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SCAR's Antarctic Climate Change and the Environment (ACCE) Review Report

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Introduction

1. The Antarctic climate system varies on time scales from sub-annual to millennial and is closely coupled to other parts of the global climate system. The Antarctic Climate Change and the Environment review discusses these variations in the geological timeframe and over the last 50 years, discusses their consequences for the biosphere, and shows how the latest numerical models project change into the future, taking into account human interference in the form of the release of greenhouse gases and chlorofluorcarbons into the atmosphere. For recommendations relevant to the Treaty Parties, see paragraphs 78 - 81.

The Geological Dimension (Deep Time)

2. Studying the history of Antarctica's climate and environment provides the context for understanding present day climate and environmental changes. 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. Knowing this natural variability enables researchers to identify when present day changes exceed the natural state. The palaeorecords show that change is normal and the unexpected can happen.
3. 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 million years ago (Ma) 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. During these times there was little or no ice on land.
4. The first continental-scale ice sheets formed on Antarctica around 34 Ma, most likely in response to a decline in atmospheric CO_2 levels caused by a combination of reduced CO_2 out-gassing from mid-ocean ridges and volcanoes, and increased carbon burial. This decline dropped global temperatures at that time to levels around 4º C higher than today. The ice sheet reached the edge of the Antarctic continent, but was most likely warmer and thinner than today's. Further sharp cooling took place at around 14 Ma, probably accelerated by the growing physical and thermal isolation of Antarctica as other continents drifted away from it, and as the Antarctic Circumpolar Current (ACC) developed, rather than due to any change in atmospheric CO_2 levels. At that time the ice sheet thickened to more or less its modern configuration, which is thought to have persisted to now. During the Pliocene (5-3 Ma), mean global temperatures were 2-3º C above pre-industrial values, CO_2 values may have reached 400 ppm, and sea levels were 15-25 m above today's.
5. There has been a marine biota around Antarctica since at least the Cretaceous (65 Ma). The earliest cold-climate marine fauna is thought to date from the latest Eocene-Oligocene (c. 35 Ma). The establishment of the Polar Front separating warm water in the north from cold water in the south created a barrier for migration of shallow and open water marine organisms between the Antarctic and lower latitudes. This promoted adaptive evolution to cold temperature and extreme seasonality to develop in isolation, and led to the current Antarctic marine biota, which is second only to coral reefs in terms of species diversity and biomass. In contrast to marine faunas elsewhere the Antarctic fish fauna is dominated by a single highly endemic taxonomic group - the suborder Notothenioidei. The evolution of antifreeze proteins and the loss of haemoglobin in some groups of fish is a particularly advanced adaptation to the environment. The development of sea-ice made the success of krill possible and, consequently, shaped the higher trophic levels of the open ocean ecosystem. Invertebrates inhabiting the deep-sea experienced considerable exchange with northerly adjacent areas due to sharing similar environmental conditions.

6. In an analogous fashion, circumpolar atmospheric circulation patterns isolated terrestrial habitats from potential sources of colonists at lower latitudes. In some contrast with the marine environment, the combination of continental scale ice sheet formation and advance, and extreme environmental conditions, led to large-scale (but incomplete) extinction of pre-existing biota, and to evolutionary radiation amongst the remaining survivors.

The Last Million Years

7. The long periods of cold of the Pleistocene glaciation (post 1.8 Ma) were subject to cycles of warming and cooling with frequencies of 20,000, 41,000 and 100,000 years in response to variations in the Earth's orbit around the Sun. These led periodically to the development of short warm interglacial periods like that of the last 10,000 years. Over the past 400,000 years interglacial periods have recurred at intervals of around 100,000 years.
8. Ice core data from glacial cycles over the last 800,000 years show that CO_2 and mean temperature values ranged globally from 180 ppm and 10º C in glacial periods to 280-ppm and 15º C in interglacial periods. Temperature differences between glacial and interglacial periods in Antarctica averaged around 9°C. Ice sheets expanded in glacial periods, with sea level dropping by 120 m on average. Ice cores from both Antarctica and Greenland show that over the past 400,000 years interglacial temperatures were between 2-5ºC higher and sea levels were 4-6 m higher than they are today.
9. Diatom data from sediment cores show that at the Last Glacial Maximum (LGM), about 21,000 years before present, Antarctic sea ice was double its winter extent and double its summer extent. Related sea surface temperature calculations show that both the Polar Front and the subAntarctic Front shifted to the north during the LGM by between 2° and 10° in latitude from their present locations.
10. The expansion and contraction of the Antarctic ice sheets 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 a result of whether the species survived the glacial maxima in refugia, then recolonised deglaciated areas, or arrived through post-glacial dispersal from lower latitude lands that remained ice free, or are present through a combination of both mechanisms.
11. Continuous evolutionary development, especially during glacials in isolated refugia, is assumed to be a major driving force explaining the relatively high biodiversity of benthic (bottom-dwelling) marine organisms. Expansions and contractions of the sea ice will also have had an impact on marine mammal and seabird distributions. These various expansions and contractions continued into the Holocene.

The Holocene

12. The transition from the Last Glacial Maximum to the present interglacial period (the Holocene, beginning around 12,000 years ago) was the last major global climate change event. Geological evidence from land in the Antarctic shows that there were two marked warm periods in the Holocene, one between 11,500 - 9000 years ago, and one between 4,000 - 2,000 years ago. Some marine records show evidence of a climate optimum between about 7,000 - 3,000 years ago. During the warm periods, some sediment cores from the Southern Ocean show there was reduced sea ice coverage.
13. Besides these changes, the ice core record shows dramatic changes in atmospheric circulation in the Antarctic, first at 5400-5200 years ago, with abrupt weakening of the Southern Hemisphere westerlies, and second around 1200 years ago with intensification of the westerlies and the Amundsen Sea Low Pressure cell.
14. Links between the climates of the northern and southern hemispheres exist, but through most of the Holocene and in the prior ice age northern hemisphere climate events lagged southern hemisphere ones by several hundred years. In contrast, in recent decades the northern hemisphere signal of rising temperature since about 1800 AD has paralleled the southern

hemisphere one. Temperature change in the two hemispheres (at least as far as West Antarctica is concerned) now appears to be synchronous - a significant departure from former times, which suggests a new and different forcing, most likely related to anthropogenic activity in the form of enhanced greenhouse gases.

Changes During the Instrumental Period

15. The instrumental period began in the Antarctic with the International Geophysical Year, about 50 years ago. Here we discuss key changes in the atmosphere, ice and ocean system.

The large scale circulation of the atmosphere

16. The major mode of variability in the atmospheric circulation of the high southern latitudes is the Southern Hemisphere Annular Mode (SAM), a ring of variability surrounding Antarctica and defined by the gradient of air pressure between mid-latitudes (high pressure) and the Antarctic coast (low pressure). Over the past 50 years the SAM became more positive, as pressure dropped around the coast of the Antarctic and increased at mid-latitudes. Since the late 1970s this change increased westerly winds over the Southern Ocean by 15-20%.
17. The SAM changed because of the increase in greenhouse gases and the development of the Antarctic ozone hole, the loss of stratospheric ozone having the greatest influence. The ozone hole occurs in the Austral spring. At that time of year the loss of stratospheric ozone cools the Antarctic stratosphere, so increasing the strength of the polar vortex – a large high altitude cyclonic circulation that forms in winter in the middle and upper troposphere and stratosphere over the Southern Ocean around Antarctica. During the summer and autumn the effects of the ozone hole propagate down through the atmosphere, increasing the atmospheric circulation around Antarctica at lower levels. As a result, the greatest change in the SAM, which is indicative of surface conditions, is in the autumn.
18. Changes in the SAM from 1958-1997 led to a decrease in the annual and seasonal numbers of cyclones south of 40°S. There are now fewer but more intense cyclones in the Antarctic coastal zone between 60-70°S, except in the Amundsen-Bellingshausen Sea region.
19. In recent decades there have been more frequent and more intense El Niño events. During some of them a signal of the El Niño cycle can be seen in the Antarctic. There is no evidence that this trend has affected long term climate trends in the Antarctic.

Atmospheric temperatures

20. Surface temperature trends show significant warming across the Antarctic Peninsula and to a lesser extent West Antarctica since the early 1950s, with little change across the rest of the continent. The largest warming trends occur on the western and northern parts of the Antarctic Peninsula. There the Faraday/Vernadsky Station has experienced the largest statistically significant (<5% level) trend of +0.53° C per decade for the period 1951 - 2006. The 100-year record from Orcadas on Laurie Island, South Orkney Islands, shows a warming of +0.20°C per decade. The western Peninsula warming has been largest during the winter, with winter temperatures at Faraday/Vernadsky increasing by +1.03°C per decade from 1950 - 2006. There is a high correlation during the winter between sea ice extent and surface temperatures, suggesting more sea ice during the 1950s - 1960s and reduction since then. This warming may reflect natural variability.
21. Temperatures on the eastern side of the Antarctic Peninsula have risen most during the summer and autumn (at +0.41°C per decade from1946 - 2006 at Esperanza), linked to the strengthening of the westerlies that took place as the SAM shifted into its positive phase. Stronger westerly winds bring warm, maritime air masses across the Peninsula to the low-lying ice shelves on the eastern side.
22. Based on data from satellites and automated weather stations, West Antarctica has warmed by about 0.1°C/decade, especially in winter and spring. Ice core data from the Siple Dome

suggest that this warming began around 1800. There have been few statistically significant changes in surface temperature over the instrumental period elsewhere in Antarctica.

23. On the plateau, Amundsen-Scott Station at the South Pole shows a statistically significant cooling in recent decades, interpreted as due to fewer maritime air masses penetrating into the interior of the continent.
24. Temperatures reconstructed from ice cores show large inter-annual to decadal variability, with the dominant pattern being anti-phase anomalies between the continent and the peninsula, which is the classic signature of the SAM. The reconstruction suggests that Antarctic temperatures increased on average by about 0.2°C since the late nineteenth century.
25. Antarctic radiosonde temperature profiles show that the troposphere has warmed at 5 km above sea level, and that the stratosphere above it has cooled over the last 30 years. This pattern would be expected from increasing greenhouse gases. The tropospheric warming in winter is the largest on Earth at this level. It may, in part, be a result of the insulating effect of greater amounts of polar stratospheric cloud during the winter. These clouds form in response to stratospheric cooling related also to the ozone hole.

Snowfall

26. On average, about 6 mm global sea level equivalent falls as snow on Antarctica each year, but with no statistically significant increase since 1957. Snowfall trends vary from region to region. Snowfall has increased on the western side of the Peninsula, where it has been linked to decreases in Adélie penguin populations, which prefer snow-free nesting habitat.

The Antarctic ozone hole

27. Stratospheric ozone levels began to decline in the 1970s, following widespread releases of CFCs and halons into the atmosphere that destroyed virtually all ozone between heights of 14 and 22 km over Antarctica. Owing to the success of the Montreal Protocol, the amounts of ozone-depleting substances in the stratosphere are now decreasing by about 1% per year. As a result the size and depth of the ozone hole have stabilised; neither are yet reducing.

Terrestrial biology

28. The best example of Antarctic terrestrial organisms responding to climate change is given by the two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis)* in the maritime Antarctic, which have increased in abundance at some sites. Warming encourages the growth and spreading of established plants and increased establishment of seedlings. Changes in temperature and precipitation have increased biological production in lakes, mainly due to decreases in the duration and extent of lake ice cover. Some lakes have become more saline due to drier conditions.
29. Alien microbes, fungi, plants and animals introduced through human activity occur on most of the sub-Antarctic islands and some parts of the continent. They have impacted the structure and functioning of native ecosystems and their biota. On Marion Island and Gough Island it rates of establishment through anthropogenic introduction outweigh those from natural colonization processes by two orders of magnitude or more.

The terrestrial cryosphere

30. Ice shelves in the Antarctic Peninsula have changed rapidly in recent decades. Warming has caused retreat of ice shelves on both sides of the Peninsula. Loss of ice on the eastern side results from warm air being brought over the peninsula by the stronger westerlies forced by changes in the SAM. Ice-shelf retreat results from increased fracturing via melt-water infilling of pre-existing crevasses, and the penetration of warm ocean masses beneath ice shelves. Removal of ice shelves has led to the speeding up of glacier flow from inland.
31. Some formerly snow- and ice-covered islands are now increasingly snow-free during the summer. Glaciers on Heard Island reduced by 11% since the 1940s, and several coastal

lagoons have formed there. On South Georgia, 28 of 36 surveyed glaciers are retreating, 2 are advancing, and 6 are stable. On Signy Island ice cover has reduced by around 40%.

32. Of the 244 marine glaciers that drain the ice sheet and associated islands of the Antarctic Peninsula, 212 (87%) have shown overall retreat since 1953. The other 32 glaciers have shown small advances.
33. The Amundsen Sea sector is the most rapidly changing region of the Antarctic ice sheet. The grounding line at Pine Island has retreated, and the Pine Island Glacier is now moving at speeds 40% higher than in the 1970s. The Thwaites Glacier and four other glaciers in this sector show accelerated thinning. Smith Glacier has increased flow speed 83% since 1992. 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. The current rate of mass loss from the Amundsen Sea embayment ranges from 50 to 137 Gt per year, equivalent to the current rate of mass loss from the entire Greenland ice sheet, and make a significant contribution to sea level rise.
34. The changes result from warming of the sea beneath the ice shelves connected to the glaciers. The stronger winds associated with the more positive SAM drive warm Circumpolar Deep Water up against the western Peninsula coast and the Amundsen Sea coast.
35. Changes are less dramatic across most of the East Antarctic ice sheet, with the most significant changes close to the coast. The ice sheet shows 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 recent passive microwave data.

Sea level changes

36. Data from tide gauges and satellite altimeters suggest that in the 1990s-2000s global sea level rose at a rate of 3 mm per year or more, which is higher than expected from IPCC projections. There is concern about possibly large contributions resulting from the dynamic instability of ice sheets during the 21^{st} century. Around 2005, the Antarctic Peninsula was estimated as contributing to global sea-level rise at a rate of 0.16 ± 0.06 mm per year

The Southern Ocean

37. The waters of the ACC have warmed more rapidly than the global ocean as a whole, increasing by 0.17°C at depths between 700 – 1100 m over the 1950s to 1980s.The change is consistent with a southward shift of the ACC in response to a southward shift of the westerly winds driven by enhanced greenhouse forcing. There is no evidence for an increase in ACC transport. Recent studies suggest that an increase in wind forcing causes an increase in the meridional transport of heat and salt by eddies rather than a change in zonal transport by the current. Small changes are evident in the character of the Ross and Weddell Seas, but neither show major long-term trends apart from slight freshening. During the 1970s a persistent gap in the sea ice, the Weddell Polynya, occurred for several winters. A great deal of heat is transferred from the ocean to the atmosphere from these ice-free zones.

Biogeochemistry

38. The Southern Ocean plays ventilates the global oceans and regulates the climate system by taking up and storing heat, freshwater, O_2 and atmospheric CO_2. From 1991 - 2007 the concentration of CO_2 in the ocean increased south of 20°S in the Southern Indian Ocean. At latitudes pole-ward of 40°S, CO_2 in the ocean increased faster than it did in the atmosphere, suggesting that the ocean became less effective as a sink for atmospheric CO_2. These changes seem to be linked to the increase in wind strength driven by the more positive SAM. An increase in the ocean's CO_2 content makes the ocean more acidic.

Sea ice

39. For the first half of the Twentieth Century, ship observations suggest that the extent of sea ice was greater than seen in recent decades, although the validity of such observations is questioned. The sea ice extent data derived from satellite measurements from 1979 - 2006 show a positive trend of around 1% per decade. The trend is positive in all sectors except the Bellingshausen Sea, where sea ice extent has been significantly reduced. The greatest increase, at around 4.5% per decade, is in the Ross Sea. Winds rather than temperature *per se* may play a key role in governing sea ice abundance in both polar regions.

Permafrost

40. There is little information on permafrost in the Antarctic. On Signy Island the active layer (the layer experiencing seasonal freeze and thaw) increased in depth by 30 cm from 1963 - 1990, when Signy Island was warming, then decreased by the same amount from 1990 – 2001, when Signy Island cooled. In McMurdo Sound, the permafrost temperature at -360 cm has remained stable, despite a slight decrease in air temperature of 0.1°C per year.

Marine biology

41. The Southern Ocean ecosystem was significantly disturbed by whaling during the early part of the Twentieth Century, and by sealing before that. About 300,000 blue whales were killed within the span of a few decades, equivalent to more than 30 million tonnes of biomass. Most were killed on their feeding grounds in the southwest Atlantic in an area of some 2 million km^2, which translates to a density of one blue whale per 6 km^2. Following near-extinction of some whale populations, the krill stock was expected to increase due to release from grazing pressure. It did not. While predation by seals and birds increased, the total bird and seal biomass remained within only a few percent of that of the former whale population.
42. For the past 50 years Antarctic marine biota have lived in a rather stable environment that may represent the marine ecosystem that is least directly affected by humans. However, this ecosystem is affected by climate change, especially on the western side of the Peninsula, with its warm water and reduction in sea-ice. There we find a decline in the fish *Pleuragramma antarcticum*, whose reproduction is associated with sea ice, along with a decline in krill stocks, a decrease in phytoplankton and a southward shift in the population of gelatinous salps. The decline in phytoplankton may reflect a decrease in iron input from the continental margin that is in turn related to a reduction in the formation of sea ice in this region and hence to climate change.

The Next 100 Years

43. Determining how the environment of the Antarctic will evolve over the next century presents challenges yet has implications for science and for policymakers. Climate evolution can only be predicted with some degree of confidence by using coupled atmosphere-ocean-ice models. The model outputs improve on simple projections of current trends, as they take a large number of parameters into consideration. They are the only means we have of providing synoptic views of future environmental behaviour, albeit crudely and at coarse resolution. The models do not accurately simulate the observed changes that have taken place over the last few decades, so there is still some uncertainty about their forward projections, particularly at regional scales. 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, which is sensitive to changes in atmospheric and oceanic conditions. The models can be weighted according to their skill in simulating modern conditions.
44. Numerically based biological models cannot yet approach the relative sophistication of models of the physics of the climate system, while physical models do not approach the level of

spatial scale or resolution required for application to biological systems, providing yet a further limitation on what can be said about biotic and ecosystem responses.

45. The degree to which the Earth's climate will change over the next century is dependent on the success of efforts to reduce greenhouse gas (GHG) emissions. The ACCE report focuses on outputs from IPCC models that assumed a doubling of CO_2 and other gases by 2100.

Atmospheric circulation

46. The recovery of the ozone hole combined with a continued increase in greenhouse gas emissions should continue strengthening the positive phase of the SAM, but with a trend that is less rapid than seen in the last two decades. We can thus expect to see further increases of surface winds over the Southern Ocean in the summer and autumn. This will lead to continuance of the pole-ward shift in the Southern Ocean storm track.

Temperature

47. The models project significant surface warming over Antarctica to 2100 AD, by 0.34°C/decade over land and grounded ice sheets, within a range from 0.14 to 0.5°C/decade. Over land, the largest increase is projected for the high-altitude interior of East Antarctica. Despite this change, the surface temperature by the year 2100 will remain well below freezing over most of Antarctica and will not contribute to melting inland.
48. The largest atmospheric warming projected by the models is over the sea ice zone in winter (0.51 ± 0.26°C/decade off East Antarctica), because of the retreat of the sea-ice edge and the consequent exposure of the ocean.
49. While we are confident in the overall projection of warming, we have low confidence in the regional detail, because of the large differences in regional outcomes between models.
50. The annual mean warming rate in the troposphere at 5 km above sea level is projected to be 0.28°C/decade - slightly smaller than the forecast surface warming.
51. As yet we cannot forecast changes to extreme conditions over Antarctica – something that biologists need to assess potential impacts. The extreme temperature range between the coldest and warmest temperature of a given year is projected to decrease around the coasts and to show little change over the interior.
52. The warming of 3°C over the next century is faster than the fastest rate of rise seen in Antarctic ice cores (4°C per 1000 years), but it is comparable to or slower than the rates of temperature rise typical of Dansgaard-Oeschger events during glacial times in Greenland, of the Bolling-Allerød warming in Greenland 14,700 years ago, and of the warming in Greenland at the end of the Younger Dryas around 11,700 years ago. Thus however unlikely such rapidity may appear, it is feasible in terms of what we know about the natural system.

Precipitation

53. Current numerical models generally underestimate precipitation for the 20th century. This is due to problems in parameterizing key processes that drive precipitation (e.g. because polar cloud microphysics is poorly understood), and because the smooth coastal escarpment in a coarse resolution model causes cyclones to precipitate less than they do in reality. Warmer air temperatures and associated higher atmospheric moisture in most models cause net precipitation to increase in the future. Most climate models simulate a precipitation increase over Antarctica in the coming century that is larger in winter than in summer. Model outputs suggest that the snowfall over the continent may increase by 20% compared to current values. 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

54. By the middle of the 21st century we expect that springtime concentrations of stratospheric ozone will have significantly recovered, but not to 1980 values. That is because increasing greenhouses gases will have accumulated in and warmed the troposphere, so further cooling the stratosphere. Destruction of ozone is more likely to continue in a colder stratosphere.

Tropospheric chemistry

55. Various trace gases, such as dimethyl sulphide (DMS) generated by plankton, are released from the oceans around Antarctica. Any projected loss of sea ice will enhance these emissions, which have seasonal cycles closely linked to the extent of sea ice and to the Sun. In a warmer world, with reduced sea ice extent, emissions of gases such as DMS would likely increase, with a wintertime minimum and an extended summer maximum. DMS is a source of cloud condensation nuclei (CCN) via its oxidation to sulphate. Increasing the number of CCN may increase cloudiness and albedo, thus influencing the Earth's climate.

Terrestrial biology

56. Increased temperatures may promote growth and reproduction, but also cause drought and associated effects. Changes to water availability have a greater effect than temperature on vegetation and faunal dynamics. Future regional patterns of water availability are unclear, but climate models predict an increase in precipitation in coastal regions. An increase in the frequency and intensity of freeze–thaw events could readily exceed the tolerance limits of many arthropods. With increases in temperature, many terrestrial species may exhibit faster metabolic rates, shorter life cycles and local expansion of populations. Even subtle changes in temperature, precipitation and wind speed will probably alter the catchment of lakes, and of the time, depth and extent of their surface ice cover, water volume and chemistry, with resulting effects on lake ecosystems. Warming also increases the likelihood of invasion by more competitive alien species carried by currents and by humans.

The terrestrial cryosphere

57. Existing ice-sheet models do not properly reproduce the observed behaviour of ice sheets, casting doubt on their predictive value. The models fail to take into account either mechanical degradation (e.g. water causing cracks to propagate in summer), or lubrication of the base of the ice by downward percolating surface water. Predictions of the future state of ice sheets are based on a combination of inference from past behaviour, extension of current behaviour, and interpretation of proxy data and analogues from the geological record.
58. The most likely regions of future change are those changing today. Warmer waters will continue to well up onto the continental shelf in the Amundsen Sea, eroding the underside of the ice sheets and glaciers. It has been suggested that there is 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. In addition there is a concern that the ice in the Amundsen Sea Embayment could be entering a phase of collapse that could lead to de-glaciation of parts of the West Antarctic Ice Sheet. Ultimately, this sector could contribute 1.5 meters to global sea level, so a contribution from this sector alone of some tens of centimetres by 2100 cannot be discounted.
59. On the Antarctic Peninsula, most of the effects leading to loss of ice are confined to the northern part, which contains a few centimetres of global sea-level rise. Increased warming will lead to a southerly progression of ice shelf disintegrations along both coasts. These may be preceded by an increase in surface melt-water lakes, and/or progressive retreat of the calving front. Prediction of the timing of ice shelf disintegration is not yet possible. Removal of ice shelves will cause glaciers to speed up. The total volume of ice on the Peninsula is 95,200 km^3, equivalent to 242 mm of sea-level or roughly half that of all glaciers and ice caps

outside of Greenland and Antarctica. Increased warming may lead to the Peninsula making a substantial contribution to global sea level.

Sea level

60. The IPCC's Fourth Assessment Report projected a range of global sea-level increase from 18 to 59 cm between 1980-1999 and 2090-2099. This did not include a contribution from the dynamic instability of the Greenland or Antarctic ice sheets. Sea level will not rise uniformly. The spatial pattern of sea-level rise projections shows a minimum in sea-level rise in the Southern Ocean and a maximum in the Arctic Ocean.

Biogeochemistry

61. Model projections suggest that the Southern Ocean will be an increased sink of atmospheric CO_2. The magnitude of the uptake will depend on how the ocean responds to increases in ocean warming and stratification, which can drive both increases in CO_2 uptake through biological and export changes, and decreases through solubility and density changes.

The ocean circulation and water masses

62. Ocean models are deficient in having a typical grid spacing of around 100 km in the horizontal, which is larger than the typical ocean eddy, and so limits the ability of the models to simulate ocean behaviour - an important constraint given the key role of ocean eddies in north-south heat transport in the Southern Ocean. The models generally predict an intensification of the ACC in response to the forecast southward shift and intensification of the westerly winds over the Southern Ocean. The increase in ACC transport projected for 2100 reaches a few Sverdrups (1 Sv = one million cubic metres/second) in the Drake Passage. The enhanced winds induce a small southward displacement of the core of the ACC (less than 1° in latitude on average).
63. The observed mid-depth warming of the Southern Ocean is projected to continue, reaching nearly all depths. Close to the surface, the warming is expected to be weaker than in other regions. Ocean ventilation could be enhanced because of enhanced divergence of surface waters induced by the increase in the wind stress and associated upwelling.

Sea ice

64. The models suggest that the annual average total sea-ice area will decrease by 2.6×10^6 km^2, or 33%. Most of the retreat is expected to be in winter and spring, so decreasing the amplitude of the seasonal cycle of sea ice area.

Permafrost

65. It is likely that there will be a reduction in permafrost area, accompanied by subsidence of ground surface and associated mass movements. Change is most likely in the northern Antarctic Peninsula and the South Shetland and South Orkney Islands and coastal areas in East Antarctica. The forecast changes imply risks to infrastructure.

Marine biology

66. Most evidence for how benthic organisms may cope with temperature rise is experimental. Being typically 'stenothermal' (able to live within a limited range of temperature) is a key trait of Antarctic marine animals. If they are truly so limited they would be highly sensitive to significant warming. Experiments show most species have upper lethal temperatures below 10°C. Some can survive just a 5°C change. However, a rise of this magnitude in the Southern Ocean is extremely unlikely by 2100. That being said, the behaviour of organisms can be affected at lower temperatures long before lethal levels are reached; whether populations or species will survive future temperature rises may be dictated by their ability to carry out critical activities e.g. feeding.

67. Model projections suggest that bottom water temperatures on the continental shelf by 2100 AD are likely to be warmer by between 0.5 and 0.75ºC, except in the Weddell Sea where the warming is likely to be less. The lack of projected warming of surface and bottom waters by more than about 0.75ºC suggests that the effects of warming on the marine biota may be less than has been feared from laboratory experiments. Projected warming greater than 1.5ºC is restricted to the surface waters near the core of the ACC.
68. Several Antarctic taxa are distributed across sites or depths with a much greater temperature range than ‘typical Antarctic conditions’. South Georgia has populations of many typical Antarctic species, despite experiencing maximum summer temperatures 3°C warmer than the Antarctic Peninsula. In several taxa up to 40% of Antarctic species have ranges stretching into temperate waters where seasonal minimum temperatures exceed maximum values in the Southern Ocean. Thus there may be a conflict between experimental and ecological evaluations of vulnerability. The ecological context may be crucial.
69. If the sea-ice cover continues to decrease, marine ice algae will begin to disappear due to loss of habitat, which may cause a cascade through higher trophic levels in the food web. Given a complete removal of sea ice we might expect extinction of those species that presently depend on it for survival, including some fish, penguins, seals and whales. Climate models suggest that complete removal is unlikely within the next 100 years. With the decline in sea ice there should be more algal blooms supplying food to benthic organisms on the shelf. A resulting increase in phytodetritus on the shelf may cause a decline in suspension feeders adapted to limited food supplies, and to their associated fauna.
70. When ice shelves collapse, the changes from a unique ice-shelf-covered ecosystem to a typical Antarctic shelf ecosystem, with high primary production during a short summer, are likely to be among the largest ecosystem changes on the planet.
71. If surface ocean pH levels become more acid by 0.2 to 0.3 units by 2100 it seems likely that there will be some thinning of the aragonite skeletons of the pteropods that are an important part of the plankton at the base of the food chain. The Southern Ocean is at higher risk from this than other oceans because it has low saturation levels of $CaCO_3$.
72. Given the slow rates of growth and high degree of endemism in Antarctic species, continued ocean warming and expanded tourism and scientific activity may lead to the wider establishment of non-indigenous species by 2100, and consequent reduction or extinction of some local species. Invasion by new species will likely remain restricted to isolated areas where invaders can survive at their physiological limits. As yet it is unclear if the finding of a very few macroalgal and one crustacean invasive species along the Antarctic Peninsula represent rare occurrences at their natural southern distribution limits, or the first stages of a marine biogeographical shift induced by warming.
73. Acute agents of disturbance to the marine biota include: 1) increased ice-loading and coastal concentrations of large icebergs from ice shelf collapse, resulting in more ice scour; 2) increased coastal sedimentation associated with ice melt, smothering benthos and hindering feeding; 3) freshening of surface waters leading to stratification of the water column; and 4) thermal events like those associated with El Niños.
74. Chronic impacts of climate change include: 1) ice shelf disintegration, exposing new habitats; 2) long-term decreases in ice scour by icebergs, leading to increased local but decreased regional biodiversity; 3) the physiological effect of direct warming, leading to reduced performance of critical activities and thus geographic and bathymetric migration; 4) benthic responses to changes in the pelagic system, especially in the food web; 5) increased acidification, leading to skeletal synthesis and maintenance problems; and 6) slight deoxygenation of surface waters, ultimately leading to more serious deoxygenation in deeper layers. The absence of wide latitudinal and environmental gradients around the Antarctic continent minimises the advantage of migration for survival.

75. Species such as fur seals are likely to respond most to changes in extreme climate events, for instance caused by changes in the El Niño - Southern Oscillation. Emperor penguins and other ice-dependent species depend on the sea-ice habitat to complete their life cycle. A significant decline in sea ice is likely to affect their populations, and may lead to true Antarctic species being displaced by immigrating subAntarctic species.
76. It seems likely that only a few species will become extinct by 2100, either because they proved unable to cope ecologically and physiologically with such an increase, or because they were restricted in their occurrence to an area with an above average temperature increase. Studies of biodiversity, coupled to sound data handling and dissemination, will bring a better understanding of how life has evolved in the marine environment, and to what extent it can potentially respond to change. Bridges between different disciplines and international programmes will provide a legacy of knowledge for future generations in the form of a comprehensive information system.

Concluding remarks

77. 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 their expected increase 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 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.

Recommendations

78. SCAR encourages all Treaty parties to take note of the latest scientific findings regarding climate change in Antarctica, notify SCAR of the latest research results from climate research being conducted by National Antarctic Programs, and communicate the latest findings to appropriate stakeholders and the general public in their respective countries, emphasizing the central role that the polar regions play in the Earth system.

79. SCAR encourages all Treaty parties to support and foster research on Antarctic climate change focusing on those aspects that are least understood (such as models of the behaviour of the ice sheet, for example) with particular attention paid to establishing and sustaining long-term, interdisciplinary observing projects.

80. SCAR encourages Treaty parties to support research on the distribution of terrestrial species and the spatial distribution of genetic diversity especially in rapidly warming areas, and areas that seem prone to an elevated risk of biological invasion owing to climate change.

81. SCAR encourages all treaty parties to assess the contributions that their Antarctic operations make to global warming with a particular regard to greenhouse gas emissions and to adopt suitable mitigating protocols commensurate with the potential for impact.