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TRANSIENT RESPONSE TO INCREASING GREENHOUSE GASES USING MODELS WITH AND WITHOUT FLUX ADJUSTMENT

by

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1. Introduction

Until recently, coupled ocean atmosphere models required artificial fluxes of heat and moisture to produce an acceptably accurate and stable simulation of sea surface temperatures, sea ice and thermohaline circulation (eg Kattenberg et al, 1996). The use of these flux adjustments has led to questioning of the credibility of estimates of climate change using such climate models (for example, Lindzen, 1990). On the other hand, the poor simulation of present day climate in models without flux adjustment can clearly lead to errors in the response to perturbations. For example, Gregory and Mitchell (1997) compared the response of two versions of the same model, one with and one without flux adjustments, to a gradual increase in CO_2. The pattern of zonal mean temperature response was similar in the two models but there were some quite marked regional differences. In particular, the unadjusted model had much more sea ice in the north Atlantic than observed (and in the adjusted model). This produced an exaggerated enhancement of the temperature-sea-ice feedback, giving a much larger local warming than in the model with the more realistic climatology. This illustrates the importance of accurately simulating current climate in models that are used for assessing climate change.

In this paper, we extend the work of Gregory and Mitchell (1997) by repeating the climate change experiment with a revised model HadCM3 that gives a much improved simulation of present day climate in the absence of artificial flux adjustments. (Gordon et al, 1998). This has been obtained by a number of improvements to the atmosphere and ocean components (Pope et al, 1998; Gordon et al 1998). We compare the response in the new model HadCM3 with that in the older model HadCM2 with flux adjustments forced with a similar greenhouse gas emissions scenario. In the next section we describe the models and the experiments. In section 3, we compare the global and zonal averaged response in the experiments. In section 4 we compare the geographical distribution of changes in surface temperature, precipitation, soil moisture and mean sea level pressure in the two models. We also, where appropriate, speculate on the reasons for the difference in response in the two models. In view of the numerous changes made from the original model, we have not made a comprehensive assessment of the effect of each individual change in formulation, or the cause of each difference in response.

2. The models and experiments

a Models

The flux adjusted model HadCM2, is described in full by Johns et al, 1997. It uses a horizontal resolution of 2.5 degrees latitude by 3.75 degrees longitude (equivalent to about T42 truncation in a spectral model). There are 19 levels in the atmosphere and 20 levels in the ocean. The atmospheric component includes detailed parametrizations of radiation, cloud, convection, large-scale precipitation, the boundary layer and the land surface. The radiative transfer scheme includes the effect of clouds, water vapour, ozone and carbon dioxide. The ocean component, developed from the formulation of Cox (1984), includes an explicit oceanic mixed layer parametrization, isopycnal diffusion, a simple parametrization of Mediterranean outflow and a sea-ice model which allows for thermodynamic processes and simple free-drift. The equilibrium sensitivity of the model to doubling atmospheric CO_2, estimated from a long coupled simulation of HadCM2 is 3.3K.

The model without flux adjustments, HadCM3, uses the same resolution in the atmosphere as HadCM2. In the atmospheric component, HadAM3, a new radiative transfer scheme includes in addition the radiative effect of aerosols, oxygen and of minor trace gases including methane, nitrous oxide, CFC11, CFC12, HCFC22, HFC134a, HFC125 and CFC113 (Edwards and Slingo,1996). The land surface scheme now includes the freezing and melting of soil moisture, and the effect of carbon dioxide on stomatal resistance to evapotranspiration (Cox et al, 1998). The plant rooting depths have also been increased, reducing the tendency of the soil to dry out in summer in the control climate. The convective parametrization has been extended to include the convection of momentum (Gregory et al, 1997). The cloud prediction scheme has been modified, principally through reducing the critical relative humidity above which cloud is assumed to form. This increases the coverage of water cloud, but reduces the amount of ice cloud. Pope et al (1998) give a more detailed account of the changes in the atmospheric model and the impact on the model simulation.

The major change in the ocean is the increase in horizontal resolution to a 1.25 by 1.25 degree latitude-longitude grid. This allows us to use much lower ocean viscosities, thereby improving the simulation of the detailed ocean circulation, and ocean boundary currents in particular. The deep circulation has been improved by including an explicit parametrization of the flow over the Greenland-Iceland sill. A parametrization of mixing of tracers based on the formulation of Gent and McWilliams (1990), modified as suggested by Visbeck et al (1997) to enhance mixing in regions of strong mesoscale eddy activity, has been added.

The errors in sea surface temperature are less than 2K over most of the ocean (Figure 1a). In an unfluxadjusted version of HadCM2, the errors in sea surface temperature were greater than 2K over most of the ocean (Figure 1b). (Note that no attempt was made to reduce the global mean error in sea surface temperature in the simulation shown in Figure 1b. However, subtracting the global mean error would leave a pattern of differences which are still much larger and more extensive than in the new simulation). The global mean sea surface temperature drifts by less than 0.2K from present day values in the first 400 years of the new simulation. The north Atlantic overturning circulation is maintained with a strength of about 22 Sv, and does not collapse as in many previous unfluxadjusted models (see, for example Gates et al, 1995). A fuller description of the oceanic component and the performance of the coupled model are given by Gordon et al (1998).

The equilibrium sensitivity of the model to doubling atmospheric carbon dioxide, estimated from an early version of HadAM3 coupled to a mixed layer ocean, is about 3.3K (Senior, pers comm), similar to that estimated for HadCM2.

b The experiments.

HadCM2 was forced with increases in atmospheric carbon dioxide which gives the historical increase in radiative forcing from 1860 to 1990, and subsequently with a 1%/year increase in carbon dioxide up to 2100. The forcing approximates closely to the IPCC scenario IS92a (see Mitchell and Gregory, 1992). An ensemble of four experiments was run (see Mitchell et al, 1998). The response in the first member of the ensemble is described in Mitchell and Johns (1997). Here we present results from the ensemble average, denoted as HadCM2.

HadCM3 was forced using the historical increase in the individual greenhouse gases from 1860 to 1990, and then using the individual increases in greenhouse gases in IS95a (Kattenburg et al, 1996) [1]. We have omitted tropospheric ozone change because it is not well mixed and IPCC did not specify a geographical distribution. Our estimates for N_2O and CH_4 changes are slightly lower than those given for IPCC. Only one simulation was made, referred to here as HadCM3.

A parallel pair of experiments in which carbon dioxide is increased at 1%/year (and with no previous historical increases) has also been completed. These will be referred to here as CD2 and CD3.

The forcing in HadCM3 from 1990 to 2100 is less than the IPCC estimate of Kattenberg et al (1996). The IPCC estimate assumes a forcing of 4.39 Wm^{-2} on doubling CO_2, whereas the model produces 3.74Wm^{-2}, taking into account stratospheric adjustment and solar absorption (W. Ingram, pers comm, see Table 1). The change in radiative flux at the tropopause due to doubling CO_2 obtained with the model's radiation scheme is in good agreement with line-by-line calculations for idealised atmospheres (Cusack et al, 1998). It appears that the IPCC estimate neglects the effect of stratospheric adjustment discussed by Schneider (1972). Recently, Myre et al (1998) have estimated the net forcing due to doubling CO_2 to be 3.71 Wm^{-2}, in good agreement with the current model. The total forcing is 20% less than the IPCC estimate, or 10% less if one corrects the IPCC CO_2 forcing, with half the remaining discrepancy due to neglecting changes in ozone.

Table 1 Contributions to radiative forcing , 1990-2100

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[1] The forcing in HadCM2 experiment is relative to 1765, giving a forcing of 0.3Wm^{-2} at 1860. The forcing in HadCM3 control is effectively closer to that at 1866. The concentration of carbon dioxide in the control was specified at its 1877 value, that of methane at its 1779 value and N_2O at its 1904 value. This gives 0.03 Wm^{-2} MORE than the 1860 value, so the HadCM3 greenhouse gas experiment starts in 1860 with a COOLING of 0.03 Wm^{-2} compared with its control when the historical concentrations are used. This partly compensates for the "cold start" due to ignoring pre 1860 forcing.

	HadCM3	IPCC, 1995	Difference
Carbon dioxide	3.8	4.4	0.6
CH_4, N_2O	0.7	1.0	0.3
(H)CFCs	0.05	0.04	0.0
Trop O_3	0.0	0.3	0.3
Total	4.5	5.8	1.2

The estimated radiative forcing seen by the models is slightly greater in HadCM2 than HadCM3 (Figure 2). The gradually increasing difference in the future arises because a 1% /year increase in carbon dioxide gives a faster rate of change than IS95a.

3 Global and zonally averaged results.

a Global means

The rate of global mean warming in the two experiments is almost identical (Figure 3a, which shows the warming relative to the 1880-1920 mean). Note also the stability of the global mean temperature in the control simulation of HadCM3. The warming at 2100 is about 5% smaller in HadCM3, which is reasonably consistent with the smaller forcing (Figure 2). A comparison of CD2 and CD3 indicates that in HadCM3 the mixing of the warming is less deep than in HadCM2 (J Gregory, pers comm) which would, all other things being equal, give a greater warming in HadCM3. This compensates for the greater forcing used in HadCM2. When the global mean changes over land and sea are considered separately (Figure 3b), the similarity in response is again evident.

The global mean sea level rise due to thermal expansion is smaller in HadCM3 than HadCM2 (Figure 4). By 2100, the change in HadCM3 is about 29 cm, about 10% less than in HadCM2.

b Zonal means

In the rest of this paper, we consider differences between the anomaly simulations, averaged over years 2070 to 2100, and the respective control simulations (averaged over 130 years in HadCM2 and 100 years in HadCM3).

In both models, there is a maximum warming in northern high latitudes, a minimum warming near 60S and a secondary maximum warming over Antarctica, similar to many other studies with or without flux adjustment (eg see Kattenberg et al, 1996). The warming in HadCM2 is greater in the Tropics than in HadCM3 and slightly smaller in mid-latitudes (Figure 5a). The differences are particularly pronounced over the tropical oceans where the zonally averaged warming is almost 1K greater in HadCM2 than in HadCM3 (Figure 5c). This is sufficient to give a secondary maximum in warming in the Tropics in HadCM2, whereas in HadCM3 there is merely an increase in the south-to-north temperature gradient across the Tropics. The contrast between models is less clear over land, though the warming is substantially greater in HadCM2 in the northern Tropics.

There are some similarities in the broad scale patterns of changes in precipitation, with increases in high latitudes, decreases in parts of the subtropics and increases over the tropical oceans (Figure 6). However, there are differences in the details of the changes in precipitation. In HadCM3, the tropical precipitation increases north of the equator, and decreases to the south. This corresponds to a northward shift of the ITCZ, consistent with the increased south-to-north temperature gradient which shifts the area of maximum surface temperatures northwards. In HadCM2, there is a local increase in tropical precipitation above the maximum in warming in the Tropics and a decrease in the surrounding zones (Figure 6a). This is more like an enhancement of the ITCZ, consistent with the local enhancement of surface temperature under the ITCZ, rather than a simple northward shift.

Why do the tropical oceans warm so much more in HadCM2? The mixed layer depths are shallower in HadCM3 than in HadCM2 (Figure 7). Thus it is unlikely that the difference arises due to the warming being spread over a shallower layer in HadCM2 than in HadCM3. However, the cloud feedback is more positive in the Tropics in HadCM2 (Figure 8) suggesting that this is the main reason for the greater tropical warming in HadCM2.

The longwave cloud feedback is more positive in HadCM2 at most low latitudes (Figure 8b). High cloud moves up when greenhouse gases are increased producing a reduction in the longwave cooling to space and hence a warming of the surface (see, for example, Senior and Mitchell 1993, Senior, 1998). There are greater high cloud amounts in HadCM2s control simulation, so this effect is larger. (It is also possible that there are larger increases in longwave emissivity in HadCM2 which would have a similar effect). The shortwave feedback is more negative in HadCM2 in lower mid-latitudes. In both models, low cloud amounts are reduced (a positive feedback) and cloud water paths increase (a negative feedback). There are smaller low cloud amounts in the HadCM2 control, and hence less cloud to reduce, giving a weaker positive feedback (Figure 8a). Hence the warming in HadCM2 is smaller in mid-latitudes than in HadCM3. In higher latitudes, low cloud increases in both models (a negative feedback). There is more low cloud in the HadCM2 control to increase giving a stronger negative feedback.

In summary, it appears that the appearance of a local maximum in warming in the Tropics in HadCM2 but not in HadCM3 is a result of a stronger positive cloud feedback in the tropics and weaker feedback in mid-latitudes. A comparison of equilibrium 2x CO_2 experiments run with HadAM2b (an atmosphere-only model using the same cloud parametrization as HadCM2) and HadAM3 each coupled to a mixed layer ocean model, shows a qualitatively similar but smaller difference in zonally averaged temperature response. This indicates that the difference in response is at least in part due to changes in cloud parametrization.

The vertical distribution of the zonally averaged atmospheric warming in HadCM3 shows the expected features- enhanced warming in the upper tropical troposphere, in the lower troposphere in the Arctic and to a lesser extent in the Antarctic, a minimum low level warming over the southern ocean, and stratospheric cooling (Figure 9a). The main differences in HadCM3 compared to HadCM2 (Figure 10a) include smaller tropospheric warming in the Tropics and larger warming in mid-latitudes following the differences at the surface. There is greater vertical penetration of the warming into the stratosphere (Figure 9a). In HadCM3, some of the increase in CO_2 in HadCM2 has been replaced by increases in the other trace gases that cool the stratosphere less strongly (Ramanathan et al, 1985).

The zonally averaged temperature changes in the ocean vary considerably with longitude (Figure 9b). The warming is confined to a shallow layer in the Tropics due to upwelling cold water from deeper layers that have not been in contact with the surface warming. The warming penetrates deeper in the subtropics due to downwelling in the subtropical gyres. The deepest penetration of the warming occurs around 60N in the north Atlantic where convection leads to localized sinking to several thousand metres in winter. The warming also extends to the ocean bottom in high southern latitudes, although the magnitude of the warming here is much smaller. The downward penetration of the southern hemisphere mixing is smaller than in HadCM2 (Figure 10b). This is likely to be due to the differences in simulation of oceanic mixing, including smaller diffusion coefficients and the use of the Gent and McWilliams (1990) parametrization. The warming extends further downwards near 60N (Figure 9b) than in HadCM2 (Figure 10b), possibly as a result of the changes tobottom topography. Recall also that HadCM2 has no parametrization of flow over the Greenland- Iceland sill, and uses a much higher lateral diffusion.

4 Geographical distribution of the changes

The main emphasis in this section is in changes over land since these are of principal interest to those studying impacts. The approach is mainly "show and tell" although we also speculate on the reason for some of the more pronounced differences in response in the two models.

a. Annual mean

The pattern of surface warming in HadCM3 shows the usual broad-scale features found in experiments with a gradual increase in greenhouse gases- maximum warming in the Arctic, greater warming over the land than the sea, a minimum warming over the Southern Ocean and the northern North Atlantic (Figure 11a). The main differences from HadCM2 (Figure 11b) include the smaller warming in the Tropics and greater warming in mid-latitudes. Other regional differences include the changes over tropical South America. This warms more in HadCM3, associated with a greater drying of the surface and the increase in stomatal resistance with higher levels of CO2, a mechanism not included in HadCM2 (see later). The extratropical North Atlantic warms less in HadCM3.

There are increases in precipitation in the extratropics, especially poleward of 45 degrees latitude, and larger local increases in the Tropics (Figure 12a). There are decreases over much of the subtropics, and more marked areas of decrease in the

Tropics, especially south of equator. As noted in the previous section, precipitation increases less than in HadCM2 in the ITCZ, and increases more in the subtropics, especially over India (Figure 12b). Elsewhere differences are small in absolute terms, with slightly smaller increases/larger decreases in HadCM3 over the northern continents from 30 to 50 degrees N.

b Seasonal means

i December to February

The temperature change in HadCM3 is similar to the annual mean change (Figure 10a), but with greater warming in the Arctic and a smaller warming around the periphery of Antarctica (Figure 13). The warming over the Southern Hemisphere tropical land masses is smaller, associated with increases in precipitation discussed below. The differences with the response in HadCM2 are similar to that in the annual mean (Figure 11c), but with a much smaller warming than in HadCM2 in the Arctic and eastern Canada. There is also enhanced warming in Hudson's Bay and in the Barents Sea, associated with the more extensive sea-ice in the HadCM3 control simulation.

Sea level pressure reduces in the Arctic and around Antarctica, and increases around 45S in common with the response in HadCM2 (Figure 14). However, in HadCM3 there is a marked increase in surface pressure over the Atlantic and east Pacific in northern mid-latitudes (Figure 14a). This contrasts with the reductions found in HadCM2, and reverses the anomalous southeasterly flow to northwesterly flow over the British Isles and Western Europe (Figure 14b).

The broad pattern of increased precipitation in the northern extratropics, southern high latitudes and along parts of the ITCZ is repeated in both models (for example, Figure 15a). The largest changes in the Tropics are over the oceans, and the tropical pattern is generally shifted north in HadCM3. There are more extensive decreases in tropical South America and southwest Africa in HadCM3 although southeastern Africa becomes wetter (Figure 15b). The changes in flow in mid latitudes are probably responsible for the change from increases in HadCM2 to decreases in HadCM3 over California and southwestern Europe.

We also compare the changes in soil moisture in the two models. Note that there are quite large differences in the treatment of soil moisture in the two models- HadCM3 has considerably larger rooting depths allowing greater water storage in the soil, and hence capacity for larger changes. We show changes in available soil moisture in HadCM3 which excludes the frozen ground moisture; in effect this is included in the quantity diagnosed in HadCM2. These differences in formulation must be kept in mind when comparing the difference maps.

In HadCM3, soil moisture increases in most regions north of 35N and over southeast Asia and equatorial and eastern Africa (Figure 16a). There is a marked drying over tropical South America and southwestern Africa. In HadCM2, there are decreases rather than increases over western Europe, and increases are greater in central Asia, despite smaller increases in precipitation (Figure 16b). Over western Europe, the larger increase in soil moisture is due in part to the increase in stomatal resistance due to increased CO_2, neglected in HadCM2. In high latitudes, the addition of the effects of freezing and melting soil moisture also tends to give a greater increase in available moisture (Cox et al, 1998). The drying over tropical South America is more moderate, and southeastern Africa becomes drier rather than wetter, again reflecting the different response in precipitation. Part of the reduced drying over South America can be attributed to the effect of increased CO_2 on stomatal resistance

ii June to August

The warming in HadCM3 is enhanced relative to the annual mean in the northern subtropics, associated with a drying of the surface, and around Antarctica, and is reduced in the Arctic and the surrounding regions (Figure 17a). The differences with the response in HadCM2 are similar to those in the annual mean, including the enhanced warming in HadCM3 over North America, Europe and eastern Asia and the reduced warming over Africa and India (Figure 17b).

Sea level pressure reduces mainly over the land-masses, probably as a result of the increased land-sea temperature contrast, and over and around Antarctica (Figure 18a). The reductions over land are generally less in HadCM2 (Figure 18b), and there are rises in pressure over the Indian Ocean extending into western India and over much of North America not found in HadCM3. There are increases around 45S in both models, except south of Australia in HadCM2.

The changes in precipitation are similar to other models including increases in high northern latitudes, reductions in central North America and around the Mediterranean, and increases in southeast Asia and much of equatorial Africa (Figure 19a). The increases in Southeast Asia and the decreases in northern mid-latitudes are more pronounced than in HadCM2 (Figure 19b). This is consistent with the greater increase in land sea contrast in HadCM3 and consequently greater lowering of pressure over the continents (see Mitchell and Johns, 1997). East Africa becomes wetter in HadCM3 rather than drier, but the drying over the north of South America is more pronounced.

In HadCM3, soil moisture increases over the northern continents in high latitudes (Figure 20a, gray shading), associated with the melting of frozen soil water in the warmer climate. There are substantial decreases in mid latitudes immediately to the south (Figure 20a, black shading). There is also a marked drying over northern South America. Most of the remaining land surface becomes marginally drier, apart from eastern Africa and parts of South America. The main differences with HadCM2 include larger increases over northern high latitudes, due to including the effects of frozen soil moisture, and stronger drying in mid latitudes (Figure 20b). Over Europe and North America, the amplitude of the annual cycle of changes (from moistening in winter to drying or little change in summer) is more pronounced. Over Southeast Asia, tropical Africa and South America, there are increases in HadCM3 where there are smaller increases, or decreases, in HadCM2 probably because of reduced evaporation in HadCM3 due to the effect of increased CO_2 on stomatal resistance.

5 Summary and conclusions.

The new model provides a stable simulation of present day climate without recourse to flux adjustments or the need for a sophisticated initialisation procedure. The errors in sea surface temperature are generally less than 2K, and the oceanic thermohaline circulation does not collapse.

The new model HadCM3 was forced with the historical increase in forcing from 1860 to 1990 and the IS95a forcing scenario thereafter. The results were compared with an ensemble of similar experiments carried out with an older flux adjusted model HadCM2 in which future CO_2 levels were increased by 1%/year. The following similarities and differences were noted.

- The global mean warming over time is similar in both models even though the forcing in the HadCM3 is slightly smaller.
- The sea level rise from 1860 to 2100 due to thermal expansion is some 8% smaller in HadCM3.
- The zonally averaged warming in HadCM2 reached a secondary maximum in the Tropics, whereas this feature is absent in the HadCM3. This is due in part to a weaker net cloud feedback in HadCM3, which can be related to there being less high cloud in its control simulation, giving a smaller warming in the Tropics. Other more subtle differences in the control cloud simulation lead to a larger warming in mid latitudes in the new model.
- The peak in zonally averaged precipitation in HadCM3 is shifted northwards, whereas in HadCM2 it tends to amplify over the local maximum increase in sea surface temperatures.
- The tropospheric warming extends slightly higher in HadCM3 due to the explicit representation of individual trace gases rather than a CO_2 equivalent.
- In HadCM3, the warming penetrates deeper in the Atlantic and less deep in the southern ocean, due in part to the changes in the parametrization of oceanic mixing processes.
- In HadCM3, the warming over the northern continents in summer is greater. This is associated with greater reductions in soil moisture which are largely due to the inclusion of changes of phase in the soil moisture parametrization. The enhancement in Indian summer monsoon rainfall is also greater in the new model.
- Most of the land surface in the Tropics dries less/ moistens more in HadCM3 due in part to the addition of the effect of increased CO_2 reducing transpiration.
- In HadCM3, sea level pressure increases over much of the mid-latitude north Atlantic and Pacific oceans in winter whereas it decreases in the older model.
- The increase in available soil moisture over north America and western Europe is greater in the new model. This is partly due to increased westerly flow and precipitation, and partly due to the inclusion of the effects of melting and freezing of soil moisture in the land surface parametrization.

In addition, the thermohaline circulation weakens. This is under further investigation and will be discussed in a separate paper.

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Figure Captions

Figure 1. Decadal mean differences between the simulated sea surface temperatures and observations from GISST for 1961-1990 (Rayner et al, 1996)

(a) after 250 years of the control simulation.

(b) For years 90 to 110 of the HadCM2 control.

Contours every 2K.

Figure 2. Global annual mean forcing (Wm-2) in HadCM2 (red curve) and HadCM3 (green curve) relative to the 1880-1920 average.

Figure 3. Global annual mean 1.5m temperature response relative to the 1880-1920 average.

a) Averaged over all points in HadCM2 (red or dashed curve) and HadCM3 (green or solid curve)

The blue curve shows the deviation of the global mean sea surface temperature in the control from observations from GISST (Rayner et al., 1996) which are averaged over 1961-1990 .

b) Averaged over land (HadCM2, red and HadCM3, blue) and sea (HadCM2, orange and HadCM3, green)

Figure 4 Global mean changes in sea level due to thermal expansion (m) in HadCM2 (dashed curve) and HadCM3 (solid curve) relative to the 1880-1920 average.

Figure 5. Zonal annual mean temperature changes averaged over 2071-2100 (K), relative to the control run. Dashed line, HadCM2. Solid line, HadCM3

a) All points

b) Land only

c) Ocean only

Figure 6. As Figure 5, but for total precipitation (mm/day). Dashed line is HadCM2, solid line is HadCM3.

Figure 7. Annually and zonally averaged mixed layer depth(m) from the control simulations. Black line is HadCM2, red line is HadCM3.

Figure 8. Changes in cloud forcing (Wm-2) averaged over 2071-2100.
Dashed line, HadCM2, Solid line, HadCM3

a) Shortwave

b) Longwave

c) Net

Figure 9 Zonally averaged temperature changes (K) in HadCM3.

a) in the atmosphere differenced between the 2069-2099 average in the anomaly simulation and 100 years of the control. Positive contours every 1K, and a contour at –2K.

b) in the ocean, differenced with years 2069-2099 of the control simulation. Contours every 0.5K between –0.5K and 2.0K.

Figure 10. As for Figure 9 but for HadCM2 for the period 2070-2100. In (a), 130 years of data from the control simulation are used.

Figure 11. Changes in annual mean 1.5m temperature, 2071-2100. Contours every 1K. Differences are from the 100 year control in HadCM3 and the 130 year control in HadCM2.

a) HadCM3
b)HadCM2
c)HadCM3-HadCM2

Figure 12. Change in annual mean precipitation, 2071-2100. Contours every 1mm/day.

a) HadCM3
b) HadCM3-HadCM2.

Figure 13. Changes in December to February mean 1.5m temperature. Contours every 1K.

a) HadCM3
b) HadCM3-HadCM2

Figure 14. Changes in sea level pressure (hPa) averaged over December to February. Contours at 0,+_1,2,3,4,6,8,10 hPa with regions of decrease shaded. The figures have been adjusted to allow for loss of mass in each model at the rate of about 0.2 hPa /century.

a) HadCM3
b) HadCM2

Figure 15. As Figure 13 but for precipitation. Contours every 1mm/day between –5 and +5 mm/day.

Figure 16. As Figure 13 but for soil moisture. Contours at 0 and +/- 5, 10 and 30mm water equivalent.

Figure 17. As Figure 13, but averaged over June to August.

Figure 18. As Figure 14, but averaged over June to August.

Figure 19. As Figure 15, but averaged over June to August.

Figure 20. As Figure 16, but averaged over June to August.

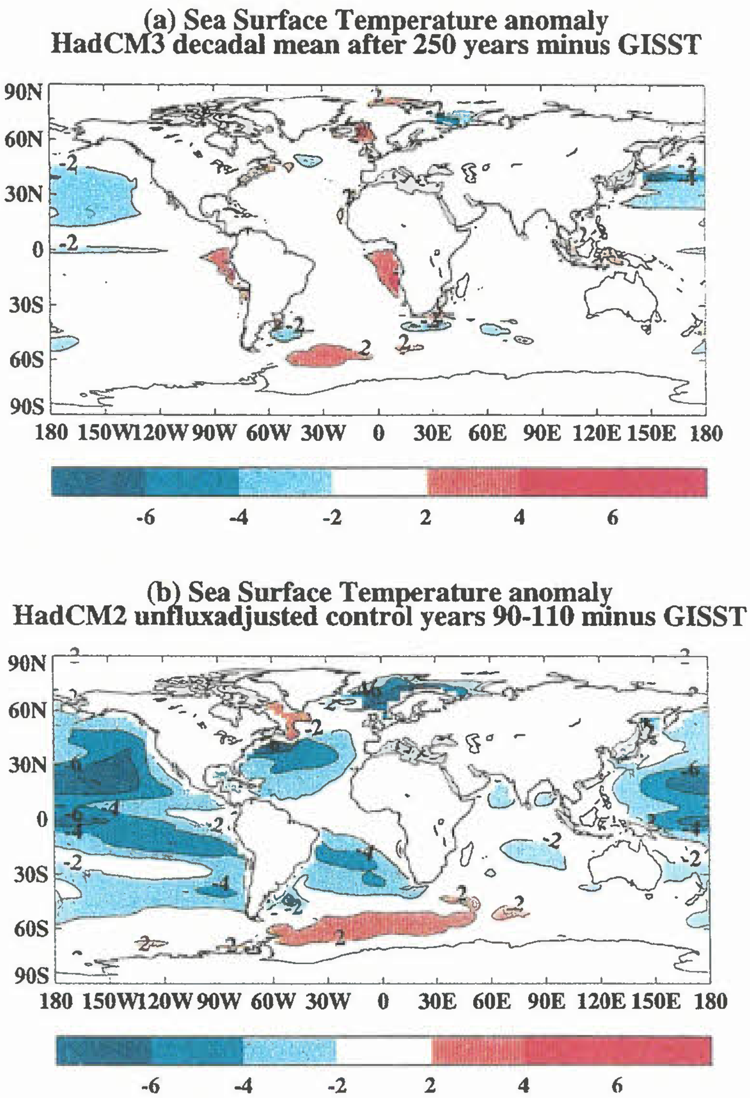

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Figure 1

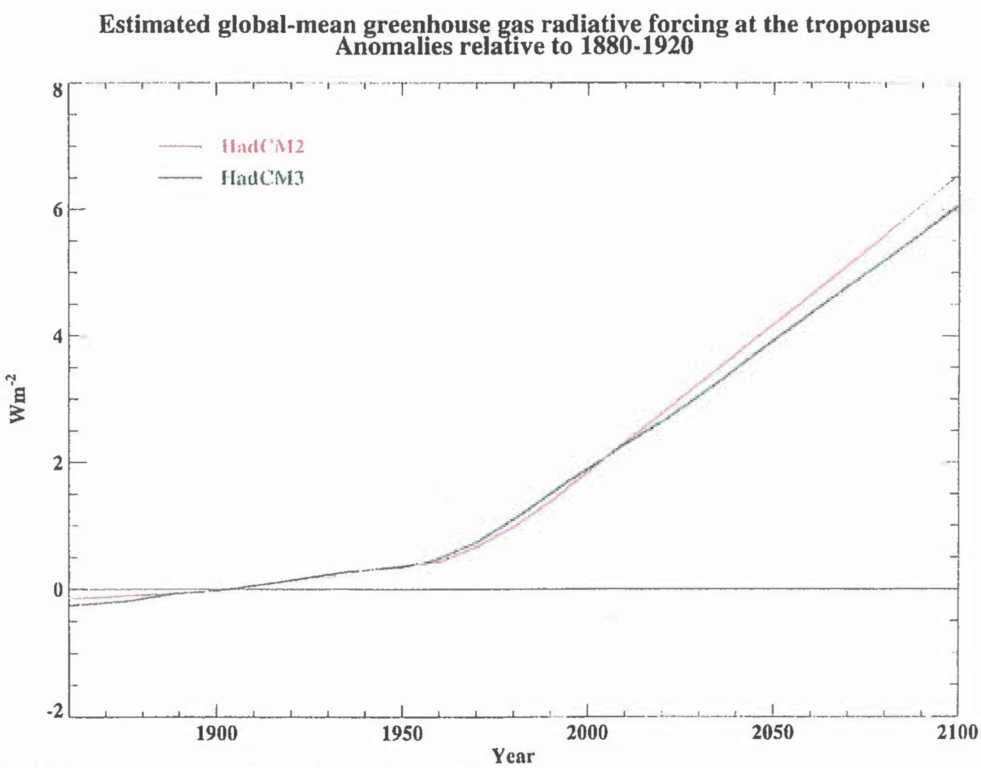

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Figure 2

Global mean temperature response in HadCM2 and HadCM3
Anomalies relative to 1880 to 1920

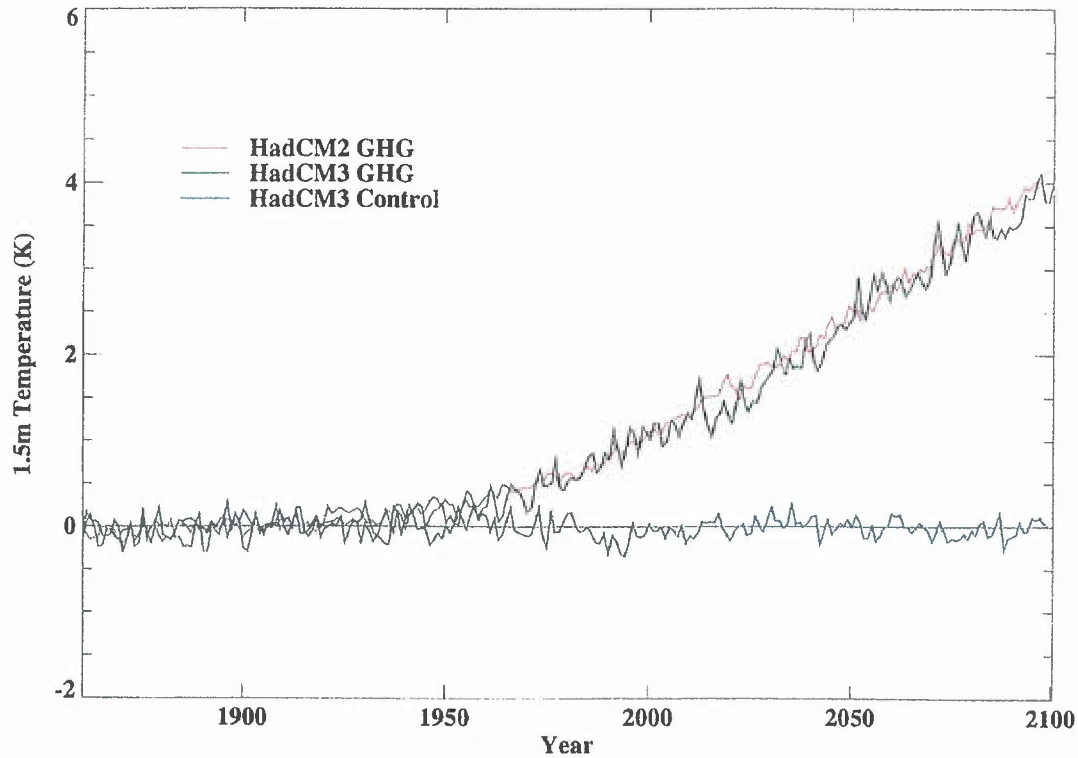

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Figure 3a

Land/Sea temperature response in HadCM2 and HadCM3
Anomalies relative to 1880 to 1920

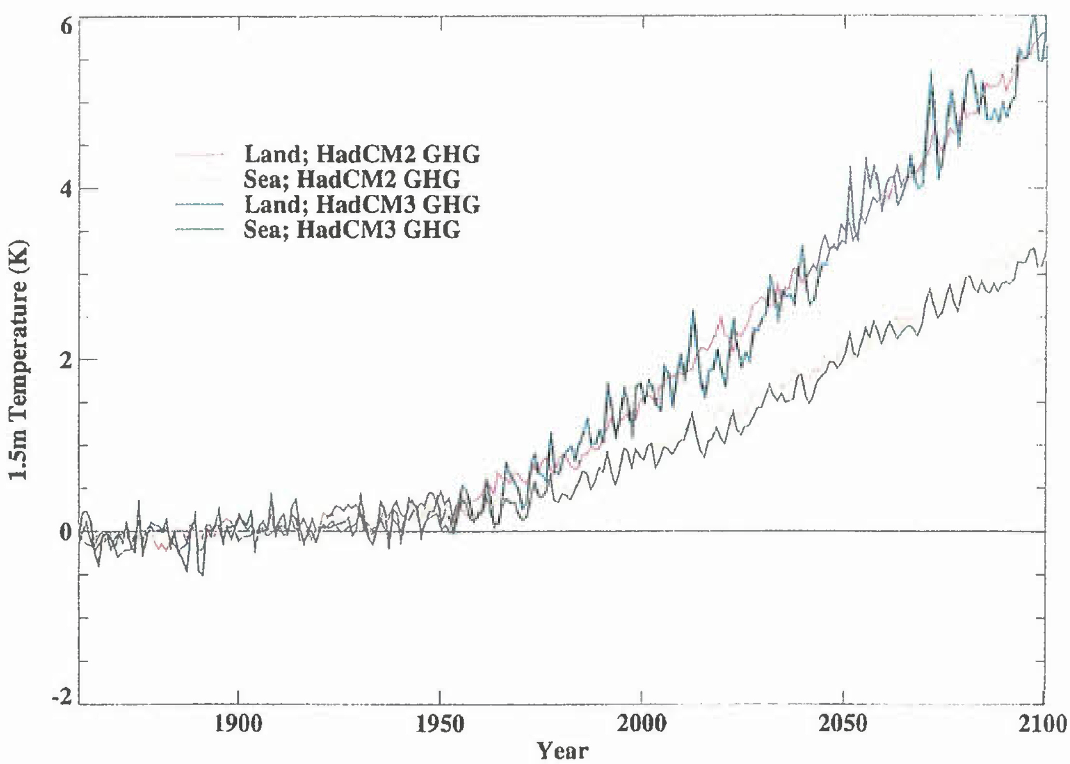

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Figure 3b

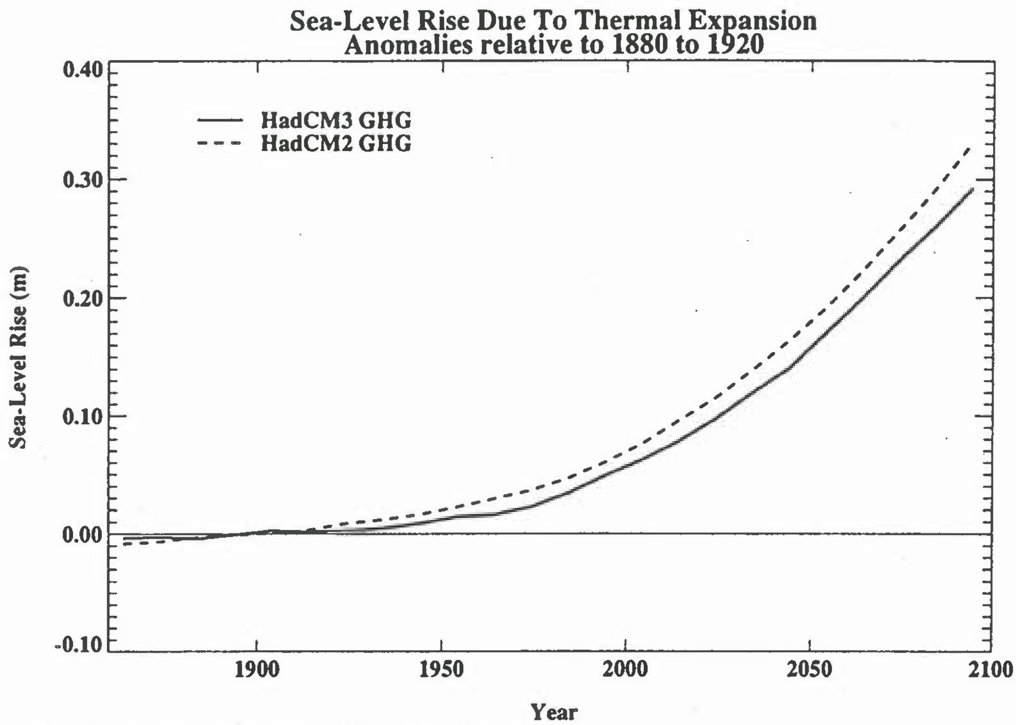

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Figure 4

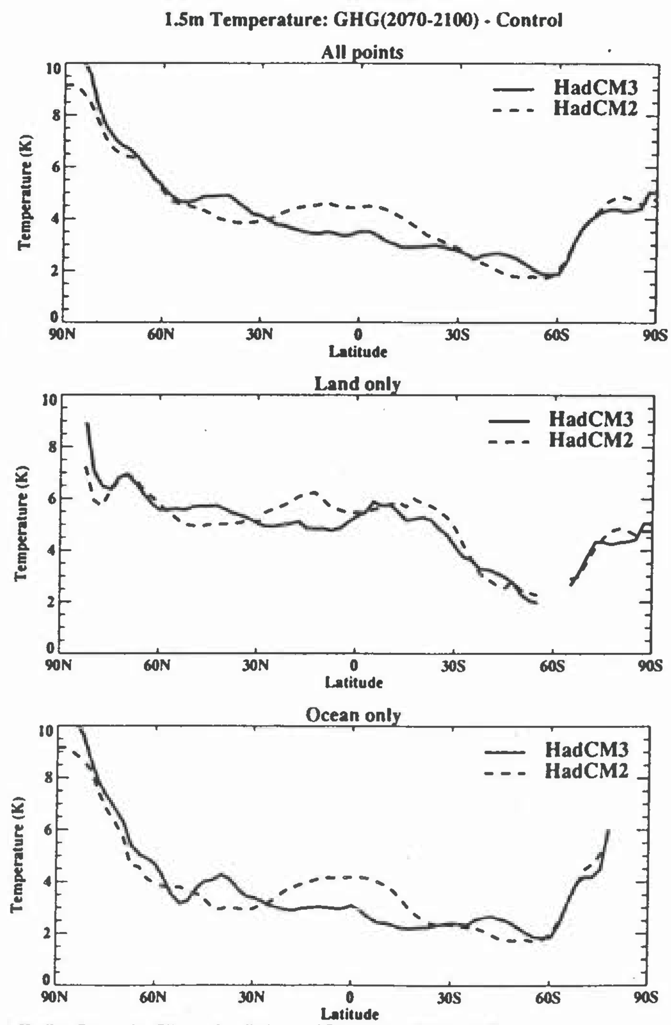

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Figure 5

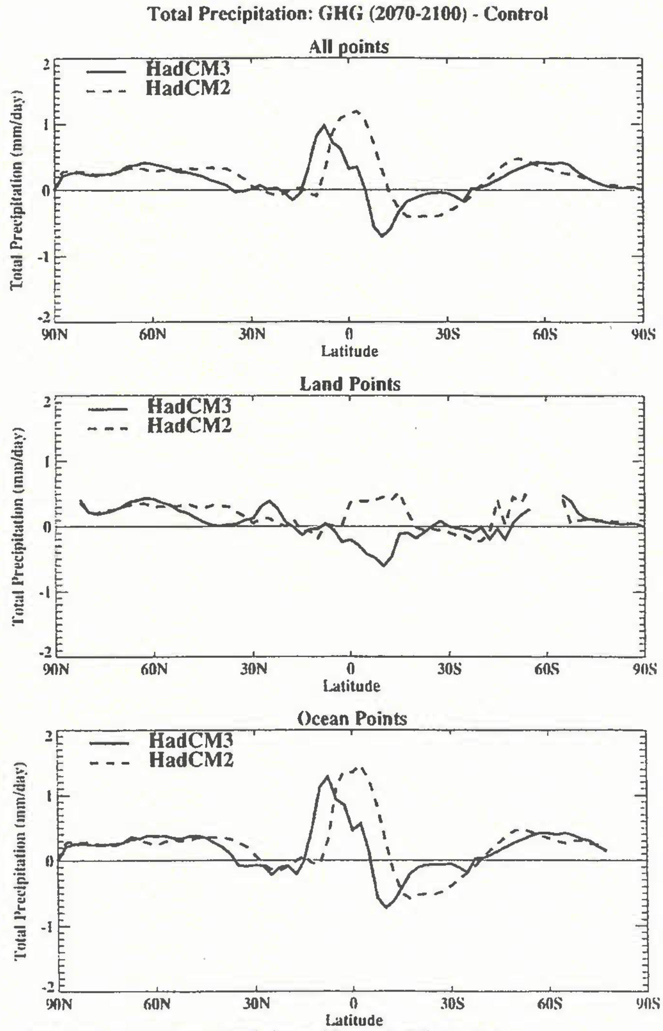

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Figure 6

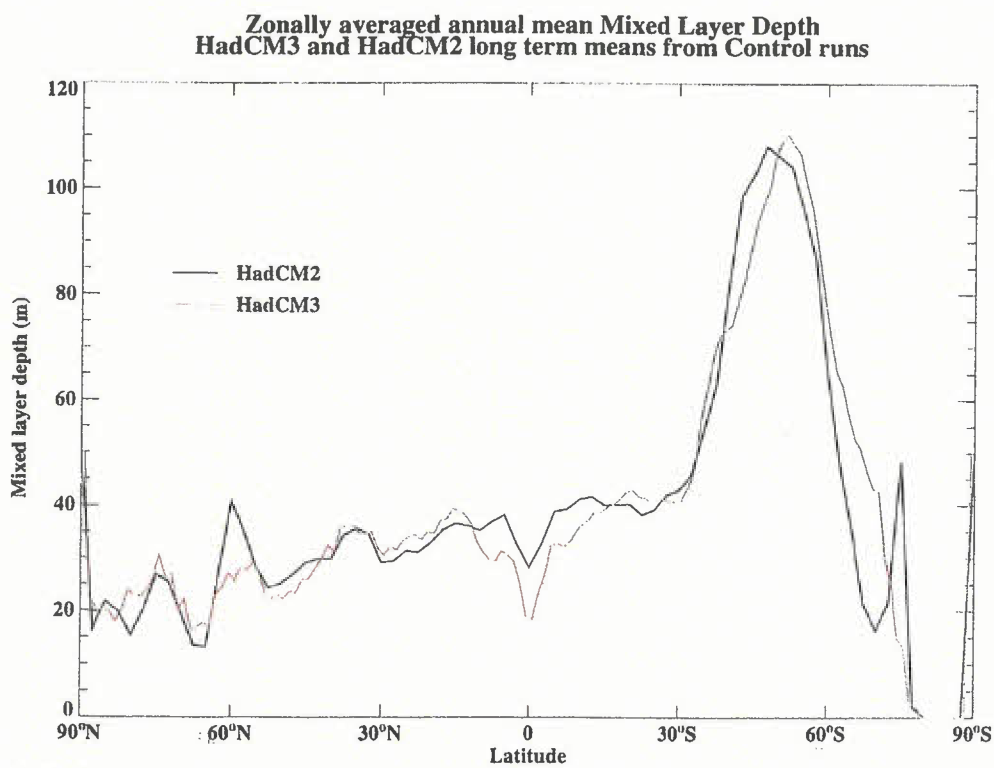

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Figure 7

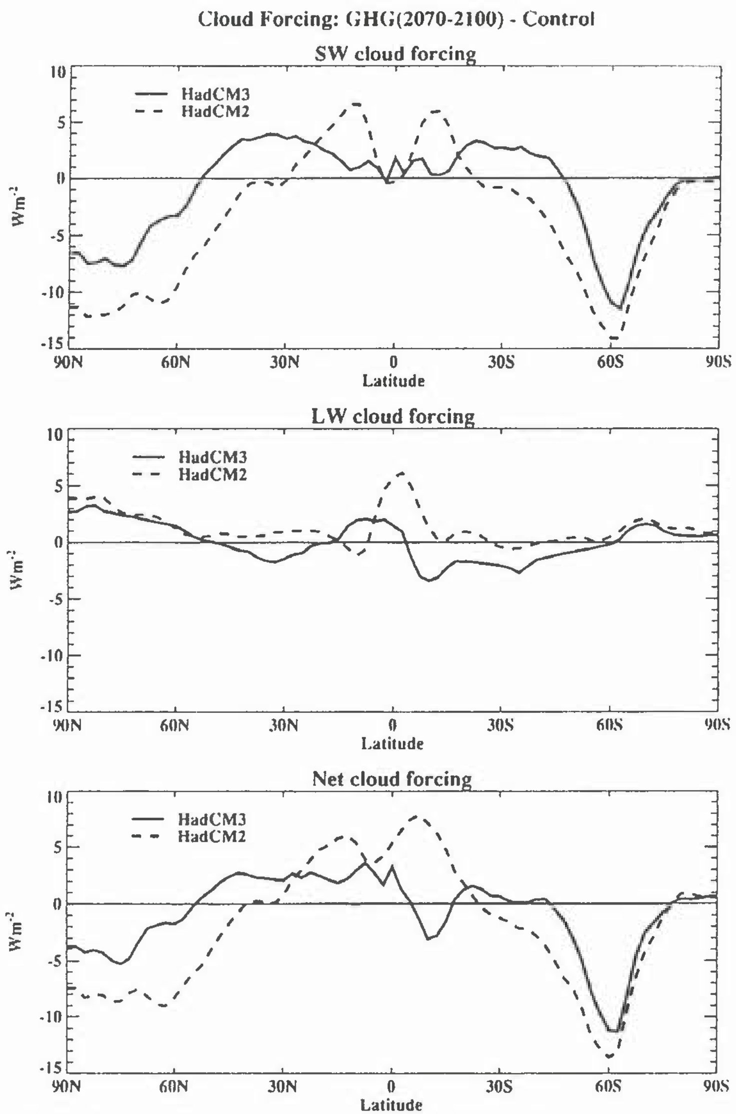

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Figure 8

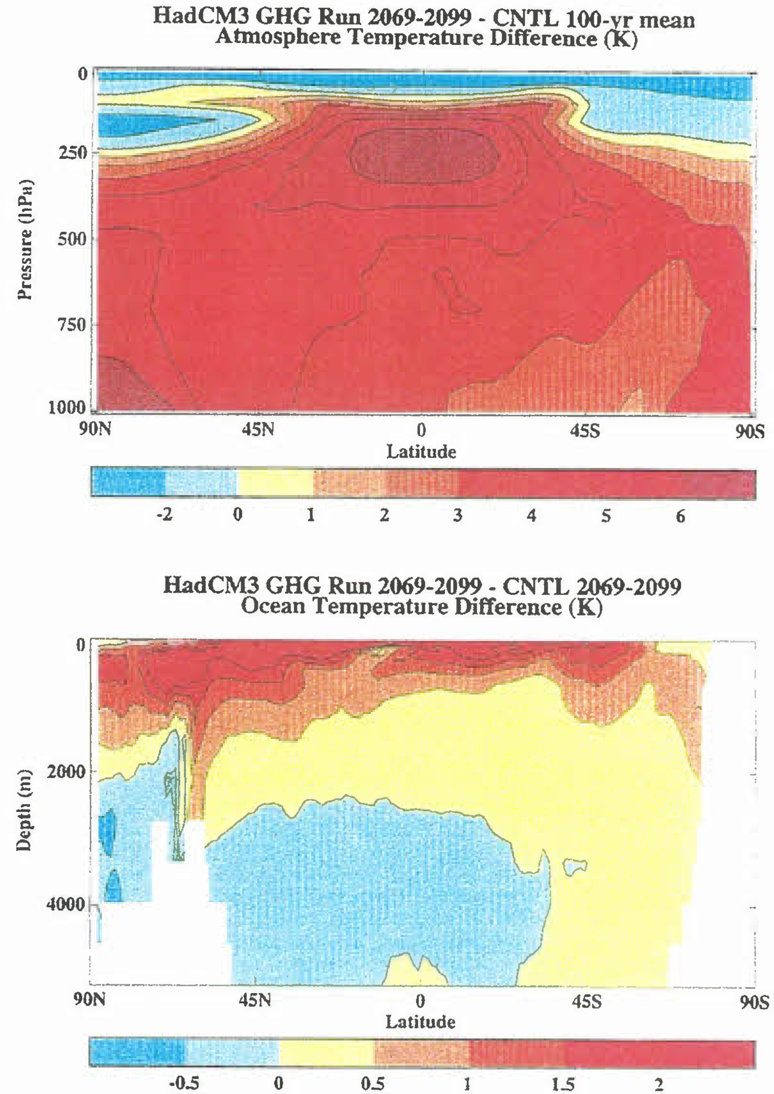

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Figure 9

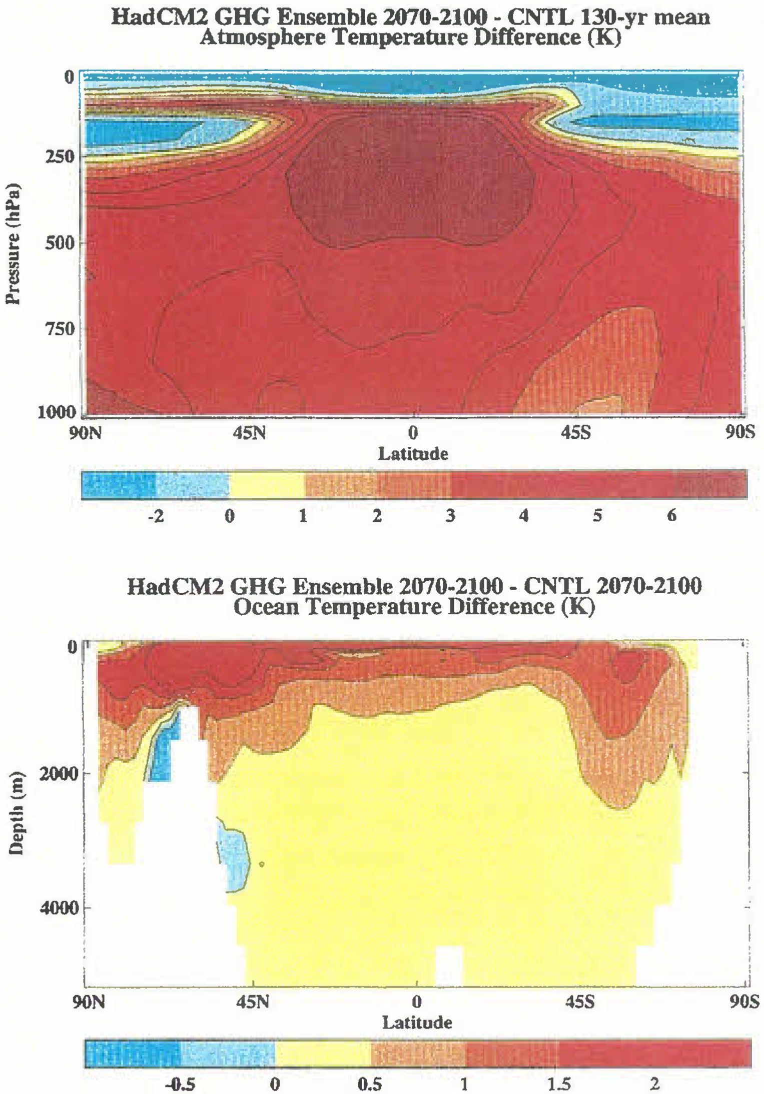

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Figure 10

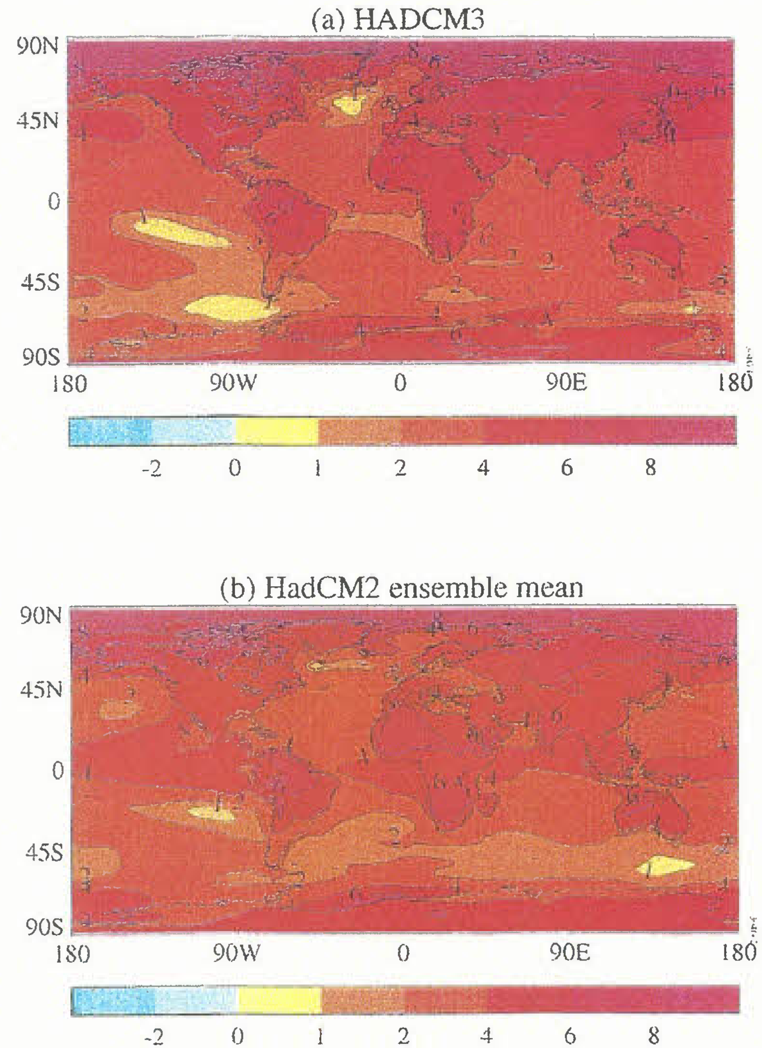

Figure 11 a & b

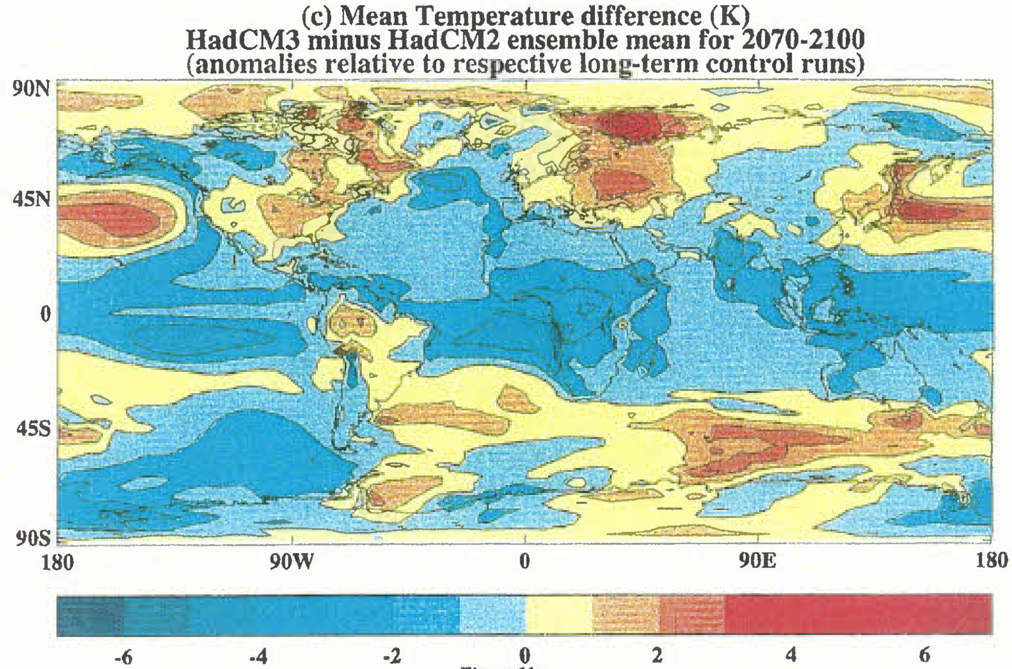

Figure 11c

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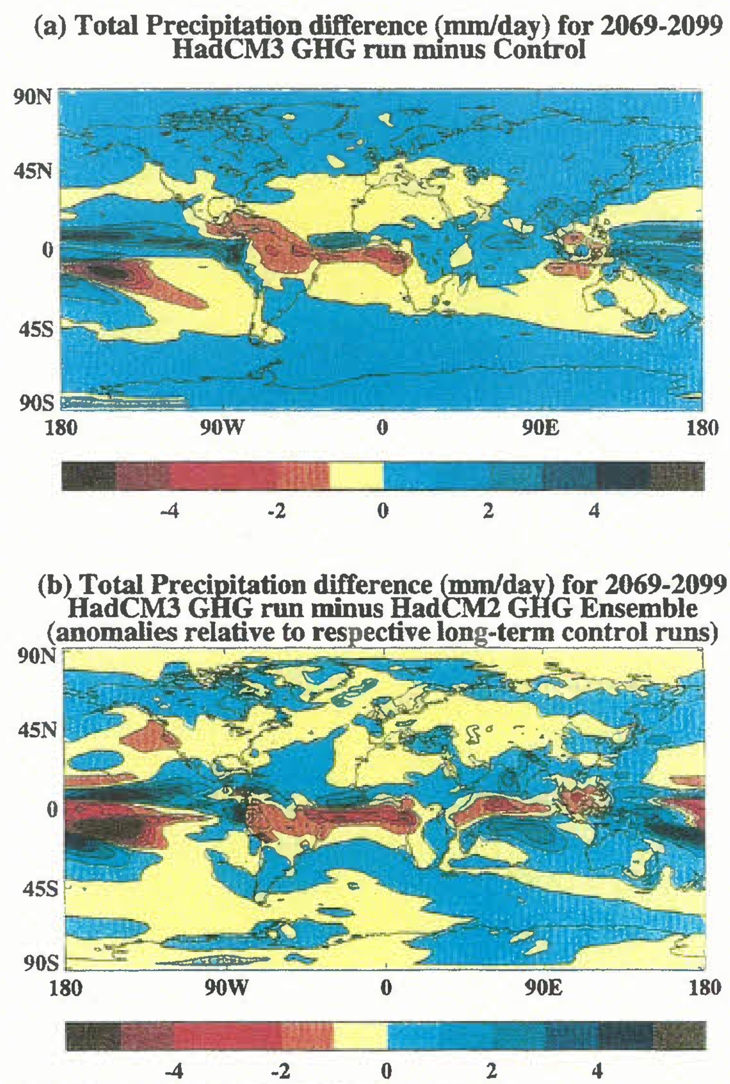

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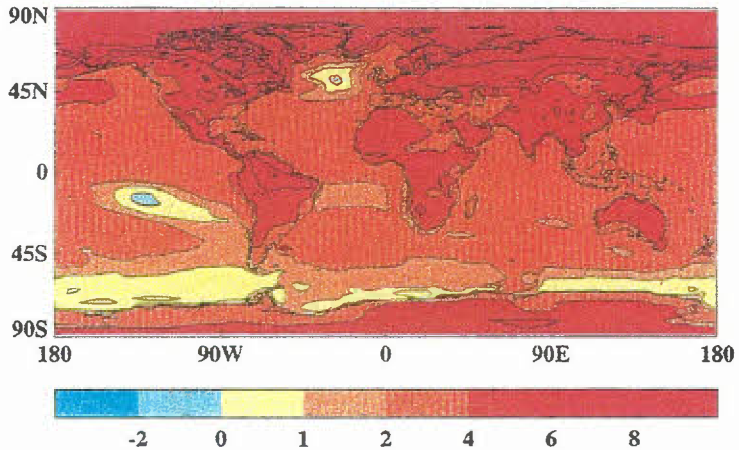
Figure 12

(a) T1.5m difference (K) for DJF 2069-2099
HadCM3 GHG run minus Control



(b) T1.5m difference (K) for DJF 2069-2099
HadCM3 GHG run minus HadCM2 GHG Ensemble
(anomalies relative to respective long-term control runs)

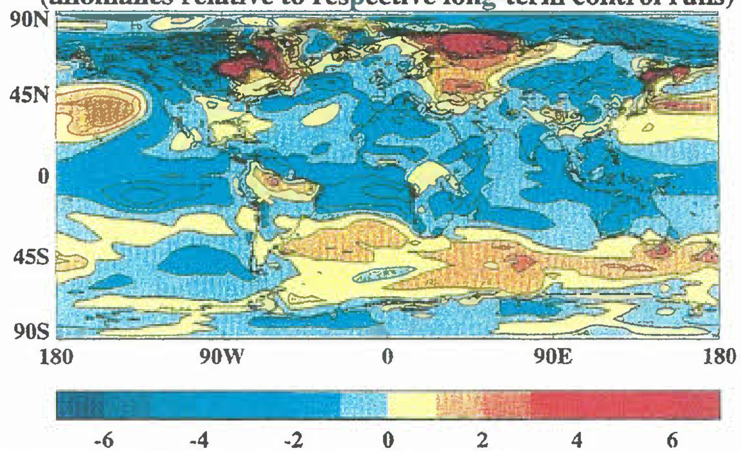


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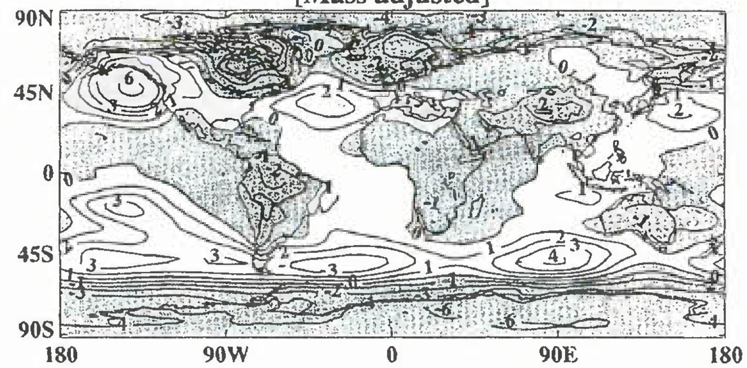
Figure 13

(a) PMSL difference (hPa) for DJF 2069-2099
HadCM3 GHG run minus Control
[Mass adjusted]



(b) PMSL difference (hPa) for DJF 2070-2100
HadCM2 GHG Ensemble minus Control
[Mass Adjusted]

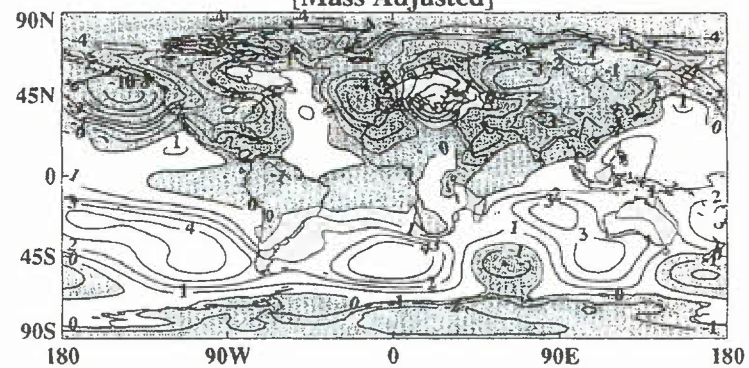


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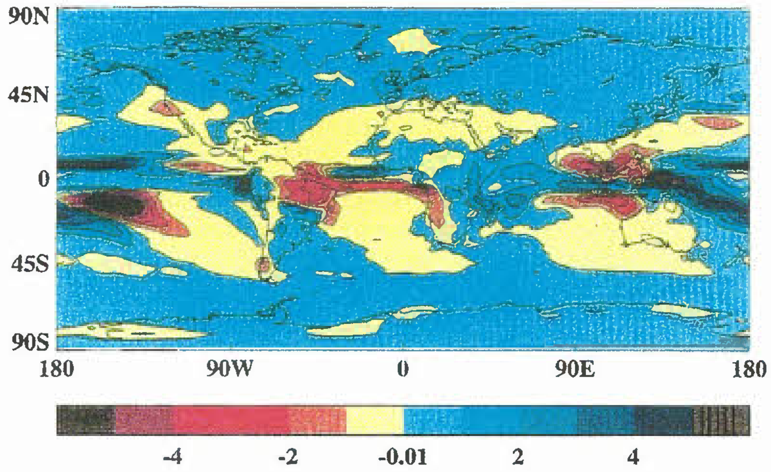
Figure 14

(a) Total Precipitation difference (mm/day) for DJF 2069-2099
HadCM3 GHG run minus Control



(b) Total Precipitation difference (mm/day) for DJF 2069-2099
HadCM3 GHG run minus HadCM2 GHG Ensemble
(anomalies relative to respective long-term control runs)

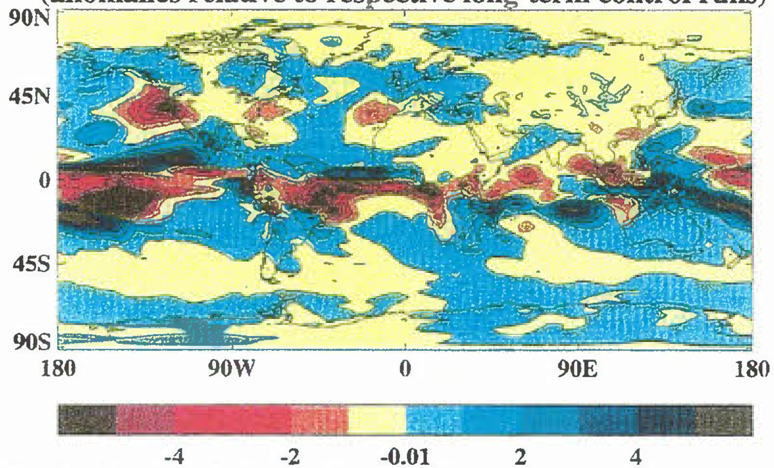


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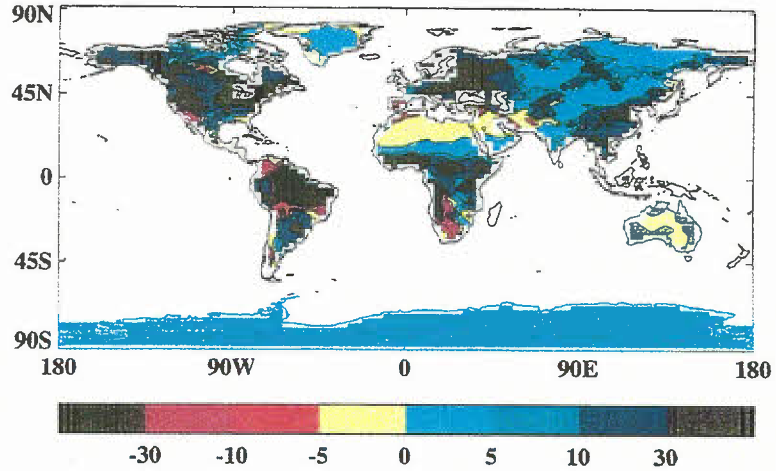
Figure 15

(a) Soil Moisture Content difference (mm) for DJF 2069-2099
HadCM3 GHG run minus Control



(b) Soil Moisture Content difference (mm) for DJF 2070-2100
HadCM2 GHG Ensemble minus Control

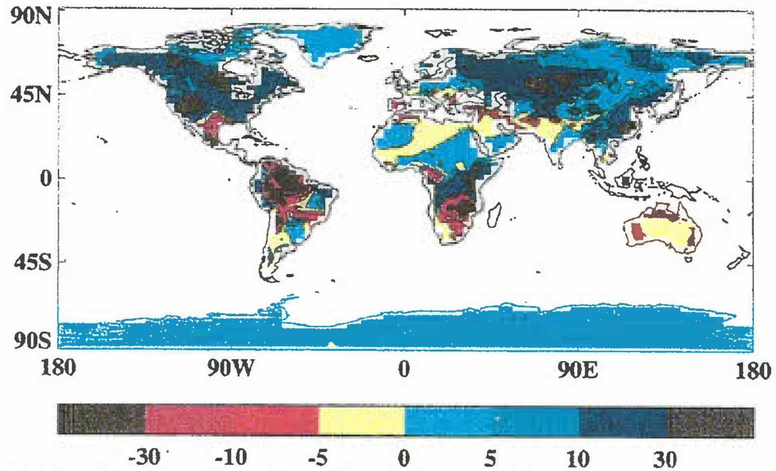


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Figure 16

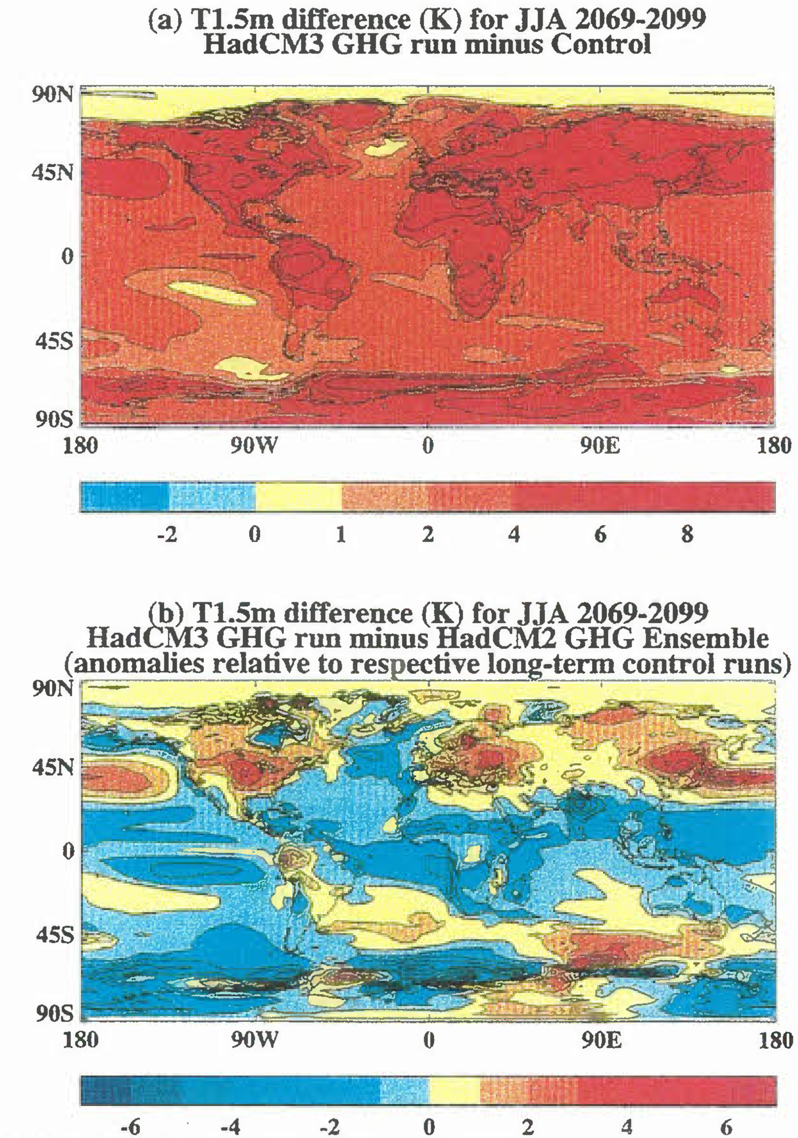

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Figure 17

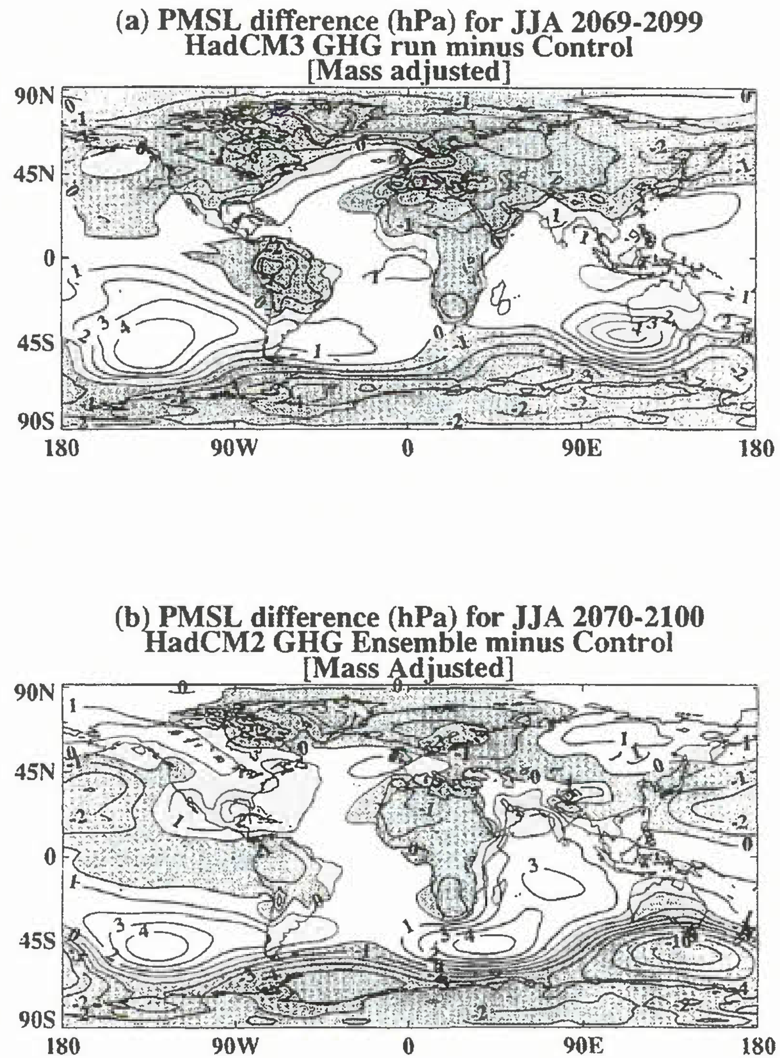

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Figure 18

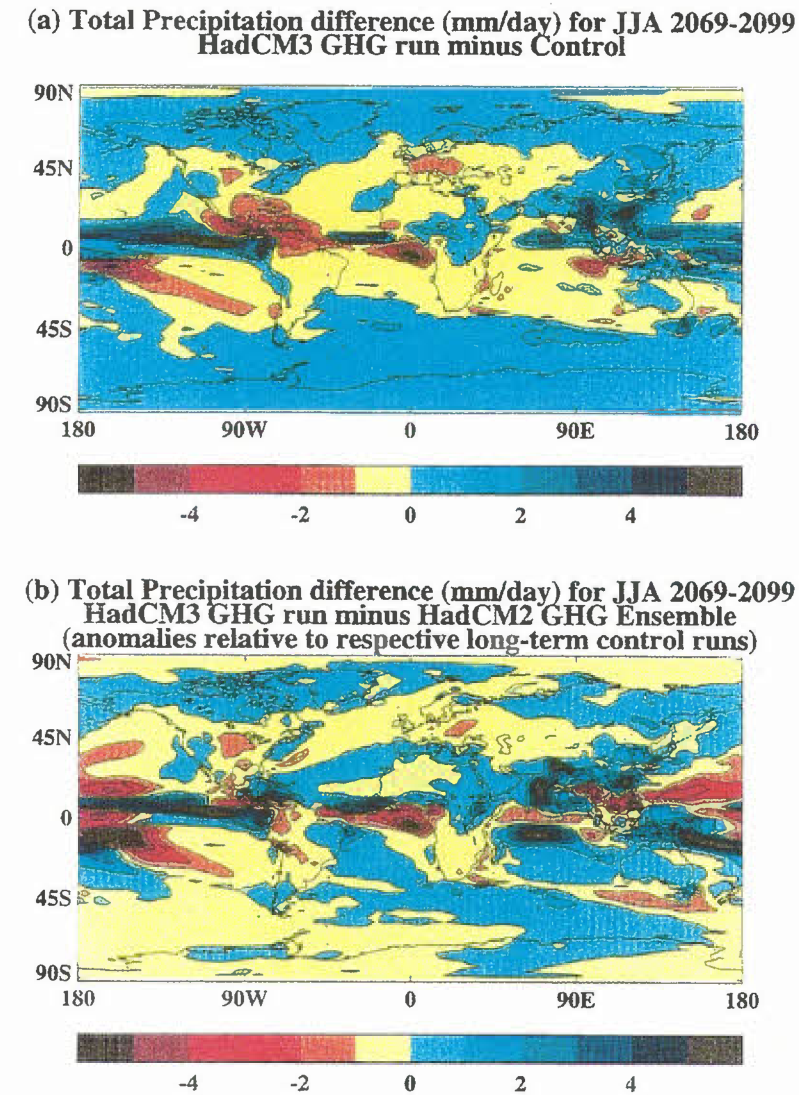

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Figure 19

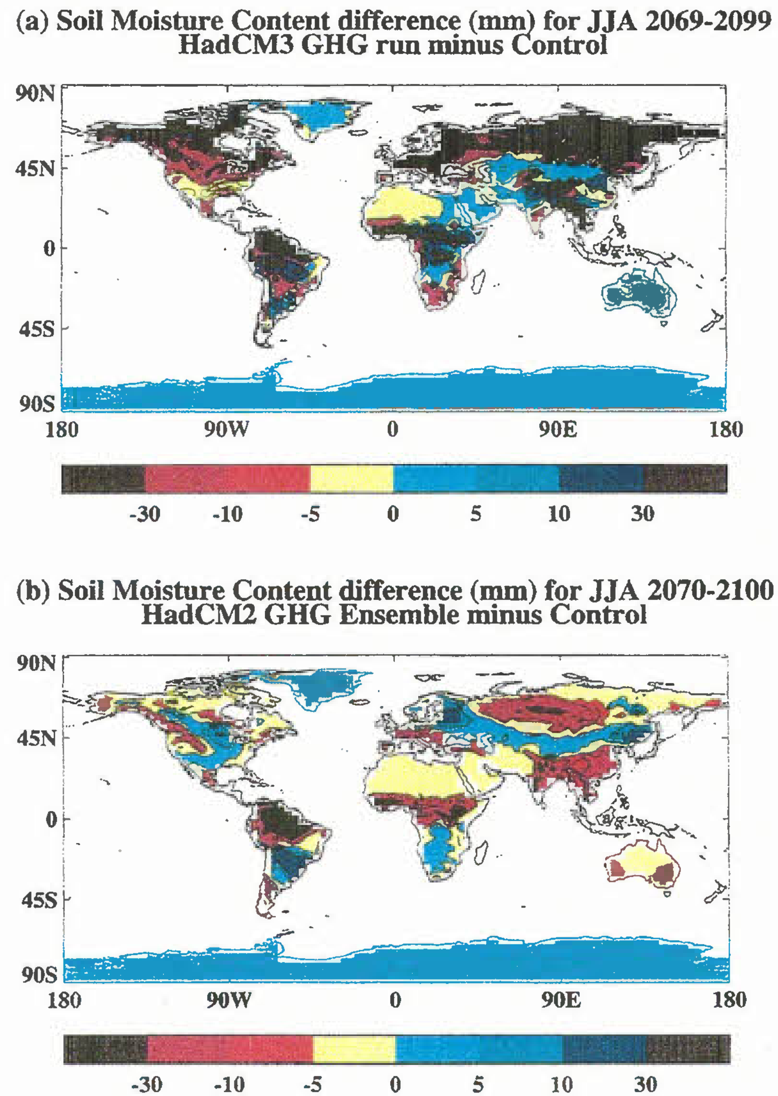

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Figure 20