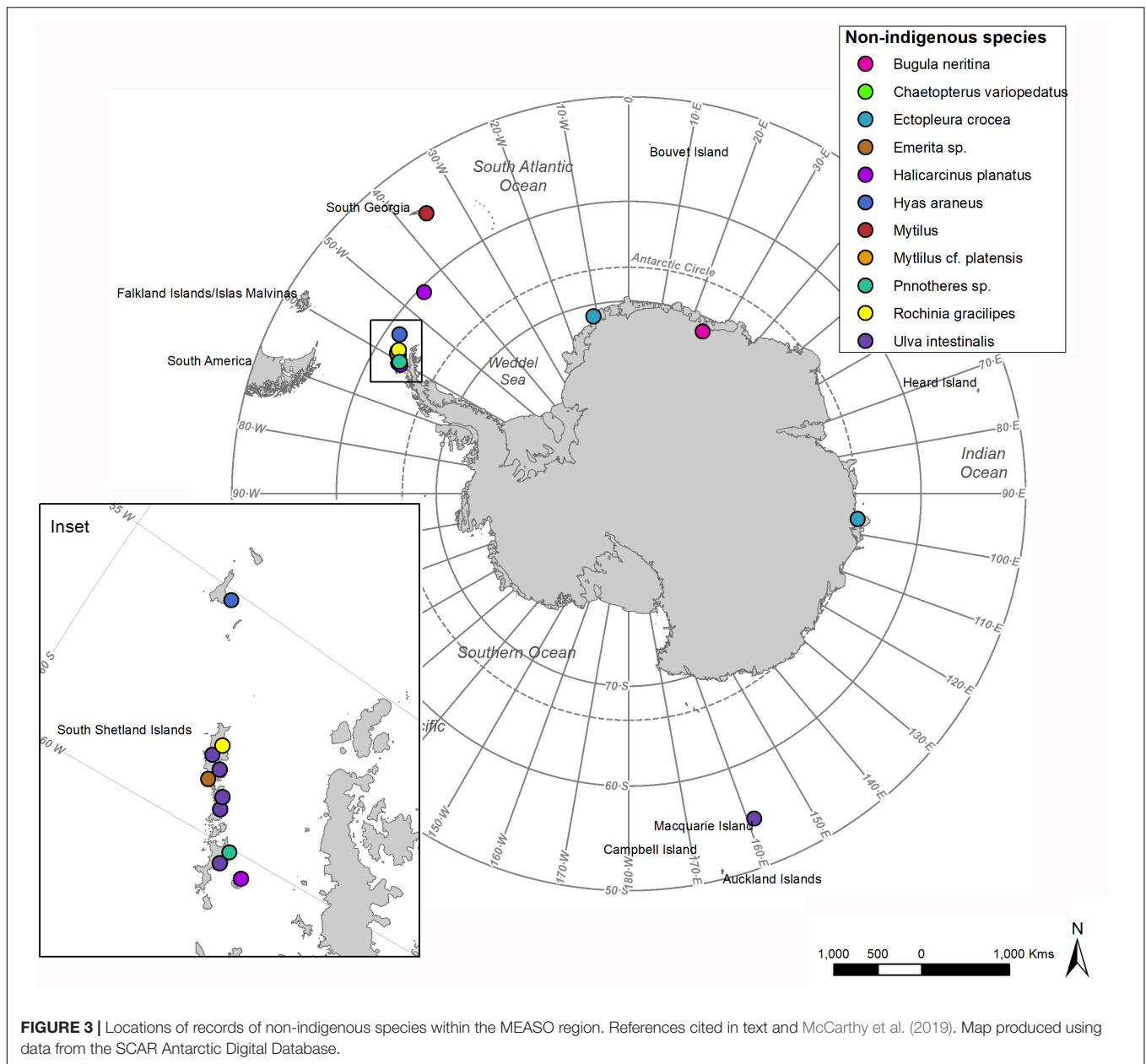
All of these developments are highly likely to increase the footprint of Antarctic tourism, potentially increasing the impact on marine ecosystems, particularly through the risk of the introduction of non-indigenous species. There are also concerns about the risk of tourists transferring anthropogenic diseases to Antarctic seabirds. However, the greatest health concern for the cruise ship industry are over human disease transmission within the close quarters of cruise ships (Hill, 2019). These concerns have been amplified by the COVID-19 pandemic and the trajectory of SO tourism is now much less certain.

Pollutants

Many anthropogenic pollutants are resistant to environmental degradation and can be transported from human population sources to remote regions of the world, such as the Southern Ocean. Heavy metals have been detected in ice core samples, with, for example, lead from Australian mining operations appearing at concentrations of up to 6 pg.g⁻¹ after the start of the industrial revolution (McConell et al., 2014). Radioactive isotopes of elements such as chlorine (³⁶Cl) are, also, still being released

¹www.iaato.org

²<https://www.adventuresmithexplorations.com/cruises/antarctica/new-expedition-ships/>



from the cryosphere after nuclear bomb tests in the 50's and 60's (Pivot et al., 2019). The persistent organic pollutants (POPs; Krasnobaev et al., 2020) and marine debris, amongst which the plastics have become a focus for policy makers and the public alike (Rochman et al., 2016), will be discussed in detail here. Increase in atmospheric CO₂ is covered within the previous biogeochemistry section and the impact of CFCs are covered in discussions about SAM/ENSO.

POPs consist of a number of different chemicals, including polychlorinated biphenyls (PCBs), organochloride pesticides (O) and polybrominated diphenyl ethers (PBDEs). A recent study of these compounds in the East Pacific region found comparable PCB and OCP concentrations to those detected 10 years earlier, but detected PBDEs for the first time (Krasnobaev et al., 2020).

In contrast to some previous studies, there was no indication of local sources for this pollution, e.g., from research stations (Wild et al., 2015), rather that the pollution was highly likely to have come from atmospheric sources (Krasnobaev et al., 2020). This atmospheric origin is supported by the highest concentration of POPs being recorded in the surface phytoplankton, early in the summer, soon after the sea ice, and any snow cover has melted (Casal et al., 2018, 2019; Krasnobaev et al., 2020). With changes in the cryosphere, particularly the reduction in sea ice duration, and the associated changes in phytoplankton bloom dynamics, the seasonal pattern of POPs is projected to become less pronounced (*high confidence*). Global legislation, such as the Montreal protocol can only control chemicals that are widely used and once their effects are clearly demonstrated.

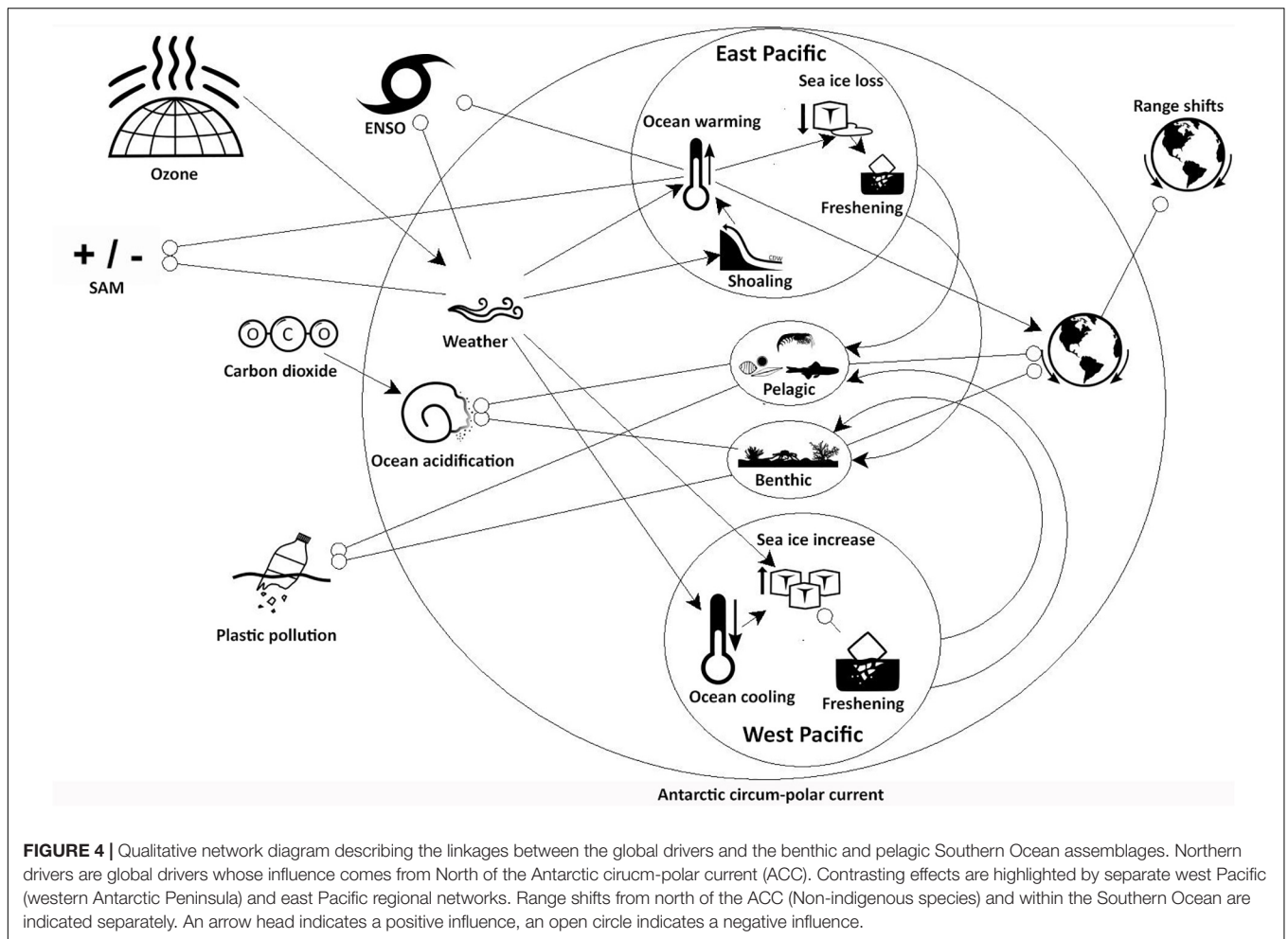


FIGURE 4 | Qualitative network diagram describing the linkages between the global drivers and the benthic and pelagic Southern Ocean assemblages. Northern drivers are global drivers whose influence comes from North of the Antarctic circumpolar current (ACC). Contrasting effects are highlighted by separate west Pacific (western Antarctic Peninsula) and east Pacific regional networks. Range shifts from north of the ACC (Non-indigenous species) and within the Southern Ocean are indicated separately. An arrow head indicates a positive influence, an open circle indicates a negative influence.

TABLE 1 | Assessment of the current direction of each of the identified global drivers within the MEASO sectors, in recent times (R) and in the future (F).

Region	Zone	Ozone		SAM		ENSO		Temperature		Tourism		Pollution		Sea Ice		Ice Shelves		Salinity		pH		NIS	
		R	F	R	F	R	F	R	F	R	F	R	F	R	F	R	F	R	F	R	F	R	F
Atlantic Ocean	A	+	+	+		+	+		+	+	?	+	+	-	?	-	-	-	-	?	-	No	+
	S	+	+	+		+	+	+	+	+	+	+	+	-	?	N/A	N/A	-	?	-	+	+	
	N	+	+	+		+	+	+	+	+	+	+	+	N/A	N/A	N/A	N/A	-	+	-	+	+	
Central Indian	A	+	+	+		+	+		+	N/A	?	+	+	-	?	No	No	-	-	?	-	No	+
	S	+	+	+		+	+		+		+	+	+	N/A	N/A	N/A	N/A	-	?	-	+	+	
	N	+	+	+		+	+		+		+	+	+	N/A	N/A	N/A	N/A	-	+	-	+	+	
East Indian	A	+	+	+		+	+	-	+			+	+	+	?	No	No	?	-	?	-	No	+
	S	+	+	+		+	+	-	+			+	+	+	?	N/A	N/A	-	?	--	No	+	
	N	+	+	+		+	+	-	+			+	+	N/A	N/A	N/A	N/A	-	+	-	?	+	
West Pacific	A	+	+	+		+	+	-	+			+	+	+	?	No	No	-	-	?	-	No	+
	S	+	+	+		+	+	-	+			+	+	+	?	N/A	N/A	-	?	-	No	+	
	N	+	+	+		+	+	-	+			+	+	N/A	?	N/A	N/A	-	+	-	?	+	
East Pacific	A	+	+	+		+	+	+	+	+	?	+	+	-	?	-	-	-	?	?	-	No	+
	S	+	+	+		+	+	+	+	+	?	+	+	-	?	N/A	N/A	-	+	-	No	+	
	N	+	+	+		+	+	+	+	+	?	+	+	N/A	?	N/A	N/A	+	+	-	No	+	

The assessment is drawn from the reviews in the previous text and the citations therein. + indicates an increase, - indicates a decrease, No indicated no change, ? indicates a known uncertainty. N/A means the category is not applicable in that zone. The MEASO regions and sectors are defined in Figure 2. Full explanations behind the assessment and references are cited in the text. Currents and eddies are not included due to large uncertainties over their future projections.

BOX 1 | Research Gaps and Priorities.

Modeling the trajectories of climate change is one of the biggest challenges to understanding the future impacts of drivers on the Southern Ocean and a key limitation to future projections. Whereas arctic environmental responses to climate over the last decade have been continuous and homogeneous, Antarctic and SO changes are regional and variable (Stammerjohn et al., 2012; Parkinson, 2019), resulting in ambiguous effects when looking at the global scale.

There is also a degree of uncertainty over when tipping points will be reached (e.g., Timmermann and Hellmer, 2013; Hellmer et al., 2017). Current model predictions for sea ice extent and duration have been poor despite the mechanisms driving sea ice formation/melting having such a profound impact on the SO (Reid and Massom, 2015). This is typified by the retreat of tidewater glaciers and floating ice shelves and the number of icebergs that will be present to scour the sea floor. At a certain point the trend will move from increasing to reducing numbers of icebergs being present, starting to reverse the trends in ice scour (Barnes et al., 2020). Whether this will happen before irrecoverable change has occurred within benthic communities is hard to predict.

The very limited availability of long-term time series hinders our ability to discern between interannual/interdecadal changes and long-term trends in ecosystem shift. It is difficult to inform policy and decision makers without a clear distinction between natural variability and global change impacts. Funding agencies must allocate money to maintain long-term sampling programs. Continued and improved data collection through international effort to obtain standardized datasets, developments in modeling and integrated work programs, such as the Southern Ocean Observing System (Newman et al., 2019) are allowing improved coverage and better predictions of future drivers across the Southern Ocean. Only through funding of extended time series can trajectories of change be monitored and tipping points be better constrained.

As with all remote regions, data coverage is better near locations with the greatest human footfall. This footfall is also higher in summer than winter. Remote sensing from satellites and remote monitoring stations are key tools to increase the spatio-temporal coverage and improve the reliability of projections that can significantly reduce the cost of long term sampling programs. The increase in continuous observing systems will be key to improving data coverage. Innovation, technological advancements on autonomous vehicles and other platforms (e.g., oceanographic moorings), including the ability to measure under the seasonal ice cover and floating ice sheets should contribute towards improving our understanding of processes occurring during the winter, and how they change in longer time-scales.

Understanding if human behavior will change, and how international treaties will limit the pace of climate change, will be key. Industrial process are developing novel chemicals, some of these are designed to replace substances that are currently controlled, such as CFCs. However, some of these replacements, such as SF₆, are known to be potent climate gases (Widger and Haddad, 2018) which could markedly change rates of atmospheric warming. The fate of new industrial chemicals needs to be tracked and understood so that their impacts can be determined and impacts controlled before they have major impacts.

History shows that novel industrial chemicals will continue to be developed with a considerable time lag before they are recognized as POPs.

Plastics are a global problem with levels in remote regions of the Atlantic. There has been a 10 fold increase in the quantity of plastic debris on beaches in the remote Falkland, Tristan da Cunha, St Helena and Ascension Islands in the last decade (Barnes et al., 2018b). The number of items increasing from approximately 1 to 10 per meter of beach (Barnes et al., 2018b). Large items of plastic drifting onto the Antarctic Peninsula were first reported nearly 20 years ago (Barnes and Fraser, 2003). These were first recognized as vectors for the introduction of non-indigenous species but in more recent times, the break down products of waste plastic, the micro- and nanoplastics have become a major concern as they can affect suspension and deposit feeders which are dominant members of the Antarctic benthos (Waller et al., 2017; Horton and Barnes, 2020), even affecting the immune system, as recently described in the sea urchin, *Sterechinus neumayeri* (Bergami et al., 2019). A recent study has also demonstrated effects of nanoplastics on keystone species such as the Antarctic krill (Bergami et al., 2020). The local sources of microplastics are discussed in the local drivers manuscript but there is also recent evidence of global transport of microplastics to the SO in the ocean currents and precipitation (Åslund, 2018).

BIOLOGICAL DRIVERS

Non-indigenous Species

The shallow seas of the SO and its outer lying archipelagos have high levels of endemism in the region; up to 70% in some taxa

(David and Saucède, 2015). Here we term species not native to the region as non-indigenous species – NIS. Its relative historic isolation, means that it still has an almost entirely native biota (Convey et al., 2014; de Broyer et al., 2014), and is the only large surface environment on the planet where this is still the case (Bax et al., 2003; Early et al., 2016). There are thought to be many factors causing this, including its large size, historic geographic and environmental isolation by the ACC, and long periods of relatively constant environment (Ruiz and Hewitt, 2009). These attributes mean that NIS that are able to establish are likely to outcompete or prey upon native biota and entire native communities could be disrupted.

However, there are “barriers” to species movement. The Polar Front is both semi-porous and migratory over time (Clarke et al., 2005). Species can cross the Polar Front in short ecological time frames in eddies and rafting as well as over longer time frames with glaciation-interglacial shifts of ocean fronts and crawling along the seafloor (Sands et al., 2015; Fraser et al., 2018). Recent human activity, including increasing tourist visitation and more widespread national Antarctic operator logistical and research activity (Tin et al., 2014; Bender et al., 2016; Pertierra et al., 2017), have increased the types of vectors and opportunities, including ship hulls and plastic in the sea (Barnes, 2002; Lewis et al., 2003, 2004). Furthermore changes in the cryosphere and sea temperatures described above have also changed the potential survivorship of NIS propagules in transit to the region, their establishment and spread (Clarke et al., 2007; Turner et al., 2009; McCarthy et al., 2019). Risk of NIS transport and establishment in marine environments is not evenly spread around the southern polar region (Barnes et al., 2009) and threat levels are strongly coincident with human transport routes and

destinations (Hughes et al., 2019; McCarthy et al., 2019). One of the main threats is seen as the bivalve mollusc genus *Mytilus* which are already well documented NIS elsewhere in the world (Hughes et al., 2019).

Preventative/biosecurity measures have been considerably ramped up and enforced within the last decade, including with the production of a Non-native Species Manual by the Committee for Environmental Protection (CEP, 2017) and biosecurity checklists by the Council of Manager of National Antarctic Programs (COMNAP/SCAR, 2010). Some steps have been taken to address NIS within ballast water, with the Antarctic Treaty Consultative Meeting and International Maritime Organisation (IMO) having agreed ballast water exchange protocols for ships entering the Southern Ocean (ATCM, 2006; International Maritime Organisation Marine Environment Protection Committee [IMO], 2007) and more stringent internationally applicable ballast water regulations, having entered into force in 2017, which require ships to treat or exchange ballast water (International Maritime Organisation [IMO], 2004). However, there is still little progress to reduce marine NIS risk associated with hull fouling, possibly due to the perceived expense and impact on itineraries of hull cleaning activities. There may also be the perception that traveling through sea ice will scour the hulls free of NIS, thereby removing the risk, but research has shown fouling species persisting in sea chests and water intakes ports on the ship hull (Lee and Chown, 2007; Hughes and Ashton, 2017) and many vessels operating in polar water actively avoid sea ice, removing any potential biosecurity benefit (McCarthy et al., 2019). Marine invasions are harder to detect and much harder (if not impossible) to reverse (Ojaveer et al., 2014) and effective biosecurity practices depend more on national operator measures rather than the action of individuals (e.g., the cost and coordinated effort required to clean a ship's hull).

The majority of NIS records have been in the Atlantic and East Pacific regions where the majority of boat transits into the Southern Ocean occur (Figure 3). For example, a NIS marine algae (*Ulva intestinalis*) arrived and established at Deception Island (Clayton et al., 1997). It has also been reported from other frequently visited locations, Half Moon, Livingston, Robert, Nelson, King George, Penguin and Elephant Islands and sub-Antarctic Macquarie Island (Figure 3). There have been concerted efforts to bring experts together for NIS risk assessment, to identify most likely invader species and vectors and to provide stronger prevention and management advice (Key, 2018; Roy et al., 2019), which could be usefully undertaken within other regions of Antarctica.

New approaches to threats to native species (Morley et al., 2019) and most likely invaders (Hughes et al., 2019) have been through risk analysis. More than a hundred likely potential invaders were considered, mainly likely to come from southern South America and establish in the northern Antarctic Peninsula and Scotia Arc locations. Mytilid mussels were highest on the NIS risk, because they are abundant in ports, widely successful invaders elsewhere, have survived journeys to the SO (Lee and Chown, 2007) and tend to smother coastal life on establishment (Hughes et al., 2019). The strength of these approaches has been

illustrated by the recently discovered population of *Mytilus cf. platensis* which settled in a shallow subtidal habitat of the South Shetland Islands (Cárdenas et al., 2020).

Poleward movement of species to bottlenecks such as Patagonia, South Africa and Australasia is likely to intensify over the coming decades, increasing propagule pressure of potential NIS (Ruiz and Hewitt, 2009). The number of vessels, people and water-borne debris set to reach the region also seems likely to continue to increase, as does climate-mediated environmental change (Barnes, 2002; Barnes et al., 2018b; McCarthy et al., 2019). Consideration of the problem and preventative action have both been stepped up for some pathways, but the challenge is considerable and the impacts and costs of NIS can clearly be seen in every other major non-polar environment.

Migratory Species and External Impacts

Migratory species in Southern Ocean ecosystems include pinnipeds, cetaceans and seabirds. Many of these species travel long distances to Antarctic and sub-Antarctic waters during the austral summer to forage on low-trophic level prey. Migratory species are uniquely vulnerable to changing environmental conditions due to their long-distance travel and reliance on a number of unique integrated factors (Leaper et al., 2006; Tulloch et al., 2017). These include whole suites of discrete sites remaining intact, the resources they require at those sites being available at the right time, and the connections between sites remaining within reach given a species' movement capability (Newson et al., 2009).

Migratory species moving through Southern Ocean ecosystems face numbers of direct and indirect pressures from changing physical environments and human activities across their range. Within Antarctic waters, changing climate drivers will alter productivity regimes, which will very likely affect low trophic prey such as krill (Flores et al., 2012), with possible flow-on effects to dependent migratory fur seal (*medium confidence*; Croll and Tershy, 1998), baleen whale (*high confidence*; Tulloch et al., 2019) and seabird (*medium confidence*; Barbraud et al., 2012) predators that travel to Antarctic waters to forage. Many of these species are particularly vulnerable due to low abundances and slow population growth. Historical commercial exploitation of migratory fur seals and whales across the Southern Oceans pushed many species almost to extinction. Although some heavily depleted populations of seals and whales have begun to recover (Hucke-Gaete et al., 2004; Tulloch et al., 2017), populations of whale species including blue, fin and Southern rights are still well below their pre-exploitation numbers despite international protection. Some populations of Southern Ocean seabirds are very low numbers due to historical fisheries interactions, and are likely vulnerable to changes in adult mortality given their life history characteristics (*high confidence*; Phillips et al., 2016).

The long distance movements of Southern Ocean migratory species make them susceptible to other external anthropogenic impacts, such pollution, ship strikes fishing gear interactions diminishing food supplies, and reduced breeding habitats, all of which can reduce population numbers or negatively affect the fitness of an animal (Rosenbaum et al., 2014; Clapham, 2016).

While pollutant exposure is generally low within the SO, pollutants pose a serious risk to SO migratory species. Migratory seabirds such as south polar skuas (*Catharacta maccormicki*) and brown skua (*Catharacta skua lönnbergi*) have up to 20 times higher levels of the persistent organic pollutant (polybrominated diphenyl ethers) than endemic species that live year round within the SO, likely due to exposure to contamination events at lower latitudes during the non-breeding season when they migrate northward (*high confidence*; Yogui and Sericano, 2009; Corsolini et al., 2011).

Due to this exposure when outside of the SO, migratory species likely act as vectors for transporting pollutants into the SO (*medium confidence*; Yogui and Sericano, 2009; Corsolini et al., 2011). Marine debris can also enter the Antarctic ecosystem carried by nektonic animals such as seabirds and seals (Barnes et al., 2004). Fur seals can become entangled on the South American continental shelf or along populated shores (Laist, 1997; do Sul et al., 2011). During the austral winter migratory marine biota reach lower latitudes, when seabirds ingest floating plastics in the open ocean; on nesting areas, plastics may then be regurgitated to chicks (*medium confidence*; Fry et al., 1987; van Franeker and Bell, 1988; Wilcox et al., 2015). Greater quantities of plastics traveling in the SO likely increase the possibility of transport of colonists to Antarctica (*medium confidence*; Barnes, 2002). Terrestrial threats such as disease and predation may affect migratory seabirds nesting on land (Phillips et al., 2016). Introduced mammals are the foremost land-based threat to seabirds on sub-Antarctic islands (*high confidence*; Jouventin and Weimerskirch, 1991; Baker et al., 2002).

Since the early 90s, efforts conducted by the Committee for the Conservation of Antarctic Living Marine Resources (CCAMLR), via a series of conservation measures, have been very successful in addressing the problem of incidental mortality, especially seabirds, in the Convention area. However, during migrations outside of the SO bycatch and entanglement in fisheries gear are recognized as the most significant threat to the survival of cetacean and seabird species and populations globally (Read, 2008; IWC, 2010; Barbraud et al., 2012). Continued industrialization of fisheries have led to intensification of fishing effort in many regions (Pauly, 2009), including increased presence of fishing gear in whale habitat (Lewison et al., 2004; Read et al., 2006), increasing the risk of interactions with such gear (Cassoff et al., 2011). Binding legal requirements to reduce bycatch exist in the national legislation of many countries. However, despite new technologies and industry recognition of the issue, monitoring and management can be costly, and/or ineffective, and bycatch remains a major global problem (Tulloch et al., 2020). Unregulated or increased longline and trawl fishing in key breeding areas for vulnerable species of albatross (e.g., *Thalassarche melanophrys*, *Diomedea* spp.) is likely to lead to continued population declines (*high confidence*; Tuck et al., 2003; Phillips et al., 2016). Some baleen whale populations (e.g., southern right whales in the southeastern Pacific off Chile and Peru) are small and endangered, and, for them, even small numbers of fisheries gear entanglements are potentially significant (low confidence; Reeves et al., 2013).

Other external drivers affecting SO migratory species include vessel traffic and mining activities. Ship strike/collision can result in injury, displacement, disturbance, and behavioral modification (*high confidence*; van der Hoop et al., 2015; Pirota et al., 2019). The number of reported vessel strike incidents has increased over the last 2 decades (Peel et al., 2018), but reporting biases exist related to species identification, spatial coverage of reports and type of vessels involved, and quantifying the rate of occurrence of these collisions is difficult because many incidents are not detected. Southern right whale (*Eubalaena australis*) populations off South Africa and off eastern South America (Brazil, Uruguay and Argentina) have historically suffered high mortality due to vessel strikes (56 reported cases before 2007, *high confidence*; van Waerebeek et al., 2007). Studies show likely behavioral modifications of migratory whales including southern right and humpback whales (*Megaptera novaeangliae*) with reduced foraging and shifting of traditional use areas in response to noise from human activities such as shipping and seismic surveys (*high confidence*; Parks et al., 2007; Dunlop et al., 2010; Blair et al., 2016).

Some migratory animal populations may also be susceptible to diminishing food supplies in regions where fisheries are poorly managed, or where climate change impacts may affect lower trophic prey populations. Overfishing can have profound implications for higher-order predators. Population-level impacts on seabirds such as albatrosses and petrels may occur through direct competition with fisheries for prey (*medium confidence*; Croxall and Gales, 1998; Baker et al., 2002). The level (and the effects) of competition for food resources between seabird populations and fisheries, however, is uncertain. Lower trophic prey such as krill are expected to be affected by future warming oceans given climate change (*high confidence*; Flores et al., 2012). It is uncertain how climate change may facilitate or hinder the recovery of species that forage heavily on krill or rely on stable sea-ice conditions in rapidly warming regions of the SO (Simmonds and Isaac, 2007). Blue (*Balaenoptera musculus*), fin (*Balaenoptera physalus*) and humpback whales that forage in mid-latitudes may be the most at risk from climate-induced impacts on their prey (*medium confidence*; Tulloch et al., 2019).

ASSESSMENT

Main Drivers and Their Interactions

The global physical and human drivers, along with their interactions, were summarized from the proceeding text into a qualitative network diagram (Figure 4). The Northern drivers, those whose influence on the SO comes from North of the region, dominate the changes happening within the SO. The major effect of the ozone hole on atmospheric circulation and wind strength which, in turn, have had contrasting regional effects on the cryosphere of the West Pacific (Ross Sea) and East Pacific (western Antarctic Peninsula) sectors of the SO, were a consistent theme throughout the assessment. The importance of the additive interactive effects of SAM and ENSO were

also repeated. The other key human driver is the increase in CO₂, which is not only linked to warming, and its impact on the cryosphere, but will also lead to ocean acidification and affect the carbon cycle (*high confidence*). This is expected to have an impact on both benthic and pelagic ecosystems (*high confidence*). Unless human emissions are controlled, the comparatively limited current impact of pollution and non-indigenous species is expected to increase into the future (*high confidence*).

Future Prognosis and Priorities

The future projections of the global drivers highlighted in the preceding literature review are summarized through the assessment in **Table 1**. One of the main themes running through this assessment are the large uncertainties in the models that are used to make these projections. Only a concerted international effort will enable these uncertainties to be reduced (**Box 1**). International frameworks, working groups and grants, such as the Antarctic Treaty System and CCAMLR, the Southern Ocean Observing System (SOOS) and MEASO, and the EU Rise network project CoastCarb, are essential to ensure consistent approaches are applied across the region.

Many of the changes in global drivers that have affected SO marine ecosystems over recent decades were strongly linked to the loss of atmospheric ozone since the 1970s (*very high confidence*; **Table 1** and **Figure 4**). One of the key future uncertainties about how global drivers of SO marine ecosystems will change, therefore, relates to the impact of the expected reversal of the ozone hole. Will this start to reverse some of the recent physical changes, or will global and regional increases in temperature override this? The best estimates suggest that within decades the global increase in temperature is highly likely to override any cessation of warming in the Eastern Pacific sector, particularly the Antarctic Peninsula (*high confidence*; Turner et al., 2016; Rogers et al., 2020). Depending on the trend in SAM, the reversal of the stronger winds may reduce the cooling influence in the East Indian and West Pacific zones, ultimately leading to warming across the whole of the SO (*medium confidence*).

While the reversal of the winds may slow the shoaling of warm water onto SO shelves (*medium confidence*), the increase in global air temperatures is very likely to continue the disintegration (giant iceberg formation) and melting of ice shelves. The number of glaciers in retreat and their retreat rate will further increase and many will soon reach ground lines (*very high confidence*). To make predictions for sea ice change is much less clear. The mechanisms underlying the recent drop from near recent maximum to minimum sea ice extent since spring 2014 including the time-scale over which these drivers are operating, is uncertain (*low confidence*). As one of the key drivers for SO marine ecosystems, and crucial for key SO species such as krill and some top predators, this leaves a large area of uncertainty around the future of sea ice.

Some pollutants such as CFC's, are subject to global agreements, their levels are controlled and their impacts are

reversing (*medium confidence*). As the impact of other industrial climate gases are identified (e.g., sulfur hexafluoride, SF₆; Widger and Haddad, 2018) research on which pollutants need to be controlled will need to keep pace with technological developments. However, even under the best case future emission scenarios atmospheric CO₂ will continue to increase (*high confidence*), adding to global increases in temperature. CO₂ will continue to dissolve into the ocean, lowering the pH. Year round measurements from a wider variety of locations, are required to constrain uncertainties in the models.

Other anthropogenic drivers also have degrees of uncertainty. Until very recently global tourism was expected to increase in parallel with economic prosperity, however, growing health concerns over mass tourism (Hill, 2019) have been amplified by the COVID-19 pandemic and the trajectory of near future SO tourism is now highly uncertain. There are also concerns about the risk of tourists transferring anthropogenic diseases to Antarctic seabirds which may become reflected in future recommendations of IAATO and the Antarctic Treaty (Cerdà-Cuéllar et al., 2019).

In particular the necessity of determining between trends that are the result of natural variability and those that are anthropogenic or the result of climate change requires an increased number of extended time series. Process studies, to understand the underlying mechanisms of this variability, must be a priority. Efforts to improve the observational records around Antarctica are critical to understand the nature of change around the continent and to predict the impacts on marine ecosystems.

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