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The Antarctic Peninsula Under a 1.5°C Global Warming Scenario

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Warming of the Antarctic Peninsula in the latter half of the twentieth century was greater than any other terrestrial environment in the Southern Hemisphere, and clear cryospheric and biological consequences have been observed. Under a global 1.5°C scenario, warming in the Antarctic Peninsula is likely to increase the number of days above 0°C, with up to 130 of such days each year in the northern Peninsula. Ocean turbulence will increase, making the circumpolar deep water (CDW) both warmer and shallower, delivering heat to the sea surface and to coastal margins. Thinning and recession of marine margins of glaciers and ice caps is expected to accelerate to terrestrial limits, increasing iceberg production, after which glacier retreat may slow on land. Ice shelves will experience continued increase in meltwater production and consequent structural change, but not imminent regional collapses. Marine biota can respond in multiple ways to climatic changes, with effects complicated by past resource extraction activities. Southward distribution shifts have been observed in multiple taxa during the last century and these are likely to continue. Exposed (ice free) terrestrial areas will expand, providing new habitats for native and non-native organisms, but with a potential loss of genetic diversity. While native terrestrial biota are likely to benefit from modest warming, the greatest threat to native biodiversity is from non-native terrestrial species.

Keywords: polar change, glaciers and climate, sea ice, marine biology, terrestrial biology

BACKGROUND TO 1.5°C

Since the industrial revolution average global temperatures have risen ~1°C. The goal of the UN Paris Agreement is to hold global warming to well below 2°C and endeavor to limit it to 1.5°C, relative to preindustrial levels[1]. Thus, a 1.5°C scenario relates to additional global warming of 0.5°C. Here, we look at the potential impacts of a 1.5°C scenario on the Antarctic Peninsula. Studies show that such an outcome is possible but requires ambitious societal transformation pathways between now and the middle of this century (IPCC, 2018). There is more than one way to achieve a 1.5°C outcome, which is why it is referred to correctly as "a" scenario as opposed to "the" scenario.

[1] https://unfccc.int/sites/default/files/english_paris_agreement.pdf

INTRODUCTION TO THE ANTARCTIC PENINSULA

We interpret the Antarctic Peninsula liberally as including the Peninsula itself and its off-lying islands (e.g., South Shetland Islands), as well as the surrounding continental shelf and nearby oceans. We do not include more northerly islands (e.g., the maritime Antarctic South Orkney and South Sandwich Islands and sub-Antarctic South Georgia). In the south, the Antarctic Peninsula extends to the southern end of George VI Sound and the northern edge of the Ronne Ice Shelf. Thus defined, the Antarctic Peninsula is divided down its lengthy mountainous spine by strong West to East gradients in atmospheric and ocean circulation, which makes for distinct characteristics in oceanography, glaciology and biology either side of its spine. The Peninsula is also affected by North-South changes from the fringe of the sub-Antarctic to the deep polar region. As a consequence of direct and remote scientific measurements over the last 100 years, we have more knowledge about natural processes and change in the Antarctic Peninsula than any other part of the continent.

HOW WILL THE ANTARCTIC PENINSULA RESPOND TO A 1.5°C SCENARIO?

Atmosphere

Climate model projections suggest that Antarctic Peninsula temperatures will increase by more than the global average in a world 1.5°C warmer than pre-industrial levels (Hoegh-Guldberg et al., 2018). Indeed, we note that warming since 1850 in the northernmost region of the Peninsula has already exceeded 1.5°C (Turner et al., 2005), despite a pause in rising temperatures during the first two decades of the twenty-first century (Turner et al., 2016). Nevertheless, projections show that regional temperatures could increase further beyond current levels in a 1.5°C scenario, by another 1–2°C in winter and 0.5–1.0°C in summer (Li et al., 2018), reducing the magnitude of the annual temperature cycle. Moreover, temperatures of the coldest nights will rise significantly more than those of the hottest days (Li et al., 2018). Of importance for terrestrial ecosystems, a 1°C mean annual warming will likely result in a 50–150% increase in days per year above 0°C, from 25–80 each year in the northern Antarctic Peninsula to 35–130. This introduces greater opportunity for rain, rather than snowfall, especially at low elevations.

Climate model projections also indicate a likely increase of 10–20% in precipitation (relative to the pre-industrial period) with an intensification of extreme precipitation events (Hoegh-Guldberg et al., 2018). Again, in the southern Peninsula, observed rates of precipitation change to date have been much higher (Thomas et al., 2008). There is unlikely to be much further increase beyond current levels (Li et al., 2018). The principal projected change in circulation affecting the Peninsula is a weakening of the circumpolar westerlies around Antarctica during summer, in response to ozone recovery.

We note that these projections are derived from climate models with known difficulties in reproducing Antarctic Peninsula climate. Models have also had limited success in reproducing the observed warming in the twentieth century. Discrepancies occur in replicating both large-scale atmospheric circulation variability (Hosking et al., 2013) and important regional processes (Marshall and Bracegirdle, 2015), such as the Föhn winds that develop on the eastern Antarctic Peninsula and cause extremely rapid local warming (Turton et al., 2018).

Southern Ocean

The Antarctic Circumpolar Current (ACC) buffers the Antarctic continent from the global ocean and it extends the Antarctic environment to its northern boundary, the Polar Front. South of the Polar Front, the ocean circulates clockwise around Antarctica with two large clockwise gyres in the Weddell and Ross Seas. A few hundred meters beneath the surface is a large volume of relatively warm water called Circumpolar Deep Water (CDW). Because of the ocean circulation, on the west of the Peninsula CDW arrives from the west. In contrast on the east of the Peninsula the circulation around the Weddell Sea and sea ice formation cools the CDW so that waters are much colder (Meredith and Brandon, 2017). We know that much of the Earth's anthropogenic warming has been absorbed in the Southern Ocean (Llovel and Terray, 2016), but we have no clear evidence that it is moving the Polar Front as a result (Gille, 2014). However, the CDW is both increasing in temperature and becoming more shallow (Schmidtko et al., 2014), and the amount of turbulence in the Southern Ocean is increasing (Hogg et al., 2015). We can expect these trends to continue.

Sea Ice

Satellites can measure the area of frozen ocean—the sea ice extent—and the record extends back to October 1978. From July 1987 there are daily measurements. While thickness has not been routinely measured from satellites the way the ice extent has, sea ice thickness is typically in the range 2–4 m but it can, in places, pile up to form "ridges" more than 10 m thick (Williams et al., 2014). However, because satellites cannot currently measure sea ice thickness routinely, our knowledge of the "normal" state, and rates of change, are relatively poor.

The two sides of the Antarctic Peninsula have very different conditions. For any given month the ice edge is at higher latitude on the Peninsula's west compared with the east. In summer, virtually the whole Bellingshausen Sea is ice free, but on the east in the Weddell Sea the sea ice typically extends to the northern end of the Antarctic Peninsula, and is much thicker so even the highest classification ice-breaking ships have great navigational difficulty.

In total, since satellite records began around 30 years ago, there has been a modest increase in the total sea ice extent of ~70,000 km^{-2} yr^{-1}. In 2016/7 the summer sea ice extent for the Antarctic as a whole reached historic lows (Schlosser et al., 2018), but observed trends are comparable with reconstructed records of but past 200 years (Jones et al., 2016). Despite the overall positive trends in sea ice extent, inter-annual variability has increased (Turner and Comiso, 2017) and there have been large regional and seasonal changes. For example, to the Antarctic Peninsula's west, sea ice extent has decreased ~6–10% per decade with the greatest changes in autumn and summer (Turner et al., 2015). The length of the sea ice season on the west of the Peninsula has reduced by ∼4 days (Massom et al., 2018). To the east, summer sea ice coverage has increased, while decreasing in winter. Whilst current models of Antarctic sea ice extent simulate a wide range of historical sea ice conditions, their overall ability to reproduce current trends is poor (Zunz et al., 2013). Nevertheless, we expect increased variability on the west of the Peninsula, compared with the east as the climate warms.

Land Ice

The glaciers of the Antarctic Peninsula are generally steep and fast flowing, and respond rapidly to climatic changes. Hundreds of glaciers mapped north of 70°S terminate in the sea while remaining grounded, scores have floating termini and only a handful are land-terminating (Cook et al., 2014). Most of the glacierised area comprises large outlet glaciers flowing from the spine of the Antarctic Peninsula to the ocean. North of Alexander Island, one third of the total volume of grounded ice rests on rock below sea level, meaning that it is vulnerable to ice-shelf break-up and changes to ocean circulation and temperature (Huss and Farinotti, 2014).

Thinning and recession of glaciers and ice caps in the Peninsula, observed in recent decades (Wouters et al., 2015; Shepherd et al., 2018; Rignot et al., 2019), is expected to accelerate, driven by increased upwelling of CDW and increased sea surface temperatures around the western Antarctic Peninsula. However, it is worth noting that the loss of marine-terminating glaciers will probably be greater than for land-terminating glaciers, because they receive warmth from the ocean as well as direct atmospheric heating in the Peninsula (Cook et al., 2016). Hence, it is possible that glaciers will retreat to their land margins and then experience less thinning subsequently.

In the southern Peninsula, there is a small potential for more rapid glacier retreat under a marine ice sheet instability mechanism as glaciers here are grounded deeply below sea level (Turton et al., 2018). If the number of positive degree days increases substantially (Barrand et al., 2013), and if surface temperatures are influenced by occasional Föhn wind heat (Luckman et al., 2014; Turton et al., 2018), glaciers on land will experience more rainfall and direct surface melting than they do at present. The consequent ice loss may be at least partially balanced by increased snowfall, however.

Ice Shelves

Ice shelves are continuous layers of floating ice formed by land-based glaciers feeding into enclosed shoreline embayments. Ice shelves are prominent along the Antarctic Peninsula, where they cover an area of ∼120,000 km^2 with the largest being Larsen C (∼50,000 km^2; Cook and Vaughan, 2010). Importantly, ice shelves buttress the flow of upstream glaciers, modulating sea-level rise. Although ice shelves naturally lose mass by iceberg calving, and through surface and basal melting, they are susceptible to irrecoverable collapse if their extent and/or thickness reduce below a threshold of physical support.

In recent decades, seven out of twelve ice shelves around the Antarctic Peninsula have either receded significantly (e.g., Wilkins in 2008) or collapsed almost completely (e.g., Larsen B in 2002). The −9°C mean annual isotherm marks the transition between stable and potentially unstable ice shelves on the Antarctic Peninsula (Morris and Vaughan, 1994), and is migrating southwards. Under a 1.5°C scenario, it is likely that Antarctic Peninsula ice shelves will continue to thin, mainly due to increased surface melting (Trusel et al., 2015) driven by widespread increases in air temperature and locally-enhanced Föhn winds, also increasing the exposure of low-albedo blue ice (Lenaerts et al., 2016). This surface melting will likely lead to increased surface ponding, which may cause ice-shelf flexure and fracture, particularly when lakes drain; a process implicated in the collapse of Larsen B (Banwell et al., 2013). In contrast, surface rivers flowing over impermeable refrozen ice (Hubbard et al., 2016) may mitigate against future ponding and ice-shelf instability (Bell et al., 2017). Ice shelves will also thin in response to sub-shelf melting due to the ingress of buoyant, warm ocean water (Bentley et al., 2005). While ice-shelf thinning increases the likelihood of iceberg calving, the largest of Antarctic Peninsula ice shelves (e.g., Larsen C and George VI) still have sufficient surface area to probably avoid catastrophic failure.

Thus, under a 1.5°C scenario, Antarctic Peninsula ice shelves will experience more surface melting and consequent structural change, but not imminent regional collapse. However, in the absence of a temperature reversal, longer-term feedback cycles such as that between surface melt and albedo, or incursions of warm ocean water, increase the likelihood of eventual wholescale ice shelf disintegration, especially for those known to have disappeared previously under slightly warmer conditions, such as George VI (Bentley et al., 2005).

Marine Ecosystems

The past and future response of marine biota to ongoing climate change is complicated by the effects of marine resource extraction. Sequential over-exploitation of seals, whales and some species of fish over the last two centuries has severely perturbed the food web, making it hard to unravel its effect from that of climate (Trivelpiece et al., 2011).

A warming Antarctic Peninsula has multiple effects including increasing water temperatures, seabed scour from icebergs, ocean acidification, meltwater, sediment inflow and ice free habitat, plus decreases in sea-ice habitat. Responses of the biota are also diverse, including changes in behavior, physiology, geographic- or depth- distribution plus evolutionary adaptation. Stresses can act either directly—for example rain reducing Adélie penguin breeding success—or they can act through the food web by changing the availability of their prey (Trivelpiece et al., 2011).

A pragmatic approach to estimate the future is to examine how the biota have already responded to rapid warming of the last century (Henley et al., 2019) and use that as a yardstick, although the potential existence of tipping points should not be discounted. The spatio-temporal distribution is the net response to multiple stressors, and a common pattern across multiple taxa is a southwards range shift (Constable et al., 2014). Despite variation and strong non-linearities in this response (Atkinson et al., 2019) we can project that these shifts will continue with warming, since the Antarctic Peninsula offers a long, north-south continuum of broadly similar habitat across an environmental gradient. The strong juxtaposition of multiple stressors along the western Antarctic Peninsula last century may de-intensify under a 1.5°C scenario due to the reduced amplitude of projected sea ice and temperature changes in this particular area (Gutt et al., 2014). Nevertheless, benthic community structure is under threat from increased ice scour, ocean acidification and changes in seabed temperature (Turner et al., 2014).

Terrestrial Ecosystems

Terrestrial biology is limited to ice-free areas, currently about 3% of the Antarctic Peninsula, of which only a fraction is currently visibly colonized. The seasonally-exposed terrestrial area of the Peninsula is expected to expand by 2100 (Lee et al., 2017). This retreat of permanent ice cover will provide new habitats for colonization by both native and likely, non-native organisms. It will also lead to the coalescing of some areas that are currently isolated and, thus, to a loss of genetic diversity through genetic homogenization. Native terrestrial biota are well-adapted to the variable conditions of the Antarctic Peninsula (Peck et al., 2006; Pertierra et al., 2017) and, in the absence of other influences, are likely to benefit from modest levels of warming (Convey, 2011).

Warming to date has been associated with rapid expansion of native higher plant and moss populations (Cannone et al., 2016, 2017), and local-scale colonization of newly exposed ground. However, movement of the "southern limit" of these plants has yet to be observed. This "greening" is expected to continue through the twenty-first century. While natural colonization of the region is expected to occur, rates of anthropogenic (human-assisted) introduction far outweigh natural colonization. It is already known that a wide range of non-native species could survive in parts of the Antarctic Peninsula region if given the opportunity to arrive. Thus, the threat of non-native species to native biodiversity likely far outweighs the impacts of climate change under a 1.5°C scenario.

IMPLICATIONS FOR OPERATIONS

Antarctic Peninsula infrastructure is likely to be affected by a 1.5°C scenario. Increased levels of surface water run-off (from rain and snow/glacial melt) and/or melting of any thin layers of sediment, may alter the geotechnical properties of ice-free land considerably, albeit for limited periods of the year. Such change may impact research station buildings and, potentially, air strips. Increased iceberg production, and inter-annual variability in sea ice conditions, will also need to be accounted for by shipping. The increased viability of alien species, coupled with expanded ice-free regions, means environmental protection of the Antarctic Peninsula must remain resolute.

CONCLUSION

The Polar Regions have warmed twice as much as the global average since 1850. This has led to glacier retreat, ice shelf decay and the expansion of exposed land on which some plants have been able to grow. By restricting global temperature increase to 1.5°C above 1850 values, we can limit the damage to the Antarctic Peninsula's ecosystems. However, we cannot avoid further loss of ice, expansion of vegetation and invertebrate communities on land (potentially with alien species), and alteration to marine ecosystems that are still recovering from marine resource extraction decades ago. If we fail to restrict average global warming to 1.5°C, the Antarctic Peninsula will likely experience irreversible and dramatic change to glacial, terrestrial, ocean, and biological systems.

AUTHOR CONTRIBUTIONS

All authors have contributed to this multidisciplinary work, either in providing text, editing and/or contributing to the infographic.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00102/full#supplementary-material

Supplementary material includes an abridged version of this paper that was submitted by the UK Foreign and Commonwealth Office to the XLII Antarctic Treaty Consultative Meeting held in Prague 1-11 July 2019 (**Supplementary Data Sheet 1**), and a modified version of the paper as an informal Grantham Institute Policy Briefing Note (**Supplementary Data Sheet 2**).

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

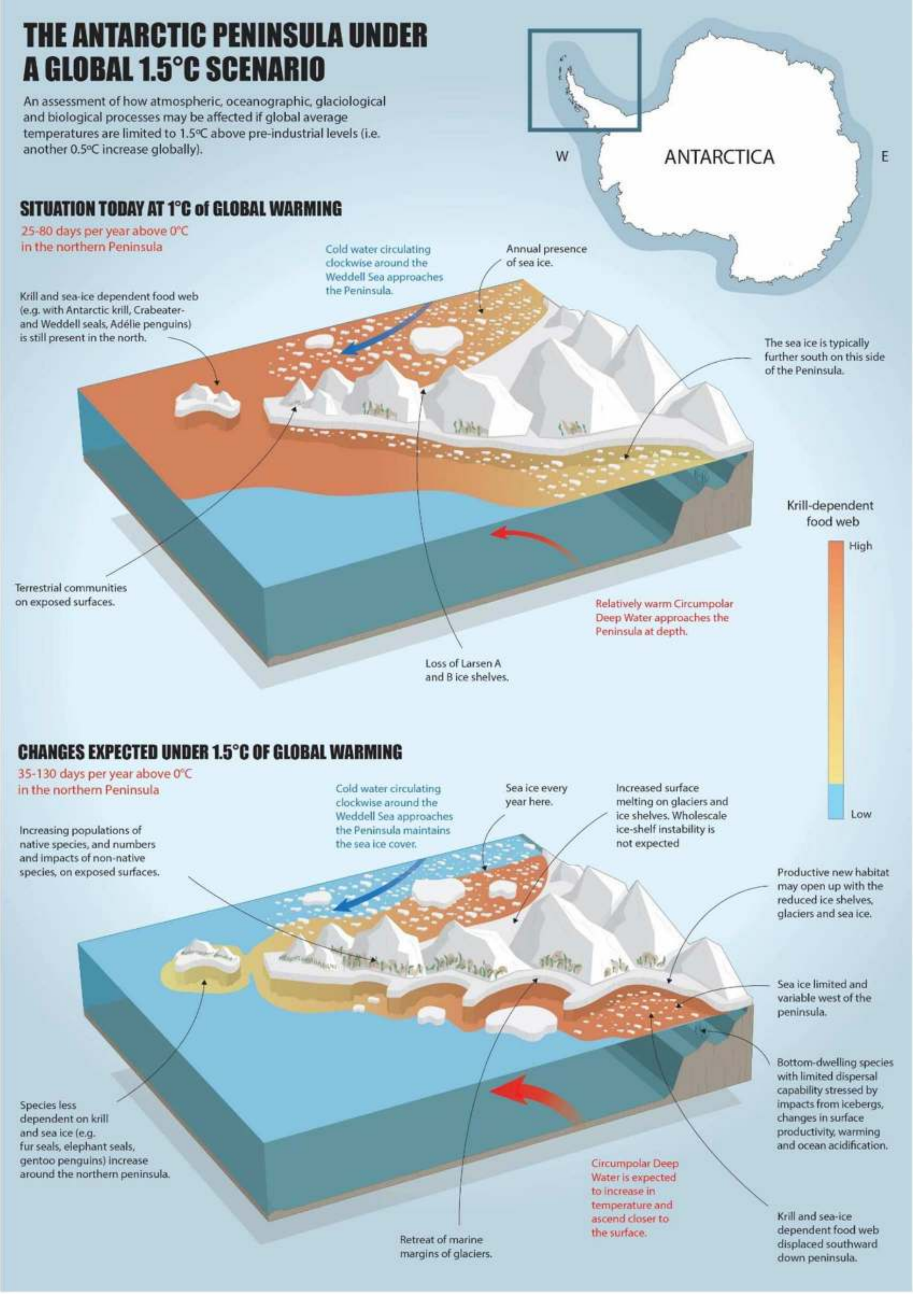

FIGURE A1 | Infographic.