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Impacts of Climate Change on Antarctic Ecosystems

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Summary

Over the past 50 years, the Western Antarctic Peninsula has warmed more than four times faster than the average rate of Earth's overall warming, making it one of the regions that is experiencing the most rapid warming on the planet. Although warming is neither evident nor uniform across the Antarctic, substantial evidence indicates major regional changes in terrestrial and marine ecosystems in areas that have experienced warming. Successful invasions of non-indigenous species to sub-Antarctic islands have been identified as a likely consequence of the continuing trend of increasing human activities and increasing temperatures.

Climate change is no longer an issue limited to the developed and more populated parts of the world. The Consultative Parties to the Antarctic Treaty have committed themselves to provide comprehensive protection to the Antarctic environment and its dependent ecosystems under the Environmental Protocol. Therefore, and based on the precautionary principle, Consultative Parties should recognize the adverse impacts of climate change on Antarctica and the Southern Ocean and take proactive action within the framework of the Treaty System to contribute towards climate change mitigation and adaptation efforts.

1. *Introduction*

Climate change has emerged as a recurrent and important topic on the ATCM agenda over the past few years. While most papers[1] submitted to the ATCM on climate change have focused primarily on changes in the physical environment in Antarctica, less attention has been given on the impacts of climate change on Antarctica's ecosystems. The present paper aims to bring attention to this subject, drawing from recent peer-reviewed scientific reviews, including the UN Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment report.

Over the past 50 years, Western Antarctic Peninsula has warmed more than four times faster than the average rate of Earth's overall warming[2], making it one of the regions that is experiencing the most rapid warming (Turner et al., 2005; IPCC, 2007a). The vast Southern Ocean has warmed all the way down to a depth of 3,000 m (Jacobs, 2006). The ozone hole continues to deepen, leading to continued acceleration of the polar vortex (Thompson and Solomon, 2002). Partially as a consequence, winds in the zone of westerlies are increasing and wind directions have changed dramatically (Russell et al., 2006; Stammerjohn et al. 2008) leading to regional changes in sea ice persistence: increasing in the Ross Sea/western Pacific region and decreasing in the Bellingshausen/Amundsen sea region (see also Zwally et al. 2002; Parkinson et al. 2002; IPCC, 2007b).

Substantial evidence indicates major regional changes in Antarctic terrestrial and marine ecosystems in areas that have experienced warming (IPCC, 2007b). Increasing abundance of shallow-water sponges and their predators, declining abundances of krill, Adélie and emperor penguins, and Weddell seals have been recorded (Atkinson et al., 2004; Ducklow et al. 2007). The abundance and distribution of the two only species of native flowering plants have also increased, likely as a result of increasing summer temperatures (Fowbert and Smith, 1994). Changes in the phenology of seabirds in East Antarctica have been observed (Barbraud and Weimerskirch, 2006). Successful invasions of non-indigenous species to sub-Antarctic islands

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[1] ASOC: The Antarctic and Climate Change. ATCM XXVIII IP 104; ATCM XXIX IP 62; ATCM XXX IP 82 Rev. 1; SCAR: State of the Antarctic and Southern Ocean Climate System (SASOCS) ATCM XXX IP 5; Norway: Climate Changes. ATCM XXX WP 28.

[2] Warming rate of Vernadsky / Faraday = 0.56°C per decade over past 50 years (Turner et al., 2005); Rate of global warming = 0.13°C per decade over last 50 years (IPCC, 2007a)

have been identified as a likely consequence of the continuing trend of increasing human activities and increasing temperatures (Frenot et al., 2005).

Climate change is no longer an issue limited to the developed and more populated parts of the world. In Antarctica, not only the complexities of climate change are being studied but the impacts of climate change are also becoming manifest. Of course, uncertainties still exist in how the complex physical and biological systems in Antarctica will interact as the Earth continues to warm; and indeed, many of the possible solutions to climate change need to be addressed at a global level. However, the Consultative Parties to the Antarctic Treaty have committed themselves to provide comprehensive protection to the Antarctic environment and its dependent ecosystems under the Environmental Protocol. Therefore, and based on the precautionary principle, Consultative Parties should recognize the adverse impacts of climate change on Antarctica and the Southern Ocean and take proactive action within the framework of the Treaty System to contribute towards climate change mitigation and adaptation efforts.

At this ATCM, ASOC requests the Consultative Parties to take the following steps as part of the global effort to address climate change:

Mitigation efforts

- Issue a Resolution or other appropriate instrument acknowledging the adverse impacts of climate change on the Antarctic and Southern Ocean, and pledging to take steps both in the Antarctic and at the global level to avoid dangerous climate change.
- Establish a mandatory obligation to record the greenhouse gas emissions from stations, field camps, aircraft and vessels of all types – including tourism, fishing, whaling, scientific research, logistical supply, and fuel delivery vessels and aircrafts.
- Initiate additional steps to reduce the greenhouse gas emissions from these sources through energy efficiency, conservation and renewable energy initiatives at each station and field camp, and through other approaches for other sources.
- Establish a formal program to off-set greenhouse gas emissions from all stations, vessels and aircrafts, given that those are not covered by the Kyoto Protocol, and put it into operation by 2009.

Adaptation strategies

- Recognize the need to incorporate potential impacts of climate change in all future management decisions. Implement strategic, long-term, large-scale planning that integrates the potential impacts of climate change.
- Take action in order to minimize the risk of introductions of non-indigenous species. Practicable approaches include: cessation of imports of foreign biological material and soil, and on-station cultivation of biological material; control of visitor numbers and access to sensitive or pristine sites; cleaning or sterilization of high risk transport locations for aliens, such as cargo surfaces, foodstuffs and clothing; establishment of a code of conduct for all visitors to minimize the risk of transfer of propagules to pristine locations (Frenot et al., in press).
- Take action to minimize the risk of introduction of invasive marine organisms by ships in their ballast water through immediate application of the Guidelines For Ballast Water Exchange in the Antarctic Treaty Area.
- Urge CCAMLR Members to take full account on a precautionary basis, of the potential impact of climate change on the marine ecosystem when taking management and conservation decisions over Antarctic marine living resources.
- Recognize the need for climate change adaptation strategies, including the value that a network of Marine Protected Areas can bring to climate change adaptation.

2. Impacts of Climate Change on the Antarctic Terrestrial Ecosystem

A. Native species

The most widely quoted example of a rapid response to recent climate warming in the Antarctic terrestrial ecosystem relates to populations of the only two native Antarctic flowering plants, Antarctic hair grass (*Deschampsia Antarctica*) and Antarctic pearlwort (*Colobanthus quitensis*) (Fowbert and Smith, 1994; Grobe et al., 1997; Convey, 2006). Both species grow on the western coast of the Antarctic Peninsula. Long-term studies have shown that some populations have increased by one to two orders of magnitude in as little as 30 years. Other populations have colonized new areas of ice-free ground in the vicinity of existing specimens, although there is no overall increase in the species' ranges. These increases have been attributed to warmer summer temperatures that, in turn, enhanced seed maturation, germination and seedling survival (Convey, 2006).

Field manipulation experiments that make use of some form of chamber or screen to alter aspects of the thermal and radiation climates have shown spectacular responses in both floral and faunal communities (Convey, 2001). Under warmer conditions, existing flora shows greater ground coverage, lusher growth forms and greater reproductive output. Arthropod communities have shown rapid expansion. Nematode worms showed very rapid local increases of one to three orders of magnitude in population density (Convey, 2001).

Enhanced temperature under climate change may, firstly, increase the germination rate of native plants. However, changes in temperature and water availability are also expected to affect seed output and fertility and seedling survival, making the combined consequences of climate change on the colonization success of individual species hard to predict (Hennion et al., 2006). On subantarctic Macquarie Island, Whinam and Copson (2006) have reported recent and considerable decreases in the occurrence of the boggy mire moss (*Sphagnum falcatulum*) over the last two decades. A combination of higher than average temperatures and wind speeds, and lower than average humidity and precipitation, are proposed to underlie this observation, through increasing the desiccation stress on this plant. This example is likely to forewarn of many similar consequences in Antarctic terrestrial ecosystems (Convey, 2006). For some invertebrate species, the possibility exists that microhabitat warming may exceed their upper thermal limits (van der Merwe et al., 1997; Convey, 2001).

B. Alien species

It is clear from transplant experiments carried out during the 1960s (Edwards and Greene, 1973; Edwards, 1980), and from the many accidental introductions to sub-Antarctic islands (Frenot et al., 2005) that many non-Antarctic flowering plants are capable of establishment if the problems of dispersal can be overcome (Convey and Smith, 2006). Some of these species are invasive, and have rapidly occupied areas where indigenous plant communities have been removed by vertebrate activity, particularly grazing by introduced reindeer (Convey and Smith, 2006).

Over recent decades, the diversity and intensity of human activities in Antarctica have increased. Scientists, tourists and support personnel arrive by ship and by air. Without effective quarantine measures, alien organisms could be transported from all Southern Hemisphere continents to Antarctica by air within a 3-9 h period. Scientists and tourists are disproportionately attracted to sites of high / medium biodiversity. Sites where the two species of native flowering plants occur on the Antarctic Peninsula are likely to be those most at risk of introductions. Greater numbers of ships and tourists will lead to greater chances of introductions. Sites of high popularity are not consistent over time, meaning that the potential for human impact is not contained to a number of specific sites. The range of tourist activities is expanding, including movement through larger areas or visits to more islands, resulting in an increase in the chances of spreading alien species (Frenot et al., 2005).

A warmer climate will further enhance alien invasion as alien species will be able to establish themselves more easily in Antarctica once they arrive. Under most threat are relatively milder areas with increased human visitation and the most dramatic changes in environmental conditions. South Georgia, with climate warming, glacial retreat – itself a consequence of climate warming - and a large and increasing number of visitors, undoubtedly stands out as the most threatened area (Frenot et al., 2005). Furthermore, slow reproduction rates during rapid climate change may limit the possible relocation of native species (IPCC, 2007b).

3. Impacts of Climate Change on Antarctic Marine Ecosystems

Biological impacts are most likely to be evident in areas where the weather patterns are changing most dramatically, i.e. the Ross Sea and the Antarctic Peninsula regions. In the northwestern Weddell and southern Bellingshausen seas (Domack et al., 2003), surface air temperature records, reveal a warming in winter of 5–6°C over the past 50 years, a warming rate that exceeds any other observed globally (Vaughan et al. 2003; Ducklow, 2007). On the other hand, cooling is occurring in the Ross Sea/western Pacific sector of the continent.

A. Antarctic Peninsula: fastest warming on Earth

Along the Western Antarctic Peninsula, sea ice extent has decreased by 40% over the 26-year period from 1979 to 2004 (Ducklow et al., 2007; Stammerjohn et al., 2008). The advance of sea ice now occurs later and the retreat occurs earlier, resulting in a decrease of approximately three months in the winter sea ice period (see also Parkinson, 2002). Air temperature has risen well above freezing for much of the year and in some years, the region have been completely free of sea ice. Where average annual temperatures have risen above -6°C, ice shelves have begun to disintegrate (Vaughan and Doake, 1996), shown most graphically by the Larsen B and Wilkins ice shelves.

In the Antarctic Peninsula region, populations of Adélie penguins (*Pygoscelis adeliae*) have dropped by 65% over the past 25 years. Antarctic krill (*Euphausia superba*) and silverfish (*Pleuragramma antarcticum*) – Adélie penguins' primary food source during summer– have been decreasing (Atkinson et al. 2004; Emslie and Patterson 2007). Warmer temperatures also have allowed the atmosphere to hold more moisture, thus bringing more snow and hence a reduced land area on which Adélie penguins can nest (Ducklow et al., 2007). Meanwhile, the open-water cousins of the Adélies - the chinstrap (*Pygoscelis antarctica*), and gentoo (*Pygoscelis papua*) penguins – have invaded this region as the sea ice disappears. These two species are not affected by the increased snowfall since they breed much later, once any fallen snow has melted (Ducklow et al., 2007). Studies of fossilized bones have shown that chinstrap and gentoo penguins began to appear in this region only recently, just as the area started to warm up (Emslie, 2001). The Adélie has evolved to live around sea ice and also needs snow-free nesting habitat. It is likely to lose out if it has to compete with the chinstrap and gentoo, which are much more adapted to warmer environments (Croxall et al., 2002).

Other marine organisms living around the Antarctic Peninsula and the southwest Atlantic also appear to have experienced population changes in recent decades. These include dramatic increases in Antarctic fur seal (*Arctocephalus gazella*) populations, an ice-avoiding species, and possible decreases in the pack-ice seals, especially crabeater (*Lobodon carcinophagus*) (Ducklow et al., 2007; Siniff et al., in press). Atkinson et al. (2004) have shown that a significant decrease in Antarctic krill abundance in this region correlates well with declining sea ice.

Breeding success of several species has been linked to environmental variables such as sea surface temperature and sea ice cover. Fraser and Hofmann (2003) demonstrated a direct, causal relationship between variability in ice cover, krill recruitment, prey availability and predator foraging ecology. Leaper et al. (2006) showed that the calving success of southern right whales (*Eubalaena australis*) breeding in Argentina is related to sea surface temperatures at South Georgia, probably their major feeding ground in the southwest Atlantic. Poor calving output followed years with warm temperature anomalies, and better calving output followed years with cold temperature anomalies. Trathan et al. (2006) and Forcada et al. (2005) showed that strong links exist between the breeding performance of Antarctic fur seals at South Georgia and sea surface temperatures during the preceding winter period.

The link between large-scale environmental changes and biological response has often been explained through the mechanism by which changes in sea surface temperatures and sea-ice extent in the Antarctic Peninsula/Scotia Sea region affect krill recruitment and biomass that in turn affects predator survival and breeding performance. Longer-term studies are still needed in order to fully understand how the physical environment affects krill population dynamics and upper trophic levels (Trathan et al., 2007).

Human extraction of biological resources presents a confounding factor in the identification of climate change response. Harvesting has had various impacts upon the Southern Ocean marine ecosystem, particularly that of the Scotia/Antarctic Peninsula region, i.e. loss and failure to recover of whales and ground fish during the 1960s-early 1970s (Ballance et al. 2006; Koch, 1992), such that many species interactions are now likely absent or reduced and some feedback mechanisms in the food web may be absent. Thus, in the face of the Southern Ocean's recovery towards a new equilibrium after large-scale alteration of the food web, signals reflecting ecosystem recovery post harvest are likely to confound signals of climate change, making it difficult to disentangle patterns of distribution, movement, density, phenology, behavior and community-interaction for a given species (Trathan et al., 2007).

B. Observed changes: big and small, shallow and deep

In the western Pacific and Ross Sea sector, a shift from a cooler to a warmer, much windier period took place in the mid 1970s. Jenouvrier et al. (2005 a, b) and Ainley et al. (2005) demonstrated changes in the population trajectories for Adélie and emperor (*Aptenodytes forsteri*) penguins and several other marine organisms which corresponded to changes in weather and sea-ice patterns. In the case of the Adélie penguins in the Ross Sea sector, increased winds and increasing air temperature resulted in enough dissipation of spring sea ice which provided individuals easier access to their prey at seas (see also Parkinson 2002). This allowed a greater proportion of adults to breed and subsequently led to an increase in population.

Air temperatures over the northern portion of the Indian Ocean sector of the Southern Ocean have increased steadily over the past 50 years (Weimerskirch et al., 2003). The warmer and windier conditions had an opposite effect on the emperor penguin population at Pointe Géologie on Terre Adélie. A yet-to-be-adequately explained adult mortality event occurred during the mid 1970s, leading to a population decline of 50% (Barbraud and Weimerskirch, 2001). Nesting areas on fast ice suffered dramatic changes due to the change in environmental conditions. Warmer winter temperatures and stronger winds led to thinner fast ice which was then broken up and swept out to sea by an increased frequency of strong wind events. At a higher frequency of years, eggs and chicks of emperor penguins were blown away before they were hatched or ready to survive on their own (Barbraud and Weimirskirch 2001, Ainley et al., 2005; Jenouvrier et al. 2005a).

The shift to a windier period led to a decrease in the thickness of fast ice in McMurdo Sound in the Ross Sea in the mid-1970s. Correspondingly, the population of Weddell seals (*Leptonychotes weddellii*) decreased at least from 1973 to 1987 and has not shown signs of recovery since. These seals, like emperor penguins, depend on fast ice in order to successfully produce young (Ainley et al., 2005). Warmer oceanic conditions have also probably allowed the formation of the sponge *Homaxinella balfourensis* at depths < 30m in McMurdo Sound after mid-1970s (Dayton 1989). In colder waters, anchor ice would have likely crystallized around the sponges and by increasing their buoyancy, ripped them out and floated them upward in the water column, thereby preventing the sponge's establishment (Ainley et al., 2005).

Deeper in the Southern Ocean, at 200-400 m deep in the Weddell Sea, the slow-growth of the erect bryozoan *Cellarinella nutti* has been shown to have undergone significant growth increases over the last 20 years. In particular, 2003 was a year of exceptionally high growth, which may have arisen as a result of the anomalously warm year of 2002 through direct or indirect (through influences on phytoplankton production) influences (Barnes et al., 2006).

Although climate change responses of Antarctic marine species are still relatively sparsely documented, existing evidence indicates that major system shifts have probably taken place in the Pacific and Indian Sectors with similar patterns present throughout the high latitudes of the Southern Ocean (Ainley et al., 2005; Trathan et al., 2007).

C. Future scenarios

Sea-ice extent in winter has a profound influence on the breeding and life cycle of Antarctic krill as well as in the case of a number of higher predators. In winter, extensive sea ice not only provides plentiful winter food from ice algae, promoting krill larval recruitment and replenishing the stock, but also refuge from air breathing predators. In summer, melting of winter sea ice favors phytoplankton blooms which are also essential krill food (Atkinson et al., 2004). Future reductions in sea ice may therefore lead to changes in distribution and abundance in krill populations, with consequent impacts on food webs where krill are currently key prey items for many predator species. (IPCC, 2007b).

The relation between sea ice and animal species, such as snow petrel (*Pagodroma nivea*), southern fulmar (*Fulmarus glacialoides* Smith), and Adélie and emperor penguins, is based on a 'habitat optimum' (see Smith et al. 1999), where both too much or too little ice has negative consequences, and a medium amount is ideal. The shape of the curve differs among species. Too much ice has been shown to decrease hatching success in emperor penguins (probably due to increasing the time taken for adults to reach open-water feeding areas), adult survival in snow petrels (perhaps due to suppression of polynya), and population size of Adélie penguins in the Ross Sea (where too much ice may compromise juvenile survival and adult breeding productivity). Not enough ice has been well shown to have consequences for penguins in the Antarctic Peninsula region (Ducklow et al. 2007, Forcada et al. 2006, Hinke et al. 2007). For the open-water chinstrap and gentoo penguins, further warming and diminishing sea ice in future years could allow them to expand into ice-free areas (Croxall et al., 2002). However, if food becomes less available because of reduced sea ice or increased industrial fishing, existing populations of both species of penguins may decline (Forcada et al., 2006).

Among the pack-ice seals, the Weddell seals are likely to be most affected as the extent, persistence and type of annual sea ice continues to decrease (Siniff et al., in press). Ross (*Omataphoca rossi*) and leopard (*Hydrurga leptonyx*) seals are predicted to be influenced least by changes in pack-ice characteristics but, as may be the case for crabeater and Weddell seals also, will be disadvantaged through changes in food-wed dynamics due to alterations in the composition and distribution of their prey base. The open-water but ice-tolerant species, the southern elephant (*Mirounga leonina*) and Antarctic fur seals, are likely to respond to changes in pack-ice characteristics in ways opposite to the pack-ice species, but could also be influenced by the effects of climate changes and fisheries on their food resource (Siniff et al., in press).

One important potential confounding factor to predicting future trends in the populations of upper trophic level marine predators in the Southern Ocean is the profound alteration of food webs that has occurred or is occurring by commercial fishing (Gon and Heemstra, 1990; Kock, 1992; Pauly et al,. 1998, 2005; Ainley et al., 2007). Food-web alterations owing to fish depletion may have been as important as climate-change effects for some species, thus complicating study of climate change effects on Southern Ocean vertebrates (Siniff et al., in press).

For other species the uncertainty in climate predictions leads to uncertainty in projections of impacts, but increases in temperatures and reductions in winter sea ice would undoubtedly affect the reproduction, growth and development of fish and Antarctic krill, leading to further reductions in population sizes and changes in distributions. In addition, the potential for species to adapt is mixed (IPCC, 2007b). While the absolute changes in oceanic temperature recorded to date are, in physiological terms, small, it is possible that continued warming will induce subtle sublethal effects on physiological performance which have the potential to disrupt ecological relationships (Clarke et al., 2007).

In addition, regional warming can have subtle effects on the food web as a whole. There is increasing evidence that the network of many weak interactions play an important role in stabilizing communities (Berlow, 1999) and also that the degree of omnivory exerts a strong effect on ecosystem functioning and stability (Bruno and O'Connor, 2005). Perturbation to these weak interactions, or extinction of some of the species participating in them, thus has the potential to cause significant disturbance to food-web structure and dynamics (Clarke et al., 2007).

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