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Transient response of a coupled model to estimated changes in greenhouse gas and sulfate concentrations.

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Abstract.
This study investigates changes in surface air temperature (SAT), hydrology and the thermohaline circulation due to the the radiative forcing of anthropogenic greenhouse gases and the direct radiative forcing (DRF) of sulfate aerosols in the GFDL coupled ocean-atmosphere model. Three 300-year model integrations are performed with increasing greenhouse gas concentrations only, increasing sulfate aerosol concentrations only and increasing greenhouse gas and sulfate aerosol concentrations. A control integration is also performed keeping concentrations of sulfate and carbon dioxide fixed. The global annual mean SAT change when both greenhouse gases and sulfate aerosols are included is in better agreement with observations than when greenhouse gases alone are included. When the global annual mean SAT change from a model integration that includes only increases in greenhouse gases is added to that from a model integration that includes only increases in sulfate, the resulting global SAT change is approximately equal to that from a model integration that includes increases in both greenhouse gases and sulfate aerosol throughout the integration period. Similar results are found for global annual mean precipitation changes and for the geographical distribution of both SAT and precipitation changes indicating that the climate response is linearly additive for the two types of forcing considered here. Changes in the mid-continental summer dryness and thermohaline circulation are also briefly discussed.

1. Introduction

Carbon dioxide has increased in concentration from approximately 280ppmv in pre-industrial times to over 360ppmv at the present day (IPCC, 1996). The atmospheric lifetime of carbon dioxide is estimated as 50 to 200 years which allows for uniform mixing throughout the atmosphere. Concentrations of other greenhouse gases such as methane, nitrous oxide and the halocarbons have also increased due to anthropogenic activity. Concentrations of atmospheric aerosols are also thought to have increased. Modeling studies (e.g. Langner and Rodhe, 1991; Kasibhatla *et al.*, 1997) indicate that the atmospheric burden of sulfate aerosol has increased by 200-300% due to anthropogenic emissions. However, the lifetime of sulfate aerosol is estimated as 4 to 5 days (IPCC, 1996) which means that concentrations are highest close to regions of emission. Thus the geographic distribution of the DRF that is exerted by sulfate aerosol differs substantially from that exerted by greenhouse gases (IPCC, 1996). This study uses the GFDL R15 coupled ocean-atmosphere model of Manabe *et al.* (1991) to investigate the changes in SAT and precipitation paying particular attention to the linear additivity of the results. Additionally, changes in mid-continental summer dryness and the thermohaline circulation due to increases in greenhouse gases and sulfate aerosols are discussed.

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2. Method

This study uses estimates of past, present and future sulfate and equivalent carbon dioxide concentrations from the IS92a scenario of IPCC (1992); these are identical to those used in the UK Meteorological Office (UKMO) coupled ocean-atmosphere model simulations of Mitchell *et al.* (1995a). The DRF of sulfate aerosol is simulated by increasing the surface albedo, R_s, by ΔR_s (Mitchell *et al.*, 1995b) where,

$$\Delta R_s \approx (1 - R_s)^2 k_e B_{SO4} \beta sec\theta \ , \qquad (1)$$

where k_e is the specific extinction coefficient of sulfate aerosol, B_{SO4} is the total column burden of sulfate, β is the backscattered fraction, and θ is the solar zenith angle. k_e and β are set to globally constant values of $7.6 m^2 g^{-1}$ and 0.21, values that are consistent with relative humidities of approximately 80% at a wavelength of $0.7 \mu m$ (Haywood and Shine, 1995). These values differ from those used by Mitchell *et al.* (1995a, b) (k_e=$8 m^2 g^{-1}$ and β=0.29) but the global DRF calculated off-line is similar at -0.62Wm^{-2} for 1990.

Four 300-year model integrations are performed from the year 1765 to 2065. 'CTL' is a control integration where concentrations of greenhouse gases and sulfate

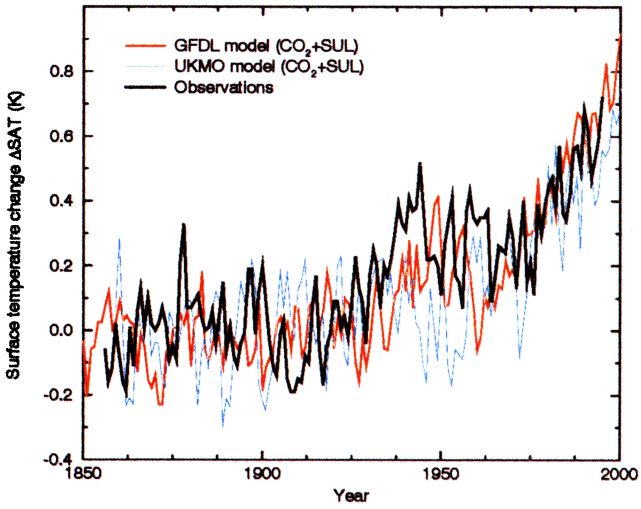

Figure 1. The change in global mean annual SAT, ΔSAT, (K) for the GFDL R15 coupled ocean-atmosphere model normalized to the period 1880-1920 for 'CO2+SUL'. The results from the UKMO and the observations of Jones (*pers. comm.*) are also shown.

experiment using an ocean-atmosphere mixed layer configuration is approximately 3.7K for the GFDL R15 model (Manabe *et al.*, 1991) and 2.5K for the UKMO model (IPCC, 1996). Despite these differences in model sensitivity, Figure 1 shows that the global annual mean SAT trend and the inter-annual variability from both the GFDL model and the UKMO integration are in reasonable agreement with the observations.

While the issue of linearity in response to forcing by greenhouse gases and aerosols has been addressed by others for both global means (e.g. Mitchell *et al.*, 1995b; Ramaswamy and Chen, 1997) and spatial distributions (Penner *et al.*, 1997), such investigations have been equilibrium experiments using mixed-layer ocean-atmosphere models rather than fully coupled ocean-atmosphere GCMs. The issue of linearity is important as, if the system proves to be linear, one may address many different scenarios (e.g. magnitude uncertainties in aerosol DRF) by scaling and summing the results from only a few coupled ocean-atmosphere integrations.

The global annual mean ΔSAT for 'CO2', 'SUL', 'CO2+SUL' and 'CO2'+'SUL' over the period 1850

tions from 1990 to 2065 is summarized in Table 1; the rate of change of $\Delta SAT_{CO2+SUL}$ is within 1% of that of $\Delta SAT_{CO2}+\Delta SAT_{SUL}$.

The results from 'CO2+SUL' are in better agreement with the observations (Figure 1) than those from 'CO2'. By the year 2065, ΔSAT_{CO2} is greater than $\Delta SAT_{CO2+SUL}$ by approximately 0.5K.

To investigate whether the geographical pattern of $\Delta SAT_{CO2+SUL}$ is similar to $\Delta SAT_{CO2}+\Delta SAT_{SUL}$, 100-year mean SAT and precipitation fields were produced from the last 100 years of the 300 year model integrations for each of the experiments. The choice of 100 year means is arbitrary; a 100-year mean is chosen to reduce the influence of natural variability in the signal. The difference between the 100-year mean SAT from the control run and each of the perturbed runs was calculated. The results for 'CO2+SUL' and 'CO2'+'SUL' are shown in Figures 3a and 3b respectively.

The spatial pattern is strikingly similar (correlation coefficient, r=0.97) when comparing Figure 3a and Figure 3b indicating that linear additivity of SAT may be assumed, results that are consistent with equilibrium response experiments performed with the model (Ramaswamy and Chen, 1997). The only region where the SAT decreases slightly is in the circumpolar southern hemisphere oceans, an area associated with a region of deep vertical mixing (Manabe *et al.*, 1991). The inter-hemispheric asymmetry in the warming is apparent (e.g. Manabe *et al.*, 1991); the hemispheric mean SAT change is ~2.1K for the northern hemisphere and ~1.5K for the southern hemisphere despite the fact that sulfate concentrations are higher in the northern hemisphere. The mean warming in 'CO2+SUL' is greater over land (~2.2K) than over ocean (~1.6K) despite the sulfate burden being largest over land. This is because the oceans have a larger thermal inertia and there is a larger surface cooling due to evaporation. Note that the inter-hemispheric and land-sea contrasts in SAT change are averages over the last 100 years of the integration which masks complex temporal behavior.

4. Changes in hydrology

Reliable measurements of changes in the global precipitation are difficult, sparse and noisy (IPCC, 1996) therefore the model results are not compared against global measurements in this study.

Table 1. The rate of change of global mean annual SAT and precipitation over the period 1990 to 2065 for the model integrations described in the text.

Model Integration	Rate of change of SAT (K/yr)	Rate of change of Precipitation (mm/yr)
'CO2'	+0.0370	+0.77
'SUL'	-0.0059	-0.16
'CO2+SUL'	+0.0309	+0.58
'CO2'+'SUL'	+0.0311	+0.61

To investigate whether the linear additivity holds for precipitation, an identical method to that for SAT change was pursued. Once again, the results indicate that the change in annual global mean precipitation for 'CO2'+'SUL' is approximately equal to that for 'CO2+SUL'. The rate of change of global annual mean precipitation for the four model integrations from 1990 to 2065 is summarized in Table 1 which supports linear additivity in the global precipitation change.

An identical method to that for SAT was applied to examine the spatial changes in the precipitation. The results indicate that the spatial distribution for 'CO2+SUL' is similar to 'CO2'+'SUL' over most regions (not shown for reasons of brevity), again supporting the results of the equilibrium response experiments performed with the model (Ramaswamy and Chen, 1997). The agreement in the pattern is not as good for precipitation as for SAT (correlation coefficient, r=0.76) in part due to the the fact that precipitation is inherently much noisier spatially than SAT. The increases in precipitation tend to be largest at high latitudes in both hemispheres. The mean increase in precipitation over this 100-year period for 'CO2+SUL' is approximately 30mm over land and approximately 34mm over ocean, despite the fact that the SAT increase is greatest over land.

Earlier experiments have shown that as atmospheric CO_2 concentrations increase, the soil moisture over mid-latitude continental areas decreases in the summer season (Manabe *et al.*, 1981). A June-July-August soil moisture time series computed from 'CO2+SUL' over northern mid-latitude continental regions shows that the inter-annual variability is quite large and that the summer dryness signal occurs later than for 'CO2'. The signal becomes evident only after the year 2000, when increases in downward longwave irradiance due to increased greenhouse gas concentrations together with increases in downward solar radiation due to reduced cloud amount (Wetherald and Manabe, 1995) combine to more than offset decreases in downward solar irradiance due to greater sulfate loading. The increased net radiation incident at the surface of the Earth results in increased evaporation thereby drying the continents.

5. Changes in the thermohaline circulation

The increase in the precipitation rate in high latitudes (section 4) leads to an increased fresh water supply at the ocean surface in high latitudes. This fresh water acts to cap the ocean surface, inhibiting the cooling of the water column by the atmosphere thereby slowing down the thermohaline circulation (THC) in the Atlantic Ocean (Manabe *et al.*, 1991). As the THC slows down, the northward heat transport into the North Atlantic Ocean reduces, leading to the relatively smaller warming seen in Figure 3a. The THC in 'CO2+SUL' only starts to weaken significantly from 'CTL' after 2010. By 2065, the maximum value of the THC in

the Atlantic is about 10SV for 'CO2+SUL' and 9SV for 'CO2' compared to 18SV for 'CTL'.

6. Discussion

In the real atmosphere, atmospheric constituents other than greenhouse gases and sulfate aerosol may also exert a substantial influence on climate. Examples include changes in stratospheric and tropospheric ozone, stratospheric aerosols due to volcanic eruptions and other aerosols such as black carbon, organic carbon and mineral dust due to anthropogenic activity. Additionally, IPCC (1996) state the range of the present day DRF of sulfate aerosol to be $-0.2\mathrm{Wm}^{-2}$ to $-0.8\mathrm{Wm}^{-2}$; a value of approximately $-0.62\mathrm{Wm}^{-2}$ is used in this study. The indirect effect whereby aerosols affect the micro-physical and radiative properties of clouds remains highly uncertain (IPCC, 1996) and is not included in this study although Mechl *et al.* (1996) have included both direct and indirect effects in their coupled ocean-atmosphere study. Nevertheless, the inclusion of the DRF due to sulfate aerosol leads to modeled SAT changes that are in better agreement with observations than if increases in greenhouse gas concentrations alone are considered.

7. Conclusions

It has been shown that the GFDL R15 model is capable of a reasonable reproduction of the observed SAT behavior when the radiative forcing due to greenhouse gases and the DRF due sulfate are applied. Not only is the trend adequately described but the inter-annual variability of the model SAT also appears reasonable (see also Manabe and Stouffer, 1996). Global mean SAT and precipitation changes from a model integration where the effects of both greenhouse gases and sulfate aerosols are included are consistent with those obtained when model integrations including the effects of carbon dioxide alone and sulfate aerosol alone are added together. The spatial distribution of changes in SAT and precipitation may also be approximated by adding the changes due to the effects of carbon dioxide to the effects due to sulfate aerosol indicating that, for this model and these forcing mechanisms, both temporal and spatial linear additivity may be assumed. Significant changes in mid-continental summer dryness and the THC occur early in the next century in the model integration that includes both greenhouse gases and sulfate aerosol. The emergence of both of these signals is later than in the model integration that includes greenhouse gases alone.

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