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The Response of Antarctic Climate in General Circulation Model Experiments with Transiently Increasing Carbon Dioxide Concentrations [and Discussion]

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The response of Antarctic climate in general circulation model experiments with transiently increasing carbon dioxide concentrations

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SUMMARY

Coupled models of the atmosphere–ocean and land surface provide important tools for prediction of climate change. The results of experiments carried out at the Hadley Centre, Meteorological Office, in which such models have been used in studies of climate change due to increased levels of greenhouse gas concentrations are described, with particular reference to simulation of climate change in the region of Antarctica. Although, as yet, the ability of such models to represent regional climate change is relatively low, processes in the southern ocean around Antarctica are important for determining the global pattern of transient temperature change as CO_2 increases. This is illustrated by results from two experiments. Firstly, an experiment with a high resolution ($2.5° \times 3.75°$) atmospheric model coupled to a simple slab ocean in which the response of climate to an instantaneous doubling of greenhouse gas concentrations was examined, and which showed the largest induced warming to be in the polar regions in winter similar to the results of previous experiments carried out at the Meteorological Office and elsewhere. However, an experiment with a deep ocean model and a (more realistic) 1% per annum increase in greenhouse gas concentrations shows the pattern of global warming to be shifted to give minimum values around Antarctica as a result of deep oceanic mixing processes in the southern ocean, consistent with similar experiments carried out at other centres.

1. INTRODUCTION

Global coupled models of the atmospheric and oceanic general circulation and of the land surface are essential tools for studies of climate and climate change. They have been developed over the past decade or so at a number of modelling centres. The models are based on the physical and dynamical equations of the component systems, with coupling provided via the momentum, heat and freshwater fluxes across the air–sea interface (figure 1) and the heat and freshwater fluxes across the air–land interface. In addition some models include the effects of river runoff from the land to the ocean. The implementation of such models requires the use of major supercomputing resources. When run with the seasonal variation of observed sea surface temperatures and ice extents, their atmospheric components have the ability to simulate many of the features of observed atmospheric climate, including its variability (see, for example, Houghton *et al.* (1990)). However, when run interactively with ocean models, the coupled system experiences a climate drift, producing, in particular, simulations of sea surface temperature and sea-ice extents with marked differences from observed climatology and which, in the current generation of models, is corrected by application of so-called flux corrections (Sausen *et al.* 1988). Such climate drift arises partly because of the relatively low resolution and therefore high viscosity of the ocean models which it is possible to run in coupled mode on the current generation of computers, and partly because of inadequacies in the methods of parametrization and simulation of the surface exchanges themselves. Nevertheless, such coupled models have been shown to reproduce interannual and decadal timescale variability of a magnitude similar to that observed (Manabe *et al.* 1991).

A current major application of such models is the examination of the transient response of climate to the gradual anthropogenic increase in concentrations of atmospheric greenhouse gases, an area of considerable current concern. This represents an important development in studies of climate change which previously concentrated on determination of the equilibrium response of climate to a specified increase in greenhouse gas concentrations, in particular to a doubling of carbon dioxide (CO_2) (e.g. Manabe & Stouffer 1980; Washington & Meehl 1986; Wilson & Mitchell 1987; see also Houghton *et al.* (1990) & Houghton *et al.* (1992) for a summary of current status). The models used for these equilibrium experiments utilized atmospheric general circulation models (GCMs) cou-

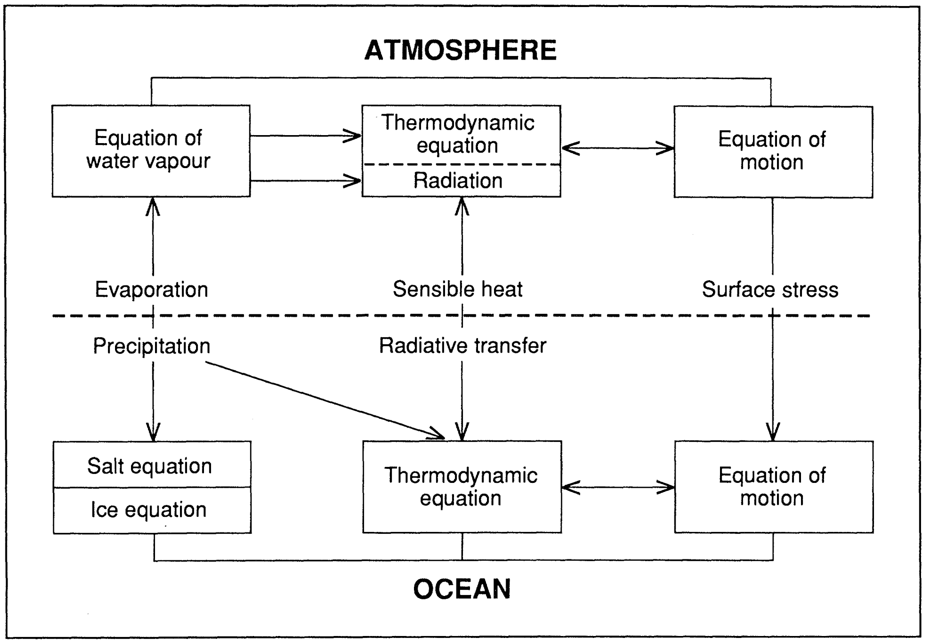

Figure 1. Component equations and coupling of atmosphere and ocean GCMs.

pled to simple 'slab' ocean models in which the ocean is represented by a slab of water some tens of metres deep, with prescribed oceanic heat flux convergence to enable the models to approximate observed sea surface temperature fields but interactive (thermodynamic) ice models. By contrast, full atmosphere–ocean GCMs employ dynamical ocean models which estend to the full depth of the ocean basins and so have the ability to represent the effects of oceanic deep convection and the associated thermohaline circulation.

As yet, confidence in the ability of models to represent regional climate change is rather low (Houghton *et al.* 1990). Caution must therefore be exercised in interpreting the results of such models in specified geographical regions such as that of the Antarctic. However, the ability of coupled models to represent processes previously excluded, related in particular to oceanic processes in the Antarctic region, proves to be important for the patterns of climate change associated with transient greenhouse gas warming. Inclusion of Antarctic processes in climate models is therefore of some importance.

This paper concentrates on the Antarctic response in simulations of greenhouse gas induced climate change from coupled models. In particular it describes the Antarctic response in experiments carried out at the Hadley Centre to examine both the equilibrium response of climate to a doubling of CO_2, for which a high resolution atmosphere–slab-ocean model was used and the response to transiently increasing levels of CO_2 concentrations carried out with an atmosphere–deep-ocean model.

2. EQUILIBRIUM RESPONSE TO CO_2 DOUBLING

Before considering the transient climate response to a gradual increase in CO_2, we first consider the response to an instantaneous doubling of the atmospheric CO_2 concentration. The global response in well known (see, for example, Houghton *et al.* (1990)). Such model sensitivity studies show the surface and lower troposphere to warm and the stratosphere to cool. The equilibrium surface warming shown by the models range between 1.5°C and 4.5°C, partly because of uncertainties in modelling clouds (Mitchell *et al.* 1989). The maximum surface warming occurs over the polar regions in winter. Figure 2 shows the equilibrium warming over the Antarctic from an integration of the Meteorological Office 11 layer atmospheric GCM coupled to a simple slab ocean on a $2.5° \times 3.75°$ grid (Senior & Mitchell 1992). Oceanic heat flux convergence was prescribed and an interactive thermodynamic sea ice model, based on the zero-layer model of Semtner (1976), was used. The atmospheric component of the model was essentially that described by Smith (1990) which includes amongst its physical parametrizations the radiation scheme described by Slingo *et al.* (1989), the explicit cloud liquid water scheme of Smith (1990), the penetrative convection scheme of Gregory & Rowntree (1990) and the gravity wave drag scheme of Palmer *et al.* (1986). The Antarctic performance of earlier versions of the atmospheric model when forced by the observed seasonal cycle of sea surface temperatures and ice extent have been assessed by Mitchell & Senior (1989) and Cattle & Roberts (1988).

As will be seen from figure 2*a*, the surface temperature changes in the region of Antarctica are largest over regions of wintertime sea-ice cover where changes of up to 12°C are found. These reflect the reduced geographical extent (figure 3*a*) and thickness of the sea-ice (figure 3*b*) resulting from the CO_2 warming. The large changes in ice thickness close to the Antarctic coast which persist between summer and winter seasons are associated with excessively thick ice in the control simulation. In the region of the open

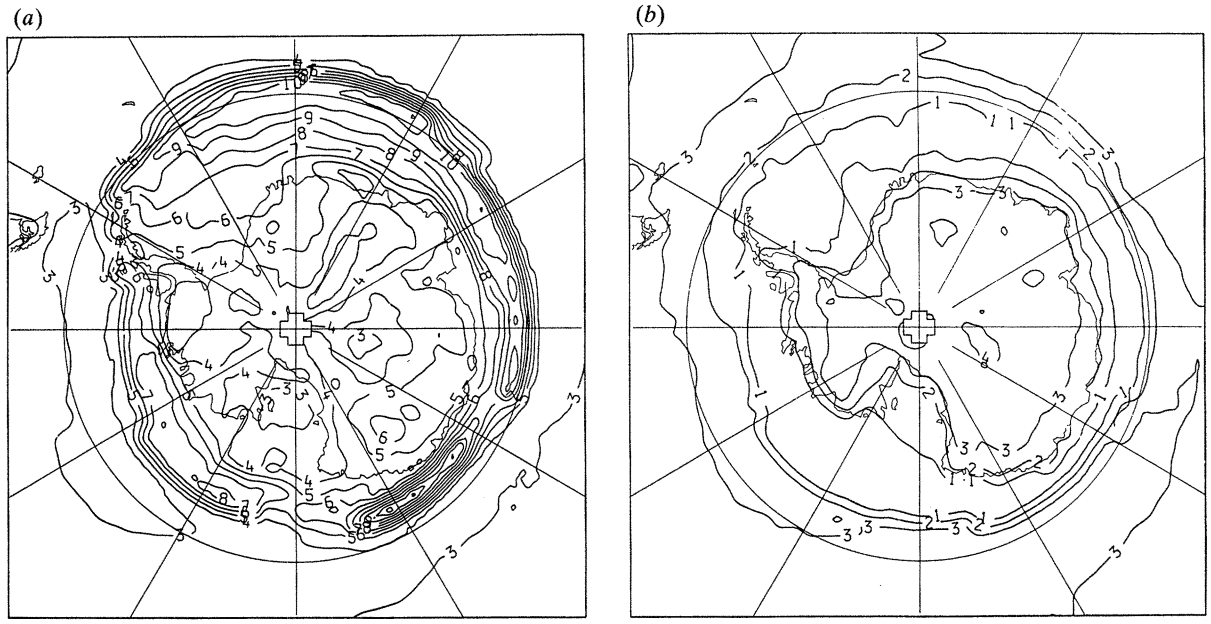

Figure 2. Equilibrium mean surface temperature change over the Antarctic for an instantaneous doubling of atmospheric CO_2 concentrations for (*a*) winter (June–August) and (*b*) summer (December–February) from an experiment using the Meteorological Office 11 layer atmospheric GCM coupled to a simple slab ocean on a 2.5° × 3.75° grid (Senior & Mitchell 1992) Contour interval: 1°C.

pack, where thicknesses of up to 1 m are found in the winter simulation, reductions of ice thickness of up to 0.4 m are seen (figure 3*b*).

Over the Antarctic continent itself, the model shows temperature changes in winter of some 4° to 5°C (figure 2*a*). In summer (figure 2*b*), temperature changes over the region are rather smaller and in particular are a minimum over the regions of summertime sea-ice loss. Over the continent, the surface temperature changes are fairly uniform in summer with values generally around 3°C. A rather larger response over both the Antarctic continent and the wintertime sea-ice zones has been found in similar equilibrium studies with other models of comparable resolution, with local changes of up to 18°C over the sea-ice zone in winter (cf. Houghton *et al.* 1990).

Consistent with the wintertime reduction in sea-ice extents, the Meteorological Office model also shows a general increase in the depth of the Antarctic circumpolar trough of up to just over 3 mb (figure 4).

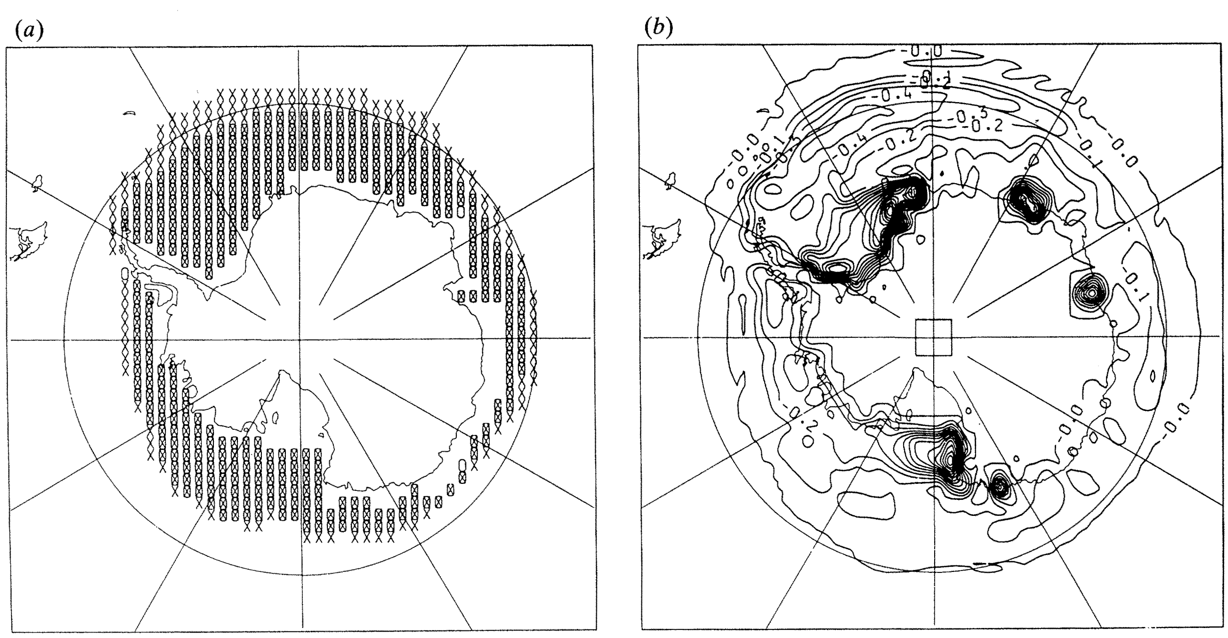

Figure 3. (*a*) Equilibrium wintertime ice cover from control (×) and anomaly (O) integrations and (*b*) changes in ice thickness (contour interval: 0.1 m) for the experiment of figure 2 in which atmospheric CO_2 concentrations were instantaneously doubled.

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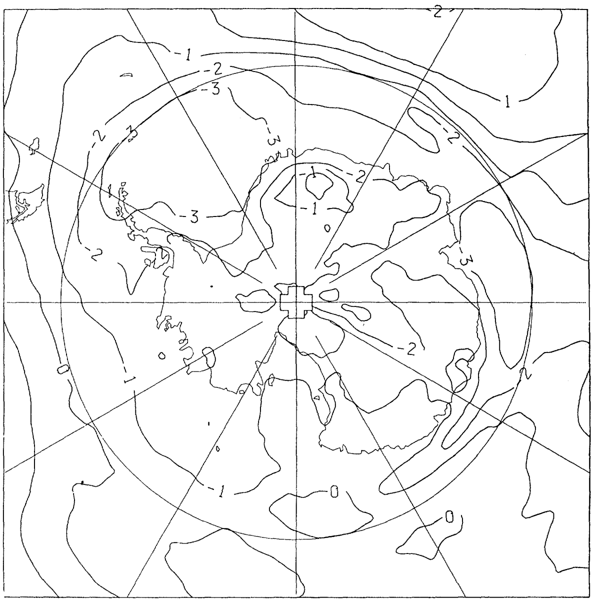

Figure 4. Equilibrium mean change in wintertime (June–August) mean sea level pressure (mb) for the experiment of figure 2.

Mitchell & Senior (1989) investigated the response of an earlier version of this model to a marked reduction in climatological wintertime ice extents. They found significant decreases in surface pressure of up to 8 mb which arose from the combined effect of surface turbulent heating from the oceans in regions of sea-ice loss and the reduction in the surface roughness which occurred when the sea-ice is removed: in the model, the value of the roughness length for sea-ice is taken as 10^{-1} m (the same as for land points) compared to a value of 10^{-4} m over the open ocean. The effect of reducing sea-ice extent is evidently to decrease the size of the low level convergence into the circumpolar trough, which itself is capable of being well simulated in the atmospheric model as Mitchell & Senior (1989) demonstrate. Changes in the mean sea-level pressure field over the region in summer (not shown) are generally smaller, though a decrease of over 3 mb is found to the northeast of the Ross Sea at about 60°S.

Winter precipitation in the control shows values which decrease from around 0.3 mm per day near the coast to 0.05 mm per day over the high continental interior (figure 5*a*). Modelled changes in Antarctic

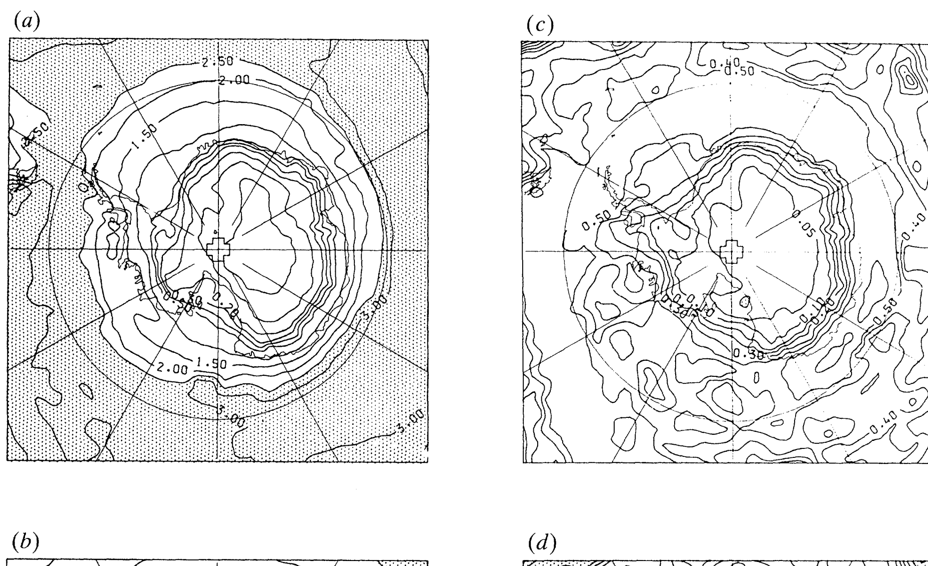

Figure 5. Surface precipitation in the control run for (*a*) winter (June–August) and (*b*) summer (December–February), and equilibrium mean change in surface precipitation (mm per day) due to an instantaneous doubling of CO_2 for the experiment of figure 2, for (*c*) winter and (*d*) summer. Contours in (*a*) and (*b*) are every 0.05 mm per day up to 0.2 mm per day, then every 0.1 up to 0.5 mm per day and every 0.5 mm per day thereafter. Values above 2.5 mm per day are shaded. Contours in (*c*) and (*d*) are every 0.05 mm per day to ± 0.2 mm per day, then every 0.1 up to ± 0.5 mm per day and every 0.5 mm per day thereafter. Negative values are shaded.

precipitation in winter between the anomaly and control (figure 5*c*) show an increase everywhere except over an isolated location on the western side of the Ross ice shelf. The size of the increase shows a marked gradient towards the centre of the continent from the coast similar to the pattern of modelled precipitation in the control to which the values of the changes are comparable. Changes over the Southern Ocean area in the proximity of Antarctica are largest over the sea-ice zones where surface heating is greatest and values of over 0.5 mm per day are found, reaching over 1 mm per day over the ocean area to the west of the Ross Sea. In summer, modelled precipitation in the control run (figure 5*b*) shows a much reduced coastal gradient with values in the centre of the continent of over 0.3 mm per day. Changes in summer are generally below 0.05 mm per day over the continent with some areas of drying around the coastal ocean areas (figure 5*d*). Other models show similar changes, with some areas of local decrease in winter as well as in summer (see, for example, Houghton *et al.* 1990).

3. THE TRANSIENT RESPONSE

(*a*) *Experimental design*

Equilibrium experiments such as that described above provide an upper bound to expected temperature changes at the time of CO_2 doubling. However, recent results from experiments in which CO_2 concentrations are gradually increased at a more or less realistic rate suggest that the equilibrium model runs grossly overestimate the Antarctic response at the time of CO_2 doubling. Consideration of the transient response requires much more realistic ocean models to be employed than is the case with the equilibrium studies, since the delay caused by the thermal inertia of the ocean to the greenhouse gas-induced radiative warming needs to be taken into account. This, in turn, requires that the ocean component of the coupled model to be employed should extend to the full depths of the ocean basins. Integrations employing such models for investigations of the climate response to transiently increasing CO_2 concentrations have been carried out in recent years at the Geophysical Fluid Dynamics Laboratory (GFDL), Princeton (Stouffer *et al.* 1989; Manabe *et al.* 1991, 1992), the Max Planck Institute, Hamburg (MPIH) (Oberhuber *et al.* 1992), the National Centre for Atmospheric Research (NCAR), Boulder (Washington & Meehl 1989) and at the Hadley Centre of the Meteorological Office (Murphy 1992). The transient experiment recently completed at the Hadley Centre employed a 75 year control simulation in which CO_2 concentrations were held fixed at 323 p.p.m. against which to compare an anomaly simulation of the same length in which CO_2 concentrations increased at 1% per year (compound). The same rate of increase was employed for the GFDL experiment. The NCAR experiment was 1% per year (simple). MPIH carried out experiments for IPCC scenarios A and D (see Houghton *et al.* 1990). All used relatively low resolution ocean models with grid scales of the same order as the atmospheric model grids. A particular restriction with the use of such relatively low resolution for the ocean models lies in the high values of viscosity which are necessary to maintain numerical stability and which, in particular, result in relatively sluggish simulation of the oceanic circulation.

The model for the Hadley Centre integrations described here employed the same global $2.5° \times 3.75°$ latitude–longitude grid for both its atmospheric and oceanic components, with 11 unequally spaced layers in the vertical in the atmosphere and 17 in the ocean. The atmospheric model was essentially that employed for the $2 \times CO_2$ experiments described above. The ocean model was derived from that of Cox (1984), and incorporated a mixed layer model formulation following Kraus and Turner (1967), stability-dependent vertical mixing (Pacanowski & Philander 1981) and the isopycnal diffusion scheme of Redi (1982). A thermodynamic sea-ice model following Semtner's zero level formulation (Semtner 1976) was again employed, but incorporated a parametrization of leads following Hibler (1979). The ice mass of the Antarctic continent is treated non-interactively in the model, being represented through the model's surface topography dataset on which the surface albedo is held constant at a value of 0.8. Open ocean albedo takes a value of 0.06, whilst the albedo of sea-ice takes a constant value of 0.8 at ice surface temperatures below $-5°C$, decreasing linearly to 0.5 between $-5°C$ and the melting point.

The control and anomaly experiment was preceded by a spin up phase which involved: (i) a 7 year spin up run of the atmospheric model with climatological sea surface temperatures and sea-ice from which ocean forcing fluxes were extracted for: (ii) a 110 year ocean model spin up run starting from initial conditions (depth dependent temperature and salinity fields) from the Levitus atlas (Levitus 1982). During this run the surface temperature, salinity and sea ice thickness fields (with appropriate adjustments to ocean heat and freshwater–salinity budgets) were relaxed back to climatology; (iii) a 40 year coupled run with initial conditions for the ocean provided by (ii) in which sea surface temperature, salinity and sea-ice were again relaxed back to climatology.

Over the last 10 years of (iii) the relaxation terms were averaged to provide constant flux corrections for the control and anomaly runs which followed. For further details of the flux correction scheme, see Murphy (1992).

(*b*) *Modelled temperature changes*

Figure 6 shows the evolution of the hemispheric mean surface temperature over the northern and southern hemispheres for both control and anomaly simulations. In the northern hemisphere the control simulation shows a general variability of amplitude of about 0.2°C with little or no evidence of climate drift until about year 50 after which there is a warming of a few tenths of a degree. By contrast, however, the control simulation shows, in the southern hemisphere, a significant gradual warming of some 1.5°C, as the

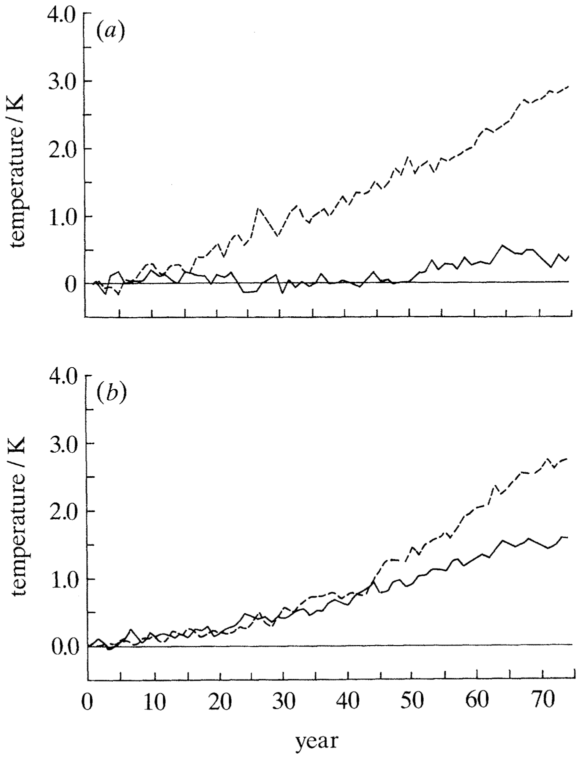

Figure 6. Annual and global mean surface temperature evolution over (*a*) the northern and (*b*) southern hemispheres for a 75 year control integration (solid line) and an anomaly integration in which carbon dioxide concentrations were increased at 1% per year (compound). Results are for the Hadley Centre (Meteorological Office) model. Temperatures in the top panel are relative to 287.1 K and in the bottom panel to 286.5 K.

integration progresses. This was accompanied by a gradual reduction in southern hemisphere sea-ice area so that by the end of the control integration the ice had all but disappeared. This reduces the scope for proper representation of ice albedo feedbacks in the southern hemisphere and considerably reduces confidence in interpreting possible patterns of Antarctic climate change from the experiment. Nevertheless, the results show certain similarities to the published results of the similar integrations at other centres referred to above and in particular to the GFDL experiment which showed no such climate drift and in which the seasonal variation of ice thicknesses and extent were fairly well represented (Manabe *et al.* 1991, 1992).

Note that over the first 20–25 years of the run, little response to the 1% per annum CO_2 increase was found in the mean surface temperatures, a phenomenon which was also found in the MPIH experiments, but which, although it was not seen in the GFDL experiment, is probably, in part, an artifact of the experimental design. Beyond this time the global mean surface warming in the anomaly run was close to linear, averaging 0.3°C per decade and with the land warming faster than the sea. By the end of the integration, the northern hemisphere had warmed by some 2.5°C compared with the control (figure 6*a*). Overall the pattern of the northern hemisphere response (not shown) at the time of CO_2 doubling (70 years) was similar to that found in the $2 \times CO_2$ equilibrium studies, but of smaller magnitude emphasising the effects of the ocean's thermal inertia. This is particularly evident in a minimum of the surface warming over the North Atlantic to the south of Greenland associated with deep convection there.

By the end of the integration, the annual mean CO_2-induced surface warming over the southern hemisphere of the anomaly integration compared to the control was about 1°C (figure 6*b*), notably smaller than for the northern hemisphere. This reflects not only the lower land area of the southern hemisphere but also the lack of warming over the southern hemisphere sea-ice zones in winter (figure 7*a*) and of the southern ocean. This may, in part, be an artifact

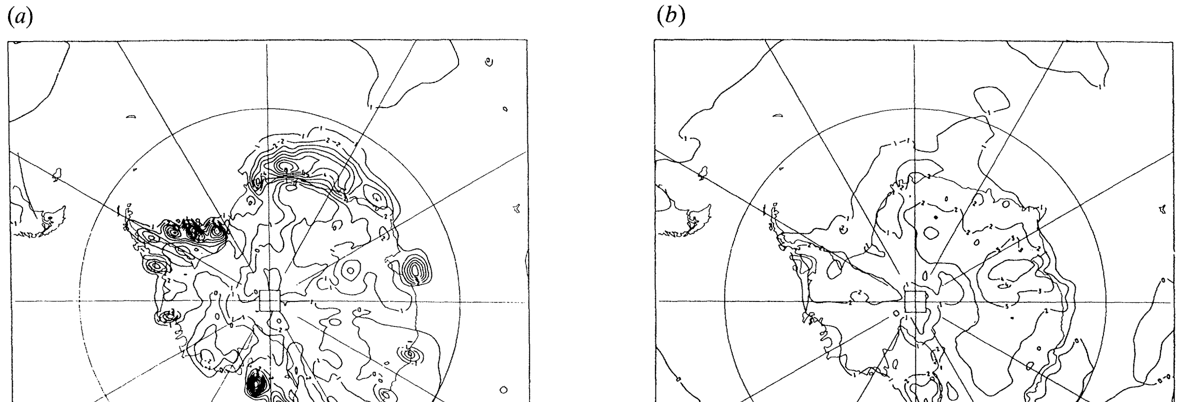

Figure 7. Surface temperature change (anomaly – control) averaged over years 66–75 (centred about the time of CO_2 doubling) of the integration of figure 6. Contour interval: 1°C. (*a*) Ten year mean (June, July, August); (*b*) ten year mean (December, January, February).

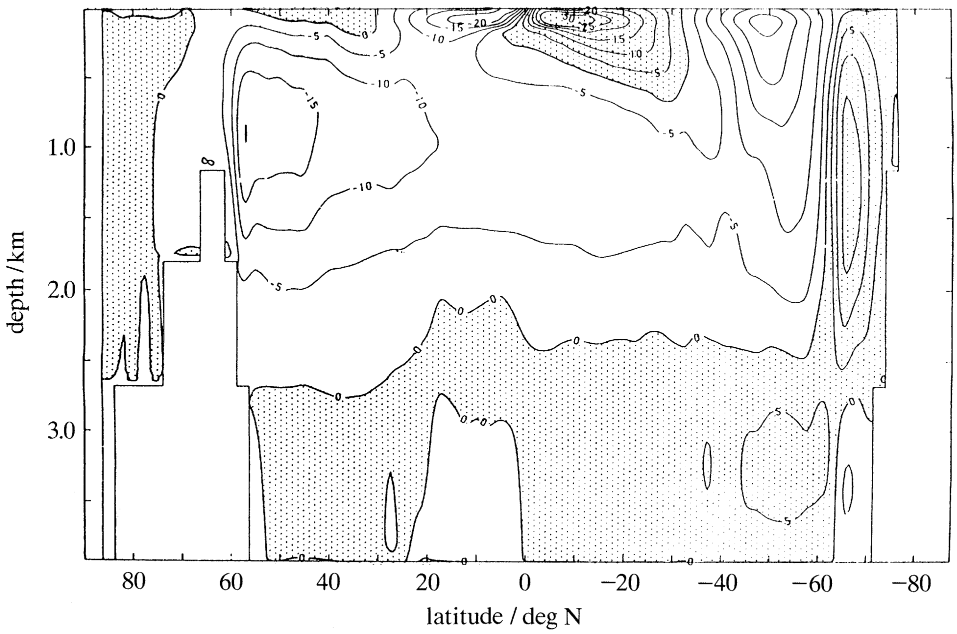

Figure 8. Streamfunction of the zonal mean meridional oceanic circulation averaged over years 66–75 of the control experiment of figure 6. Contour interval: 5 Sverdrups.

of the poor southern hemisphere sea-ice simulation in the control run, and there is indeed a marked warming over those areas of sea-ice which remain in the control simulation in winter, but it is noteworthy that a similar reduced response over the southern hemisphere oceans, including the sea-ice zones in winter, was found by Manabe *et al.* (1992). They attribute this to the presence of a deep indirect wind-driven overturning cell in the latitude range 40° to 60°S which, in company with a direct cell close to the Antarctic coast, leads to upwelling of deep cold water between about 55° to 65°S. Closer to the Antarctic coast, there is deep convective mixing associated with the polewards side of the direct cell. These features are also present in the Hadley Centre experiment (figure 8), although note that in the control run the strength of the direct cell increased from some 5 Sverdrups (Sv) at the start of the run to 15 Sv by its end. Values for the anomaly experiment differed little to those for the control. The role of deep mixing close to the Antarctic coast in taking the CO_2 heating down and of the upwelling associated with the indirect cell in keeping the surface waters of the southern ocean relatively cool is demonstrated by figure 9 which shows a meridional section of zonal mean temperature change at the time of CO_2 doubling.

Turning to the detailed temperature change over the Antarctic at the time of CO_2 doubling (figure 7)

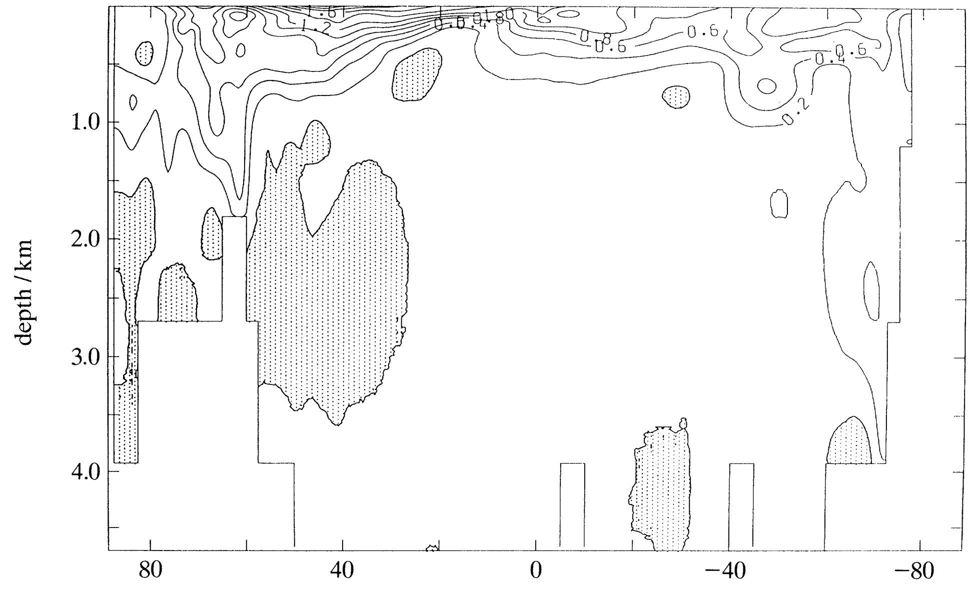

Figure 9. Meridional section of zonal mean temperature change (anomaly – control) averaged over years 66–75 of the experiment of figure 6. Contour interval: 0.2°C.

we see, in figure 7*a*, alternating areas of warming and cooling over the continent in winter in contrast to the $2 \times CO_2$ equilibrium change (figure 2*a*). These results may of course be substantially influenced by the disappearance of ice in the control simulation; the GFDL results (Manabe *et al.* 1992) indicate general warming over the continent of up to over 2°C with the largest values over its eastern side. In summer, figure 7*b* shows warming everywhere over the continent of up to 4°C, with, similar to the GFDL results, the largest area of warming occurring over East Antarctica.

(*c*) *Precipitation changes*

Precipitation changes (not shown) show both regions of increase and decrease over the continent in both summer and winter. This can be compared to the $2 \times CO_2$ equilibrium runs which generally show an increase in precipitation over the continent in winter with coastal drying in summer (figure 5*b*,*d*). In the GFDL run (Manabe *et al.* 1992), increases in precipitation over the Antarctic sea-ice zone in the anomaly experiment lead to freshening and stabilization of the surface water there and increased ice thickness over the Weddell and Ross Seas with little decrease in ice area over all, despite the increase in atmospheric carbon dioxide and in marked contrast to the Arctic response. The poor simulation of Antarctic sea-ice in the present experiment precludes discussion of its response and reduces confidence in the modelled changes in winter precipitation over the region in particular.

4. CONCLUSION

It is evident that the transient runs carried out to date emphasize the interhemispheric asymmetry in the response to transiently increasing concentrations of greenhouse gases with the response over the southern ocean, including the Antarctic sea-ice zones, being relatively small on the timescale of CO_2 doubling. Ocean processes play a key role in reducing the impact of CO_2 warming in these latitudes. The response over the Antarctic continent itself is rather larger, though not as great as is found in CO_2 doubling experiments. These show a general reduction in both sea-ice extent and thickness which contrasts with the results of the GFDL transient runs which show areas of increased thickness and little reduction in sea-ice extent as a result of the stabilising effect of increased precipitation on the upper ocean over the sea-ice zone. It is emphasized that confidence in the regional predictions of global climate models is currently relatively low. A particular restriction in the interpretation of the Hadley Centre runs described above is the poor simulation of sea-ice extents in the control run of the model. Nevertheless, the model results show generally similar characteristics in the Antarctic as well (as in their broader global response) to comparable runs at other centres, although there is evidently considerable room for improvement in the representation of processes relevant to Antarctic climate change.

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Discussion

J. F. Nye (*H. H. Wills Physics Laboratory, University of Bristol, U.K.*). I assume that the results Dr Cattle has shown are not sensitive to the initial conditions. However, we know that the results from some other models are exponentially sensitive to small changes in the starting conditions, for example, models used for weather prediction and, more to the point, some climate models. Can Dr Cattle put his finger on the essential reason why his results are not apparently sensitive in this way?

On the same topic, does he think that the shorter period wiggles shown in his results represent a real effect? Are they perhaps strongly dependent on the initial conditions?

H. Cattle. General circulation models certainly show similar responses to a given change in their forcing even when run from different initial conditions. Note, however, that we are not concerned here so much with an initial value problem (although this must be qualified in respect of the oceans) but with the response of climate to changes in the internal (in this case the greenhouse gas concentrations) or external forcing of the climate system. In the case of the atmosphere, Numerical Weather Prediction (NWP) models are certainly sensitive to the initial conditions, which is why it is important that for weather forecasting we start them from the best observed state that we can. However, after about 10 days or so they 'lose their memory' of these and will, if they are run on, develop a climatology (in a statistical sense) which resembles the observed climatology of the globe and is a product of the response of the models to the nature of the boundary conditions and the internal and external forcing factors placed on the system.

Turning to the short period wiggles, they are certainly characteristic of the sorts of variations we see in the real climate system on the decadal timescale and are considered to be a result of interactions between atmosphere and ocean, although the mechanisms are a matter for continued analysis.

J. E. Harries (*Robert Hooke Institute, Oxford, U.K.*) Can Dr Cattle explain in more detail why the temperature at the southern pole is found to rise with time even in this unperturbed ($1 \times CO_2$) case? Does this sort of variability indicate a certain internal variability in the model?

H. Cattle. As yet it is not clear to us just why the climate drift in the southern hemisphere occurs within the model. It is obviously associated with the gradual reduction in ice extents which expose a larger area of the ocean around Antarctica (particularly in winter) to direct air–sea exchanges and may be the product of an insufficient mutual adjustment of the components of the coupled system at the start of the control run. We would hope to be able to answer this question more definitively at a later stage.

A. S. McLaren (*Science News, Washington D.C., U.S.A.*). Why isn't one of W. B. Hibler's latest multilayer sea-ice models being used instead of Semtner's single-layer model?

H. Cattle. A problem with the use of Hibler's model in GCMs in the past has been computational expense compared with that of other processes represented in the models. However, Hibler himself has produced a simplified version of his model code (the so-called cavitiating fluid model; Hibler & Flato 1992) in response to the needs of GCM modellers and we are currently in the process of incorporating this into our model.

Reference

Hibler, W.D. & Flato, G.F. 1992 Modelling pack ice as a cavitating fluid. *J. phys. Oceanogr.* **22**, 626–651.

P. S. Liss (*School of Environmental Sciences, University of East Anglia, U.K.*). The results from the transient input model indicate an equator to high northern latitude differential warming of about 6°C, whereas the equivalent difference for the southern hemisphere is only 1°C. If this is correct, and it is very much dependent on the validity of the large temporal increase in temperature in the control run for the southern but not the northern hemisphere, then what implications does the result have for differences in the general circulation of the two hemispheres?

H. Cattle. Much of the larger response in the northern hemisphere high latitudes is, of course confined to a fairly shallow layer by the Arctic inversion layer so it is difficult to give a precise answer without looking at the detailed model results. The character-characteristics of the flow in the two hemispheres are, of course different by their very nature, but one implication of differing equator to pole temperature istics of the flow in the two hemispheres are, of course different by their very nature, but one implication of differing equator to pole temperature changes in terms of the dynamics is a different response in the thermal wind (the rate of change of wind with height). Further details of the atmospheric response are available in the paper by Murphy (1992).

J. A. Pyle (*Department of Chemistry, University of Cambridge, U.K.*). I noticed that, in the experiment in which CO_2 increased transiently for the southern hemisphere both it and the control experiment had very similar temperatures for about the first 45 years. Only after this time did the experiment start to show a warming compared with the control. Does Dr Cattle understand this; is it related to the coupled ocean model beneath the atmosphere or to other processes at the surface; does he believe in the result?

H. Cattle. There does seem to have been a more extended period of the 'cold start' in the southern hemisphere compared to the northern. As yet we are not too clear just why this is, but it obviously may be influenced by the climate drift seen in the model in the southern hemisphere. Given this climate drift, one should certainly be cautious in terms of interpreting the southern hemisphere response in the model. What does seem to be the case is that there is a consistent difference in the response between northern and southern hemispheres that is common to all the models run to date and which, since it can be explained in a physically reasonable way, is, in that sense, 'believable', always remembering the limitations of the models themselves.

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