Antarctic Climate Change and the Environment: A Progress Report

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Introduction

The Antarctic Climate Change and the Environment (ACCE) project is an initiative of the Scientific Committee on Antarctic Research (SCAR), which aims to provide an up-to-date assessment of the climatic changes that have taken place on the continent and across the Southern Ocean, give improved estimates of how the climate may evolve over the next century and examine the possible impact on the biota and other aspects of the environment.

The project considers the meteorology and climatology of the Antarctic, the oceanography of the Southern Ocean, biogeochemistry, the ice sheet, the ice shelves, ice caps and glaciers around the Antarctic Peninsula and sub-Antarctic islands, sea ice, frozen ground environments, and terrestrial and marine biota.

The focus of ACCE is on climatic, environmental and biological changes that have taken place over roughly the last 10,000 years (The Holocene), with particular emphasis on the last 50 years when more in-situ data are available. To set recent changes in a broader context we also consider some changes that occurred during Deep Time. A particular target was to cover attribution of past climatic changes and make useful statements about the changes that have taken place as a result of natural climate variability and the possible impact of anthropogenic factors.

For prediction of future climate change the most important factor is how greenhouse gas emissions will change over the coming decades. Within this aspect of the project we have used the various greenhouse gas emission scenarios of the Intergovernmental Panel on Climate Change (IPCC) (www.ipcc.ch). We have also drawn extensively on the series of climate model integrations that were carried out for the IPCC Fourth Assessment Report (AR4). While the IPCC was a tremendous initiative that provided a major advance in our understanding of natural climate variability, the role of anthropogenic factors in recent climate change and the best projections yet for how climate may evolve over the next century, it's scope was global and there was limited space to consider the Antarctic. The ACCE review was therefore conceived as a study that could consider in more depth than was possible within IPCC the complex environment of the Antarctic. It's goals are somewhat similar to the Arctic Climate Impact Assessment (ACIA) (http://amap.no/acia/) in that there was a need for a detailed regional review of past and possible future climate in a climatically-sensitive region.

The plan for ACCE was formulated at the SCAR Executive meeting in Sofia, Bulgaria in July 2005 and approved by the SCAR Delegates at their meeting Hobart, Australia during July 2006. The goal was to produce a substantial report that was published online and possibly in hard copy form.

A small editing team was established that was responsible for issuing the invitations to write the various sections of the report, collating the contributions and carrying out an initial editing. The members of the editing team are:

Dr. John Turner, British Antarctic Survey, UK

Dr. Pete Convey, British Antarctic Survey, UK

Prof Guido di Prisco, Institute of Protein Biochemistry, Naples, Italy

Prof. Paul Mayewski, Climate Change Institute, University of Maine, USA

Dr. Dominic Hodgson, British Antarctic Survey, UK

Dr. Eberhard Fahrbach, Alfred Wegener Institute, Germany

Dr. Bob Bindschadler, NASA, USA

Dr. Colin Summerhayes, SCAR

At the time of writing (April 2008) all the contributions to the document have been received and they are being edited prior to a draft being circulated widely to the Antarctic science community. The draft will be discussed extensively at the SCAR/IASC Open Science Conference in St Petersburg and the SCAR

Delegates' Meeting in Moscow, both of which will be held in July 2008. It is planned to publish the final report later in 2008.

The ACCE review is the first of its type and tries to place Antarctica in its global context. It has the potential to make an important contribution to our understanding of the role of the Antarctic in the Earth system. In the following sections we highlight some of the main conclusions of the ACCE report. However, it should be appreciated that some of these may change as the document goes through the review process, hence the subtitle to this document - "a Progress Report".

The Antarctic Environment in the Global System

The physical environment

The Antarctic is a major component of the Earth's climate system through its influences on the global atmospheric and oceanic circulations. Most of the heat from the Sun arrives in the tropics, with there being a large poleward transport of heat in both hemispheres as a result of the large Equator to pole temperature difference. Both the atmosphere and ocean play major roles in the poleward transfer of heat, with the atmosphere being responsible for 60 percent of the heat transport, and the ocean the remaining 40 percent.

The orography of the Antarctic and high southern latitudes plays a extremely important part in dictating the climate of the continent. The Antarctic continent is located close to the pole, with few other major orographic features being present in the Southern Hemisphere. The mean atmospheric flow and ocean currents are therefore very zonal (west – east) in nature. This means, for example, that the Antarctic Circumpolar Current (ACC), which is one of the major oceanographic features of the Southern Ocean, can flow unrestricted around the continent, isolating the high latitude areas from the intrusion of more temperate mid- and low-latitude surface waters.

The isolation of the Antarctic close to the South Pole means that it has very low temperatures, especially on the high, interior plateau. In the Antarctic coastal region temperatures are much less extreme, although at most of the coastal stations temperatures never rise above freezing point, even in summer. The highest temperatures on the continent are found on the western side of the Antarctic Peninsula where there is a prevailing northwesterly wind, and there temperatures can rise several degrees above freezing during the summer.

The cold conditions at high latitude are responsible for the presence of the vast Antarctic ice sheet, which contains around 90% of the Earth's freshwater and covers around 99.6% of what we generally consider to be the Antarctic continent. In places the ice sheet is over 4500 m thick and the ice in the deepest layers is millions of years old. As the surface snows are buried by new snowfall, they are compressed and eventually transform into solid ice, a process that captures a chemical record of past climates and environments.

The continent is surrounded by the sea ice zone where, by late winter, the ice on average covers an area of 20×10^6 km^2, which is more than the area of the continent itself. At this time of year the northern ice edge is close to 60° S around most of the continent, and near 55° S to the north of the Weddell Sea. Unlike the Arctic, most of the Antarctic sea ice melts during the summer so that by autumn it only covers an area of about 3×10^6 km^2.

The Antarctic atmosphere, ocean and cryosphere are affected in non-linear ways by changes in atmospheric and oceanic conditions in the tropics and mid-latitude regions. For example, signals of the El Niño-Southern Oscillation can be found in Antarctic ice cores, but the Antarctic expression of near identical El Niño events can be different. In addition, there is increasing evidence that signals can also be transmitted in the opposite direction from high to low latitudes. The ozone hole is another example of extra-polar changes having a profound impact on the Antarctic environment, since the CFCs responsible for the 'hole' were emitted in the industrial areas, most of which are in the Northern Hemisphere. Most greenhouse gas emissions also come from such areas, yet have a profound effect on the radiation balance of the Antarctic atmosphere.

Marine and terrestrial biota

Levels of terrestrial biodiversity in the Arctic are strikingly greater than those even of the sub-Antarctic and much more so than the maritime and continental Antarctic. In comparison with about 900 species of vascular (higher) plants in the Arctic, there are only two on the Antarctic continent and up to 40 on any single sub-Antarctic island. Likewise, the Antarctic and sub-Antarctic have no native land mammals, against 48 species in the Arctic. The continuous southwards continental connection of much of the Arctic is an important factor underlying these differences. However, despite the apparent ease of access to much of the Arctic, it is observed that a relatively low number of established alien vascular plants or invertebrates are known from locations such as Svalbard, in comparison with the *c*. 200 species introduced to the sub-Antarctic by human activity over only the last two centuries or so.

Antarctic and sub-Antarctic floras and faunas are strongly disharmonic, with representatives of many major taxonomic and functional groups familiar from lower latitudes being absent. Sub-Antarctic plant communities do not include woody plants, and are dominated by herbs, graminoids and cushion plants; flowering plants are barely represented in the maritime and not at all in the continental Antarctic. Sub-Antarctic floras have developed some particularly unusual elements – 'megaherbs are a striking element of the flora of many islands, being an important structuring force within habitats, and a major contributor of biomass. The recent anthropogenic introduction of vertebrate herbivores to most sub-Antarctic islands has led to considerable and negative impacts on megaherb-based communities

Representing the animal kingdom, across the Antarctic and sub-Antarctic there are no native land mammals, reptiles or amphibians and very few non-marine birds. Instead, terrestrial faunas are dominated by arthropods, including various insects, arachnids, the microarthropod groups of mites and springtails, enchytraeids, earthworms, tardigrades, nematodes, spiders, beetles, flies and moths, with smaller representation of some other insect groups. Although levels of species diversity are low relative to temperate communities, population densities are often comparable, with tens to hundreds of thousands of individuals per square metre. Carnivores are also present (spiders, beetles on the sub-Antarctic islands, along with predatory microarthropods and other microscopic groups throughout), but predation levels are generally thought to be insignificant.

Climate Variability and the Antarctic

The Antarctic climate system varies on time scales from the sub-annual to the millennial and is closely coupled to other parts of the global climate system. On the longest time scales it has been found that the Antarctic ice sheet fluctuates on Milankovitch frequencies (20 ka, 41 ka, 100 ka, where ka = 1000 years) in response to variations in the Earth's orbit around the Sun, which cause regular variations in the Earth's climate.

Proxy data shows that since the Last Glacial Maximum (LGM) at about 21ka before present (BP) there have been a number of climatic fluctuations across the continent. One of the most marked has been the Mid Holocene (the Holocene itself began at ~11.7ka BP = before present) warm period or Hypsithermal, which is present in various records from Antarctica. There is evidence for a Hypsithermal in East Antarctica but dating uncertainties are still high in some areas.

The instrumental period in the Antarctic is only about 50 years in length, and since proxy data shows oscillations on longer time scales than this, it only provides a snapshot of known change in the Antarctic. Nevertheless, it shows the complexity of change and a mix of natural climate variability and anthropogenic influence.

Reliable weather charts for high southern latitudes are only available since the late 1970s, but these have revealed a great deal about the cycles in the atmospheric circulation of high southern latitudes. The most pronounced climate cycle (or mode of variability) over this period has been the Southern Hemisphere Annular Mode (SAM), which is a flip-flop of atmospheric mass (as measured by a barometer) between mid-latitudes and the Antarctic coastal region. As a result of changes in the SAM there has been a marked drop in pressure around the Antarctic and an increase in mid-latitudes over the last few decades, so that

the pressure gradient has increased across the Southern Ocean resulting in stronger surface winds. This has had implications for the distribution of sea ice and the oceanography. The changes in the SAM are thought to be primarily because of the loss of stratospheric ozone during the spring (the ozone hole), although increasing greenhouse gas concentrations, along with natural variability have also played a part.

The weather charts have helped to establish the nature of the broad scale Southern Hemisphere high-low latitude climate linkages (teleconnections). There is evidence of decadal timescale variability in some of these links, but with such a short data set it is not possible at present to gain insight into how the teleconnections may vary on longer timescales. The ice core records have shed some light on teleconnections over the century timescale. The short cores can give seasonal data, which is important since some teleconnections are only present in individual seasons.

Links between the climates of the northern and southern hemispheres can be found, but they vary with time. Through most of the Holocene and in the prior ice age there has been a several hundred year time lag between Southern Hemisphere and Northern Hemisphere events, but in recent decades the Northern Hemisphere signal of rising temperature since about 1800 AD has paralleled the Southern Hemisphere one as depicted by the oxygen isotope signal at Siple Dome in West Antarctica. Temperature change in the two hemispheres (at least as far as West Antarctica is concerned) now appears to be synchronous - a radical departure from former times, which suggests a new and different forcing, most likely related to anthropogenic activity in the form of enhanced greenhouse gases.

The circulation of the upper layers of the ocean can change over months to years, but the deep ocean and the global thermohaline circulation (THC) requires decades to centuries to respond. At the other extreme, fast wave propagation in the ocean has timescales of just a few days.

On a year-to-year basis the Antarctic climate is more variable than conditions in the tropics or mid-latitude regions, as a results of feedbacks within the atmosphere-ocean-cryosphere system.

Deep Time

Studying the history of Antarctic climate and environment is important as it provides the context for understanding present day climate and environmental changes both on the continent and elsewhere. Specifically it allows researchers to determine the processes that led to the development of our present interglacial period and to define the ranges of natural climate and environmental variability on timescales from decades to millennia that have prevailed over the past million years. By knowing this natural variability we can accurately identify when present day changes exceed the natural state. The message from the palaeorecords is that change is normal and the unexpected can happen.

Levels of the greenhouse gas CO_2 in the atmosphere have ranged from roughly 3000 ppm (parts per million) in the Early Cretaceous (at 130 Ma – million years) to around 1000 ppm in the Late Cretaceous (at 70 Ma) and Early Cenozoic (at 45 Ma), leading to global temperatures 6 or 7° C warmer than present. These high CO_2 levels were products of the Earth's biogeochemical cycles. In the Cenozoic, temperatures gradually peaked around 50 Ma, with little or no ice on land.

Some 200 million years ago Antarctica was the centrepiece of the Gondwana super-continent, which began to break up around 180 Ma in the Jurassic Period of the Mesozoic Era. As the Gondwanan fragments separated by sea-floor spreading between around 100 to 65 Ma, during the Cretaceous Period, Antarctica moved into a position over the South Pole. Up until the formation of a major ice sheet in the Oligocene (33-23 Ma), the terrestrial fauna and flora of Antarctica seem to have remained typical of south-temperate rainforest. Over time, South America, Africa, India, Australia and New Zealand moved away from Antarctica, opening the South Atlantic, Indian and Southern Oceans.

There is still uncertainty over when Antarctica broke away from the tip of South America, with the best estimate being that it was between 41 and 20 Ma.

The first continental-scale ice sheets formed on Antarctica in the Oligocene Epoch, around 34 Ma, and prior to the break of Tasmania from Antarctica. The development of the Oligocene ice sheet appears to have been a consequence of a decline in atmospheric CO_2 levels caused by reduced CO_2 outgassing from ocean ridges, volcanoes and metamorphic belts, and increased carbon burial, which dropped global temperatures at that time to levels around 4° C higher than today. The Oligocene ice sheets reached the

edge of the Antarctic continent, but were most likely warmer and thinner than today's. Sharp cooling took place in the Miocene Epoch, at around 14 Ma, which was probably caused by the growing thermal isolation of Antarctica and related intensification of the ACC rather than by any change in CO_2. It thickened the ice sheet to more or less its modern configuration, which is thought to have persisted through the early Pliocene warming from 5 Ma to 3 Ma and into the colder Pleistocene at 1.8 Ma.

During the Pliocene, mean global temperatures were 2-3° C above pre-industrial values, CO_2 values may have reached 400 ppm, and sea levels were 15-25 m above modern levels.

Global cooling from around 3 Ma onwards led to the first ice sheets on North America and NW Europe around 2.5 Ma. These ice sheets enhanced the Earth's climate response to orbital forcing, taking us to the Earth's present "ice house" state, which for the last million years has been alternating between (i) long (40-100,000 years) glacial cycles, when much of the Northern Hemisphere was ice-covered, global average temperature was around 5° C colder, and sea level was approximately 120 m lower than today, and (ii) much shorter warm interglacial cycles like that of the last ~10,000 years, with sea-levels near or slightly above those of the present.

The establishment of the ACC and the Polar Front created a barrier for migration of marine organisms between the Antarctic and lower latitudes, causing adaptive evolution to develop in isolation. The perciform suborder Notothenioidei, mostly confined within Antarctic and sub-Antarctic waters, is the dominant component of the Southern Ocean fauna. Indirect indications suggest that notothenioids appeared in the early Tertiary and began to diversify on the Antarctic continental shelf in the middle Tertiary, gradually adapting to the progressive cooling.

Over the past 30-40 Ma, in parallel with the diversification of the suborder, the physico-chemical features of the Antarctic marine environment have experienced a slow and discontinuous transition from the warm-water system of the early Tertiary (15° C) to the cold-water system of today (-1.87° C). With the local extinction of most of the temperate Tertiary fish fauna as the Southern Ocean cooled, the suborder experienced extensive radiation, dating from the late Eocene at approx. 24 Ma, that enabled it to exploit the diverse habitats provided by a now progressively freezing marine environment. As temperatures decreased and ice appeared, Antarctic notothenioids acquired antifreeze glycoproteins (AFGPs), an adaptation that allows them to survive and diversify in ice-laden seawater that reaches nearly -2° C.

The Last Million Years

The Antarctic ice core data show that the Earth's climate has oscillated through eight glacial cycles over the last 800,000 years, with CO_2 and mean temperature values ranging from 180 ppm and 10° C in glacials, to 300 ppm and 15° C in interglacials. The pattern has changed through time, with a fundamental reorganisation of the climate system at 900-600 ka from a world that for the preceding 34 Ma had been dominated by 41 ka oscillations in polar ice volume, to a 100 ka climatic beat, most likely in response to the increase in orbital eccentricity with time. The effect on global sea level was profound, with sea level dropping by 120 m on average during glacial periods. Ice cores from both Antarctica and Greenland show that temperatures were between 2-5° C higher than today in recent past interglacials. At the same time, global sea levels were 4-6 m higher than today's.

Diatom assemblages from marine sediment cores can be used to indicate whether or not the sea at the core locations was covered with sea ice in the past. Such data have indicated that at the LGM sea ice was double its present extent in winter, LGM sea ice cover was similarly double its present extent in summer due to greater extent off the Weddell Sea and possibly the Ross Sea. The related sea surface temperature calculations show that the Polar Front in the Atlantic, Indian and Pacific sectors would have shifted to the north during the LGM by around 4°, 5–10°, and 2–3° in latitude, respectively, compared to their present location. In the Atlantic and Indian sector, the Subantarctic Front would have shifted north by around 4–5° and 4–10° in latitude, respectively.

The Holocene

The transition (Termination I) from the Last Glacial Maximum (beginning about 21 ka BP) to the present interglacial period was the last major global climate change event. The main glacial to interglacial changes of the Pleistocene period, appear to be driven largely by orbital forcing, and in particular by the insolation of the Northern Hemisphere.

In general, geological evidence shows that deglaciation of the currently ice-free regions was completed earlier in East Antarctica compared with the Antarctic Peninsula, but all periods experienced a near-synchronous early Holocene climate optimum (11.5-9 ka BP). Marine and terrestrial climate anomalies are apparently out of phase after the early Holocene warm period, and show complex regional patterns, but an overall trend of cooling. A warm Mid Holocene Hypsithermal is present in many ice, lake and coastal marine records from around the continent, although there are some differences in the exact timing. In East Antarctica and the Antarctic Peninsula (excluding the northernmost islands) the Hypsithermal occurs somewhere between c. 4 and 2 ka BP, whereas at Signy Island it spanned 3.6-3.4 – 0.9 ka BP. Despite this there are a number of marine records that show a marine-inferred climate optimum between about 7-3 ka BP and ice cores in the Ross Sea sector that show an optimum around 7-5 ka BP, and the Epica Dome C ice shows an optimum between 7.5 and 3 ka BP. The occurrence of a later Holocene climate optimum in the Ross Sea is in phase with a marked cooling observed in ice cores from coastal and inland locations. These differences in the timing of warm events in different records and regions points to a number of mechanisms that we have yet to identify. Thus there is an urgent need for well-dated, high resolution climate records in coastal Antarctica and in particularly in the Dronning Maud Land region and particular regions of the Antarctic Peninsula to fully understand these regional climate anomalies and to determine the significance of the heterogeneous temperature trends being measured in Antarctica today. There is no geological evidence in Antarctica for an equivalent to the northern hemisphere Medieval Warm Period, there is only weak circumstantial evidence in a few places for a cool event crudely equivalent in time to the northern hemisphere's Little Ice Age.

Holocene sediment cores from the Southern Ocean, for example off Adélie Land, East Antarctica, generally record reduced sea ice coverage during the early to mid-Holocene. This minimum in sea ice cover is broadly coincident with the timing of a Holocene climatic optimum documented in some marine palaeoclimatic records from the Antarctic continent and Southern Ocean.

The ice core record shows remarkable temporal detail that cannot be inferred from other proxy data. They show that the most dramatic changes in atmospheric circulation during the Holocene in the Antarctic are the abrupt weakening of the Southern Hemisphere westerlies at 5400-5200 years ago, and intensification of the westerlies and the Amundsen Sea Low starting around 1200 years ago.

With the exception of lake sediment studies, little terrestrial research has set out to examine changes in biodiversity, distributions and abundance over Holocene timescales. But it is becoming clear that across the continent and also the sub-Antarctic islands the contemporary biota is a result of vicariance (the separation or division of a group of organisms by a geographic barrier) and colonization processes that have taken place on all timescales between pre-LGM and pre-Gondwana-breakup. Nevertheless it is also clear that much of the tiny proportion of Antarctica that is ice-free today has been exposed over only the last few thousand years during post LGM glacial retreat. The expansion and contraction of the Antarctic ice sheets has undoubtedly led to the local extinction of biological communities on the Antarctic continent during glacial periods. Subsequent interglacial re-colonisation and the resulting present-day biodiversity is then a result of whether the species were vicariant (surviving the glacial maxima in refugia, then recolonising deglaciated areas), arrived through post-glacial dispersal from lower latitude islands and continents that remained ice free, or are present through a combination of both mechanisms.

On the oceanic islands, the biotas will have originally arrived via long-distance over ocean dispersal, with vicariance and terrestrial dispersal playing subsequent roles in shaping the biodiversity across glacial cycles.

The major impact of climate change on glacial timescales in the marine environment has been the glacial-interglacial expansion and contraction of the Antarctic ice sheet across the continental shelf and the consequent loss and recovery of benthic (bottom) marine habitats and the interglacial fluctuations in summer and winter maximum sea ice extent. Warm periods and expansions and contractions of the sea

ice have also had an impact on marine mammal and seabird distributions. For example, changes in the Holocene distribution of marine birds can be tracked through the changing distributions of their nesting sites.

Changes During the Instrumental Period

The instrumental period began with the first voyages to the Southern Ocean during the seventeenth and eighteenth centuries. However, the greatest advance came with the International Geophysical Year (IGY) in 1957/58, which saw the establishment of many research stations across the continent. The ocean areas around the Antarctic have been investigated far less than the continent itself. Here we are reliant on ship observations, which have mostly been made during the summer months. Satellite observations can help in monitoring the surface of the ocean, but not the layers below. And even here a quantity such as sea ice extent has only been monitored since the late 1970s when microwave technology could be flown on satellite systems.

The large scale circulation of the atmosphere

The largest change in the atmospheric circulation of the high southern latitudes has been the shift of the SAM into its positive phase, which has resulted in barometric pressures dropping around the coast of the Antarctic and increasing at mid-latitudes. This has increased the surface pressure difference between the Antarctic and the tropics, so increasing the westerly winds over the Southern Ocean by 15-20% since the late 1970s. This has also had oceanographic implications and influenced many other aspects of the Antarctic environment.

The SAM has changed because of the increase in greenhouse gases and the development of the Antarctic ozone hole, although the loss of stratospheric ozone has been shown to have the greatest influence. The ozone hole is a phenomenon of the Austral spring, and at that time of year the loss of stratospheric ozone has resulted in a cooling of the Antarctic stratosphere, so increasing the strength of the polar vortex. However, during the summer and autumn the effects of the ozone hole propagate down through the atmosphere increasing the circulation around the atmosphere at lower levels. The greatest change in the SAM, which is indicative of surface conditions, has been during the autumn season.

The Antarctic Circumpolar Wave (ACW) is an apparent easterly progression of phase-locked anomalies in Southern Ocean surface pressure, winds, sea surface temperatures and sea ice extent. As such, it thus represents a coupled mode of the ocean-atmosphere system. The ACW has a zonal wavenumber of 2 (a wavelength of 180°) and the anomalies propagate at a speed (6-8 cm s^{-1}) such that they take 8-10 years to circle Antarctica giving the ACW a period of 4-5 years. While some authors have suggested that an ACW signal can be observed in an Antarctic ice core over the last 2000 years, since the initial discovery of the ACW others have questioned its persistence: a number of observational and modelling studies have indicated that the ACW is not apparent in recent data before 1985 and after 1994, somewhat fortuitously the period that was chosen for the original analysis. Whether the ACW is a persistent feature or just a transitory signal is therefore still under debate.

Mid-latitude low pressure systems (depressions) are a near-constant feature of the Southern Ocean and Antarctic coastal zone. The weather analyses available since the late 1950s allow us to track individual depressions, monitor depression formation and decay and examine movement of the main storm tracks. Using these data, it has been demonstrated that annual and seasonal numbers of cyclones have decreased at most locations south of 40°S during the 1958-97 period examined, and can be related to changes in the SAM. The latter is associated with a decline in pressure around Antarctica so there has been a trend to fewer but more intense cyclones in the circumpolar trough (the climatological belt of low pressure ringing the continent over 60-70° S). One exception is the Amundsen-Bellingshausen Sea region.

In recent decades there has been a trend towards more frequent and more intense El Niño events. However, there is no evidence that this can be seen in the Antarctic. The relatively short time series that we have of Antarctic meteorological observations and atmospheric analyses do suggest that tropical

atmospheric and oceanic conditions affect the climate of the Antarctic and the Southern Ocean. However, the teleconnections (statistically significant linkages) are not as robust as those in the Northern Hemisphere. In addition, many other factors in the Antarctic climate system, such as the variability in the ocean circulation, the development of the ozone hole and the large natural variability of the high latitude climate all affect atmospheric conditions and can mask the tropical signals.

Temperatures

Surface temperature trends across the Antarctic since the early 1950s illustrate a strong dipole of change, with significant warming across the Antarctic Peninsula, but with little change (or a small cooling) across the rest of the continent. The largest warming trends in the annual mean data are found on the western and northern parts of the Antarctic Peninsula. Here Faraday/Vernadsky Station has experienced the largest statistically significant (<5% level) trend of $+0.53^{o}$ C per decade for the period 1951-2006. Rothera station, some 300 km to the south of Faraday, has experienced a larger annual warming trend, but the shortness of the record and the large inter-annual variability of the temperatures means that the trend is not statistically significant. Although the region of marked warming extends from the southern part of the western Antarctic Peninsula north to the South Shetland Islands, the rate of warming decreases away from Faraday, with the long record from Orcadas on Laurie Island, South Orkney Islands only having experienced a warming of $+0.20^{o}$ C per decade. However, it should be noted that this record covers a 100-year period rather than the 50 years for Faraday. For the period 1951-2000 the temperature trend was $+0.13^{o}$ C per decade.

Satellite-derived surface temperatures for the Antarctic have been used to investigate the extent of the region of extreme variability, since this was not possible with the sparse station data. It was found that the region in which satellite-derived surface temperatures correlated strongly with west Peninsula station temperatures was largely confined to the seas just west of the Peninsula. It was also found that the correlation of Peninsula surface temperatures with those over the rest of continental Antarctica was poor, confirming that the west Peninsula is in a different climate regime.

The warming on the western side of the Antarctic Peninsula has been largest during the winter season, with the winter temperatures at Faraday increasing by $+1.03^{o}$ C per decade over 1950-2006. In this area there is a high correlation during the winter between the sea ice extent and the surface temperatures, suggesting more sea ice during the 1950s and 1960s and a progressive reduction since that time. However, the reason or reasons for this extensive sea ice are not known. The large winter season warming on the western side of the Antarctic Peninsula may therefore be a result of natural climate variability.

Temperatures on the eastern side of the peninsula have risen most during the summer and autumn months, with Esperanza having experienced a summer increase of $+0.41^{o}$ C per decade over 1946-2006. This temperature rise has been linked to a strengthening of the westerlies that has taken place as the SAM has shifted into its positive phase. Stronger westerly winds have resulted in more relatively warm, maritime air masses crossing the peninsula and reaching the low-lying ice shelves on the eastern side.

Around the rest of the Antarctic coastal region there have been few statistically significant changes in surface temperature over the instrumental period. The largest warming outside the peninsula region is at Scott Base, where temperatures have risen at a rate of $+0.29°$ C per decade, although this is not statistically significant. The instrumental record is poorest for West Antarctica, where there are no manned stations; this is the region where, as mentioned above, the Siple Dome ice core shows significant temperature increase since 1800.

On the interior plateau, Amundsen-Scott Station at the South Pole has shown a statistically significant cooling in recent decades that is thought to be a result of fewer maritime air masses penetrating into the interior of the continent.

The temperature records from the Antarctic stations suggest that the trends at many locations are dependent on the time period examined, with changes in the major modes of variability affecting the temperature data. Since the development of the ozone hole, the trends have been towards a slight cooling around the coast of East Antarctica and a warming across the Antarctic Peninsula.

In recent decades many relatively short ice cores have been drilled across the Antarctic by initiatives such as the International Trans Antarctic Science Expedition, which provide data over roughly the last 200 years and therefore provide a good overlap with the instrumental data. The temperatures reconstructed from the cores indicated large interannual to decadal scale variability, with the dominant pattern being anti-phase anomalies between the main Antarctic continent and the Antarctic Peninsula region, which is the classic signature of the SAM. The reconstruction suggested that Antarctic temperatures had increased by about $0.2°$ C since the late nineteenth century. They found that the SAM was a major factor in modulating the variability and the long-term trends in the atmospheric circulation of the Antarctic.

Analysis of Antarctic radiosonde temperature profiles indicates that there has been a warming of the troposphere and cooling of the stratosphere over the last 30 years. This is the pattern of change that would be expected from increasing greenhouse gases, however, the mid-tropospheric warming in winter is the largest on Earth at this level. The data show that regional mid-tropospheric temperatures have increased most around the 500 hPa (roughly 5 km above mean sea level) level with statistically significant changes of $0.5 - 0.7°$ C per decade. The exact reason for such a large mid-tropospheric warming is not known at present. However, it has recently been suggested that it may, at least in part, be a result of greater amounts of polar stratospheric cloud during the winter as a result of the cooling stratosphere.

Snowfall

On average, about 6 mm global sea level equivalent falls as snow on Antarctica each year, so it is important to assess trends in Antarctic snowfall. However, measuring snowfall directly is difficult, and net accumulation (surface mass balance) is the quantity usually estimated. In recent decades, estimates of net accumulation over the Antarctic ice sheets have been made by three techniques: in-situ observations, remote sensing, and atmospheric modelling.

The latest studies employing global and regional atmospheric models to evaluate changes in Antarctic net accumulation indicate that no statistically significant increase has occurred since ~1980 over the entire grounded ice sheet, west Antarctic Ice Sheet, or the East Antarctic Ice Sheet. Ice core net accumulation records can be extrapolate in space and time using the spatial information provided by atmospheric model precipitation fields from atmospheric reanalyses. Such data indicates that the 1955-2004 continent-averaged trend is positive and statistically insignificant (0.19 ± 32 mm per year), and is characterized by upward trends through the mid-1990s and downward trends thereafter.

The continent-averaged trend is the net result of both positive and negative regional trends, with positive trends on the western side of the Antarctic Peninsula. This, among other climate change factors, has been linked to observed decreases in Adélie penguin populations on the western side of the Antarctic Peninsula, explained by a decrease in the availability of snow-free nesting habitat required by the birds.

The Antarctic ozone hole

Stratospheric ozone is an important constituent of the upper atmosphere above the Antarctic, but levels began to decline in the 1970s, following widespread releases of CFCs and Halons in the atmosphere. We now know that the presence of CFCs in the Antarctic stratosphere results in a complex chemical reaction during the spring that destroys virtually all ozone between 14 and 22 km altitude. The Montreal Protocol is an international agreement that has phased out production of CFCs, Halons, and some other organic chlorides and bromides, collectively referred to as Ozone Depleting Substances (ODSs). Because of its success, the amounts of ODSs in the stratosphere are now starting to decrease at about 1% per year. However, there is little sign of any reduction in the size or depth of the ozone hole, although the sustained increases up to the 1990s have not continued. Recent changes in measures of Antarctic ozone depletion have ranged from little change over the past 10 years (ozone hole area), to some signs of ozone increase (ozone mass deficit). The halt in rapid ozone hole growth can be ascribed to the fact that almost all of the ozone between 12 and 24 km in the core of the vortex is now being destroyed, and is therefore comparatively insensitive to small changes in ODS amount.

Terrestrial biology

Terrestrial biological research within Antarctica has been rather spatially limited, with major areas of activity restricted to the South Orkney and South Shetland Islands, Anvers Island, the Argentine Islands and Marguerite Bay along the Antarctic Peninsula/Scotia Arc, and the Dry Valleys and certain coastal locations in Victoria Land.

The best known and frequently reported example of terrestrial organisms interpreted to be responding to climate change in the Antarctic is that of the two native Antarctic flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in the maritime Antarctic. At some sites numbers of plants have increased by two orders of magnitude in as little as 30 years, although it is often overlooked that these increases have not involved any change in the species' overall geographic ranges, which are limited in practice by extensive ice cover south of the current distribution. These increases are thought to be due to increased temperature encouraging growth and vegetative spreading of established plants, in addition to increasing the probability of establishment of germinating seedlings. Additionally, warming is proposed to underlie a greater frequency of mature seed production, and stimulate growth of seeds that have remained dormant in soil propagule banks.

Changes in both temperature and precipitation have already had detectable effects on lake ecosystems through the alteration of the surrounding landscape and of the time, depth and extent of surface ice cover, water body volume and lake chemistry.

Alien microbes, fungi, plants and animals, introduced directly through human activity over approximately the last two centuries, already occur on most of the sub-Antarctic islands and some parts of the Antarctic continent. The level of detail varies widely between locations and taxonomic groups (although at the microbial level, knowledge is virtually non-existent across the entire continent). On sub-Antarctic Marion Island and South Atlantic Gough Island it is estimated that rates of establishment through anthropogenic introduction outweigh those from natural colonization processes by two orders of magnitude or more. Introduction routes have varied, but are largely associated with movement of people and cargo in connection with industrial, national scientific programme and tourist operations.

The terrestrial cryosphere

Antarctica's ice shelves have provided the most dramatic evidence to date that at least some regions of the Antarctic are warming significantly, and have shown what has been suspected for long time, that changes in floating ice shelves can cause significant changes in the grounded ice sheet. Ice shelves in two regions of the Antarctic Ice Sheet have shown rapid changes in recent decades: the Antarctic Peninsula and the northern region of West Antarctica draining into the Amundsen Sea.

Retreat of several ice shelves on either side of the Antarctic Peninsula was already occurring when scientific observations began in 1903. Since that time, ice shelves on both the east and west coasts have suffered progressive retreat and some abrupt collapse. Ten ice shelves have undergone retreat during the latter part of the 20th Century.

Wordie Ice Shelf, the northernmost large (>1000 km^2) shelf on the western Peninsula, disintegrated in a series of fragmentations through the 1970s and 1980s, and was almost completely absent by the early 1990s. The Wordie break-up was followed in 1995 and 2002 by spectacular retreats of the two northernmost sections of the Larsen Ice Shelf (termed Larsen 'A' and Larsen 'B') and the last remnant of the Prince Gustav Ice Shelf. A similar 'disintegration' event was observed in 1998 on the Wilkins Ice Shelf, but much of the calved ice remained until 2008 when dramatic calving removed about 14,000 km^2 of ice. The direct cause of the Peninsula ice-shelf retreats is thought by many to be a result of increased surface melting, attributed to atmospheric warming. Increased fracturing via melt-water infilling of pre-existing crevasses explains many of the observed characteristics of the break-up events, and melting in 2002 on the Larsen B was extreme. Specific mechanisms of ice-shelf break-up are still debated.

Some formerly snow-covered islands are now increasingly snow-free during the summer. Since the late 1940s, the total area covered by glaciers on Heard Island has reduced by approximately 11%, and several coastal lagoons have been formed as a result.

On the island of South Georgia, there are about 160 glaciers and of these, 36 have been mapped and analysed for changes over the past century. The results showed that two of the glaciers are currently advancing, 28 are retreating and 6 are stable or show a complex, ambiguous response.

The ice-cover on the Antarctic Peninsula is a complex alpine system of more than 400 individual glaciers that drain a high and narrow mountain plateau. Changes in the ice margin around the Antarctic Peninsula based on data from 1940 to 2001 have been compiled. Analysis of the results revealed that of the 244 marine glaciers that drain the ice sheet and associated islands, 212 (87%) have shown overall retreat since their earliest known position (which, on average, was 1953). The other 32 glaciers have shown overall advance, but these advances are generally small in comparison with the scale of retreats observed. The glaciers that have advanced are not clustered in any pattern, but are evenly scattered down the coast.

The Amundsen Sea sector represents approximately one third of the entire West Antarctic Ice Sheet (WAIS). Recent observations have shown that this is currently the most rapidly changing region of the entire Antarctic ice sheet. Acceleration of flow due to basal melting of its ice shelf and subsequent grounding line retreat of Pine Island Glacier, one of the two largest WAIS outlet glaciers draining into the Amundsen Sea, was first reported in 1998. This discovery of a 10% increase flow speed in 4 years was anticipated based on oceanographic evidence of very high and increasing basal melt rates beneath the ice tongue fronting the glacier. Later direct measurement of elevation loss near the grounding line revealed rates as high as 55 m per year, implying basal melting rates nearly 10 times the previously calculated value. As basal melt increased, the grounding line retreated, possibly in two stages—during the 1980s and 1994-96—each leading to a separate increase in speed. The most recent observations suggest the grounding line at Pine Island has retreated still further with a simultaneous increase in both speed and rate of speed increase. Pine Island Glacier is now moving at speeds 40% higher than in the 1970s.

Other glaciers in the Amundsen Sea sector have been similarly affected: Thwaites Glacier is widening on its eastern flank, and there is accelerated thinning of four other glaciers in this sector to accompany the thinning of Thwaites and Pine Island Glaciers. Where flow rates have been observed, they too show accelerations, e.g., Smith Glacier has increased flow speed 83% since 1992.

Calculations of the current rate of mass loss from the Amundsen Sea embayment range from 50 to 137 Gt per year with the largest number accounting for the most recent faster glacier speeds. These rates are equivalent to the current rate of mass loss from the entire Greenland ice sheet. The Pine Island and adjacent glacier systems are currently more than 40% out of balance, discharging 280 ± 9 Gt per year of ice, while they receive only 177 ± 25 Gt per year of new snowfall.

Summer temperatures in the Amundsen Sea embayment rarely reach melting conditions, and there is little reason to consider that atmospheric temperatures have had any strong role to play in the changes that have occurred there. The most favoured explanation for the changes is a change in the conditions in the sea into which this portion of WAIS flows. While there are no adjacent measurements of oceanographic change that can support this hypothesis, it appears to be the most likely option, and the recent observations of relatively warm Circumpolar Deep Water on the continental shelf and in contact with the ice sheet in this area suggest it is a reasonable one. Elsewhere within West Antarctica, the changes are not as extreme.

Both the areas of most rapid change, the Antarctic Peninsula ice shelves and the Amundsen Sea sector outlet glaciers, are thought to be linked to greenhouse-forced changes in global circulation, specifically to changes in the SAM affecting the circulation around Antarctica, and the likely-related loss of sea ice cover in the Amundsen and Bellingshausen seas. A stronger (more positive) SAM, with increased westerly winds, also drives the Antarctic Circumpolar Current, pushing Circumpolar Deep Water against the western Peninsula coast and the northern coast of West Antarctica.

Changes are less dramatic across most of the East Antarctic ice sheet with the most significant changes concentrated close to the coast. Present changes in the ice sheet are a patchwork of interior thickening at modest rates and a mixture of modest thickening and strong thinning among the fringing ice shelves.

Increasing coastal melt is suggested by some recent passive microwave data. Satellite altimetry data indicate recent thickening in the interior that has been attributed to increased snowfall, but ice core data

do not show recent accumulation changes are significantly higher than during the past 50 years. A resolution of this apparently conflicting evidence, may be that there is a long-term imbalance in this area, this could possibly be a response to much older climate changes. An alternate suggestion, based on direct accumulation measurements at South Pole, is that this thickening represents a short-period of increased snowfall between 1992 and 2000. The absence of significant atmospheric warming inland, distinct from the global trend of warming atmospheric temperatures, may have forestalled an anticipated increase in snowfall associated with the global trend.

Sea Level changes

The first three assessment reports of the IPCC arrived at similar conclusions with regard to global sea level change during the 20th century. For example, the third report concluded that global sea level had changed within a range of uncertainty of 1-2 mm per year. Since then a consensus seems to have been achieved that the 20th century rise in global sea level was closer to 2 than 1 mm per year, with values around 1.7 mm per year having been obtained for the second half of the last century in the most recent studies.

The most recent data (i.e. from the 1990-2000s) from tide gauges and satellite altimeters suggest that global sea level is now rising at a rate of 3 mm per year or more. This is at a higher rate than one might expect from IPCC projections, which has led to concern over possibly large ice sheet contributions during the 21st century, especially due to their dynamic instabilities. However, decadal variability in the rate of global sea level change makes it difficult to be confident that the apparent higher rates of the 1990s will be sustained, since high decadal rates have been observed at other times during the past century.

A recent study has shown that circa 2005, the Antarctic Peninsula was contributing to global sea-level rise through enhanced melt and glacier acceleration at a rate of 0.16 ± 0.06 mm per year (which can be compared to an estimated total Antarctic Peninsula ice volume of 95,200 km^3, equivalent to 242 mm of sea-level). Although it is known that Antarctic Peninsula glaciers drain a large volume of ice, it is not yet certain how much of the increased outflow is balanced by increased snow accumulation.

The Southern Ocean

The Southern Ocean plays a critical role in driving, modifying, and regulating global change. It is the only ocean that circles the globe without being blocked by land and is home to the largest of the world's ocean currents: the Antarctic Circumpolar Current.

Recent observational studies have suggested that the waters of the ACC have warmed more rapidly than the global ocean as a whole, with an increase of 0.17°C at depths between 700 – 1100 m over the 1950s to 1980s.

The ACC belt in the Australian sector has warmed in recent decades, as found elsewhere in the Southern Ocean. The changes are consistent with a southward shift of the ACC. Some climate models suggest the ACC will shift south in response to a southward shift of the westerly winds driven by enhanced greenhouse forcing. The southward shift of the ACC fronts has caused warming through much of the water column, resulting in a strong increase in sea level south of Australia between 1992 and 2005. However, there is no observational evidence of the increase in ACC transport also predicted by the models. Recent studies suggest the ACC transport is insensitive to wind changes because the ACC is in an "eddy-saturated" state, in which an increase in wind forcing causes an increase in eddy activity rather than a change in transport of the current. The poleward shift and intensification of winds over the Southern Ocean has been attributed to both changes in ozone in the Antarctic stratosphere and to greenhouse warming. In addition to driving changes in the ACC, the wind changes have caused a southward expansion of the subtropical gyres and an intensification of the southern hemisphere "supergyre" that links the three subtropical gyres.

Changes have been observed in several water masses in the Australian sector between the 1960s and the present. Waters north of the ACC have cooled and freshened on density surfaces corresponding to intermediate waters. South of the ACC, waters have warmed and become higher in salinity and lower in oxygen in the Upper Circumpolar Deep Water.

The Antarctic Bottom Water (AABW) in the Australian Antarctic basin has freshened significantly since the early 1970s, although the cause of this is not yet fully understood. Changes in precipitation, sea ice formation and melt, ocean circulation patterns, and melt of floating glacial ice around the Antarctic margin could all influence the salinity where dense water is formed.

Considering its remote and inhospitable location, the Weddell Sea was well observed during recent major oceanographic campaigns, with (largely summer-time) hydrographic sections across the Weddell Gyre onto the Antarctic continental shelf, and with arrays of moorings. These indicate a number of decadal-scale changes in water mass properties. The Weddell Deep Water (WDW) warmed by some 0.04^{o} C during the 1990s and has subsequently cooled. This was accompanied by a salinification of about 0.004, just detectable over the decade. A quasi-meridional section across the Weddell Gyre occupied in 1973 and 1995 revealed a warming of the WDW in the southern limb of the gyre by 0.2^{o} C accompanied by a small increase in salinity, whereas there was no discernible change in the northern limb of the gyre.

During the 1970s a persistent gap in the sea ice, the Weddell Polynya, occurred for several winters. The ocean lost a great deal of heat to the atmosphere during these events.

Biogeochemistry

The Southern Ocean, with its energetic interactions between the atmosphere, ocean and sea ice, plays a critical role in ventilating the global oceans and regulating the climate system through the uptake and storage of heat, freshwater and atmospheric CO_2. A recent study in the South Western Indian Ocean calculated surface trends of CO_2 between 1991-2007. These results show that in the Southern Indian Ocean, the oceanic CO_2 increased at all latitudes south of 20°S. More specifically, at latitudes poleward of 40°S, it was found that oceanic CO_2 increased faster than in the atmosphere since 1991, suggesting the oceanic sink decreased. In addition, when CO_2 data are normalized to temperature, the analysis shows that the system is increasing much faster in the winter in the summer. These results suggest that the increase may be due to ocean dynamics given that the largest response occurs in the Austral Winter. In the recent period (since the 1980s) the increase of CO_2 appeared to be faster compared to the trends based on historical observations 1969-2002, suggesting that the Southern Ocean CO_2 sink has continued to evolve in response to historical climate change.

Sea ice

Ship observations have been compiled especially during the whaling period and these have been examined to estimate sea ice extent in the pre-satellite era. If we can assume that the ship data provides a meaningful representation of average ice edge locations during the period, it is apparent that the data from the previous several decades show relatively more extensive ice cover than the average from the satellite data. However, the ship locations are normally to the south of the farthest north the ice extended during the satellite era.

The sea ice extent data as derived from satellite measurements covering 1979-2006 show a positive trend of 0.98 ± 0.23% per decade for the entire Southern Hemisphere. Trend analysis of the ice extent in different sectors of the Antarctic region yields positive trends of varying magnitude in all except in the Bellingshausen Sea sector. The trend is least positive in the Weddell Sea sector at 0.8 ± 0.6% per decade followed by Western Pacific and Indian Oceans at 1.1 ± 0.8% per decade and 2.0 ± 0.6% per decade, respectively. The most positive is the Ross Sea sector at 4.5 ± 0.7% per decade.

Permafrost

Permafrost monitoring in Antarctica is a relatively new topic, however, some data on change are available. An analysis of data from Signy Island indicated that the active layer (the layer experiencing seasonal freeze and thaw) thickness increased around 30 cm over the period 1963–90 (a period of warming on Signy Island) but then decreased by the same amount over the period 1990–2001 when Signy Island endured a series of particularly cold winters.

The site at Boulder Clay (McMurdo Sound) represents the longest and almost continuous data series of permafrost and active layer temperature measurements. Here there has been a substantial stability of the permafrost temperature at 360 cm, while at the permafrost table the temperature shows a slight decrease of 0.1° C per year. This slight decrease is mainly related to the decrease of the air temperature and the decrease of the snow cover in the winter, at least at this site.

Marine biology

The area covered by winter sea ice in the Southern Ocean has not changed significantly over the past decades suggesting that the impact of global environmental change on Antarctic ecosystems is not as severe as in the Arctic, where the sea ice cover is declining at an alarming rate. In the Antarctic, comparable shrinking of the winter ice cover has occurred only along the western Peninsula tip and the adjoining Scotia Sea. This is a relatively small region but home to the whale-krill-diatom food chain where more than 50 % of the Antarctic krill stock was concentrated.

Following near-extinction of the whale populations, the krill stock was expected to increase as a result of release from grazing pressure. Although predation pressure by seals and birds increased, their total biomass remained within only a few percent of that of the former whale population. About 300,000 blue whales were killed within the span of a few decades, equivalent to more than 30 million tonnes of biomass. Most of these whales were killed on their feeding grounds in the southwest Atlantic in an area of maximum 2 million km^2 (10 % of the entire winter sea-ice cover), which translates to a density of one blue whale per 6 km^2.

There has been an 80% decline in the krill stocks of the southwest Atlantic since the 1970s, accompanied by an increase in salp populations. It is likely that phytoplankton production has decreased with that of the krill stocks, a conclusion supported by the increase in the salp population. A decline in phytoplankton concentrations can only be explained by a corresponding decline in the iron supply. There is reason to believe that the reduction in ice formation has resulted in a decrease in iron input from the shelf slopes of the Western Peninsula.

However, the extent of the krill decline and the underlying factors are under vigorous debate because of difficulties in unravelling the effects of industrial whaling from those of sea-ice retreat. Nevertheless, if the trend of decline in this whale food (krill) continues, recovery of the great whale populations will be jeopardised.

Contaminants

Although some human activity in Antarctica, such as ship or aircraft transportation or the release of weather and research balloons can have widespread effects, scientists, tourists and fishermen generally cause only local disturbance of the Antarctic environment. As pesticides have neither been produced nor applied in the continent, the discovery of Dichlorodiphenyltrichloroethane (DDT) and its congeners in Antarctic marine biota in the 1960s and in the environment in the 1970s proved that persistent contaminants in the region do reach Antarctica from other continents. Since then, Hexachlobenzene (HCB), Hexachlorocycloexanes (HCHs), aldrin, dieldrin, chlordane, endrin, heptachlor and other persistent organic pollutants (POPs) have been detected in Antarctica and the Southern Ocean. These

chemicals are persistent, hydrophobic and lipophilic, accumulate in organisms and biomagnify in marine food chains

The Next 100 Years

Determining how the environment of the Antarctic will evolve over the next century presents many challenges, yet it is a crucial question that has implications for many areas of science, as well as for policymakers concerned with issues as diverse as sea level rise and fish stocks.

The evolution of the Antarctic climate over the next 100 years can only be predicted using coupled atmosphere-ocean-ice models. These have many problems in correctly simulating the observed changes that have taken place over the last few decades, so there is still a degree of uncertainty about the projections, particularly on the regional scale. The models used in the IPCC fourth assessment gave a wide range of predictions for some aspects of the Antarctic climate system, such as sea ice extent, since it is very sensitive to changes in atmospheric and oceanic conditions.

The degree to which the climate of the Earth will change over the next century is heavily dependent on the success of efforts to reduce the rate of greenhouse gas (GHG) emissions. The Antarctic is a long way from the main centres of population, but greenhouse gases are well mixed and fairly uniformly mixed across the Earth. Whatever happens it will take a long time for the levels of GHGs to drop. For instance, even if anthropogenic emissions of CO_2 were halted now it may take thousands of years for CO_2 concentrations to naturally return to pre-industrial amounts.

The IPCC developed a number of GHG emission scenarios, however, in the ACCE report we have concentrated on the most commonly used scenario, known as SRESA1B, which assumes a doubling of CO_2 and other gases by 2100. This seems a reasonable scenario considering GHG increases during the first decade of the century. In terms of temperature increase, the response to rises in greenhouse gases is fairly linear, so that a quadrupling of gases would give temperature increases that were double those presented here.

Atmospheric circulation

Since about 1980 the SAM has moved rapidly into its positive phase. With the expected recovery of the ozone hole, this particular forcing on the SAM should decline. At the same time, GHC concentrations will rise. Overall we expect the SAM to become more positive, but with a trend that is less rapid than has been observed over the last two decades. We can therefore expect to see further increases of surface winds over the Southern Ocean in the summer and autumn.

A consistent result that has emerged recently from 21st century model projections is a tendency for a poleward shift of several degrees latitude in the mid-latitude storm track.

Temperature

A significant surface warming over Antarctica is projected over the 21st century. The weighted average of the SRESA1B scenario runs of the IPCC models shows an increase of the annual average surface temperature of 0.34°C per decade over land and grounded ice sheets. All the models show a warming, but with a large range from 0.14 to 0.5° C per decade. Due to the retreat of the sea-ice edge, the largest warming occurs during the winter when the sea ice extent approaches its maximum, e.g. 0.51 ± 0.26° C per decade off East Antarctica.

Away from coastal regions there is very little seasonal dependence of the warming trend, which in all seasons according to the weighted model average is largest over the high-altitude interior of East Antarctica. Despite this large increase of temperature, the surface temperature by the year 2100 will remain below freezing over most of Antarctica and therefore will not contribute significantly to melting.

The pattern of warming for the next 100 years is different from simulations and observations of temperature change for the latter part of the 20th century. The most notable difference is that the observed and simulated maximum of warming over the Antarctic Peninsula for the latter part of the 20th century is not present in projections of change over the 21st century.

There is strong consensus for warming for Antarctica as a whole between different models, but large uncertainty in the regional detail. There is less confidence in the large warming trends forecast around the coast than in the smaller changes forecast over the high interior. This is due to the large uncertainty over the sea ice and ocean projections.

The forecast warming over the Antarctic continent is 0.5-1.0° C less than over most other landmasses around the globe (apart from south-east Asia and southern South America where increases are the same). The reasons for this are not known. Over the Southern Ocean projected warming is much smaller than the global average, due to the large heat uptake.

The annual mean warming rate in the troposphere at the 5 km level above sea level is 0.28° C per decade, which is slightly smaller than the forecast surface warming, with no evidence of the mid-tropospheric maximum, which has been observed over the last 30 years.

Very little work has been done on forecast changes to extreme conditions over Antarctica. The extreme temperature range between the coldest and warmest temperature of a given year is projected to decrease around coastal Antarctica and to show little change over most of the interior of the continent.

The IPCC warming of 3°C over the next century is considerably faster than the fastest rate of rise observed in Antarctic ice cores (4° C per 1000 years). But it is comparable to or even slower than the rapid rates of temperature rise typical of Dansgaard-Oeschger Events during glacial times in Greenland, and of the Bolling Allerød warming in Greenland at 14,700 ka BP, and the warming in Greenland at the end of the Younger Dryas around 11,700 ka BP. This tells us that however unlikely such rapidity may appear at first glance, it is quite feasible in terms of what is known about the natural system.

Precipitation

Almost all climate models simulate a robust precipitation increase over Antarctica in the coming century. The projected precipitation change has a seasonal dependency, and is larger in winter than in summer. If the IPCC model output is weighted according to the skill of the models in simulating recent change, they suggest that by the end of the century the snowfall rate over the continent would increase by 20% compared to current values. If other effects such as melting and dynamical discharge of ice are ignored, this would result in a negative contribution to global sea-level rise of approximately 5 cm.

With the expected southward movement of the mid-latitude storm track we can expect greater precipitation and accumulation in the Antarctic coastal region.

The ozone hole

Stratospheric ozone is affected by a number of natural and anthropogenic factors in addition to reactive halogens: temperature, transport, volcanoes, solar activity, hydrogen oxides, nitrogen oxides. In considering future ozone concentrations, it is important to separate the effects of these factors. Recovery of stratospheric ozone amounts will be slow. However, models suggest that by the end of the 21st Century, Antarctic stratospheric ozone will no longer be under the influence of CFCs and halons. However, it may not have reverted to 1980 values because of changes in stratospheric temperatures and dynamics caused by increased greenhouse gases, in particular because as GHGs accumulate in and warm the troposphere, they lead to cooling of the stratosphere, and destruction of ozone is more likely in spring where the stratosphere has been exceptionally cold in winter.

Tropospheric chemistry

Over the ocean, a loss of the sea ice would enhance emissions of trace gases with an oceanic origin. Various gases, such as dimethyl sulphide (DMS), that are measured in the troposphere, are known to be released from the oceans around Antarctica. Such gases are generated by phytoplankton. The seasonal cycle in the atmosphere of these trace gases is closely linked to the extent of sea ice but also to the Sun. In a warmer world with a reduced sea ice extent, emissions from the ocean would likely increase. The dominant control would then be the Sun, so that a seasonality with a wintertime minimum but an extended summer maximum could be expected. DMS plays a critical role as a source of cloud condensation nuclei (CCN) via its oxidation to sulphate. Changing the number of CCN alters cloud properties and albedo with a consequent influence on the Earth's radiation budget, surface temperature and climate. Basically more DMS means more CNN and hence more clouds.

Terrestrial biology

Climate change will impose a complex web of threats and interactions on the plants and animals living in the ice-free areas of Antarctica. Increased temperatures may promote growth and reproduction, but may also contribute to drought and associated effects. High amongst future scenarios is the likelihood of invasion by more competitive alien species, easily carried there by humans.

Many sub-Antarctic islands are showing increases in mean annual temperature. To date, there has been no suggestion that, even at the microclimate level, the increases are likely to exceed the upper lethal limits of most arthropods. But an increase in the frequency and intensity of freeze–thaw events could very readily exceed the tolerance limits of many arthropods.

In ice–dominated continental and maritime Antarctica, changes to temperature are intimately linked to fluctuations in water availability. Changes to water availability will arguably have a greater effect on vegetation and faunal dynamics than that of temperature alone. Future regional patterns of water availability are unclear, but climate models predict an increase in precipitation, especially in the Antarctic coastal region.

With increases in the temperature component of current climate change in many locations of the Antarctic, many terrestrial species may respond positively by faster metabolic rates, shorter life cycles and local expansion of populations. But subtle negative impacts can also be predicted (and are perhaps being observed) with regard to increased exposure to UV-B, as this requires greater allocation of resources within the organism to defense and mitigation strategies, reducing that available for other life history components.

Changes in temperature, precipitation and wind speed, even those judged as subtle by climate scientists, will probably have profound effects on limnetic ecosystems through the alteration of their surrounding catchment, and of the time, depth and extent of surface ice cover, water body volume and lake chemistry.

The terrestrial cryosphere

Recent observations of ice sheet behaviour in Greenland and Antarctica have forced experts to radically revise their view of ice sheet sensitivity to climate change. Existing ice-sheet models do not properly reproduce this observed behaviour, casting doubt on the value of these models at predicting future changes. In particular current models fail to take into account on the one hand of mechanical degradation, for example by water causing cracks to propagate in summer, and on the other hand of lubrication of the base of the ice sheet, glaciers and ice streams by downward percolating surface water. Predictions of the future state of ice sheets must, therefore, be based upon a combination of inference from past behaviour, extension of current behaviour, and interpretation of proxy data and analogues from the geological record.

The most likely regions of near-future change are those that have been shown to be changing today. However, most models agree that, although warming was not observed everywhere in Antarctica in the last 50 years, it will be strong in the coming century, and so it is likely that both snowfall and melt will

increase during this century. Even the relatively small increases in the rate of snowfall that are expected to parallel this warming, would cause significant volumetric growth due to the vast area of the ice sheet. But warming also leads to increased melting that not only would remove ice mass by runoff, but could cause the margin of parts of Antarctica to adopt some of the dynamic character of the present-day margin of Greenland, where surface meltwater penetrates to the ice sheet bed causing accelerated flow.

The East Antarctic ice sheet has experienced interior thickening, probably a long-term dynamic response to a distant change in climate and not recently increased snowfall. This effect is likely to continue and change only slowly. Coastal changes are more difficult to anticipate. Most of the additional snowfall may be limited to the coastal areas, compensating for present processes responsible for the observed thinning of ice shelves, however the compensation will likely only be partial.

There is currently a loss of mass from the Amundsen Sea embayment of the West Antarctic ice sheet, thought to be a result of a progressive thinning of the fringing ice shelves seaward of the Amundsen Sea outlet glaciers as warmer waters penetrate onto the continental shelf. A continuation of the positive phase of the SAM will continue the stronger circumpolar circulation, thus continuing to upwell warmer waters onto the continental shelf in the Amundsen Sea. A doubled outflux in the glaciers in this sector would contribute to an extra 5 cm of sea-level rise per century. Ultimately, this sector could contribute 0.75 m to global sea level if the area of ice lost is limited to that where the bed slopes downward toward the interior of West Antarctica, so a contribution from this sector alone of some tens of centimeters by this century's end cannot be discounted.

In 2000, a group of leading glaciologists considered that within the next 200 years there was a 30% probability that loss of ice from the West Antarctic ice sheet could cause sea level to rise at a rate of 2 mm per year, and a 5% probability it could cause rates of 1 cm per year. Since that opinion was gathered there has been enormous scientific progress made in understanding the ice sheet. Little has been discovered that would cause a reduction of the levels of risks expressed in that expert judgment. However, recent data does reinforce earlier concerns that a potential instability does exist in marine ice sheets that could lead to deglaciation of parts of WAIS, and may support the hypothesis that the Amundsen Sea Embayment could already be entering a phase of collapse. These data include the recent observations that inland ice sheets can be impacted by the loss of floating ice shelves, and that the continued acceleration of ice-sheet thinning and glacier-flow in the Amundsen Sea embayment is likely the result of glacier-acceleration.

Measurements made of the conditions in the Weddell Sea sector of West Antarctica do not raise alarms now or for the future of the terrestrial cryosphere, since the open ocean is held well away from where ice streams first enter the Filchner-Ronne Ice Shelf.

Around the Antarctic Peninsula increased warming will lead to a southerly progression of ice shelf disintegrations along both coasts. As in the past, these may well be evidenced and preceded by an increase in surface meltwater lakes, and/or progressive retreat of the calving front. Prediction of the timing of ice shelf disintegration is not yet possible.

Although at present most of the effects leading to loss of ice are confined to the more northerly section of the Antarctic Peninsula (which contains a few centimetres of global sea-level rise), the total volume contained on the Antarctic Peninsula is 95,200 km^3 (equivalent to 242 mm of sea-level). This is roughly half that of all glaciers and ice caps outside of either Greenland or Antarctica. The mechanisms that have led to recent acceleration of these glaciers as an immediate consequence of ice shelf disintegration, and glacier retreat, which could progress further south in the coming century, suggests that this ice could impact global sea level relatively rapidly, and perhaps be comparable in extent to that from the more gradual melting of glaciers and ice caps in other mountainous environments across the Earth.

Sea level

For the IPCC's Fourth Assessment Report, the range of sea-level projections, using a larger range of models, was 18 to 59 cm (with 90% confidence limits) over the period from 1980-1999 to 2090-2099. This took into account the full range of emission scenarios and climate models, but did not include a contribution from the dynamic instability of Greenland. However, sea levels might be expected to rise

around Antarctica itself at rates lower than in other parts of the world, owing to the important role of the ocean adjustment to climate forcings and, if the rise stems from Antarctic melt, then also due to the elastic response of the solid earth (the continent will rise as its ice melts).

Overlying the global sea-level rise is a large regional variability, and sea-level rise during the 21st century is not expected to be uniform around the globe. This is a result of changing atmospheric conditions, particularly surface winds, and as a result of changes in ocean currents.

The strongest signatures of the spatial pattern of sea-level rise projections in the average of 16 coupled atmosphere-ocean models used for the IPCC AR4 are a minimum in sea-level rise in the Southern Ocean south of the Antarctic Circumpolar Current and a maximum in the Arctic Ocean. The minimum sea level rise in the Southern Ocean is due the thermal expansion coefficient being lower in cold waters than warmer waters.

Biogeochemistry

The response of the Southern Ocean to climate change remains highly uncertain and simulations from coupled climate carbon models show a large range of responses.

Patterns have emerged from future scenarios that suggest that the Southern Ocean will be an increased sink of atmospheric CO_2 in the future and that the recent decrease in uptake will not continue into the future. The magnitude of the total uptake is very dependent on how the ocean responds to predicted increases in ocean warming and stratification, which can drive both increases in CO_2 uptake through biological and export changes and decreases through solubility changes and density changes. The increased absorption of atmospheric CO_2 and upwelling of deep-water impacts the ability of the ocean to store CO_2.

Studies of the future global uptake of CO_2 in coupled and uncoupled simulations show that the global marine ocean carbon cycle acts as a positive feedback on climate change i.e. amplifying climate change. This highlights the importance of the Southern Ocean, as it is expected to act as a negative feedback in the next 100 years. We note also that Southern Ocean uptake changes are vulnerable to changes in the terrestrial biosphere. Changes in uptake of CO_2, particularly at mid-latitudes, can be very large, and therefore can significantly impact the response of the Southern Ocean in the future by impacting the gradient between the atmosphere and the ocean.

The ocean circulation and water masses

Models generally predict an intensification of the ACC in response to the southward shift and intensification of the westerly winds over the Southern Ocean forecast for the 21st century. Averaged over all the model simulations performed in the framework of the IPCC AR4, the increase in ACC transport projected for the end of the 21st century reaches a few Sverdrups in the Drake Passage. The enhanced winds induce in addition a small but robust southward displacement of the core of the ACC (less than1° in latitude on average). Furthermore, nearly all the models simulate regional changes in the horizontal oceanic circulation, but the patterns of the projected changes vary significantly between the models. One exception is probably the Ross Sea, where a large number of models simulate a cyclonic anomaly at the end of the 21st century.

During the 21st century, the observed mid-depth warming of the Southern Ocean is projected to continue, reaching nearly all depths. However, close to the surface, the warming of the Southern Ocean during the 21st century is expected to be weaker than in other regions.

The ocean ventilation could be enhanced because of the surface divergence induced by the increase in the wind stress and associated upwelling and Ekman Drift projected during the 21st century.

Sea ice

With the SRESA1B scenario, over the 21st century the IPCC models suggest that the annual average total sea-ice area may decrease by 2.6×10^6 km^2, or 33% compared to current values. Most of the ice retreat is expected to be in winter and spring, when the sea ice extent is largest. The amplitude of the seasonal cycle of sea ice area will therefore decrease.

There is strong confidence in the Antarctic-wide decreases of sea ice extent. Although it is more difficult to produce regional predictions, in the regions where sea ice currently remains present throughout the summer, in particular the Weddell Sea, large reductions of sea ice extent are expected.

Permafrost

Given the possible warming scenarios in Antarctica, it is anticipated that over the next 100 years there will be a reduction in permafrost area, subsidence of ground surface, changes in hydrology and mass movements.

The areas most susceptible to permafrost degradation lie within the zones of discontinuous and sporadic permafrost, which includes the northern Antarctic Peninsula and the South Shetland and South Orkney Islands and possibly coastal areas in East Antarctica.

There are approximately 80 year-round and summer bases in Antarctica, of which about 90% are in areas that are sensitive to thermokarst and mass wasting. The forecast changes imply risks to infrastructure.

Marine biology

How the rich biodiversity of the Southern Ocean will respond to medium/long term warming is unclear. Certain changes over decades have been found in pelagic and benthic populations of some Southern Ocean species, but none definitively linked to climate change. Most of the evidence currently being discussed for how benthos might cope with temperature rises is experimental. Being typically 'stenothermal' (capable of living or growing only within a limited range of temperature) is considered a key trait characterising Antarctic marine animals and if this is the case they would be highly sensitive to predicted climate change. Experiments have shown that most species, including a wide range of invertebrates, have upper lethal temperatures below or near to 10° C. Some can survive just a 7° C temperature window. Nevertehess, even in the most severe warming scenarios a rise of this magnitude in the Southern Ocean is very unlikely by 2100. That being said, organisms can be critically affected at lower temperatures long before lethal levels are reached. Whether populations or species will survive future temperature rises or not may be more dictated by their ability to carry out critical activities e.g. feeding.

There will be acute agents of disturbance to the marine biota, including 1) rapid increases in both ice-loading and coastal concentrations of large icebergs from iceshelf collapses; 2) coastal sedimentation associated with ice melt, smothering benthos and hindering feeding; and 3) freshening of surface waters leading to, amongst other changes, stratification.

The chronic impacts of climate change considered important are 1) long term decreases in ice scour probably leading to increased local scale, but decreased regional biodiversity; 2) the physiological effect of direct warming, leading to reduced performance at critical activities and thus geographic and bathymetric migrations; 3) increased acidification, leading to skeletal synthesis and maintenance problems, and; 4) slight deoxygenation of surface waters accompanied by disruption of currents and downwelling, ultimately leading to more serious deoxygenation for deeper layers.

Concluding remarks

The climate of the high latitude areas is more variable that that of tropical or mid-latitude regions and has experienced a huge range of conditions over the last few million years. The snapshot we have of the climate during the instrumental period is tiny in the long history of the continent, and separation of natural climate variability from anthropogenic influences is difficult. However, the effects of increased greenhouse gases are already evident, and the effects of expected increases of GHGs over the next century, if they continue to rise at the current rate, will be remarkable because of their speed. We can make reasonably broad estimates of how quantities such as temperature, precipitation and even sea ice extent might change, and consider the possible impact on marine and terrestrial biota. We cannot yet say with confidence how the large ice sheets of Antarctic will respond, but observed recent rapid changes give cause for concern – especially for the stability of parts of West Antarctica.

REFERENCES will of course be comprehensively available in the final text for publication, but are available on request.

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