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Mitigating a quadrupling of CO_2 by a reduction of the solar constant: A geoengineering experiment with the EC-Earth climate model.

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Contents

1. Abstract

Here we report on the first results from a geoengineering experiment with the EC-Earth climate model. The experiment consists of three 50-year long simulations; a pre-industrial control simulation, a simulation with quadrupled CO_2, and a simulation with quadrupled CO_2 balanced by an appropriate reduction of the solar constant. The experiment conforms to the guidelines set up in the GeoMIP project for the G1 type experiment. In line with previous experiments we find that the huge responses in the quadrupled CO_2 simulation are remarkable well balanced out by the reduced solar constant. This holds both for the surface temperature and the precipitation, although the global mean precipitation has decreased. In the stratosphere the changes due to the increase in CO_2 can not be mitigated by a reduction of the solar constant. The stratospheric temperature decreases strongly in the quadrupled CO_2 experiment and even more in the experiment with both quadrupled CO_2 and a reduction in the solar constant. While most previous studies have focused on annual means we also consider the NH winter situation. Again, we find that the CO_2 induced changes are remarkably well mitigated by the reduction in the solar constant. In the quadrupled CO_2 simulation the stratospheric vortex weakens which is felt throughout the atmospheric column all the way down to the surface. With the additional reduction of the solar constant the weakening of the vortex is smaller and confined to the stratosphere.

2. Introduction

In a previous report (Christiansen, 2011) it was concluded that the Danish Climate Centre (DKC) in 2011 should begin performing solar radiation management experiments as described in the Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al., 2011) [1]. Climate model experiments with reduced incoming solar radiation is a first order attempt to study solar radiation management schemes. Among these schemes are injection of sulphur aerosols into the stratosphere (Stevens and Feingold, 2009), whitening of marine clouds (Latham et al., 2008), and placement of reflecting mirrors into space. These schemes should not be confused with another group of geoengineering methods which attempts to enhance the natural removal of CO_2 from the atmosphere. At DKC we focus at solar radiation management schemes because they are expected to have the most serious adverse effects and because these methods can be investigated with our current modelling tools. It is worth reiterating that solar radiation management methods do not solve the problem of acidification of the oceans. For general reviews of geoengineering see Shepard et al. (2009) and Robock (2008).

It was also mentioned in Christiansen (2011) that an issue of special interest could be the situation in the Northern Hemisphere (NH) extra-tropical winter. Here the effect of reduced incoming solar radiation is not direct but may come from changes in the dynamics which could possibly include the stratosphere. The EC-Earth climate model at DKC is ideal for these kind of experiments because it has a very good representation of the stratosphere.

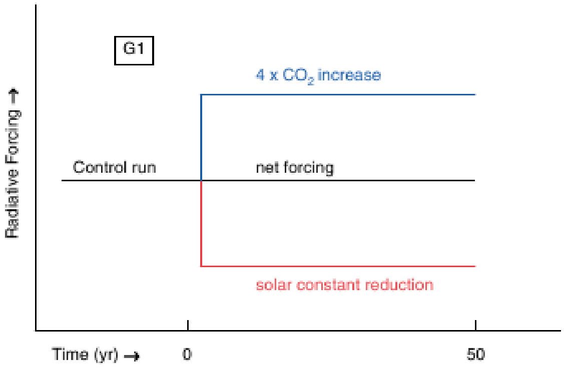

Figure 2.1: From Kravitz et al. (2011). Schematic of experiment G1. The experiment is started from a control run. The instantaneous quadrupling of CO_2 concentration from pre-industrial levels is balanced by a reduction in the solar constant until year 50.

In this report we describe the results of the first GeoMIP (G1 in the nomenclature of GeoMIP) experiment performed at the DKC. The experiment consists of a pre-industrial control simulation (CO_2 loading of 284 ppm, solar constant 1361 W/m^2), a quadrupled CO_2 simulation, and a simulation where the quadrupled CO_2 is balanced by a reduction of the solar constant. The changes to CO_2 and the solar constant are instantaneously. Both forced simulations last for 50 years and the last 25 years are used for analysis. See Fig. 2.1 for a schematic overview of the simulations. In the following the simulations are denoted as Control, 4CO2, and Balance, respectively.

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[1] For more on GeoMIP see `http://climate.envsci.rutgers.edu/GeoMIP/index.html`

The experiment is performed with the EC-Earth (Hazeleger et al., 2011) climate model. The EC-Earth core system consists of the Integrated Forecast System (IFS) of the European Centre for Medium Range Weather Forecasts (ECMWF) as the atmosphere component and the Nucleus for European Modelling of the Ocean (NEMO) developed by Institute Pierre et Simon Laplace (IPSL) with the ocean component and the Louvain-la-Neuve sea Ice Model (LIM) embedded in the NEMO. The ocean/ice model is coupled to the atmosphere/land model through the OASIS 3 coupler. The NEMO has a 1x1 degree horizontal resolution (extended to 1/3x1/3 degree in the tropics) and 42 vertical levels. The atmospheric component has a T159 horizontal spectral resolution and 62 vertical levels with the top of the atmosphere at 5 hPa.

A crude estimate of the needed reduction of the solar constant ΔS can be derived from $\Delta F = (1-a)/4\Delta S$, where ΔF is the radiative forcing from the quadrupled CO_2 ($\sim$ 8.5 W/m^2) and a is the planetary albedo ($\sim$ 0.33). This gives $\Delta S = 52$ W/m^2. The precise value will depend on the details of the model. We performed a series of brief simulations with quadrupled CO_2 and ΔS in the range 50-60 W/m^2. Monitoring the surface temperature we found that $\Delta S = 56$ W/m^2 was the best choice. This is close to the values used in other similar experiments, e.g., Lunt et al. (2008) used 57 W/m^2 and Govindasamy et al. (2003) used 49 W/m^2.

In Fig. 2.2 (left) the monthly global mean temperatures are shown as function of time for the three simulations. While the temperature in 4CO2 increases with about 4.5 K relative to Control, the temperature in the Balance simulation remains very close to that of Control. This seems to be the case for all seasons. When the anomalies relative to Control are considered (Fig. 2.2, left) it is clear that the temperature in Balance only shows a very small drift. We also find that both 4CO2 and Balance are close to equilibrium after 25 years.

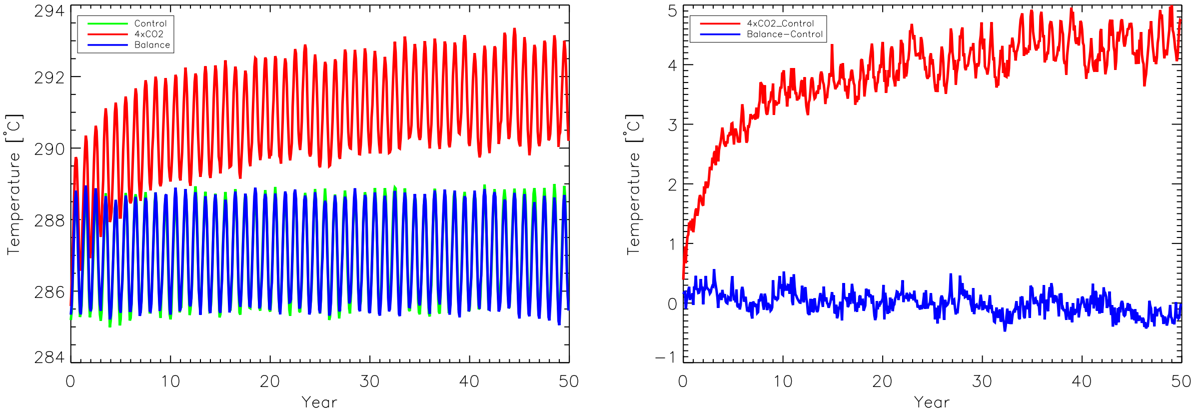


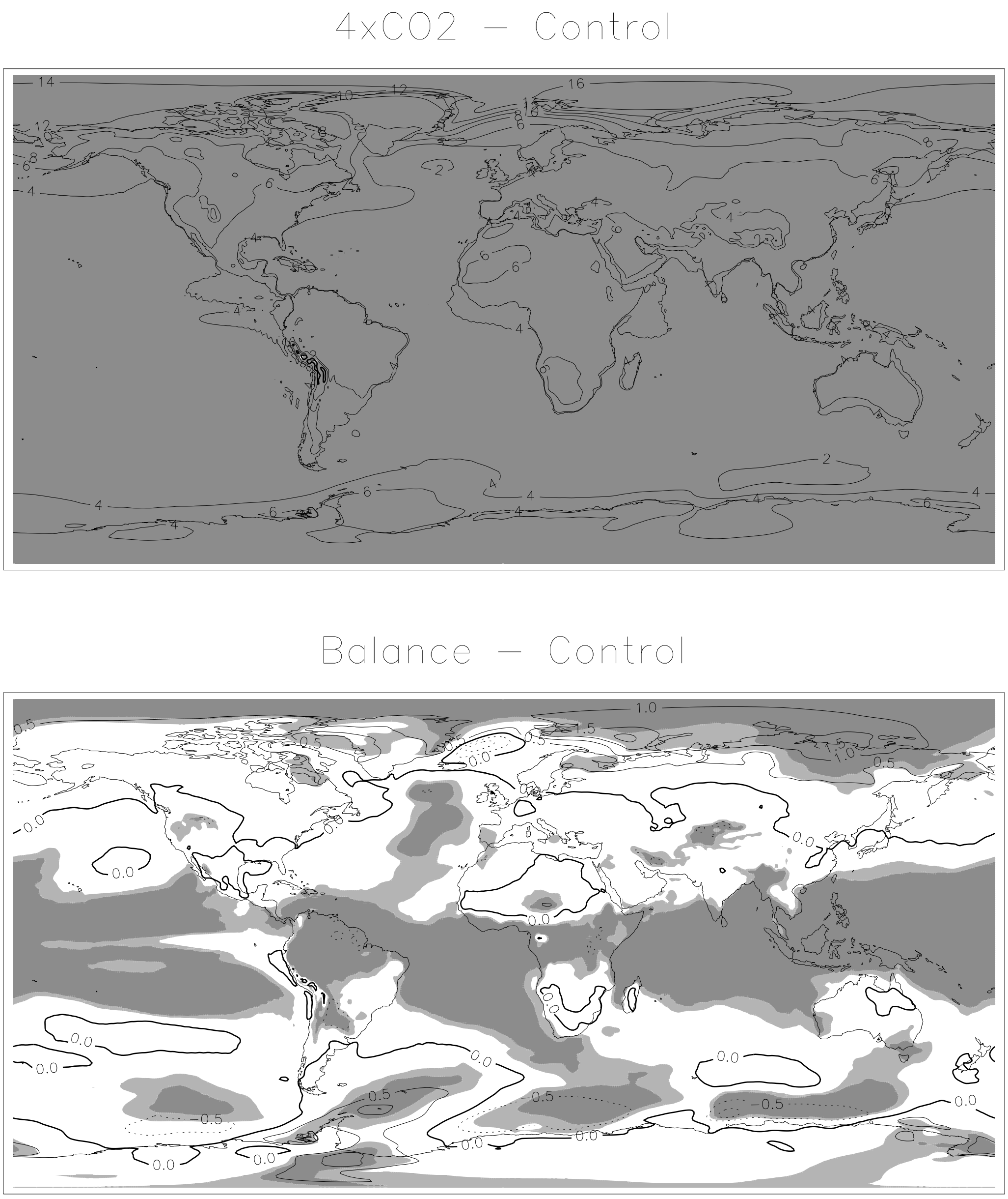
Figure 2.2: Left: The monthly global mean temperature as function of time for the three different simulations. Right: The monthly differences between the forced simulations and the control simulation.

In the following we will first investigate the annual mean temperature responses (section 3) and the annual mean precipitation responses (section 4). These diagnostics have been considered also in previous studies. In section 5 we will in some detail study the responses in the NH winter.

The statistical significance of the differences between the forced simulations and the control simulation is estimated with a t-test where the annual (or winter) means are considered as independent (i.e., 25 degrees of freedom). The absence of serial correlations seems to be a decent assumption but might involve some overestimation of the statistical significance.

3. Annual mean temperature responses

The annual mean surface temperature responses are shown in Fig. 3.1 together with the statistical significance. The response for the 4CO2 simulation shows significant warming everywhere with values ranging from 2 to more than 16 K. The largest response is found in the Arctic while the smallest response is found in the tropics and over the Southern Ocean. In the Balance simulation the responses are much lower everywhere and rarely exceed 1 K. Warming is in general found in the polar regions while the tropics has cooled a little. While the response is statistically significant in the tropics and in the Arctic, it is insignificant in much of the extra-tropics.


4xCO2 — Control

Balance — Control

Figure 3.1: Annual mean surface temperature responses calculated over the last 25 years. Top/Bottom: 4CO2/Balance. Regions where the response is statistically significant at the 99 and 95 % levels according to a t-test are dark and light shaded.

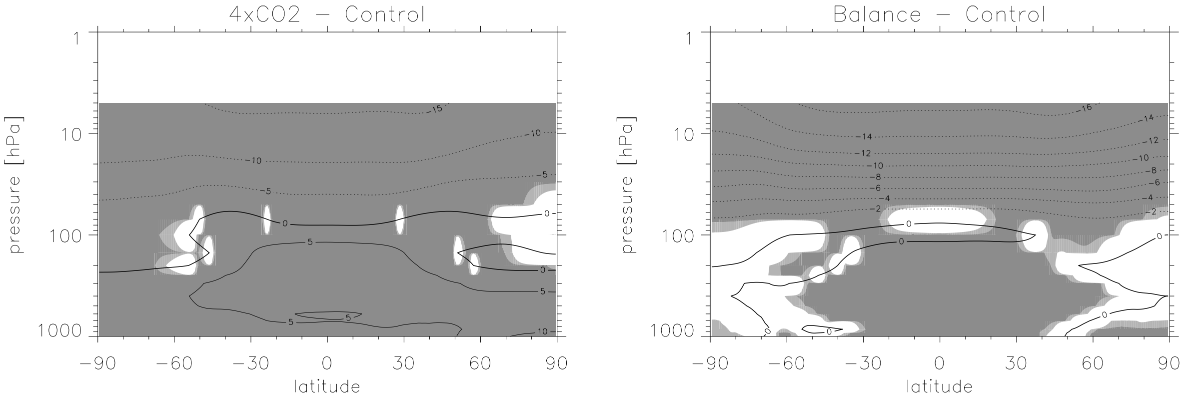


Figure 3.2: Annual zonal mean temperature response calculated over the last 25 years. Left/Right: 4CO2/Balance. Note the different contour intervals.

The zonal and annual mean temperature responses are shown in Fig. 3.2 as function of latitude and altitude. In the 4CO2 simulation the troposphere warms significantly everywhere. The largest warming is found in the mid-troposphere over the tropics (disregarding the very large warming in the Arctic near the surface). The stratosphere has cooled significantly everywhere with responses up to -15 K near the top of the model. In the Balance simulation the responses are much smaller in the troposphere with a general cooling in the tropical and extra-tropical troposphere. Here the responses are statistically significant with values down to -1 or -2 K. In the stratosphere the cooling in the Balance simulation has amplified in comparison with the 4CO2 simulation. This additional cooling (1-2 K) is a simple consequence of the fact that the changes of the radiative heating rates of both increasing CO_2 and a reduction in the solar constant are negative at these altitudes.

4. Annual precipitation responses

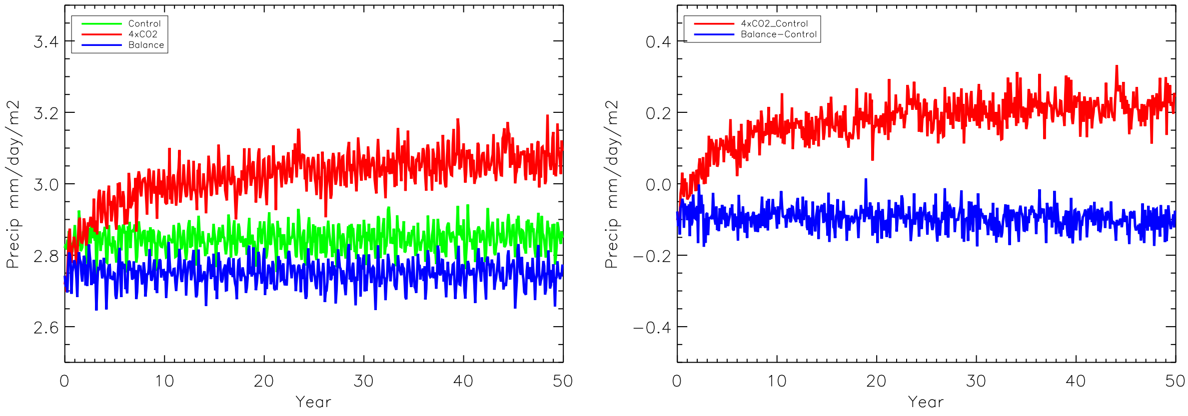
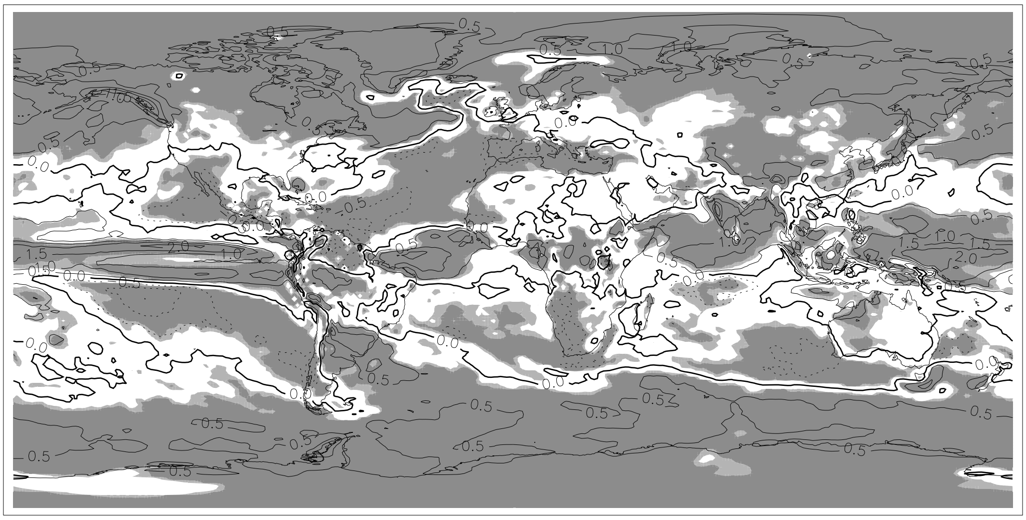
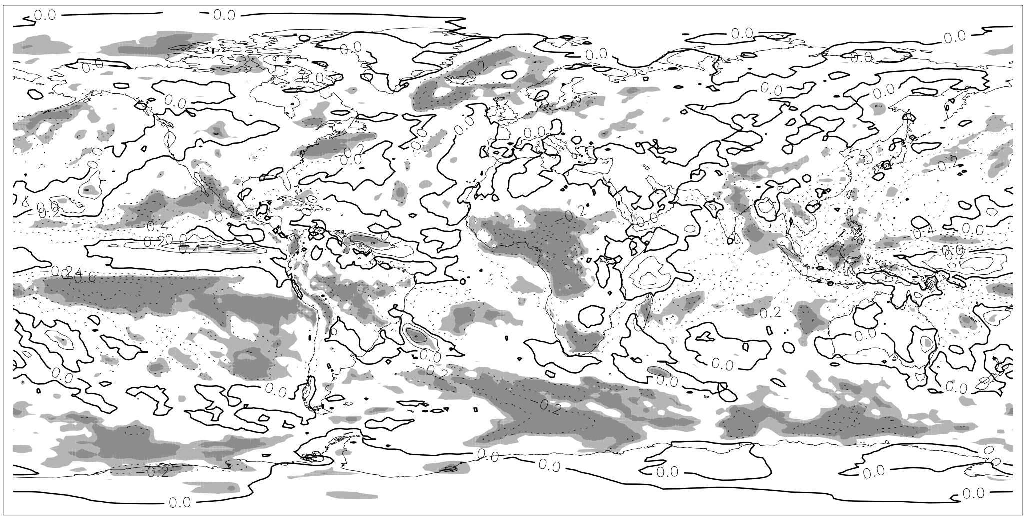


Figure 4.1: Left: The monthly global mean precipitation as function of time for the three different simulations. Right: The monthly differences between the forced simulations and the control simulation.

The monthly global mean precipitation is shown as function of time for the three simulations in Fig. 4.1. In the Control simulation this value is quite stable and fluctuates around 2.85 mm/day/m^2 (close to the observed value of 2.9 mm/day/m^2). In the 4CO2 simulation the global mean precipitation increases with around 0.2 mm/day. This increase has been argued to be a direct consequence of the Clausius-Clapeyron relation which states that the saturation water vapor pressure increases with temperature. In the Balance simulation the annual mean precipitation has decreased



4xCO2 — Control



Balance — Control

Figure 4.2: Annual mean surface precipitation response calculated over the last 25 years. Top/Bottom: 4CO2/Balance.

relative to the Control simulation with approximately 0.1 mm/day. This decrease is also found in other experiments and can be explained by a general slow-down of the hydrological cycle as a consequence of the reduced solar radiation at the surface. See Christiansen (1999) for a similar argument relating to the responses to stratospheric ozone changes.

The geographical distributions of the annual mean precipitation responses are shown in Fig. 4.2. In the 4CO2 simulation the responses are largest (and statistically significant) in the polar regions and in the tropics where the precipitation has increased. In the extra-tropics the precipitation response is weaker (in some places negative) and the significant regions more scattered. In the Balance simulation the mostly negative precipitation responses are smaller everywhere and only statistically significant in few scattered areas, most of these being over sea and over the western part of the tropical Africa. As we would expect that 5 % of the area could easily show up as statistically significant to the 95 % level by chance we can conclude that in the Balance simulation it would be difficult to detect changes in the annual mean precipitation locally from a 25 year long record.

5. NH winter responses

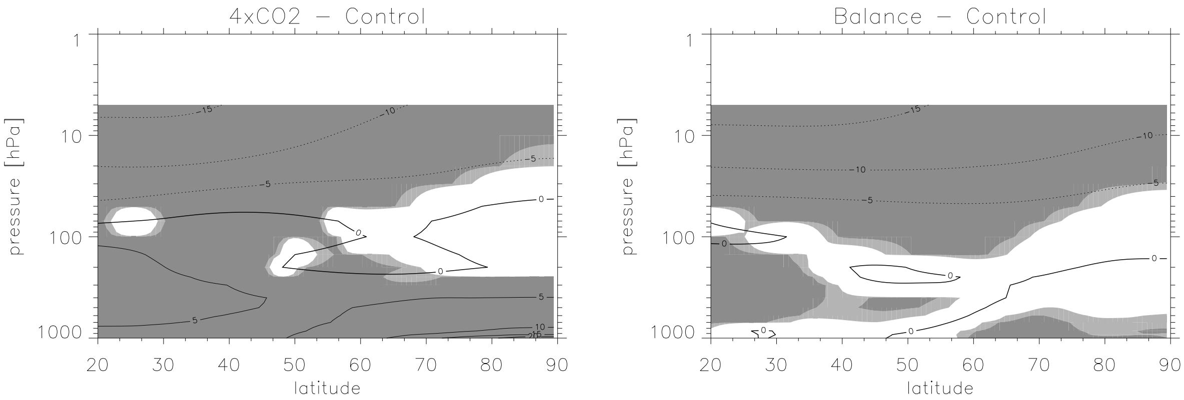


Figure 5.1: Winter (DJF) zonal mean temperature response calculated over the last 25 years. Left/Right: 4CO2/Balance.

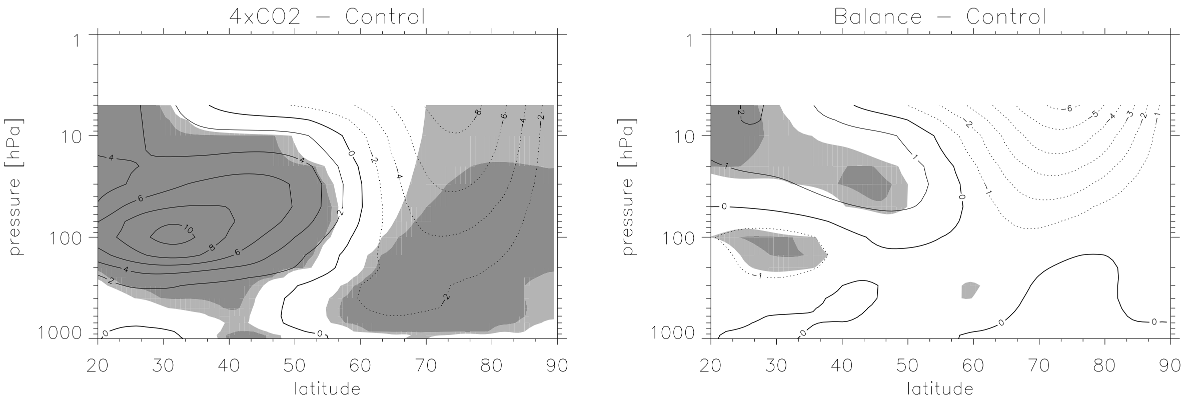


Figure 5.2: Winter (DJF) zonal mean zonal wind response calculated over the last 25 years. Left/Right: 4CO2/Balance.

The previous chapters have considered annual mean responses and the reported responses were broadly in agreement with previous studies. In this chapter we will study some seasonal aspects where existing model studies often give different results. In particular, we will consider the situation in the NH extra-tropical winter. In this region the direct impact of the reduced incoming solar radiation is small but indirect effects related to changes in the dynamics can be expected. The situation is somewhat analogue to what happens in the NH in the first winters after explosive volcanic eruptions. Here changes in the stratospheric temperature gradient induce changes in the stratospheric vortex which then is felt in the troposphere as changes in the phase of the North Atlantic Oscillation (NAO).

The zonal mean December, January, February (DJF) temperature responses are shown in Fig. 5.1. As for the annual mean in Fig. 3.2 we find that the troposphere has warmed and the stratosphere cooled in the 4CO2 simulation. This signal is statistically significant everywhere except in the polar stratosphere where the internal variability – connected to sudden stratospheric warmings – is large. However, compared to the annual mean response we find a larger pole-ward gradient in the winter temperature response in the stratosphere. This effect is related to the temperature dependence of the radiative forcing of CO_2. The induced temperature response reduces the negative temperature gradient in the stratosphere and leads to a reduced stratospheric vortex as can be seen from the zonal mean zonal wind responses shown in Fig. 5.2 (left). The change in the vortex is significant almost everywhere and can be followed all the way down to the surface corresponding to a change towards the negative phase of the NAO.

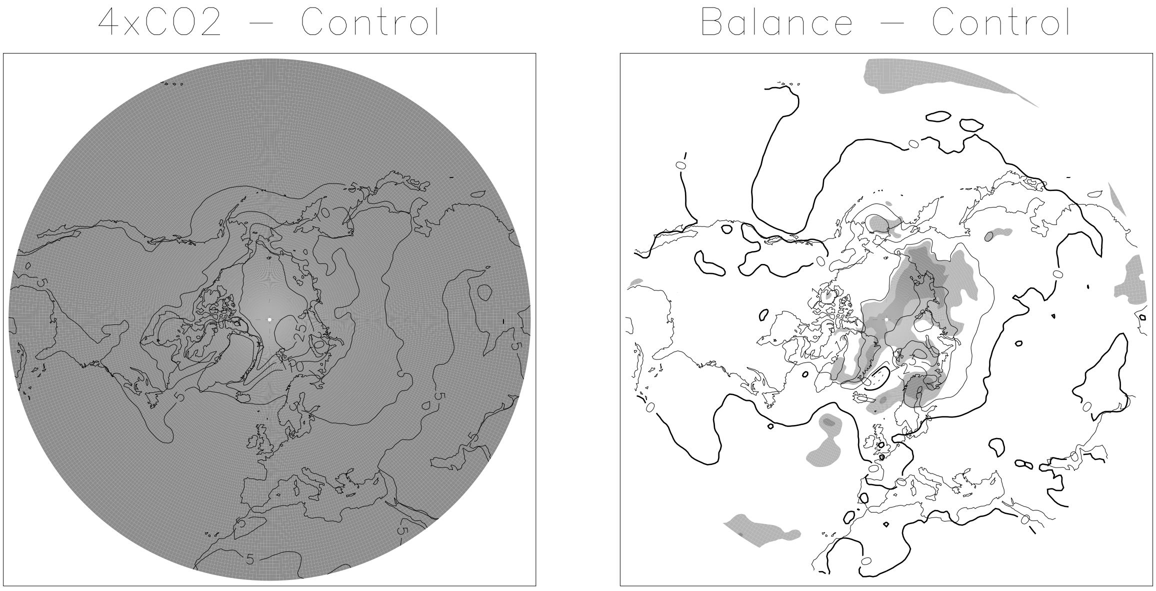


Figure 5.3: Winter (DJF) mean surface temperature response calculated over the last 25 years. Left/Right: 4CO2/Balance.

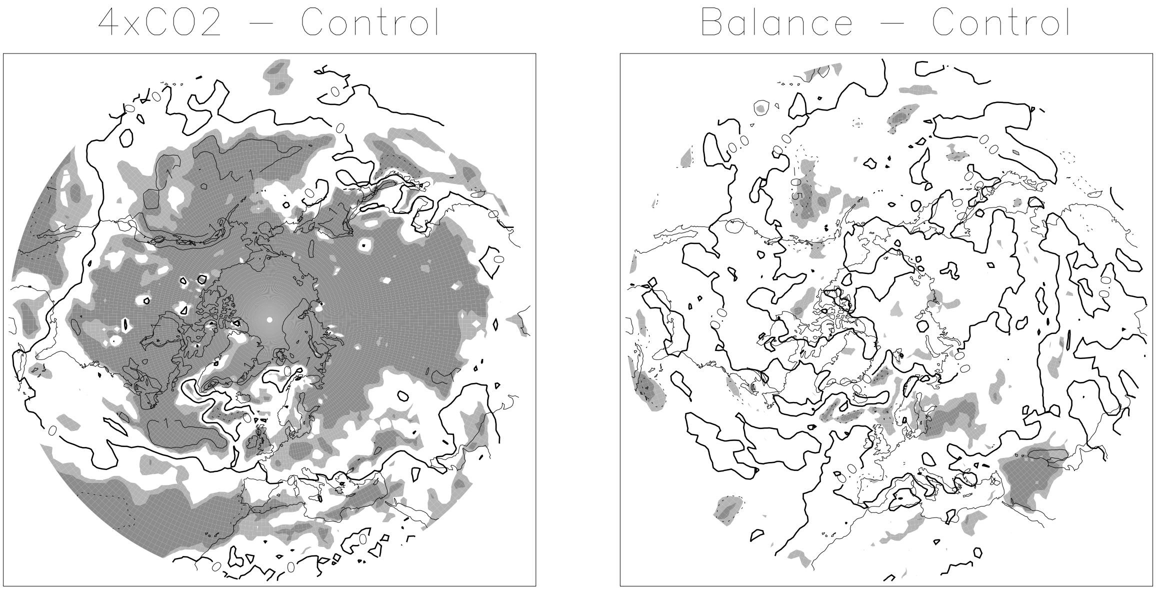


Figure 5.4: Winter (DJF) mean precipitation response calculated over the last 25 years. Left/Right: 4CO2/Balance.

In the Balance simulation the gradient in the stratospheric temperature response has almost disappeared (Fig. 5.1 right). This is due to an additional cooling in the polar stratosphere, which because of the absence of solar radiative forcing in this area must be related to a reduced dynamical down-welling. The waker change in the gradient leads to smaller (and statistically insignificant) changes in the stratospheric vortex (Fig. 5.2 right) which are now completely confined to the stratosphere with almost no changes in the troposphere.

The DJF surface temperature responses and precipitation responses are shown in Figs. 5.3 and 5.4. Again we note the strong and everywhere significant responses in the 4CO2 simulation and the surprisingly small and insignificant responses in the Balance simulation.

6. Conclusions

We have presented the first geoengineering experiment performed with EC-Earth at DKC. The experiment conforms to the GeoMIP standard for the G1 type experiment and includes a quadrupled CO_2 simulation and a simulation where the quadrupled CO_2 has been balanced by a reduction of the solar constant.

The simulations last 50 years and we have used the last 25 years – where the responses are saturated – to calculate the responses relative to a pre-industrial control simulation. The responses have been provided with estimates of the statistical significance calculated with a t-test assuming that annual (or winter) values are independent (thereby not underestimating the significance).

Our experiment confirms results from previous studies. The increase of the annual mean surface temperature due to the quadrupled CO_2 can to a remarkable degree be mitigated by the reduction in the solar constant (Govindasamy et al., 2003; Lunt et al., 2008; Matthews and Caldeira, 2007). For the precipitation a reduction of 10 % is found in the global annual mean (Bala et al., 2008) in the Balance simulation. However, locally it might be difficult to find a statistically significant change over a 25 years period.

While the mitigation works well near the surface and in the free troposphere both increasing CO_2 and a decreasing solar constant will cool the stratosphere. In the Balance simulation this cooling reaches values of -16 K in the upper stratosphere. Such a drastic cooling might have effects on stratospheric ozone (Heckendorn et al., 2009).

While most previous studies have focused on the annual mean response we have also considered the NH winter response. Here the direct radiative effect of a reduction of the solar constant is small. In the quadrupled CO_2 simulation we find a strong weakening in the stratospheric vortex which is felt throughout the whole atmospheric column and which at the surface corresponds to a change in the NAO towards its negative phase. This change has almost disappeared in the Balance simulation. Also the surface temperature and the precipitation is well mitigated when considering NH winter means.

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