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REVIEW ARTICLE

Antarctica - a critical part of the Earth system

Alan Rodger*

Climate Change – Risk and Resilience, 11 Fairway, Girton, Cambridge, CB3 0QF, UK

***Corresponding author:** alanrodger42@gmail.com

Abstract

Antarctic is remote from all civilisation but what happens there affects everyone. The paper briefly describes some science research topics of significant global relevance, where Antarctic and the surrounding ocean play a very important role. These include climate change, a sink for carbon dioxide, sea level rise, and the sustainable use of natural resources. Some suggestions are made about areas of Antarctic science that are likely to grow in importance over the next decade. In the future, Antarctic science requires a much more multi-disciplinary approach, scaling up from a local perspective to a continent-wide view and taking full account of the interactions between the Antarctic and the rest of the Earth system. New technologies are making an ever-more important contribution to Antarctic science but some developments are limited by the lack of cost-effective broad-band communications between Antarctica and the rest of the world. Computer models need to continue to be developed and data management requires major investment and coordination to address the key science questions. It is emphasised that international cooperation is essential owing to the scale and complexity of the fundamental science questions combined with the exceptionally-challenging operational conditions.

Keywords: Antarctic, climate change, sea level, krill, technology, data

Introduction

Antarctica is the fifth largest continent after Africa, Asia, North and South America. It is the highest, driest, windiest and coldest continent and about 99% is of the continent is covered by ice, which can be up to 4.5 km thick.

About 500 million years ago, Antarctica, part of the super-continent of Gondwana, straddled the equator. During this time sandstones, limestones and shales were laid down. Over time, Antarctica gradually drifted south. A key event occurred about 180 million years ago when the super-continent broke up forming the continents we know today. Antarctic continued to drift poleward and around 35 million years ago, it separated from South America. It was

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probably about this time significant icesheets first appeared but the much more substantial ice caps that cover Antarctica today formed over the last 15 million years.

The history of humans in Antarctica is very recent. Although Captain James Cook was first to cross the Antarctic Circle in 1773, it was not until the 1820s that the presence of Antarctica was confirmed. Between 1908 and 1943, seven nations made territorial claims to parts of the continent, but these were placed in abeyance as a result of the Antarctic Treaty, signed by 12 nations at the height of the Cold War in 1959. Since then, an additional 38 countries have acceded to the Treaty which, among other statutes, designates Antarctica as a continent for peace and science. Figure 1 shows the time history of nations signing the Antarctic Treaty in each decade; about 80% of the nations signed between the 1960s and 1980s. Perhaps surprisingly given the increased political visibility of Antarctica and potential for resources, only six nations have signed this century. The Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) came into force in 1998. Amongst many measures, it bans all mining in Antarctica but recently a number of countries have indicated that their geology programmes have a strong focus on minerals of commercial value.

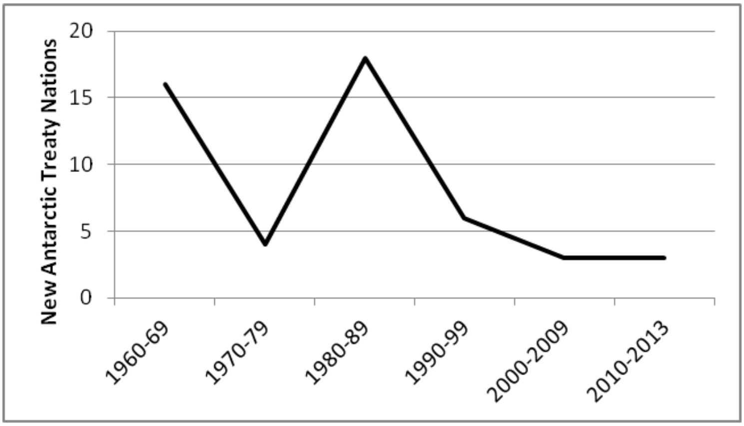

Figure 1. Number of nations signing the Antarctic Treaty in each decade since the original Treaty in 1959.

Antarctica is remote. Over 900 km separates the tip of South America to the northern-most part of the Antarctic Peninsula, and it is nearly 2500 km from the Ross Sea sector to New Zealand. Despite Antarctic being remote what happens there affects most people on Earth. This paper summarises some of the key global issues where Antarctica and its surrounding ocean play a key role, and identifies some of the 'hot' research topics and challenges for the future.

The Global Relevance of Antarctica

The Antarctic climate

The climate over most of Antarctica has remained very stable over recent centuries. The exception is the Antarctic Peninsula and West Antarctica regions where the annual average temperatures have risen by about 3°C in the last 60 years (see Figure 2). The warming is even more marked in the winter months, exceeding 4°C. Figure 3 provides the zonal average of the data in figure 2. The key feature is that there is little apparent warming around 55°S. At this latitude, there is no land, and hence reflects a modest but significant warming of the surface of the Southern Ocean.

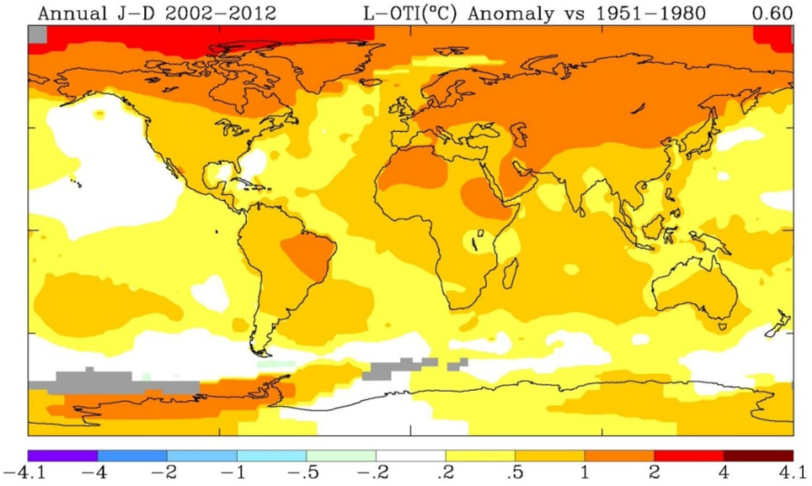

Figure 2. Map shows the annual average temperature for the period 2002-2012 relative to the annual average for the period 1951-1980 mean. The grey areas signify missing data. Source: NASA Goddard Institute for Space Studies, downloaded January 2014.

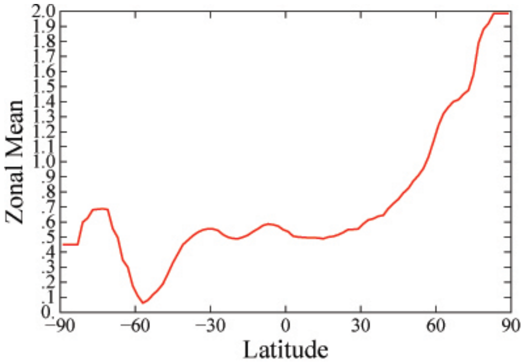

Figure 3. The zonal mean temperature for Figure 2.

The Antarctic Peninsula shows other marked changes, for example nine major iceshelves have broken up in the last 50 years and 87% of the glaciers are in retreat, thereby contributing to sea level rise (Cooke and Vaughan 2010).

The Southern Ocean

The Southern Ocean is of fundamental importance in regulating the global climate system through two main processes, as a driver of ocean currents and as a large sink for carbon dioxide.

Over about the last 100 years, the temperature of the Southern Ocean surface waters have risen by about 1°C with those around South Georgia and west of the Antarctic Peninsula having risen above the average value (Meredith and King 2005). Also warming and freshening of the Southern Ocean has occurred down to about 2000 m. There has also been an indication that Antarctic waters below 2000 m warmed between 1992 and 2005 (Purkey and Johnson 2010; 2012), but it is uncertain whether this is a recovery from the cooler conditions in the Weddell Sea during the 1970s (Robertson *et al.* 2002). However many of the statements about temperature trends have a large degree of uncertainty as the length of data sets and their spatial coverage are very limited. The freshening is thought to be a result of increases in the rate of melt occurring underneath iceshelves (Pritchard *et al.* 2012). These changes then propagate into the Pacific, Indian and Atlantic basins as shown by the red currents in Figure 4. Also at the surface is the Antarctic Circumpolar Current (ACC), the largest ocean current in the world (> 120 Sverdrups), which links the three major ocean basins of the world. The current is largely driven by the strong westerly winds. There are a number of fronts associated with the ACC where warmer waters of different origin meet cold Antarctic waters causing upwelling and creating a region high in nutrients and hence biological activity.

Antarctic Bottom Water forms through the interaction of the ocean with the cold air and the underside of iceshelves, as well as when sea ice forms; these processes lead to dense water formation that the falls and floods the abyssal plains of the three big oceans (as indicated in blue in Figure 4). Antarctic Bottom Water can reach into the northern hemisphere, and it is this process that has led to the suggestion that the Southern Ocean is a cradle for the deep sea evolution (Brandt *et al.* 2007). The return flow is at intermediate depths as indicated by the green and yellow curves in the figure and thus the Antarctic waters also play a critical role in the vertical coupling of the oceans which is fundamentally important for the storage and transport of heat, carbon and nutrients throughout the oceans. About 40% of all anthropogenic carbon is found in the oceans south of about 30° S, and the nutrient export supports 75% of the primary production in the ocean north of 30°S (Ringtoul *et al.* 2012).

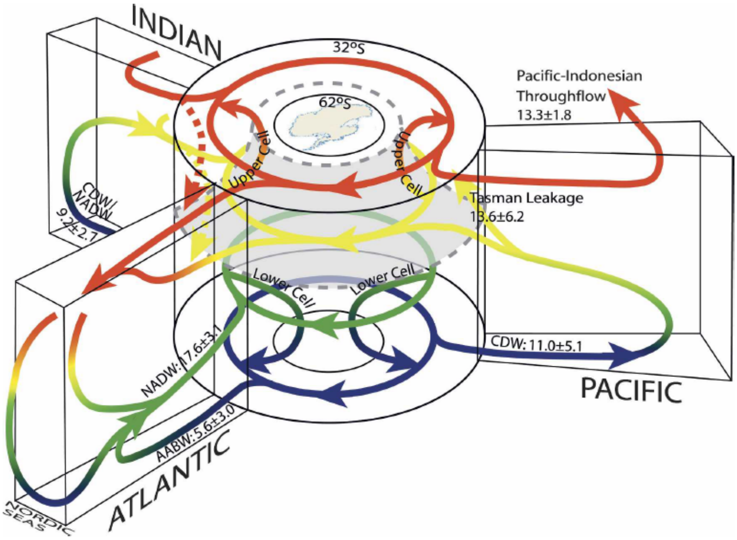

Figure 4. Schematic of global overturning circulation; see text for an explanation of the colours (from Lumpkin and Speer 2007).

Antarctic Sea ice changes

Unlike the Arctic, Antarctic sea ice is showing a modest increase in area but not uniformly around the continent (Figure 5). There are marked increases in the Ross Sea and a modest increase around the coast of East Antarctica, but a rapid reduction in the vicinity of the Antarctic Peninsula. Holland and Kwok (2012) have demonstrated, using satellite data from 1992-2010, that wind and sea ice motion are strongly coupled in Pacific and Atlantic sectors but weakly related around East Antarctica, where a coastal current dominates ice transport.

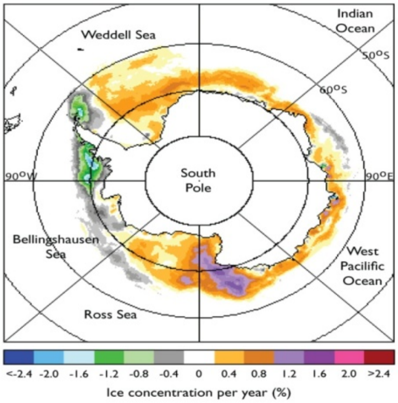

Figure 5. Variation in the concentration of sea ice in percent per annum over the period 1979-2006 (Turner *et al*. 2009).

Marine resources in the Southern Ocean

Krill are about 6 cm long, and are central to the food chain in Antarctica, being the main diet of many fish, birds, seals and whales. Krill feed on phytoplankton and algae, and there is much on the underside of sea ice. The major reduction in the sea ice conditions in winter on the western side of the Antarctic Peninsula is thought to be having a major impact on the krill abundance in the South Atlantic as shown in Figure 6. The figure also demonstrates large inter-annual variability, some of which is related to impact of El Niño (Murphy *et al.* 1998), a band of anomalously warm ocean water that periodically develops off the western coast of South America.

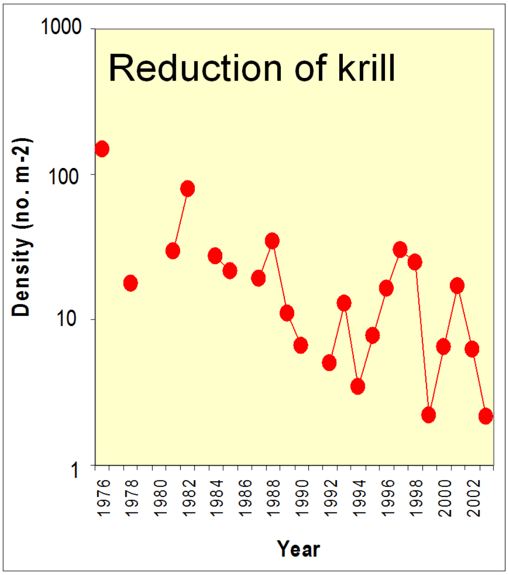

Figure 6. Change in the concentration of krill between 1976 and 2003 (Atkinson *et al.* 2004).

Marine resources of the Southern Ocean have been exploited for many centuries as demonstrated in Figure 7. As with many marine environments, progression of exploitation is to lower trophics levels with time. In all the cases, except krill, the exploitation was so severe that the animals and the fish were driven to near extinction and that industry failed. In the decade from 1904-05, 29016 whales were killed off South Georgia about 70% of which were humpbacks. This was the favoured species at that time as they were slow moving, often close to shore and more manageable than very large blue whale. However, in the quinquennium from 1925, 8711 whales were killed off South Africa of which 42% were blue whales (Tonnessen and Johnsen 1982)

Given the very long recovery times of the species, it is difficult to determine whether the extent to which recent changes to the ecosystem are a result of recovery for the highly-disturbed states over the last 200 years, or from the impacts of climate change; the reality is probably a combination of the two.

In the late 1970s to the early 1990s, krill fishing was typically taking 200,000-400,000 tonnes per annum and thereafter fell to about 100,000 tonnes each year. However there is now an upsurge in harvesting with an ever-increasing requirement to provide omega 3 fatty acids, a product of the nutraceutical industry, and a food source for the aquaculture industry, as the supply of protein from other fisheries is decreasing. New trawlers specifically designed for krill fishing have been developed whereby the net remains permanently in the water, and the krill are pumped continuously into the processing factory on-board the vessel. These new vessels can catch about twice the quantity of krill per day compared with conventional vessels. The present catches are still a long way below the total allowable catch and hence sustainable, thus the Southern Ocean is the largest under-exploited marine resource left on Earth.

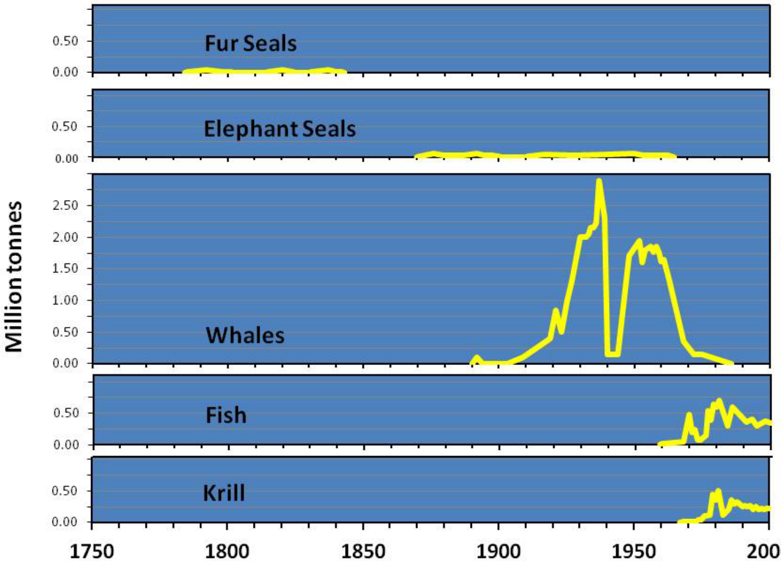

Figure 7. The harvesting of marine mammals and fish from the Southern Ocean over the last 250 years.

Sea level rise

Average global sea level rise is about 3.1 mm a^{-1} (IPCC 2013). The most recent estimates suggest that the Antarctic is responsible for 0.40 ±0.20 mm a^{-1}, with most of this contribution coming from the Antarctic Peninsula and from the West Antarctic Icesheet. The reduction in icesheet volume is partially off-set by a very modest increase over East Antarctica, possibly as a result of a slight increase in snowfall.

There are several different processes operating to cause the mass loss. In the Peninsular region, it is due to greater melting and run off, as the summer temperatures are above 0°C for more extended intervals than 50 years ago. Also some water may be percolating to the bottom of the glaciers and reducing the friction and hence the glaciers accelerate. The removal of iceshelves has caused the glaciers that used to feed them to accelerate by up to a factor of six. This too leads to increase mass loss and sea level rise.

The mass loss in the West Antarctic Icesheet in the Amundsen Sea sector has been spectacular in recent years with thinning of glaciers by up to 7 m a^{-1} (Pritchard *et al.* 2012). Here the summer temperatures are well below zero. The cause of the melting results from increased fluxes of warm water flooding the shelf and melting the iceshelves from below. Other factors which make this region particularly sensitive to change are atmospheric variability which affects the flux of warm water reaching the iceshelves, and the sea bed and iceshelf topography (Dutrieux *et al.* 2014). The thinning also changes the horizontal pressure gradient which leads to accelerated flow of glacier ice across the grounding line and hence contributes more to sea level rise. The annual expense of protecting Europe from sea level rise is about €3.2 billion per annum and rising non-linearly. In Asia, it is estimated that over 100 million people, the infrastructure that supports them and very extensive areas of high quality farming land are likely to be inundated by sea level rise by the end of 21st century.

Future Antarctic Science

Over the last few decades, there has been a rapid upsurge in the observations of Antarctic from space, from the ground, and in the ocean. Considerable progress has been made in understanding of many of the processes occurring there. The first comprehensive analysis of the state of Antarctica was the Antarctic Climate Change and the Environment (ACCE) Report produced by the Scientific Committee on Antarctic Research (Turner *et al.* 2009). There are now annual updates. However there is much new research required before accurate prediction of the Antarctic environment is possible, and, as important, are its interactions of Antarctica with the climate and the environment of the rest of the planet.

To date there has been a considerable focus on individual processes, often making the initial assumption that the processes are linear at least over limited space and time domains. However in the future there needs to be a more holistic approach; this is often termed Earth system science. The approach requires incorporation of feedback effects, cross-scale coupling, the integration of many science disciplines and moving beyond the local to the regional, continent and global interaction scales.

As an example of cross scale coupling, meso-scale ocean eddies (50 to 100 km) influence circulation by slowing the large-scale mean flow by extracting energy, and via mixing temperature and salinity both horizontally and vertically. Furthermore, ocean eddies locally affect near-surface winds, cloud properties and rainfall (Frenger *et al*. 2013). Much of the integration of these elements can be achieved through ever more sophisticated modelling using data both to initialise models and to test the outputs.

A second example of the importance of multiple scales is the complexity of the biosphere. The scales sizes stretch from the molecule, organelle, cell, tissue, organ, organ system, organism, population, community, ecosystem to the biosphere itself. In the time domain, the scale ranges from femto-seconds – the timescale of chemical reactions - to billions of years, though given the current rate of change of the planet is currently so fast, a few centuries might be a practical upper time limit. Genetic sequencing is revolutionising biological science and providing the tools to address many different key questions such as the evolution rates of species, responses of animals to multiple stresses and quantifying the resilience of animals to environmental change. The oft-stated ambition is to understand the genome to the ecosystem. This is a long way off but Antarctica and the Southern Ocean is claimed to provide simpler ecosystems than many and hence would be good initial model systems to describe, understand and model (Murphy 1995).

As indicated above, the Southern Ocean is the link between the major oceans of the world at all depths from the surface to the abyssal plane and is of critical importance in transferring heat, carbon and nutrients. Despite the rapid changes, and its global relevance, the Southern Ocean is poorly understood and has very limited observational data. As a result, a new science programme, The Southern Ocean Observing System (SOOS) has been developed (Rintoul *et al.* 2012). SOOS has six major objectives:

1. The role of the Southern Ocean in the planet's heat and freshwater balance
2. The stability of the Southern Ocean overturning circulation
3. The role of the ocean in the stability of the Antarctic ice sheet and its contribution to sea-level rise
4. The future and consequences of Southern Ocean carbon uptake
5. The future of Antarctic sea ice
6. The impacts of global change on Southern Ocean ecosystems on a circum-polar scale

SOOS is intended to be a multi-decadal research programme and will combined modelling, process studies and long term monitoring. The latter is particularly important; long data series are required to differentiate between long term trends and inter-annual variability which is particularly large in many parameters in the Southern Ocean and Antarctica.

The absorption of carbon dioxide into the ocean forms carbonic acid, and has increased the ocean acidity (decreased the pH) by about 30% since the start of industrial revolution. The impacts of ocean acidification have not yet been determined, but are likely to be larger in the polar regions as cold water absorbs more carbon dioxide than warm water. The organisms most likely to be affected are those that require calcium carbonate to build shells or skeletons. The majority of the research to date has involved laboratory experiments using decreases in pH that are far greater and far faster than is being experienced in the environment. Also there has been a tendency to experiment with adult organisms but it not clear which life stages will be most sensitive to changing pH. Thus it is not clear whether it is possible to apply the findings of these studies to the real world. Various species of phytoplankton respond differently to decreasing pH, some do better, some worse and thus assemblages are likely to change with time. There is an urgent need to determine the likely impacts of ocean acidification and the Antarctic is an excellent natural laboratory for this research.

Over the last 800,000 years, ice core records demonstrate pronounced 100,000 year cycles with evidence of much weaker periodicity at 23k and 41k years. However between 1.2 and 1.5 Myr before present, the Earth's climate showed a very dominate 41kyr cycle which is related to the obliquity periodicity of the Earth's orbit. The reason for the rather rapid change of periodicity about 1Myr ago is not known. If an ice-core record covering this change could be retrieved, providing a wide range of key parameters such as carbon dioxide, methane, sea salt and dust profiles, one of the major outstanding questions concerning longer term changes of the Earth climate system would be highly likely to be resolved. Preliminary modelling and some geophysical surveys have been undertaken to determine the most likely location for 1.5 M year old ice, but further research and surveying is necessary before drilling could be attempted.

Article 2 of the Protocol on Environmental Protection to the Antarctic Treaty (1991) commits the parties to the comprehensive protection of the Antarctic environment and designates Antarctica as a natural reserve. Under the Protocol, commercial fishing is allow but is carefully regulated through the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). However this leads to a serious scientific challenge – how many conservation areas should there be and what should be their size? An initial thought might be to suggest the foraging area of the key species but this is not practical as many of the birds and whales winter in much warmer waters north of the Antarctic Convergence where CCAMLR jurisdiction does not apply. It is also essential to establish an observational monitoring network both within the agreed fishing areas and in conservation zones with similar geophysical environments and ecosystems to be able to differentiate between the impacts of climate change, which is already significant in some areas, from those of commercial fishing.

The West Antarctic Icesheet is showing the most dramatic changes in ice loss anywhere in Antarctica. There is a pressing need to provide robust models that can describe the recent changes and make future predictions of sea level rise. There have been many nations coordinating research in the West Antarctica, with Germany, UK and USA making major contributions over an extended interval with Korean scientists participating more recently. There is an on-going requirement to make long term measurements of the icesheet to monitor change, and to provide data to assimilate into, and to test models.

Far less is known about the Weddell Sea compared with many regions of the Antarctic yet it is fundamentally important for a variety of reasons. It is the major source of Antarctic Bottom Water, which drives global ocean circulation and there is a high degree of inter-annual variability that is not well understood. Also over recent decades, there has been a considerable freshening of the water exported from the Weddell Sea (Jullion *et al.* 2013) which is of fundamental importance in driving the overturning circulation. New evidence from the glaciers that feed the Filchner-Ronne Ice Shelf suggests that this region shows similar topography to that of the Pine Island area and hence may be unstable in the long term (Ross *et al.* 2012). Therefore the Weddell Sea area is likely to attract greater research interest in the coming decades.

New technologies

The application of new technologies to Antarctic science is offering revolutionary opportunities for novel science. New instrumentation is allowing the scaling up of local measurement to a continent-wide scale; an example would be the Argo float programme (see http://www.argo.ucsd.edu/) where thousands of observations made with the floats in all seasons. Previously, measurements have been made from research vessels and occasional moorings. Technical challenges remain to allow an extensive float programme to operate over the full depth of the ocean and in areas of significant sea ice.

Ships of opportunities (e.g. tourist and fishing vessels) provide another method of collecting much more oceanographic and atmospheric data at modest cost. This approach has been used successfully in other areas of the world, and could be extended to the polar regions using "ferry boxes" (see http://www.ferrybox.org/).

In oceanography, the use of ever-increasing sophistication of autonomous marine vehicles is beginning to offer unparalleled data sets. These vehicles have more power than float systems and can be programmed. For example, the use of

Autosub-under-ice allowed major new findings about the salinity and temperature of the water under Pine Island Iceshelf, West Antarctica, which is contributing significantly to sea level rise (Jenkins *et al.* 2010). Deep sea and long duration autonomous vehicles are now being developed (http://noc.ac.uk /research-at-sea/nmfss/nmep/autosubs). Wave and sub-surface gliders are less capable than the small submarines but are much cheaper, thus fleets of such instruments are possible and complement the capabilities of the simpler and more sophisticated instrument platforms.

With the increasing miniaturisation of electronics, tagging of animals and birds is now possible and affordable. Tagging of seals has lead to new insight both into the animal behaviour and into physical and biological oceanography. The initial sensors on the tags were GPS location, dive characteristics, temperature and salinity profiles measurement (e.g. Nicholls *et al.* 2008). Such data have provided the first extended winter measurements in ice covered regions in the Antarctic and measurements of on-shelf flows of warm water. Now chlorophyll-a sensors are being added to the instrument package (Guinet *et al.* 2013) which allows much greater understanding of biological oceanography including improved interpretation of ocean colour data from space and data with which to test biogeochemistry models.

Tracking devices fitted to albatrosses and other birds have revealed a great deal about the locations to which birds travel on each trip and their behaviour at sea e.g. time spent on the wing and on the water. Such information is fundamental for determining the optimum conservation measures. Data from tagging have shown that many albatrosses feed off South America and South Africa out of the breeding season; in these locations they are vulnerable to being caught by long-line fishing vessels, now thought to be a major cause of decline of various albatross species on South Georgia. Tiny cameras fitted to penguins have shown how they catch their prey for the first time.

On land and ice the technology developments have been equally impressive, allowing new science. The first remote instruments to be deployed were automatic weather stations but now with the advent of global position and accurate timing, there are many more deployments for a wide range of science objectives. For example the Polar Earth Observatory Network (POLENET) involves the deployment of many remote, unmanned instruments that provide critical data for seismological research, isostatic rebound measurements and ice dynamics. Also there have been several generations of instruments of Automatic Geophysical Observatories deployed in Antarctica. These have been largely used for a wide variety of upper atmosphere and space science, but remote telescopes for astronomy have also been deployed.

For atmospheric studies balloon, kites and unmanned airborne vehicles are complementing more sophisticated ground-based measurements.

Whilst the quantity of data being collected in Antarctica is ever-increasing there are still serious challenges. For example, the transfer of significant quantities of data from remote instruments still tends to be carried out by a visit by humans in a plane each austral summer as broad-band data communications from very high latitudes is not yet possible. This leads to serious science limitations - new generations of high-resolution sensors could be developed, deployed and managed from the home institution giving unparalleled temporal and spatial resolution which would begin to match that of the Earth system models. Such developments would also reduce the cost of Antarctic logistics.

Ongoing measurements from space of many parameters such as the height of the ice surface, ice mass, clouds, sea ice extent, ocean currents, colour and salinity are exceptionally important but they cannot replace the need for *in situ* measurements. Space-based measurement capability is developing all the time. For example it is now possible to identify and estimate the size of some penguin colonies (Fretwell *et al*., 2012) and potentially could be used to identify and count whales, as well as geological and habitat mapping.

Data and models

Whilst there have been quite a few initiatives to make Antarctic data more available, it is still surprisingly difficult to identify all the data relating to a specific location, a given time interval, or from a suite of instruments. There are some meta-data sets collated and made available via portals, but these are not complete and not linked to the data themselves. This is seriously impeding science and in particular inter-disciplinary science progress. Scientists are normally familiar with the data sources in their own discipline area and have international colleagues who can help supply data but operating in areas of less familiarity is very challenging.

The fundamental weakness arises essentially because there has been long term under-investment in data management. Also data management is seen as less important and less prestigious as writing science papers, or indeed travelling to the Antarctic to collect more data! The development of the formal publication of data with digital object identifiers (doi), journals focused on data, and some journal insisting that data are made available with any publication are helping to address these issues. Most funding agencies now have data policies which insist on making the data available but to date there is no appetite to penalise those who do not publish data such as by preventing scientists from receiving further grants until the data are published.

Models have increase complexity and resolution however the normal resolution of Earth system models still means that the Antarctic Peninsula is only a few pixels wide, and thus many features such as the deposition of snow or local winds are not well matched to observations. High-resolution models that use

Earth system models to determine their boundary conditions give very significant improvements. The next development steps include having biological models that incorporate all the trophic levels, and incorporate feedback processes for carbon and other key chemicals fully coupled to physics-based models.

Collaboration in Antarctica

To address the environmental issues of global relevance, there is an overwhelming need for strong and sustained international collaboration. For example, *in situ* measurements are essential across the vastness of Antarctic and the Southern Ocean – something just not possible for a single nation to deliver. A multi-disciplinary approach is required for all significant science topics, and international cooperation brings the diversity of skills to make excellent scientific progress. Today Antarctic science is becoming more expensive with the need for continual investment in infrastructure, new stations and new ships, together with the ever-growing price of oil which has increased by a factor of four in the last decade.

Collaboration takes many forms. Scientist to scientist collaboration is often best for small-scale problems as the partners usually have very similar science objectives. Collaboration may be effected through visits to each other's institution, a sabbatical study visit, joint PhD students and joint research proposals. Indeed analysis of Antarctic publications demonstrates that single author papers are very rare, and international collaboration is more common than national collaboration (Dastidar and Persson 2005; Dastidar 2007: Dastidar and Ramachandran 2008).

International science research programmes form an excellent umbrella and focus for joint research. There are many examples over the last 100 years, such as the various Polar Years, the most recent being the International Polar Year 2007-08. The Scientific Committee for Antarctic Research has developed and organised a wide range of more focused science and data initiatives over the last 50 years. These programmes add considerable value to the efforts of the individual scientist or nation (see http://www.scar.org/)

In the early years, every nation established its own station. This led, amongst other things, to a proliferation of stations on King George Island, many of which carry out very similar research activities. In more recent years, there has been a move toward sharing of stations facilities. The first shared station was opened in January 1994 when the Alfred Wegener Institute and the Argentine Antarctic Institute established the Dallmann Laboratory at Argentina's Carlini Station (formerly Jubany Station) on King George Island. Another excellent example of cooperative research is between the Italian and French Antarctic programmes which, in 2005, built and still continue to operate Concordia Research Station, a station on Dome C about 3.2 km above sea level and over 1000 km from the coast. More recently the UK and Netherlands are sharing facilities at Rothera Research Station.

There are a great many similarities and differences between the Antarctic and the Arctic. Comparing and contrasting processes in the two polar regions can lead to both new insight, and robust testing of models developed in one hemisphere. Therefore both scientific and technical bi-polar collaborations between scientists and organisations should lead to more rapid progress in understanding how the planet operates. Both polar regions have significant ice caps, a major impact on the global climate system and ocean circulation, and now are dominated by a strong annual sea-ice cycle. In terms of the differences, the Arctic is an ocean surrounded by land where territorial rights are exercised and it has a significant indigenous population. Antarctica is land surrounded by ocean with territorial claims placed in abeyance and the humans are transitory. The Antarctic is much colder than the Arctic as the same latitude. Biodiversity and its evolution have followed very different trajectories. Pollution and dust levels are much higher in the North. Even the magnetic field is very different in the two hemispheres with the magnetic dip pole being displaced from the geographic North Pole by ~4° latitude and moving towards it at about 40 km a^{-1}. The corresponding numbers for the South are a ~26° displacement and moving further away from the Pole by about 10 km a^{-1}. These changes affect processes mainly in the Earth's ionosphere and magnetosphere but new research is showing how changes in the upper atmosphere affect the high and middle latitude surface climate.

Summary

i. Antarctica is remote but understanding what is happening there is essential for predicting the future of planet Earth.
ii. Some of the science topics that have global relevance that can best be addressed in Antarctica have been presented. These include climate change, sustainable use of natural marine resources and sea level rise.
iii. Suggestions for future directions of Antarctic science are made.
iv. Development and exploitation of new remote technology has enormous potential to provide more and better data sets to address key science problems.
v. Cheap, reliable broadband communications to the Antarctic would help science considerably and reduce logistics costs.
vi. The management of Antarctic data sets needs considerable development to allow ease of access for a wide range of Earth system science to be undertaken.
vii. Collaboration both in infrastructure and science is essential to provide a circum-polar perspective on the important science questions.

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