1.18 ANTARCTIC CHANGES DURING GLOBAL WARMING TOWARDS EQUILIBRIUM FOR DIFFERENT LEVELS OF STABILISATION OF GREENHOUSE GASES

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1. INTRODUCTION

Observations have shown that a small but significant amount of global warming has occurred over the past century (IPCC 1996). This is possibly due to the increase of the greenhouse gases, which have grown substantially since pre-industrial times, with that growth largely attributed to human activities, such as the burning of fossil fuel, land-use change and agriculture. The observations over the Antarctic region before the 1950s are limited compared to other regions around the world. Recent observations have revealed little change of Antarctic sea-ice extent although large reductions in both sea-ice thickness and area have been observed in the Arctic (e.g., Bjorgo et al. 1997; Rothrock et al. 1999). Modelling studies of the climate change over the past 100 years or so with fully coupled atmosphere-ocean-sea-ice models have so far primarily addressed general global issues (e.g., Santer et al. 1996; Hasselmann 1997) and the changes in polar regions have received less attention due to the lack of observations. The objective of this research is to try to examine the Antarctic changes associated with global warming, over the past century and possibly developing in the future.

2. MODEL AND EXPERIMENTS

The Australian CSIRO coupled global climate model (Gordon and O'Farrell 1997) is a comprehensive general circulation climate model comprising sub-models of the atmosphere, ocean, sea-ice and biosphere. It has horizontal resolution represented by the Gaussian grid of 3.2°lat. by 5.6°long., with 9 levels in the vertical in the atmosphere and 21 levels in the ocean. In this study the coupled model was forced with a number of different increasing greenhouse gas scenarios. These are based on observations over the past century (from 1880) and projected to different levels of stabilisation and then continuing into the future, at those fixed levels. The future atmospheric equivalent CO_2 concentration followed the IS92a (in the middle of the IS92 "family") (IPCC 1996) radiative forcing scenario to 2000 (the present, or 'P'), 2033 (two times the value of 1880, or '2x') and 2082 (three times the value of 1880, or '3x'), then continued with those respective values for the rest of the simulation. A total of 2,000 years simulation has been performed for the 3x case, and 1,200 years for the P case and 2x case, respectively.

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3. RESULTS

3.1 Surface temperature

Observations show that the mean global surface temperature has increased by about 0.3 to 0.6°C from the late 19th century to 1994 (IPCC 1996). The coupled model simulates similar but greater global mean warming of about 0.7°C over the same period. The greater warming is due to the higher warming simulated in the Northern Hemisphere because of the lack of the cooling effect of aerosols which are not included in the model (Hirst 1999). For the Southern Hemisphere the simulated mean surface temperature change compares well with observations (Wu et al. 1999). For the Antarctic (60°S poleward) the simulated change from 1881-1910 to 1980-1994 is just over 0.7°C, however, because of the lack of observations before the International Geophysical Year (1957-1958) comparisons can not be made over the past 100 years. The simulated surface temperature changes for the Antarctic region from 1950-1964 to 1980-1994 is 0.43°C which is close to the observations of 0.41°C derived from Kelly and Jones (1996). It should be noted that the data from Kelly and Jones for the Antarctic region were based on limited observations both in space and time, particularly for the early period, and the model simulations cover all regions of each time step. In addition there are large variabilities in the data for both the observations and model simulations.

The reasonable warming simulated over the past provides us with some confidence in the simulation of the future climatic changes. Figure 1

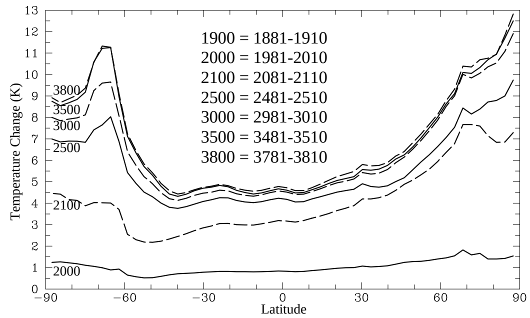

Figure 1: The annual zonal mean surface temperature change from 1900 to 2000, 2100, 2500, 3000, 3500 and 3800 from the 3x stabilisation case. Every epoch is represented with a 30-year mean.

shows the annual mean zonal mean surface temperature change from 1900 for a number of epochs for the case of 3x. Every epoch is represented by a 30-year mean as given in Fig. 1. It can be seen that for this scenario large warming is simulated between 1900 and 2100, especially for the Arctic, while the equivalent CO_2 increases up until 2082 then stabilises. For the Antarctic region large warming continues through the simulation, with the warming between 2100 and 2500 being nearly equal to the warming before equivalent CO_2 is stabilised, between 2000 and 2100. Most of the Earth's surface reaches near to equilibrium by 3000 but it takes a further 500 years for the Antarctic to reach near equilibrium, by which time it warms about twice as much as lower latitudes. This is associated with the changes of sea-ice and is discussed in the next sub-section. To compare the future warming simulated with different equivalent CO_2 stabilisation the mean temperature change from 1900 over the region south of 60°S for the three cases of P, 2x and 3x is given in Table 1. The global warming is also given for reference. By the end of this century the average warming simulated ranges from 1.4 (P) to 4.0°C (3x) over the Antarctic region while the global warming is very similar (1.4 (P) to 3.7°C (3x)). However, by 3000 the corresponding simulated warmings over the Antarctic region increase to 3.1 (P) to 8.7°C (3x) which are much greater than the corresponding global warming (2.0 (P) to 5.5°C (3x)). This suggests that the approach to equilibrium of the Antarctic region for global warming may be slower than the rest of the Earth's surface due to its extensive ice cover and its response to heating from the deep ocean after the equivalent CO_2 is stabilised. The changes can take more than 1,000 years for the Antarctic region while most of the Earth's surface would reach near equilibrium over this time. In our simulation the near equilibrium temperature changes for 3x is about 10.0°C

	P	2x	3x
2100	1.4 (1.4)	2.6 (2.4)	4.0 (3.7)
3000	3.1 (2.0)	4.7 (3.3)	8.7 (5.5)
3800	-	-	10.0 (5.9)

Table 1: The simulated area-weighted average annual mean surface temperature change (°C) over the Antarctic region (60°S poleward) from 1900 to the epochs of 2100, 3000 and 3800 for P, 2x and 3x. The global mean change is shown in parentheses for comparison.

over the Antarctic region and near 6.0°C for the global average. It is expected that small warming over the Antarctic region will continue beyond 3000 for P and 2x although the global mean warming may not change much from 2.0 (P) and 3.3°C (2x) by equilibrium.

3.2 Antarctic sea-ice

Recent observations have revealed little change of Antarctic sea-ice (e.g., Bjorgo et al. 1997) although large reductions in sea-ice extent have been suggested by De la Mare (1997) between the early 1930s and the mid-1970s. This contrasts with the Arctic where reductions in both sea-ice thickness and area have been observed (e.g., Rothrock et al. 1999). The simulated annual zonal mean Antarctic sea-ice concentration and thickness are shown in Figure 2 for the 3x case for a number of epochs. On average the simulated reduction of sea-ice over the past 100 years was about 5% in concentration and 0.1 m in thickness. The small reduction in ice concentration is within the background variability and uncertainty of the recent satellite observations. For ice thickness there are no data available to assess such a small change. However, these changes are not unreasonable considering the change of temperature over the past 45 years and 20 years (Comiso 2000) and the recent sea-ice record (e.g., Bjorgo et al. 1997). The simulated change in Arctic sea-ice thickness is about 30% over the past 100 years (not shown) which appears to be reasonable given the observed changes available over the past 30-40 years (e.g., Rothrock et al. 1999). Large future reductions in both ice concentration and thickness are simulated from 1900 to 2100 and they continue to 2500, especially for ice thickness. The Arctic changes are even more significant. The reductions continue at a lower rate to 3500, similar to the reduced surface warming rate after 2500 (Figure 1). This is expected because of the positive albedo feedback. The reduction of sea-ice is closely associated with the surface and atmosphere warming and increased net radiation received at the surface.

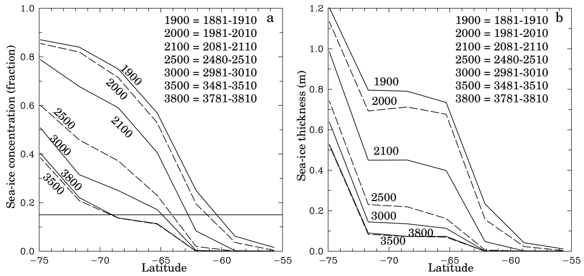

Figure 2: The simulated annual zonal mean Antarctic sea-ice (a) concentration and (b) thickness for the epochs of 1900, 2000, 2100, 2500, 3000, 3500 and 3800 for 3x.

The simulated annual mean sea-ice area (defined as the actual area covered by sea-ice (excluding open water) with 15% or more sea-ice concentration) for all three cases is given in Table 2 and the corresponding sea-ice volume is given in Table 3. Note that the time intervals are not uniform in the table. For the P case the largest reduction rate is over the past 100 years. After the equivalent CO_2 is stabilised at 2000 the reduction of both sea-ice area (also representing ice concentration) and volume (representing a combination of both ice area and thickness) becomes smaller, at about 2-3% per 100 years. For the 2x case the reduction of sea-ice is nearly constant until 2100 and only slightly greater than the P case. For the 3x case large reduction continues to 3000. Near its equilibrium the maximum sea-ice area is similar to the present day minimum sea-ice area but the sea-ice is much thinner (see also Figure 2). The ratio of sea-ice volume to area represents the simulated annual mean sea-ice thickness which reduced from 94 cm at 1900 to 86 cm at 2000. By 3000 this becomes 77, 63 and 52 cm respectively for P, 2x and 3x. The ice covered area is also much smaller by 3000, for 3x it is less than 30% of that at present.

3.3 Surface ocean freshening

Both simulated precipitation and evaporation increase at high latitudes associated with the global warming (Budd and Wu 1998). The precipitation increases more than evaporation and this results in an increase of precipitation minus evaporation (P-E). Figure 3 shows the changes of precipitation and P-E over the (fixed) maximum Antarctic sea-ice zone for three different cases of equivalent CO_2 stabilisation. The mean precipitation in the sea-ice zone increased by about 40 to 50 mm/year over the past 100 years, this is about 7-8% of the reference level (of about 600 mm/year) at 1900. By the end of next century, the changes are more than 8% (P), 13% (2x) and 20% (3x) of the 1900 value. Further increases continue through to the end of the simulation but the rate of change becomes smaller. Similar increases were simulated for evaporation but the changes are smaller in magnitude (not shown). Because of the greater reduction of sea-ice for the 3x case the increase of evaporation exceeds the increase of precipitation at about 2300-2400, thereafter the increase of P-E reduces but it is still significantly larger than that for the present. For both the P and 2x cases the change remains at a near constant level for most of the simulation conducted although a reduction is expected towards the end of the simulation. In our simulation P-E also increases significantly over the Antarctic continent mainly due to the increase of precipitation (not shown). This means that there would be a net increase in the accumulation over the Antarctic ice sheet.

	P	2x	3x
1900	10.1 (14.5)	10.1 (14.5)	10.1 (14.5)
2000	9.7 (13.5)	9.6 (13.4)	9.6 (13.4)
2100	9.4 (13.3)	8.3 (12.3)	7.1 (11.1)
3000	7.5 (11.2)	6.3 (10.1)	2.9 (5.3)
3800	-	-	1.9 (3.3)

Table 2: The simulated annual mean Antarctic sea-ice area (excluding open water) (10^{12} m^2) for the epochs of 1900, 2000, 2100, 3000 and 3800 for P, 2x and 3x. The maximum is shown in parentheses for comparison.

	P	2x	3x
1900	9.5 (14.3)	9.5 (14.3)	9.5 (14.3)
2000	8.4 (13.1)	8.3 (12.9)	8.3 (12.9)
2100	8.1 (12.7)	6.5 (10.8)	4.8 (8.7)
3000	5.8 (9.6)	4.0 (7.5)	1.5 (3.1)
3800	-	-	0.9 (1.9)

Table 3: The simulated annual mean Antarctic sea-ice volume (10^{12} m^3) (over ice concentration of 15% or more) for the epochs of 1900, 2000, 2100, 3000 and 3800 for P, 2x and 3x. The maximum is shown in parentheses for comparison.

The increase in precipitation in the sea-ice zone due to global warming leads to more snow accumulation and more snow-ice formation. The increased P-E over the sea-ice zone combined with the reduction of sea-ice (and possibly more snow-ice formation) lead to a significant freshening of the ocean surface around the Antarctic coast which increases the mixed layer stability and reduces the convection and deep water formation. This further leads to a reduced deep ocean circulation at the end of 21st century (Budd and Wu

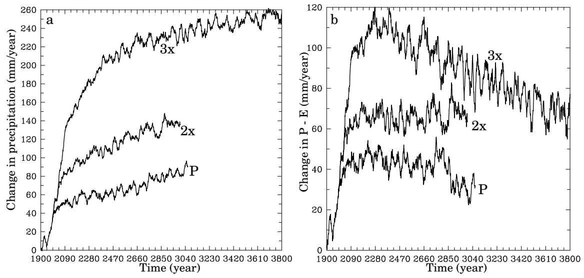

Figure 3: Time series of annual mean (a) precipitation and (b) P-E changes averaged over the fixed region of maximum Antarctic sea-ice in 1900 for P, 2x and 3x. Running-mean of 21 years has been applied. The reference levels at 1900 are 607 mm for precipitation and 378 mm for P-E.

1998; Hirst 1999).

4. CONCLUSION AND DISCUSSION

This work aims to study the Antarctic changes associated with global warming over the past century, and their possible development in the future with different levels of stabilisation of greenhouse gases. The model has simulated reasonable changes for Southern Hemisphere temperature over the past 100 years (Wu et al. 1999). The possible small reduction in both sea-ice concentration and thickness is considered to be reasonable for the Antarctic and not outside the ranges of observations (Wu et al. 1999).

For the future, our simulation suggests that the response of the Antarctic region to global warming is larger but slower than the rest of the Earth's surface due to its extensive ice cover and the deep ocean interaction. The changes for the Antarctic region can last more than 1,000 years while on this time scale most of the Earth's surface has reached near to equilibrium after the equivalent CO_2 is stabilised. For the 3x stabilisation simulation the Earth's surface has reached near equilibrium (including the Antarctic region) by 3500. By then the Antarctic is 10°C warmer than 1900. This compares with the corresponding mean global warming of nearly 6.0°C. However the deep ocean warming still continues beyond the end of our simulation. The reduction in sea-ice formation and the increase in P-E around the Antarctic coastal waters leads to a significant freshening of the ocean surface there, which increases the surface ocean stability and reduces the convection and deep water formation. It then takes several thousand years for the deep ocean to warm enough to balance the density change due to surface freshening in the polar region and for the reduced deep ocean circulation to recover (Bi et al., 2001).

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