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Key Points:

- The response of vegetation to SRM is dominated by the CO_2 fertilization effect
- Temperature and precipitation impacts are not negligible but vary regionally
- Modeled vegetation response varies, depending especially on the nitrogen cycle

Supporting Information:

- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7
- Figure S8
- Figure S9
- Figures S1–S9

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The impact of geoengineering on vegetation in experiment G1 of the GeoMIP

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Abstract Solar Radiation Management (SRM) has been proposed as a mean to partly counteract global warming. The Geoengineering Model Intercomparison Project (GeoMIP) has simulated the climate consequences of a number of SRM techniques. Thus far, the effects on vegetation have not yet been thoroughly analyzed. Here the vegetation response to the idealized GeoMIP G1 experiment from eight fully coupled Earth system models (ESMs) is analyzed, in which a reduction of the solar constant counterbalances the radiative effects of quadrupled atmospheric CO_2 concentrations (abrupt4 × CO2). For most models and regions, changes in net primary productivity (NPP) are dominated by the increase in CO_2, via the CO_2 fertilization effect. As SRM will reduce temperatures relative to abrupt4 × CO2, in high latitudes this will offset increases in NPP. In low latitudes, this cooling relative to the abrupt4 × CO2 simulation decreases plant respiration while having little effect on gross primary productivity, thus increasing NPP. In Central America and the Mediterranean, generally dry regions which are expected to experience increased water stress with global warming, NPP is highest in the G1 experiment for all models due to the easing of water limitations from increased water use efficiency at high-CO_2 concentrations and the reduced evaporative demand in a geoengineered climate. The largest differences in the vegetation response are between models with and without a nitrogen cycle, with a much smaller CO_2 fertilization effect for the former. These results suggest that until key vegetation processes are integrated into ESM predictions, the vegetation response to SRM will remain highly uncertain.

1. Introduction

Rising greenhouse gas (GHG) emissions are leading to global warming and climate change, which is affecting natural vegetation and agriculture, and will impact on human society in a number of ways [*Intergovernmental Panel on Climate Change* (*IPCC*), 2013]. To reduce the risks of these changes, efforts have begun to reduce GHG emissions through various means such as changing energy production, increased efficiency, and altered land use policies, but progress has been slow and emissions have continued to rise [*IPCC*, 2013]. Adaptation will be necessary to prepare societies for climate change and to reduce the impacts on ecosystems, but it will not be possible in all cases to effectively reduce the harms of climate change [*IPCC*, 2014]. These measures will take time, because even if emissions could be instantly halted, elevated GHG levels would persist and will continue to drive changes in the climate for many centuries [*Eby et al.*, 2009]. In part, due to the limited progress on mitigation, several ideas have been proposed for directly reducing concentrations of GHGs in the atmosphere, termed carbon dioxide removal (CDR) [*The Royal Society*, 2009]. CDR is one type of proposal under the broader term "climate engineering" or "geoengineering." Another type of proposal involves treating the symptoms of climate change, by reducing the global temperature, by reducing the amount of incoming sunlight, or by increasing the amount of outgoing short-wave or long-wave radiation; this is commonly called solar radiation management (SRM) [*The Royal Society*, 2009]. SRM would not reverse all of the effects of elevated GHG concentrations on the climate, but by cooling the climate may potentially reduce some of the risks of climate change [*Kravitz et al.*, 2014]. However, as SRM would not directly affect the concentration of CO_2, some effects, particularly ocean acidification, would remain [*Matthews et al.*, 2009].

Climate changes will impact vegetation and, in turn, the implementation of SRM would influence this impact [*Govindasamy*, 2002; *Naik et al.*, 2003; *Kravitz et al.*, 2013], leading to changes not only in biodiversity and ecosystem distributions but also to impacts on agriculture. There are many aspects of vegetation change that can be considered; in this study, the focus will be placed on the changes in carbon uptake by plants. The total carbon uptake by photosynthesis is referred to as the gross primary production (GPP); and after the loss of carbon to plant respiration (R_a, autotroph respiration), which is required for maintenance and growth of the plant, the net carbon uptake or net primary productivity (NPP) remains. NPP itself depends on climate conditions, with temperature, water availability, variability of climate, and radiation being the most important parameters [*Nemani et al.*, 2003]. Nutrient availability is also very important, depending on the region of interest; in addition to CO_2, the most important nutrients are nitrogen and phosphorus [*Thornton et al.*, 2009], though for some plant types other nutrients may also be of key importance.

The atmospheric CO_2 concentration determines how much carbon is available for vegetation; an increase in CO_2 will lead to a greater carbon uptake. This additional carbon is then used in various plant processes such as photosynthesis, which leads not only to increased plant growth but also, for example, to a change in stomatal opening, increasing the water use efficiency and thus NPP; furthermore, an increase in nutrient use efficiency will occur at higher atmospheric CO_2 concentrations [*Drake et al.,* 1997]. This effect is most important in dry regions [*Keenan et al.*, 2013]. Other limitations apart from CO_2 are also important, and some land models have begun to include the nitrogen cycle and represent the interactions of it with the carbon cycle. Models with no representation of the nitrogen cycle overestimate the influence of CO_2 fertilization and calculate such high NPP that the biosphere would need more nitrogen than is available without human influence [*Gruber and Galloway*, 2008; *Bonan and Levis*, 2010]. The significance of this nitrogen limitation on the potential CO_2 fertilization effect is not known and differs between models, but the inclusion of a nitrogen cycle does reduce the magnitude of the CO_2 fertilization effects in all models [*Thornton et al.*, 2009]. The inclusion of the nitrogen cycle in models is only a recent addition, and it is not yet known how well the implementation represents reality, as model validation is rather difficult. Climate changes will affect the nitrogen cycle and hence the productivity of plants in nitrogen limited conditions, as higher temperatures increase soil respiration, which increases the rate of nitrogen remineralization and hence plant productivity [*Bonan and Levis*, 2010]. Changes in the nitrogen cycle influence the carbon content of both the soil and the vegetation itself, and a change in climate leads to changes in both of these. The anthropogenic influence on the nitrogen cycle is substantial, through the addition of fertilizer to soils and indirectly through the deposition of nitrogen resulting from air pollution, and changes in these anthropogenic influences may dominate changes in natural sources in the future [*Gruber and Galloway*, 2008].

The most widely discussed technique for potentially implementing SRM is via injection of sulfur aerosol particles or precursors such as SO_2 in the stratosphere. This method would have many effects apart from global cooling, for example, effects on stratospheric ozone chemistry [*Rasch et al.*, 2008; *Tilmes et al.*, 2009]. Another widely discussed technique, though not very realistic with current technologies, is "sunshade geoengineering," equivalent to placing large reflecting mirrors in space. This is sometimes used as an approximation to the climate effects of stratospheric aerosol injections, since it can be simulated easily by a reduction in the solar constant in models and the effects on the surface may be similar [*Kalidindi et al.*, 2014]. Other studies, however, have shown substantial differences between the climate responses to the two methods [*Ferraro et al.*, 2015; *Niemeier et al.,* 2013]. There are great uncertainties in the climate response to sulfate aerosol injection, due to uncertainties in the aerosol cloud distribution that would result, which will be important in determining the climate response [*Pitari et al.*, 2014].

The reduction in sunlight has two effects on vegetation, a direct effect on plants through reduced light for photosynthesis and an indirect effect through climate changes [*Schmidt et al.*, 2012; *Kravitz et al.*, 2013]. In addition, a scenario with SRM would have elevated CO_2 relative to a baseline case; and hence, there would also be a CO_2 fertilization effect. The direct effect of reduced sunlight, though, has been found to have little influence on NPP [*Naik et al.*, 2003]. It is believed that the observed increase in the land carbon sink following the eruption of Mount Pinatubo was due to the increased fraction of diffuse light which gave rise to increased vegetation productivity; and hence, that sulfate injection SRM would give rise to a similar increase [*Mercado et al.*, 2009]. However, unlike sulfate aerosol injection SRM, a reduction of sunlight due to sunshade SRM would not result in a change in the ratio of direct to diffuse radiation. A number of studies have investigated the effects of elevated CO_2 concentrations together with SRM on vegetation and generally have found that the CO_2 fertilization effect is greater than the response of vegetation to the associated climate changes [*Govindasamy*, 2002; *Naik et al.*, 2003; *Jones et al.*, 2013; *Kravitz et al.*, 2013; *Xia et al.,* 2014], though the climate change impacts are not negligible. The earlier GeoMIP studies, which used most of the same models used in this study, found a wide range of vegetation responses within the ensemble but did not investigate the reasons behind this [*Jones et al.*, 2013; *Kravitz et al.*, 2013]. An exception to this is *Xia et al.* [2014], who used

Table 1. List of All Earth System Models With Their Respective Land Models Used in This Study and Some Key Features; Citations Are Included Where Available

Models (GCM)	Land Models	Dynamic Vegetation?	Nitrogen Cycle?
CCSM4 (*Gent et al.* [2011])	CLM4 (*Oleson et al.* [2010])	Yes	Yes
CESM-CAM5.1-FV	CLM4 (*Oleson et al.* [2010])	Yes	Yes
NorESM1-M (*Bentsen et al.* [2012])	CLM4 (*Lawrence et al.* [2011] and *Oleson et al.* [2010])	No	Yes
CanESM2 (*Arora et al.* [2011])	CLASS 2.7; CTEM 1.0 (*Verseghy et al.* [1993] and *Arora and Boer* [2010])	Yes	No
HadGEM2-ES (*Collins et al.* [2011])	MOSES 2 (*Essery et al.* [2003])	Yes	No
MIROC-ESM (*Watanabe et al.* [2011])	MATSIRO (*Takata et al.* [2003])	Yes	No
MPI-ESM-LR (*Giorgetta et al.* [2013])	JSBACH (*Raddatz et al.* [2007])	Yes	No
GISS-E2-R (*Schmidt et al.* [2006])	GISS-LSM (*Aleinov and Schmidt* [2006])	No	No

output from the GeoMIP ensemble and a crop model to simulate the impacts of sunshade SRM on different kinds of crops in China.

This study makes use of the data from the Geoengineering Model Intercomparison Project (GeoMIP) [*Kravitz et al.*, 2011] to examine the effects that SRM techniques would have on vegetation, and, by comparing the results from eight different fully coupled Earth system models, investigates the drivers for the range of model behavior within this ensemble.

2. Methodology

This study draws on results from experiment G1 of the Geoengineering Model Intercomparison Project (GeoMIP) [*Kravitz et al.*, 2011], an extension of phase 5 of the Coupled Model Intercomparison Project (CMIP5) [*Taylor et al.*, 2009]. In G1, the atmospheric CO_2 concentration is quadrupled, producing a positive radiative forcing which is counterbalanced by a reduction of the solar constant, leaving the radiative forcing the same as in the preindustrial control simulation. The other two experiments examined here are piControl and abrupt4 × CO2 (both from CMIP5) [*Taylor et al.*, 2009]. piControl is the control run which simulates ongoing preindustrial conditions; the different models do not agree on the exact conditions due to their large differences in describing some processes. The boundary conditions were fixed for piControl, and the simulations lasted many hundreds or thousands of years before the 40 year averaging period used in this study. abrupt4 × CO2 has the same setup as piControl but with an abruptly quadrupled atmospheric CO_2 content. For the analysis in this study, the years 111–150 after the initial increase in CO_2 concentration are chosen for each model to be able to examine a time period without rapid changes in global mean temperature. The experiment is still in a transient state, but we have sought to minimize the effects of this on the results by allowing this spin-up period. Experiment G1 [*Kravitz et al.*, 2011, Figure 1] has abrupt4 × CO2 as a basis but includes a simultaneous reduction of the solar constant in order to counterbalance the radiative forcing due to the increase in the atmospheric CO_2 content. For this study, the years 11–50 have been averaged, because after the initial 10 years the simulation there is little change in global climate conditions, and thus the remaining 40 years can be used for the analysis [*Kravitz et al.*, 2013]. This highly idealized experiment is not very realistic, but it has the advantage of a high signal-to-noise ratio and is a simple representation of SRM that should be informative for later analyses of more realistic scenarios. Both G1 and abrupt4 × CO2 have a fixed atmospheric CO_2 content, providing an unlimited source of carbon for vegetation, which would normally act to reduce CO_2 concentrations. Comparisons between G1 and abrupt4 × CO2 allow the effect of climate differences on vegetation to be isolated as both experiments have the same CO_2 content. All data were regridded to a uniform grid of 1° by 1° for the following analysis.

The experiment G1 has been performed by 13 models. *Kravitz et al.* [2013] analyzed the basic climate response to this experiment. However, not all of these models produced the necessary vegetation output for the analysis in the present study. The eight models that produced the output used here are listed in Table 1. The models in this ensemble differ in many respects, but the most significant difference for this study is the difference in the land surface scheme. The land surface models differ in their treatment of the carbon uptake from the atmospheric CO_2 content and in their treatment of photosynthetic and respiration processes. Whether or not a model has dynamic vegetation is important, as this allows the land surface type to adjust to changes in climate rather than retaining potentially uncompetitive, poorly adapted plant species. Which models have dynamic vegetation can be found in Table 1. Furthermore, only three out of eight models include a representation of the nitrogen cycle. The information in Table 1 is, to our best knowledge and belief, correct; however, the details of each model simulation, such as which models include dynamic vegetation and which do not, are often not documented in detail in publications describing and using the models. All assumptions made here about model setup are based on the information we found in literature, as well as following up with individual modelling groups in some cases.

Three models considered here which include a nitrogen cycle, Community Climate System Model Version 4 (CCSM4), CESM-CAM5.1-FV, and NorESM1-M all share the same land model (Community Land Model version 4.0, CLM4), which means that differences in the response of these models originate only from their atmospheric and oceanic components or from internal variability. Additionally, the climate models themselves are not wholly independent.

Most of the data used in this study is freely available on the site of the Program for Climate Model Diagnosis and Intercomparison (PCMDI; http://pcmdi9.llnl.gov/esgf-web-fe/) from where they have been downloaded. For both MPI-ESM-LR and NorESM1-M, G1 results can be found on the IMPLICC (Implications and Risks of Novel Options to Limit Climate Change) site (http://implicc1.dkrz.de:8080/thredds/catalog.html). For some of the data that could not be found on either of these two sites, the modeling groups were contacted directly, who made their data available for use.

A good overview of the overall performance of the latest generation of Earth system models can be found in *IPCC* [2013, chapter 9] which shows that the climate is generally sufficiently well represented in these models to support carrying out studies on model responses to various types of climate forcing. For the climate parameters, such as temperature and precipitation, a number of studies have investigated the performance of the CMIP5 models in detail [*Anav et al.*, 2013; *Tian et al.*, 2013]. Figure S1 in the supporting information shows a simple comparison between observations of surface air temperature and precipitation from the ERA40 (European Centre for Medium-Range Weather Forecasts Reanalysis) data set for 1961–1990 [*Uppala et al.*, 2005] and the ensemble mean of the piControl experiment. Making such comparisons between models and observations is more challenging for terrestrial vegetation processes, since direct measurements of many processes are not possible except at specific sites and key variables have to be determined indirectly from remote sensing data, resulting in considerable uncertainties [*Anav et al.,* 2013]. In Figure S1, we compare the ensemble mean of piControl NPP against the 2000–2013 mean of the MODIS (Moderate Resolution Imaging Spectroradiometer) NPP record, which estimates NPP by passively observing radiation returned from the land surface at a global scale. Despite the mismatch in time periods, these comparisons show that the models reproduce the general pattern of temperature and precipitation. For terrestrial vegetation variables, the models differ more from observations, though the models still capture the general picture quite well (Figure S1). For a more detailed assessment of the performance of CMIP5 models for terrestrial vegetation, see, for example, *Raczka et al.* [2013] and *Foley et al.* [2013], who find that the performance depends strongly on the regions, plant functional types, and other factors. Despite the limitations of current models' representation of terrestrial vegetation, they perform well enough to justify performing sensitivity simulations like those examined here [*Mao et al.,* 2012], and furthermore are the best tools available with which to gauge the effects of SRM on vegetation at a global scale.

3. Results

3.1. Global Vegetation Changes

Figure 1 shows the global mean NPP, GPP, and R_a for each model for the three experiments. Across the ensemble NPP, GPP, and R_a are all greater or substantially greater in abrupt4 × CO2 and G1 than in piControl; for example, NPP is about 90% greater in the ensemble mean, with relatively small differences between abrupt4 × CO2 and G1. GISS-E2-R skews these results as it has a remarkably low preindustrial NPP but shows some of the highest NPP values for abrupt4 × CO2 and G1 compared to the rest of the ensemble. If GISS-E2-R is excluded from the ensemble mean; NPP increases by less than 70% for both cases. For R_a, the differences between the experiments are not as large, showing that the large increases in NPP mainly come from the increases in GPP, which is because the CO_2 fertilization effect has a greater effect on GPP than on R_a. In contrast, these NPP results make clear that the differences in the atmospheric CO_2 content are the primary

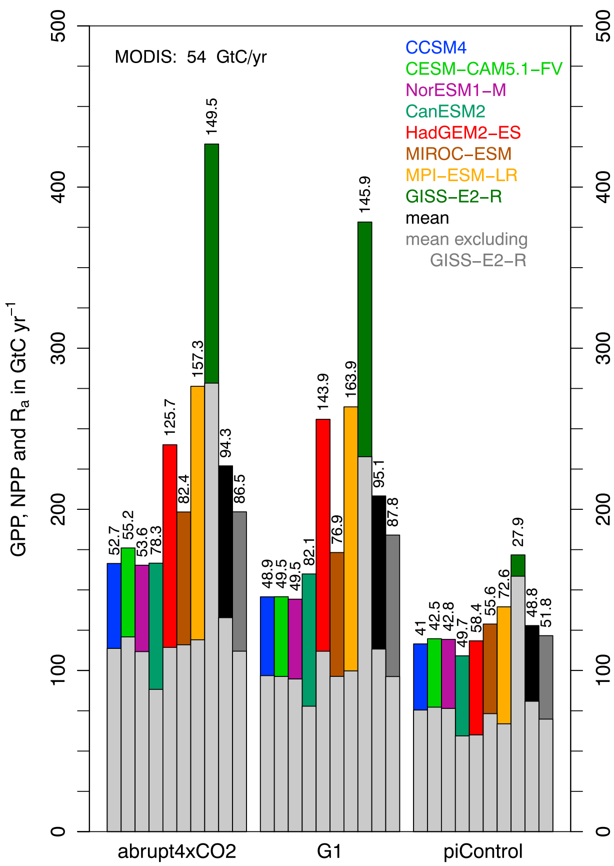

Figure 1. Global mean values for NPP averaged over land (colored with numbers above), R_a (grey) and GPP (total) for all models of the three experiments abrupt4 × CO2, G1, and piControl. The number in the top left corner is the global average of NPP determined from MODIS data.

driver of the differences in the global vegetation response as the NPP results for G1 and abrupt4 × CO2 are similar despite the difference between the climate in abrupt4 × CO2 and G1 being much larger than between G1 and piControl. Similar results were found by *Govindasamy* [2002] and *Naik et al.* [2003], as well as within GeoMIP by *Jones et al.* [2013] and *Kravitz et al.* [2013].

There is a wide range of responses for NPP, GPP, and R_a across the ensemble. However, the models results are consistent in that the responses to G1 and abrupt4 × CO2 for the individual models are similar. Three models (CCSM4, CESM-CAM5.1-FV, and NorESM1-M) share the same land model, CLM4, and these three models show a very similar response for both G1 and abrupt4 × CO2 which is much weaker than for the other models in this ensemble. This weaker response is likely due to the fact that CLM4 includes a nitrogen cycle, which is known to reduce the CO_2 fertilization effect relative to models that do not consider the limits imposed by the scarcity of nitrogen [*Thornton et al.*, 2009]. The presence or absence of a representation of the nitrogen cycle is not the only factor which affects the NPP response, which can be seen from the wide range of responses among the other models. Only three of the models, namely CanESM2, HadGEM2-ES, and MPI-ESM-LR, show a larger increase in global mean NPP for G1 than for abrupt4 × CO2, although this is enough to shift the ensemble mean response, which indicates that there are differences in how the models respond to different climates at the same atmospheric CO_2 concentration. GISS-E2-R (dark green in Figure 1) stands out from the rest of the ensemble, heavily influencing the ensemble mean, while it is unclear what the reason behind this is, an important consideration is that it does not have dynamic vegetation. Changes in climate conditions will normally lead to reduced productivity of the original plant type and ultimately a change in plant functional types. Models with fixed vegetation do not simulate this properly and will keep a certain prescribed plant functional type although it cannot persist, which leads to unrealistic values for the carbon exchanges. Given the extremely large climate and CO_2 concentration changes in this study this shortcoming means that GISS-E2-R will not be considered in the main analysis of this study.

3.2. Regional Climate and Vegetation Response to Geoengineering

Many aspects of the climate response to the G1 experiment have been investigated in a number of studies that appeared in a special section of the *Journal of Geophysical Research* (see *Kravitz et al.* [2013] for a general overview of the climate response); here a number of the key findings will be reiterated. Global mean temperature will rise in a scenario with higher CO_2 without sunshade geoengineering, with greatest increases at high latitudes and lesser increases in the tropics. G1 could counteract this on a global mean scale, but there would still be a small residual warming in the high latitudes compared to preindustrial times, and the tropics would generally see a slight overcooling (see Figure S2 for more details) [*Kravitz et al.*, 2014]. abrupt4 × CO2 would strengthen the hydrological cycle, increasing precipitation in wet regions and

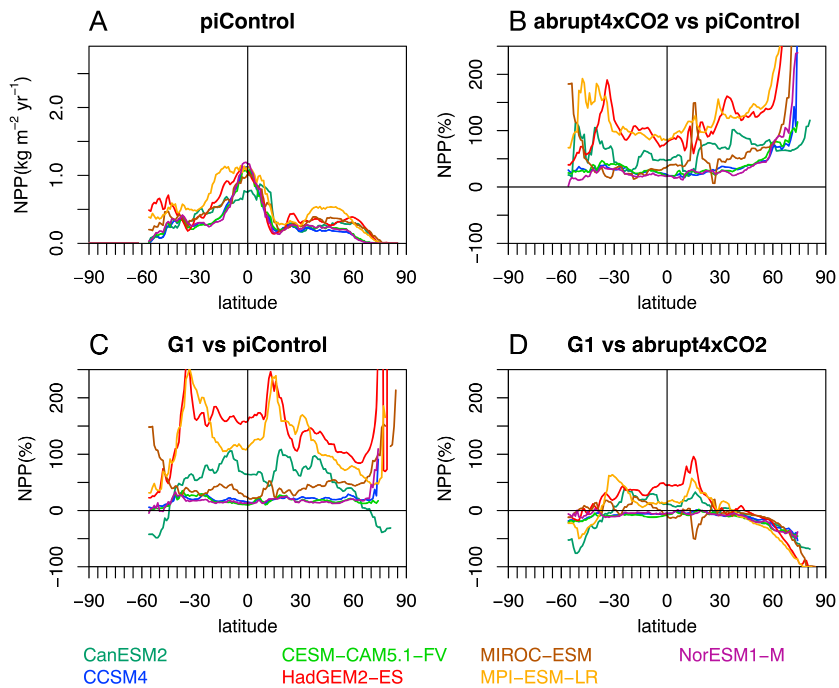

Figure 2. (a) Zonal mean values of NPP averaged over land for all models except GISS-E2-R, (b) percentage changes for the experiments abrupt4 × CO2 versus piControl, (c) G1 versus piControl, and (d) G1 versus abrupt4 × CO2.

decreasing it in dry regions [*Held and Soden*, 2006]. Here too, SRM would serve to counterbalance this, but in G1 the intensity of the global hydrological cycle is reduced below its preindustrial strength [*Tilmes et al.*, 2013]. The reductions in precipitation in G1 are strongest in the wettest regions, and models show a significant reduction in the intensity of the monsoons [*Tilmes et al.*, 2013]. SRM cannot simultaneously restore both the preindustrial global mean temperature and precipitation to the values of a low-CO_2 climate [*Irvine et al.*, 2010; *Ricke et al.*, 2010]; nevertheless, the models are generally in agreement that the climate of G1 is more similar to piControl than abrupt4 × CO2 [*Kravitz et al.*, 2014].

NPP is generally high in low and midlatitudes, and lower in high latitudes and in the dry subtropics for piControl (Figure 2a). Low NPP in high latitudes and montane regions is due to the short length of time every year when conditions are warm enough to allow vegetation to grow, whereas dry regions, which occur primarily in the subtropics, have low NPP due to there not being enough water available [*Nemani et al.*, 2003]. This general distribution of NPP is very similar across the ensemble, although there are substantial differences in the amount of NPP each model simulates; for example, in the midlatitudes MPI-ESM-LR has a value twice as high NPP than CCSM4. This shows how differently the models simulate the baseline state of the climate system which will have an influence on the response to a changing climate.

In the abrupt4 × CO2 experiments, all models show an increase in NPP everywhere, but the magnitude of change varies substantially, with small increases of about 20% for some models (CCSM4, CESM-CAM5.1-FV, and NorESM1-M) and large increases of about 100% for others (HadGEM2-ES and MPI-ESM-LR) across many latitudes (Figure 2b). This increase is likely due to the CO_2 fertilization effect in most regions, except that the warming in the coldest regions is likely more important there than the CO_2 fertilization effect. Although the models disagree on the amount of changes, they agree on the regions where the largest changes most likely would take place. The pattern of response for G1 versus piControl is similar to that of abrupt4 × CO2 versus piControl with higher NPP everywhere, except for CanESM2 in high latitudes (Figure 2c), which again provides evidence of the key role of the CO_2 fertilization effect in driving the response.

By comparing the experiments G1 and abrupt4 × CO2, the effect of climate changes can be investigated in the absence of the CO_2 fertilization effect (Figure 2d). For G1 versus abrupt4 × CO2, most models agree on higher NPP in low latitudes and lower NPP in higher latitudes. In the tropics, model differences are larger, and although some models compute an increase of NPP, others predict very small changes.

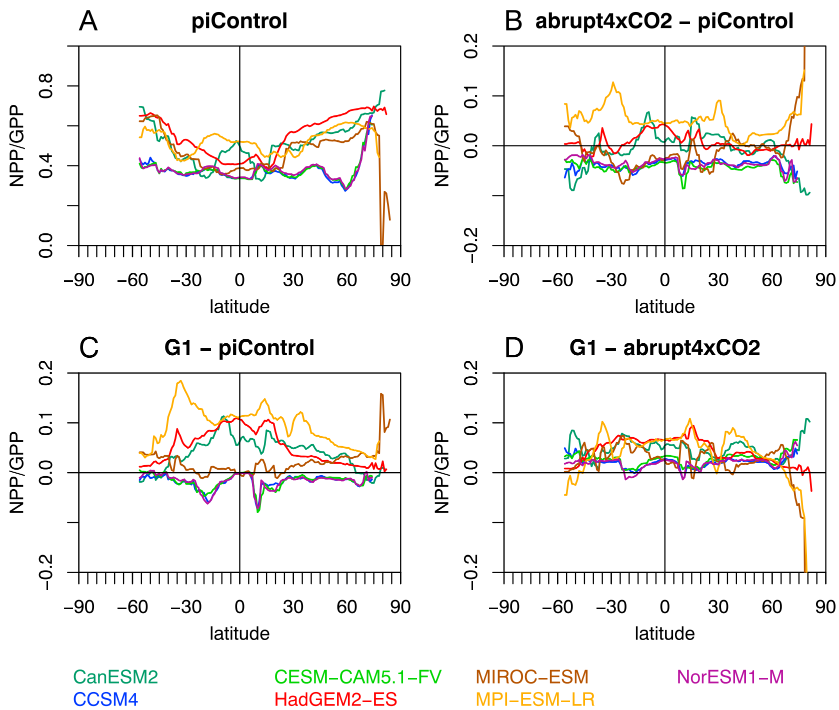

Figure 3. (a) Zonal mean values of NPP/GPP averaged over land for all models, absolute changes for the experiments (b) abrupt4 × CO2-piControl, (c) G1-piControl, (d) G1-abrupt4 × CO2.

Those models with CLM4 as land model predict a reduction in nearly all latitudes, which is likely due to differences arising from the inclusion of the nitrogen cycle; this issue will be discussed in greater detail in section 4. A change in heat stress will also play an important role in the vegetation distribution; abrupt4 × CO2 is much warmer than G1 and thus plants are more likely to suffer from heat stress, which in turn reduces NPP. In high latitudes, the effect of a shifting vegetation border is evident in all experiments; abrupt4 × CO2 versus piControl is considerably warmer, allowing vegetation growth and shifting the vegetation border poleward, thus resulting in NPP values greater than zero. For G1 versus abrupt4 × CO2, NPP is lower there, because the cooler climate of G1 influences the position of the vegetation border. For more details on this response, see Figures S3–S6.

The ratio NPP/GPP measures the carbon use efficiency of vegetation, as it is the ratio of the net uptake to the total uptake of carbon [*Choudhury*, 2000]. NPP/GPP cannot be greater than 1 and the highest observed annual means are about 0.8 [*Choudhury*, 2000]; if NPP is negative, NPP/GPP will also be negative and the vegetation will be dying back and losing mass. Changes of this ratio show how the carbon use efficiency changes with different conditions [*Choudhury*, 2000]. In piControl (Figure 3), the models range between 0.3 and 0.7 in high latitudes and generally show a lower ratio in low latitudes, but the CLM4 models show a more even distribution across all latitudes of around 0.35–0.4. In abrupt4 × CO2-piControl, the models disagree on the sign of the change in many regions but show little change ranging between about −0.05 to 0.05, whereas for G1-piControl the values of the change are higher and in most regions range between −0.02 and 0.1. For G1-abrupt4 × CO2, where it is only the climate changes that drive the response, the models all agree on the sign of the change, showing an increase of the carbon use efficiency. This may be due to the reduction of the temperature, leading to a lower respiration burden [*Tjoelker et al.*, 2001], which increases productivity. The temperature reduction leads to an increase in NPP/GPP as also shown by *Zhang et al.* [2014], who found a negative correlation between the ratio and temperature for all ecosystems.

3.3. Results for Representative Regions

Many factors influence the response of vegetation to climate changes; and therefore, a regional analysis is performed. For this, regions with known limitations or properties are chosen, in order to represent cold and dry regions, regions with high productivity, and regions in which drought is expected for global warming.

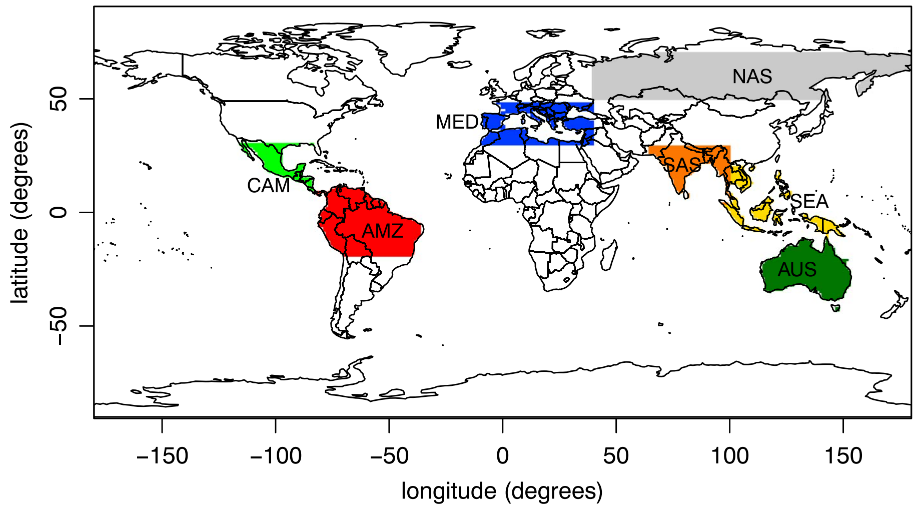

Figure 4. Regions as used in this study: NAS, North Asia; CAM, Central America; SAS, Southern Asia; MED, Mediterranean; AUS, Australia; AMZ, Amazon; SEA, South East Asia. The boundaries of the regions are the same as in *Giorgi and Francisco* [2000].

The region boundaries are the same as in *Giorgi and Francisco* [2000] and are shown for the regions used in this study in Figure 4. The ensemble of models in this study agrees on the general properties of the preindustrial climate conditions rather well (Figure 5). In piControl, regions such as the Mediterranean (MED), Australia (AUS), and Central America (CAM) are dry with lower precipitation minus evapotranspiration (P − E) and also less precipitation than other regions. Slight differences are seen in the models: in AUS, HadGEM2-ES, and MPI-ESM-LR have a very low precipitation, about half as much as the CLM4 models or MIROC-ESM. For P − E, the differences are even larger; in South East Asia (SEA), the models range between about 1 and 3 mm/d. North Asia (NAS) is cold, with a very low NPP for all models as the number of days with temperatures high enough for growing is low. NPP in piControl again shows similar features for all models, but there are some obvious differences. For example, the Amazon (AMZ), a warm and wet region, has a large difference in NPP depending on the models as well as in the hydrological cycle (both precipitation and P − E) and the same can be found for AUS. CLM4 models do have similar NPP in all regions; however, the climates are different, as generally CESM-CAM5.1-FV has a slightly weaker hydrological cycle than the other two, and temperatures are generally about 1°C higher for CESM-CAM5.1-FV, except in NAS.

In these regions, for changes in NPP in G1-piControl, the CO_2 fertilization effect dominates over the effects from climate change (Figure 6), which can be seen since in all regions and all models NPP increases for G1-piControl, although climate has changed in various ways. Overall, the climate changes are small, as cold regions (NAS) have slightly higher temperatures (about 1°C, depending on the model), while temperature changes in other regions are much smaller. In MED and CAM, both dry regions, precipitation is reduced, as has also been shown by *Schmidt et al.* [2012] and *Kravitz et al.* [2013], although for some models the change is very small. Water use efficiency will be higher in G1 than in piControl because of more CO_2 available, the plants will need to have their stomata open less frequently and thus will transpire less [*Keenan et al.*, 2013]. In a higher CO_2 world, plants are also expected to adapt to have fewer stomata per leaf area, which would similarly lead to an increase in water use efficiency if this were to be included in the models. However, models represent this effect very differently, and while, for example, MPI-ESM-LR shows a clear increase in water use efficiency, other models predict a much smaller effect. This means that water limitations for plants will change, and in G1 they might be able to grow better in drier regions than in piControl, which can be seen in the increase of NPP in these regions. In AUS, however, the models disagree on the sign of the change for the hydrological variables, which is also seen in the uncertainty concerning the NPP change. abrupt4 × CO2-piControl (Figure S7), which shows the effects of a higher atmospheric CO_2 content without Climate Engineering, has similar results to G1-piControl for NPP, which is due to the CO_2 fertilization effect. Climate changes between abrupt4 × CO2-piControl are very different than between G1-piControl, with a decrease in precipitation in dry regions (such as CAM and MED) and an increase of P − E in the same regions, suggesting that they get drier. Also, for abrupt4 × CO2-piControl, the cold regions get much warmer.

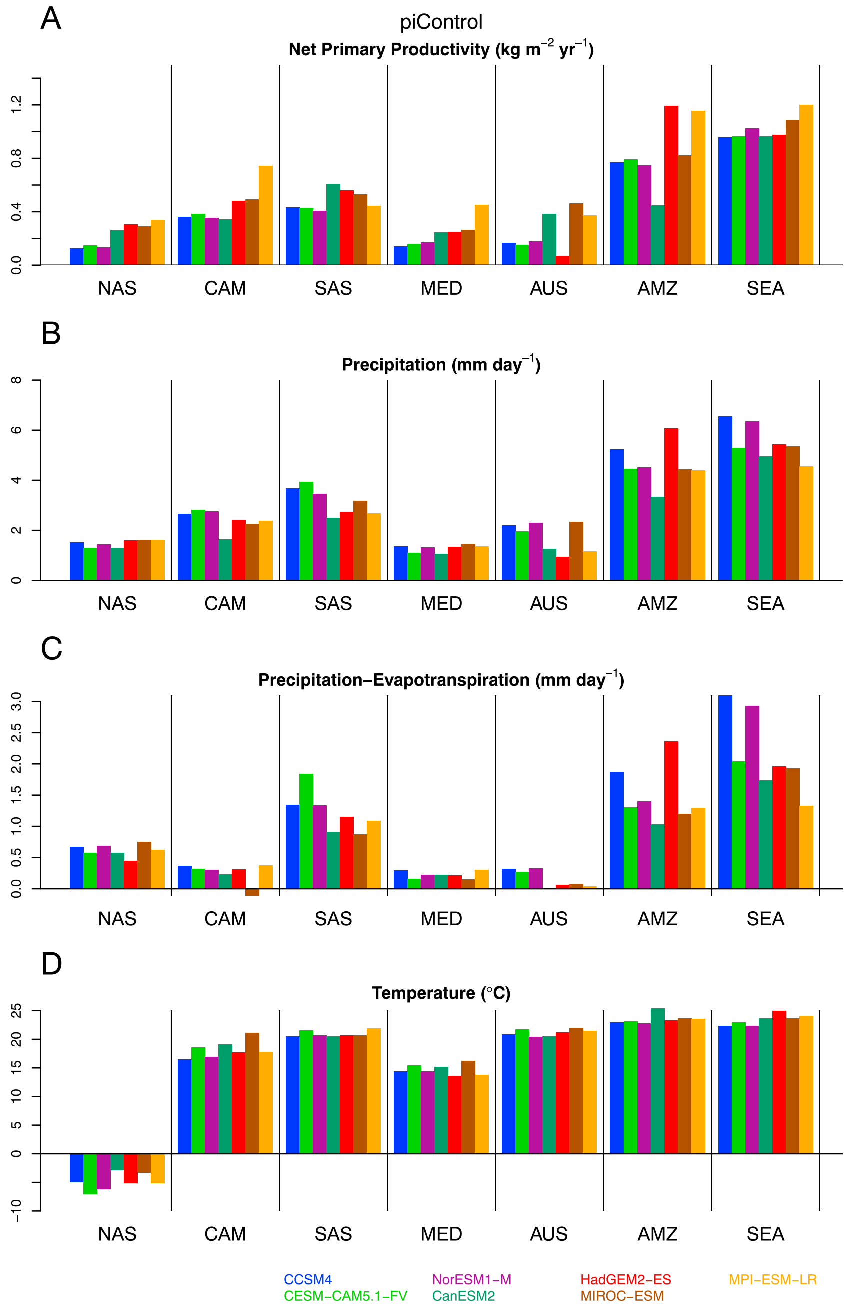

Figure 5. Actual values averaged over seven different regions from piControl per m^2, for (a) NPP, (b) precipitation, (c) P − E, and (d) temperature.

NPP in G1-abrupt4 × CO2 does not change much, which is mainly due to the fact that the CO_2 fertilization effect is present in both simulations, which masks some of the other effects climate differences may have. A comparison between G1 and abrupt4 × CO2 is able to show the effects of climate differences more clearly, because they both have the same atmospheric CO_2 concentrations. There are large increases in global mean and regional temperatures in abrupt4 × CO2 compared to piControl, as well as compared to G1. The hydrological cycle will change substantially for both abrupt4 × CO2 and G1 compared to piControl, having large effects on the environment. For abrupt4 × CO2-piControl, the hydrological cycle will strengthen, resulting in a drying of dry regions and wet regions getting wetter [*Held and Soden*, 2006]. G1 counteracts this so that there is even a weakening of the hydrological cycle in G1-piControl, with dry regions becoming wetter and vice versa [*Schmidt et al.*, 2012; *Tilmes et al.*, 2013], which means there is a strong change for

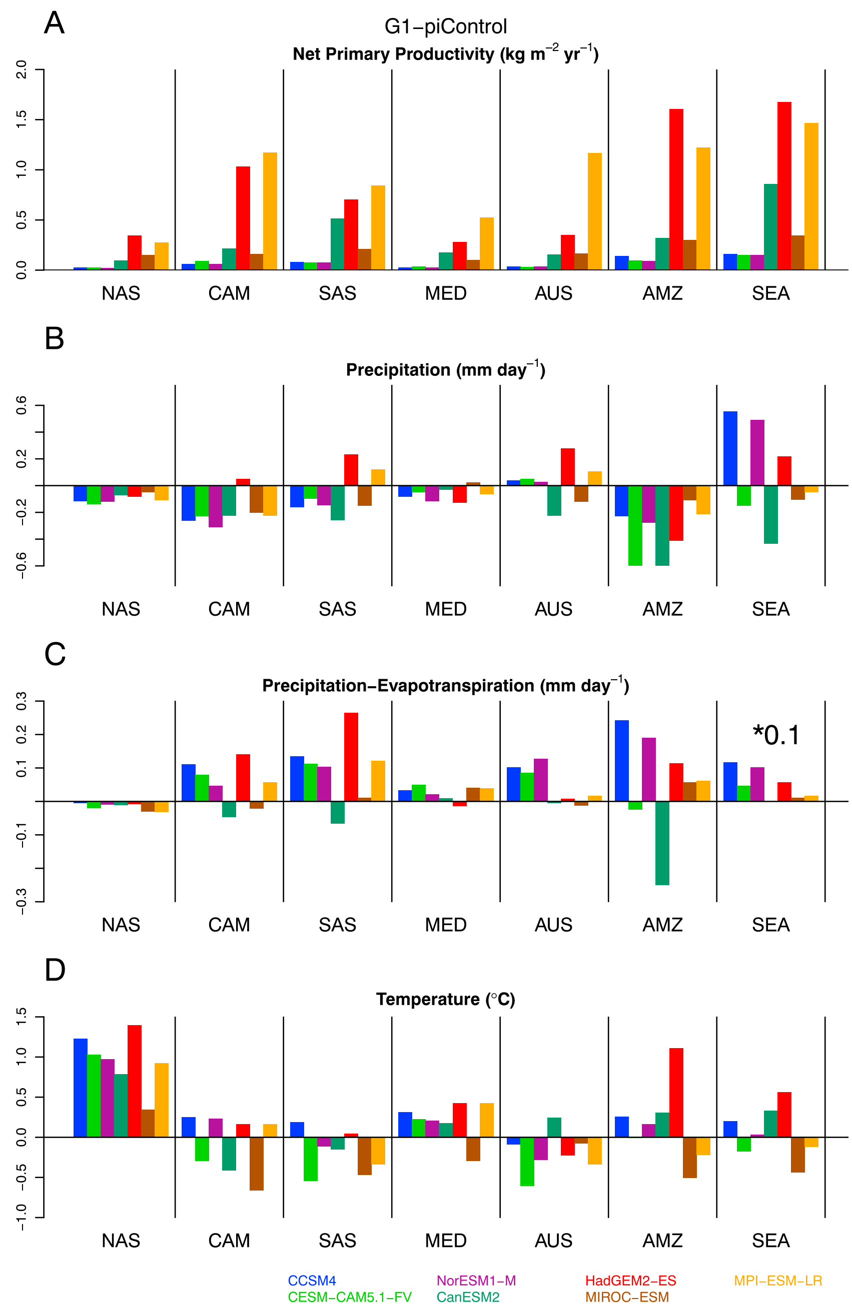

Figure 6. Same as Figure 5 but for the changes due to G1-piControl. For better visualization, values for precipitation-evapotranspiration in SEA are multiplied by 0.1.

G1-abrupt4 × CO2 of −10.7% in the global ensemble mean precipitation. This reduction of the water cycle leads to decreases in precipitation in wet regions, such as South Asia (SAS) and SEA. However, other components of the water cycle also change, such as evaporation and thus P − E, and a full examination of water cycle changes would be necessary before prediction of drought can be made; initial analyses along these lines are provided by *Tilmes et al.* [2013] and *Curry et al.* [2014]. Furthermore, the vegetation water demand changes, with lower evapotranspiration for lower temperatures, which can be seen here for G1-abrupt4 × CO2, which is similar to the findings of *Pongratz et al.* [2012], showing an increased crop yield in a geoengineered scenario. This shows that there are increases in NPP despite large reductions in precipitation, which means that lower gross water availability does not necessarily lead to less vegetation.

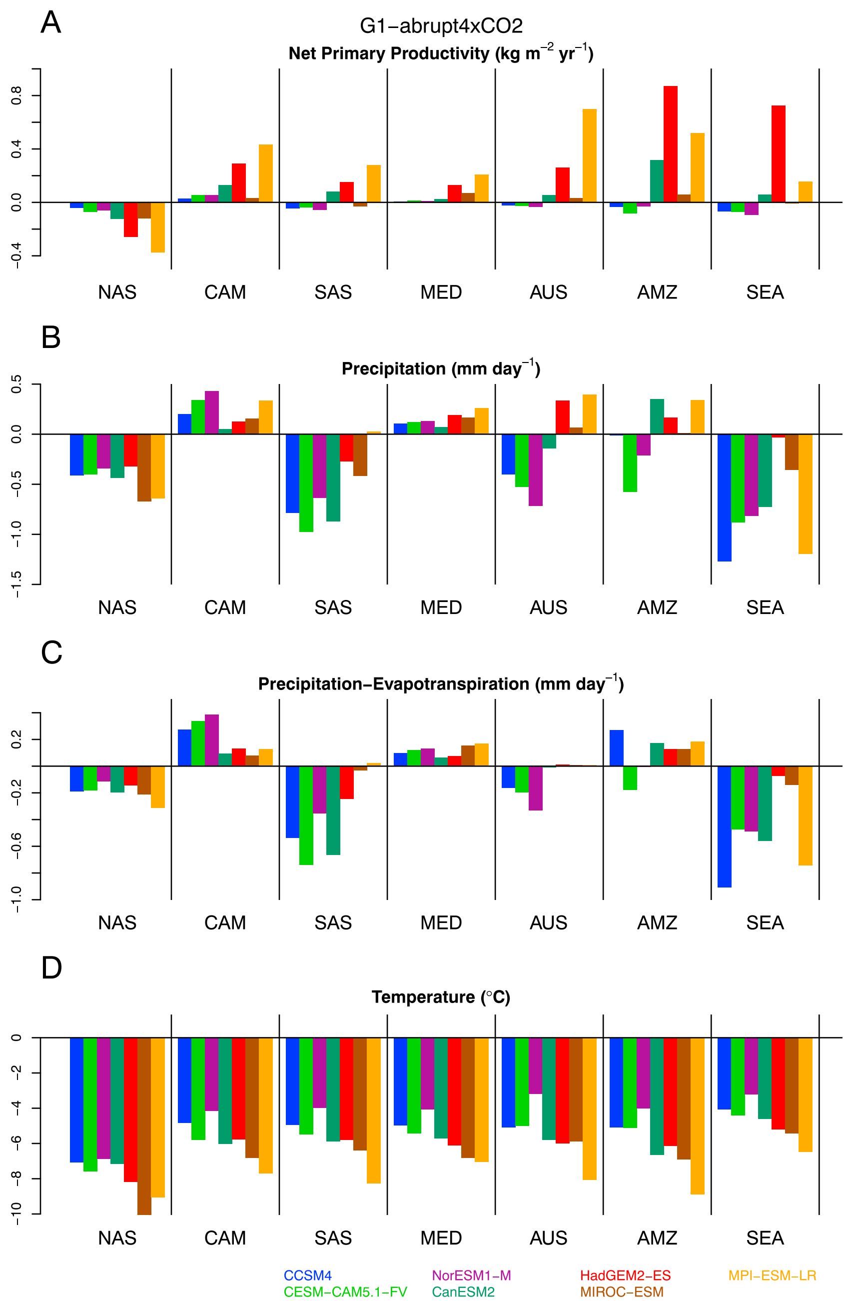

Figure 7. Same as Figure 5 but for G1-abrupt4 × CO2.

Climate changes in G1-abrupt4 × CO2 affect vegetation differently in each region, and although here only NPP is examined, it is clear that vegetation changes manifest themselves also in other ways. The global mean NPP in G1 and abrupt4 × CO2 is very similar due to the CO_2 fertilization effect, but there are regional differences due to climate changes. In all regions, all models show lower temperatures for G1-abrupt4 × CO2, with clear effects on vegetation extent in the cold NAS region (Figure 7; also compare to Figure 2d). In warm regions, however, a temperature decrease does not necessarily reduce NPP; in both SAS and SEA, temperature decreases, but some models still predict an increase in NPP (CanESM2, HadGEM2-ES, and MPI-ESM-LR), whereas the models that use CLM4 all show decreased NPP in these regions. In cool regions, the increase in temperature increases NPP as GPP increases due to the extended growing season which more than offsets the increased respiration rate at higher temperatures. For example in SEA, the ensemble mean respiration is approximately 11% less in G1 than in abrupt4 × CO2. Changes in the hydrological cycle will also affect

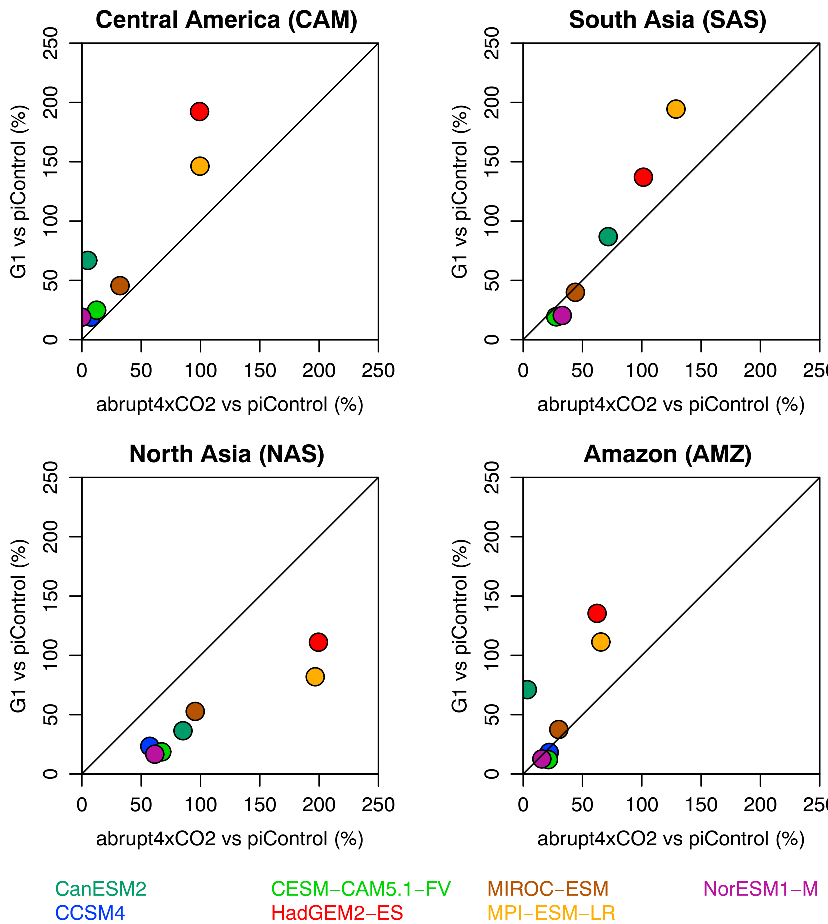

Figure 8. Percentage changes of the annual mean of NPP for all models for G1 and abrupt4 × CO2, both with respect to piControl for different regions. The diagonal line is a one-to-one line indicating where G1 and abrupt4 × CO2 show the same change for abrupt4 × CO2 compared to piControl as for G1 compared to piControl, which would be the case when the CO_2 fertilization effect is the only driver for NPP and the climate differences play no role or are all counterbalanced. Deviations from this line toward one axis indicate in which experiment the climate is more favorable for NPP, and the distance from the point of origin shows the strength of the CO_2 fertilization effect.

vegetation, with a potential increase of droughts in both experiments; some regions may be drier in G1, others in abrupt4 × CO2. MED and CAM, two dry regions, shift toward more precipitation and higher P − E, which suggests more water availability for G1-abrupt4 × CO2; this is reflected in the higher NPP. Model differences are particularly notable in AUS and AMZ, with different reasons for each; while in AUS, the higher precipitation results in higher NPP, in AMZ given the large role of transpiration in recycling precipitation in this region it is unclear which factor is leading the other. Model uncertainties in NPP and the hydrological cycle are clearly linked, as they influence each other through their interactions, which can be seen for both AMZ and AUS and has also been shown by *Irvine et al.* [2014]. In very high productivity regions, such as SEA, there is a very large difference in simulated NPP, which might be reduced by inclusion of the nitrogen cycle [*Thornton et al.*, 2009].

To assess the overall changes in NPP, the percentage changes for both experiment G1 and abrupt4 × CO2 relative to piControl for all models are shown in Figure 8, for four representative regions, NAS, CAM, SAS, and AMZ. The same can be found for the regions AUS, MED, and SEA in Figures S8 and S9 for the same regions as in Figure 8 but including the model GISS-E2-R. The black identity line in the figure indicates the values where the percentage change is the same for abrupt4 × CO2 compared to piControl as for G1 compared to piControl, which would be the case when the CO_2 fertilization effect is the only driver for NPP and the climate differences play no role or are all counterbalanced. Values deviating from this line toward one axis indicate that the climate is more favorable for NPP in the associated experiment, i.e., below the line, abrupt4 × CO2 is relatively more productive and G1 relatively less productive, and vice versa. The regions chosen represent four different conditions: CAM was chosen as a dry region, NAS as a cold region, AMZ as one of the highest productivity regions, and SAS was chosen because previous studies have pointed to the possibility of increasing droughts under a geoengineering scenario in this region [*Schmidt et al.*, 2012].

As seen above, the CO_2 fertilization effect, which is represented by the spread along the diagonal line in Figure 8, varies between the models and strongly influences the resulting NPP. HadGEM2-ES and MPI-ESM-LR have a particularly strong CO_2 fertilization effect, much more so than CCSM4, CESM-CAM5.1-FV, and NorESM1-M, the three models with a nitrogen cycle. NAS shows consistently and substantially higher NPP for abrupt4 × CO2, roughly twice the G1 value, due to the longer growing period for vegetation at higher temperatures in this region. In warm regions, such as SAS and SEA, the temperature changes do not have such a clear effect; on the one hand, a lower temperature means less respiration, increasing NPP, but the lower soil respiration decreases nitrogen availability, thus potentially reducing NPP in models that include a nitrogen cycle. This feedback is only considered in the models that use CLM4, which do indeed show a decrease in NPP for G1. Changes in the hydrological cycle, another important aspect of climate change, will have the greatest influence on dry regions, such as CAM. CAM shows a decrease in precipitation for G1 but an increase in $P - E$, which along with the reduction in temperature is responsible for the substantially greater NPP in G1 seen in all models. Another factor that will increase NPP for both G1 and abrupt4 × CO2 is that the water use efficiency increases with a higher CO_2 level, allowing greater productivity in dry conditions. For abrupt4 × CO2, the simulated drying of CAM leads to little change in NPP compared to piControl in some models, despite this increase in water use efficiency in this water limited regions.

In summary, for all models the largest effect in abrupt4 × CO2 and G1 is the CO_2 fertilization effect, but there are large differences between the models, especially due to the effect of including the nitrogen cycle. The impacts of the different responses of temperature and the hydrological cycle to G1 and abrupt4 × CO2 depend on the region under consideration. The clearest signal is the increase in NPP in high latitudes (NAS) in response to warming due to the extended growing season. The response to the reduction in temperature in G1 compared to abrupt4 × CO2 is less clear in other regions. This is because lower temperatures lead to three competing effects: reduced respiration, which would tend to increase NPP; and reduced cycling of nitrogen in soils, which suppresses NPP in models that include a nitrogen cycle; in cold regions, a lower temperature shortens the growing season, reducing NPP. The increased water use efficiency at elevated CO_2 concentrations means that dry regions would have higher NPP if climate conditions did not differ from the preindustrial. However, precipitation is reduced in most regions in G1-abrupt4 × CO2, while the demand for water for evapotranspiration is reduced by even more in some dry regions, driving an increase in NPP in these regions.

4. Discussion

4.1. Linked Carbon, Water, and Nitrogen Cycles

Two important feedbacks of the terrestrial carbon cycle are the concentration-carbon feedback and the climate-carbon feedback, both represented differently in each of the models examined in this study, which adds uncertainties to the results [*Bonan and Levis,* 2010]. These are the most important feedbacks in the context of this study, and the only ones examined here. The positive concentration-carbon feedback describes the CO_2 fertilization effect with increased plant growth at higher atmospheric CO_2 concentrations, which has been shown to have a large effect on vegetation everywhere on the planet. However, there is also contrasting evidence that this effect might be much smaller, and that trees might not increase growth at all with an increased water use efficiency [*van der Sleen et al.,* 2014]. Including the nitrogen cycle reduces this feedback, as models with no nitrogen cycle tend to overestimate the CO_2 fertilization effect due to representing more vegetation than could realistically be sustained with the available nitrogen. The magnitude of this effect depends on the model; CLM4 includes a nitrogen cycle, but a much larger reduction of the CO_2 fertilization effect within CLM4 compared to other models has been noted in another study [*Bonan and Levis*, 2010], which could suggest that CLM4 may not be representative of the general effect of including a nitrogen cycle in land surface models.

The most significant aspects of the climate-carbon feedback is the reduced net carbon uptake at higher temperatures due to increased respiration [*Bonan and Levis*, 2010]. However, in cold regions this is overcompensated by the importance of the temperature limitation, which limits plant growth. Furthermore, nitrogen availability is affected by temperature; a rise in temperature increases soil respiration, in turn overcoming nitrogen limitations by increasing nitrogen availability and hence NPP in nitrogen limited regions. This acts against the general climate-carbon feedback, weakening it and increasing plant growth as well as CO_2 uptake. Generally, for abrupt4 × CO2-piControl, this effect is not as important because it is dominated by the large CO_2 fertilization effect. For G1-abrupt4 × CO2, the climate effect is much more important because the CO_2 levels are the same, and thus the climate impacts dominate. The effect of climate on the nitrogen cycle dominates in the models which include CLM4 (the only land surface model with a nitrogen cycle in this study), whereas in the others the effect of temperature on respiration is the dominant factor outside of the high latitudes (Figure 7). In tropical rainforests, this nitrogen-climate feedback might be especially important, because nitrogen is limited there and thus changes in nitrogen have a large effect [*Thornton et al.*, 2009].

The CO_2 fertilization effect affects the terrestrial hydrological cycle substantially and this is represented rather differently by the models. Higher atmospheric CO_2 concentrations reduce the necessity for the plants to open their stomata to gain the CO_2 they require; this in turn has a large influence on the hydrological cycle as the plants will transpire less [*Franks et al.*, 2013; *Gerten*, 2013]. Also, if the plants lose less water, they will be able to better survive in dry regions where there is low water availability due to their increased water use efficiency [*Franks et al.*, 2013], thus this effect has a large influence in dry regions. With the inclusion of a nitrogen cycle in all the models, it could be expected that the range of the simulated NPP would decrease because the nitrogen would act as an upper limit to it [*Thornton et al.*, 2009]. This again would result in changes in the climate and particularly in the hydrological cycle. As transpiration declines with increasing CO_2 concentrations and increases with elevated NPP, this leads to less precipitation recycling in models which simulate smaller increases in NPP [*Irvine et al.*, 2014], indicating an influence of the nitrogen cycle on the hydrological cycle.

4.2. Limitations to the Approach

There are several potential limitations to this study. First, the limited number of models is likely to not be representative of the real response of the Earth system to changes. An ensemble mean is only of limited usefulness, because the models are related to each other in varying degrees [*Knutti et al.*, 2013], which influences the results. CCSM4 and CESM-CAM5.1-FV are closely related, and together with NorESM1-M they share the same land model (CLM4). Still, many model differences can be found, as each model includes different climate processes and most models have differences in the land surface representations, especially the inclusion of the nitrogen cycle has a major influence on the results. Unfortunately, CLM4 is the only land model with a representation of the nitrogen cycle in this ensemble, and in order to isolate effects it would be useful to compare it to other models with a nitrogen cycle. However, the land models that are integrated into global climate and Earth system models have only recently started to include the nitrogen cycle, and thus such a comparison may have to wait until the next generation of models is developed.

It is difficult to attribute changes clearly to only one cause due to the complexity of the Earth system and because many components of it change simultaneously in a changing climate. Temperature changes seem to have different effects in different regions; in cold regions, the increase of temperature results in a higher number of growing degree days in a year, increasing NPP, but in warm regions there are various effects and drivers of NPP changes. Counteracting effects complicate it further, such as the increase of respiration with temperature leading to a reduction of plant productivity on the one hand, but on the other hand increasing the nitrogen availability for those models including the nitrogen cycle. A comparison of piControl to both abrupt4 × CO2 and G1 is always dominated by the CO_2 fertilization effect, masking the changes due to climate changes; in the comparison G1-abrupt4 × CO2, this is not the case, allowing the response to the climate differences to be isolated. Vegetation changes are not limited to changes in NPP, for example, the length of the growing season or plant types and their distribution are important factors. Some models included dynamic vegetation, whereas others did not, but given that this choice was not always clearly presented, we generally encourage modeling groups to better document the model setups employed. A more detailed analysis could be made. by using land models that include more processes, such as nitrogen and phosphorous cycles, or by analyzing the changes in vegetation type distributions. Also, by coupling the same land model to different climate models or comparing different land models coupled to the same

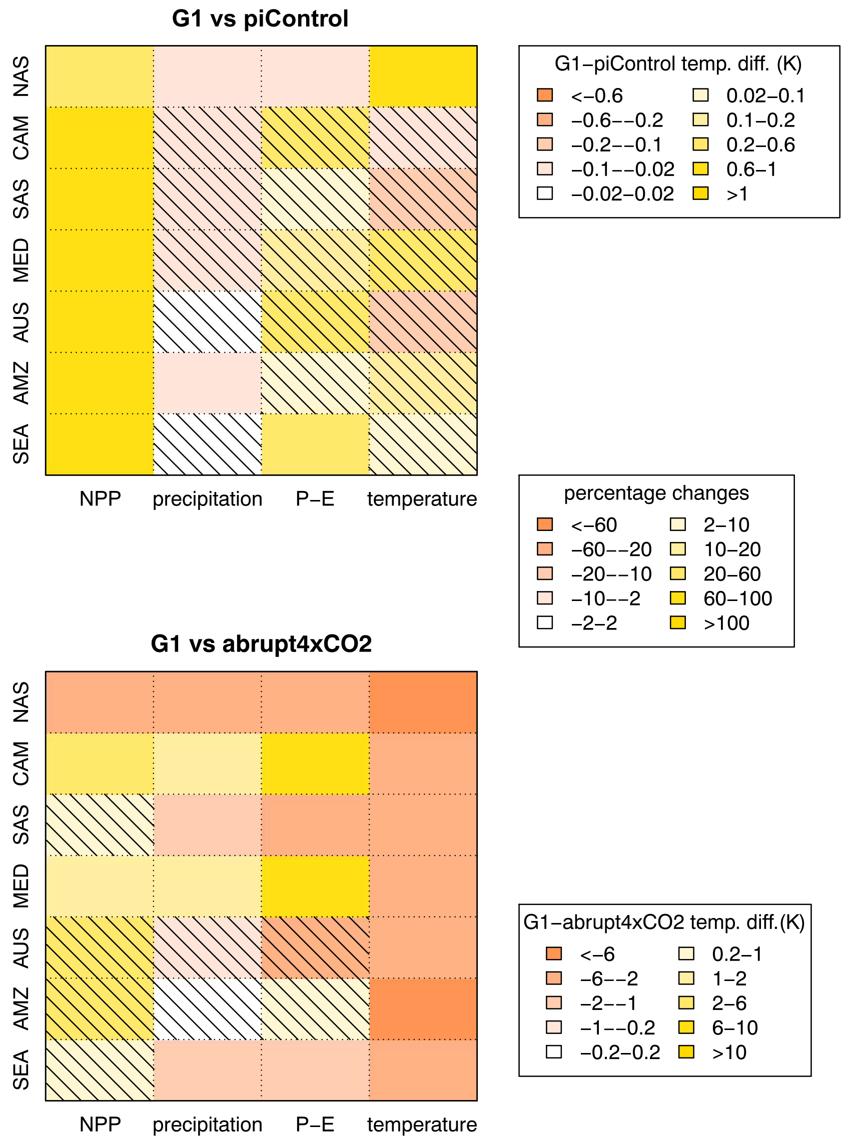

Figure 9. Ensemble mean change in each region; hashing shows where models disagree on sign of change, NPP, precipitation, and P − E all have the same legend and are in %, temperature is in °C.

climate model, it would be possible to identify which processes result in the simulated changes. Additionally, further experiments could help to understand the interactions; for example, running a land model without accounting for the increase of CO_2, but still including the climate changes, would isolate the effects of a changing climate without the CO_2 fertilization effect.

The experiments in this study are not meant to be realistic, being based on the CMIP5 and GeoMIP protocols for an instantaneous quadrupling of CO_2, but experiments such as these are useful to elucidate the interactions between climate and vegetation. In these long simulations, transient effects have been neglected. Under more realistic scenarios, vegetation types would need time to change and to develop a new equilibrium and the changes during this adjustment period would be relevant. Other issues are also important, such as anthropogenic nutrient addition, which modifies the cycles of nitrogen and other substances like phosphorus, in turn having large effects on vegetation, especially in regions with low natural nutrient availability [*Gruber and Galloway*, 2008]. In some regions, such as the tropics, changes in phosphorus, which no model in this study represented, might have large effects on the ecosystem. These are some of the many aspects of the response of the Earth system to SRM which could be examined in more detail in future studies.

5. Conclusions

In examining output from three simulations performed by a set of models as part of GeoMIP, this current study has found that for changes in vegetation growth in a scenario with quadrupled CO_2 levels (abrupt4 × CO2) and another in which the mean warming is balanced by a reduction in the solar constant (G1), the most important factor influencing changes is the CO_2 fertilization effect, significantly outweighing the effects of changes in climate parameters. Higher NPP for both G1 and abrupt4 × CO2 than for the preindustrial control run (piControl) can be seen for all models in all regions, but the models that use CLM4 as the land model have a somewhat smaller response to the CO_2 fertilization effect due to the reduced concentration-carbon feedback that occurs when the nitrogen cycle is included. The higher atmospheric CO_2 content also leads to increased water use efficiency in all models, because the plants have more CO_2 available and thus they do not need to open their stomata as long as otherwise in order to take up the same amount of CO_2, which results in reduced water loss from the plants. This means the plants can survive at lower water availability for higher CO_2 concentrations, and they can thus increase their productivity in dry regions [*Donohue et al.*, 2013].

The best way to show the climate impacts on vegetation is to compare the two experiments with the same atmospheric CO_2 content in order to eliminate the large effect from CO_2 fertilization, which largely masks the other changes. The comparison G1-abrupt4 × CO2 (Figure 9b) shows the different effects that a temperature decrease has in different regions; in cold, temperature limited regions, a decrease in temperature leads to a reduction of NPP, whereas in warmer regions a reduction of temperature can lead to a decrease of respiration and thus to an increase in the net carbon uptake. An increase of temperature also leads to increased nitrogen availability through an increase in soil respiration, which is important for those models with a nitrogen cycle (CCSM4, CESM-CAM5.1-FV, and NorESM1-M). Changes in the hydrological cycle are evident; abrupt4 × CO2 shows a strengthening whereas G1 shows a weakening of the hydrological cycle compared to piControl (Figure 9a). This weakening of the hydrological cycle in G1 does not necessarily imply a drying for vegetation, however, since the effects of reduced precipitation are often counteracted by reduced evapotranspiration, leading to a net increase in precipitation-evaporation in most regions. The higher CO_2 content could also improve water use efficiency, reducing the risks for the plants due to a weakened hydrological cycle. However, in some dry regions, such as Central America and the Mediterranean, both precipitation and evapotranspiration are greater in G1 than abrupt4 × CO2 leading to substantial increases in NPP for G1-abrupt4 × CO2. The reduction in precipitation that has been highlighted as a concern for SRM is mostly found in wet regions, where water is often not the limiting factor.

Vegetation and climate interact and influence each other, having large effects on ecosystems and hydrology. Models simulating this have large differences but generally agree well on the sign of changes, although not on the magnitude. The vegetation changes between G1 and piControl vary notably, depending on the model as well as the regions, even more so than the climate changes, on which the models agree better. The inclusion of a nitrogen cycle was found to significantly alter the magnitude of the CO_2 fertilization effect; CCSM4, CESM-CAM5.1-FV, and NorESM1-M agree on most results for vegetation changes, with small differences in the climate results, which is due to the shared land model CLM4. All three of the models thus include the nitrogen cycle, which reduces the CO_2 fertilization effect by influencing both the climate-carbon feedback and the concentration-carbon feedback, which is the reason why these have much smaller changes in NPP for G1-piControl than all other models for most regions. If models with a nitrogen cycle are more realistic than others, it would be very important to include the cycle in all other models to see how vegetation changes, as there are even differences in the sign of the prediction of the change of NPP in some regions.

Vegetation changes influence the climate and vice versa, which is the reason why these changes are so important for shaping the hydrological cycle and broader climate response on land and for determining the uncertainties surrounding these [*Irvine et al.,* 2014]. Although the hydrological cycle would be weakened by SRM, this might not lead to a reduction of vegetation productivity, which could even be increased relative to a low-CO_2 baseline due to improved water use efficiency at higher CO_2 concentrations. This study has provided several insights into the changes expected in vegetation under scenarios of climate change and implementation of SRM; further studies elucidating the details of these responses, especially with future generations of improved models, would be valuable for providing a more extensive information basis for making decisions about potential future deployment of various proposals for SRM geoengineering.

Acknowledgments

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References

Aleinov, I., and G. A. Schmidt (2006), Water isotopes in the GISS ModelE land surface scheme, *Global Planet. Change*, *51*(1–2), 108–120, doi:10.1016/j.gloplacha.2005.12.010.

Anav, A., P. Friedlingstein, M. Kidston, L. Bopp, P. Ciais, P. Cox, C. Jones, M. Jung, R. Myneni, and Z. Zhu (2013), Evaluating the land and ocean components of the global carbon cycle in the CMIP5 Earth system models, *J. Clim.*, *26*, 6801–6843, doi:10.1175/JCLI-D-12-00417.1.

Arora, V. K., and G. J. Boer (2010), Uncertainties in the 20th century carbon budget associated with land use change, *Global Change Biol.*, *16*(12), 3327–3348, doi:10.1111/j.1365-2486.2010.02202.x.

Arora, V. K., J. F. Scinocca, G. J. Boer, J. R. Christian, K. L. Denman, G. M. Flato, V. V. Kharin, W. G. Lee, and W. J. Merryfield (2011), Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases, *Geophys. Res. Lett.*, *38*, L05805, doi:10.1029/2010GL046270.

Bentsen, M., et al. (2012), The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation, *Geosci. Model Dev. Discuss.*, *5*, 2843–2931, doi:10.5194/gmdd-5-2843-2012.

Bonan, G. B., and S. Levis (2010), Quantifying carbon-nitrogen feedbacks in the Community Land Model (CLM4), *Geophys. Res. Lett.*, *37*, L07401, doi:10.1029/2010GL042430.

Choudhury, B. J. (2000), Carbon use efficiency, and net primary productivity of terrestrial vegetation, *Adv. Space Res.*, *26*(7), 1105–1108, doi:10.1016/S0273-1177(99)01126-6.

Collins, W. J., et al. (2011), Development and evaluation of an Earth-System model—HadGEM2, *Geosci. Model Dev.*, *4*, 1051–1075, doi:10.5194/gmd-4-1051-2011.

Curry, C. L., et al. (2014), A multi-model examination of climate extremes in an idealized geoengineering experiment, *J. Geophys. Res. Atmos.*, *119*, 3900–3923, doi:10.1002/2013JD020648.

Donohue, R. J., M. L. Roderick, T. R. McVicar, and G. D. Farquhar (2013), CO_2 fertilization has increased maximum foliage cover across the globe's warm, arid environments, *Geophys. Res. Lett.*, *40*, 3031–3035, doi:10.1002/grl.50563.

Drake, B. G., M. A. Gonzalez-Meler, and S. P. Long (1997), More efficient plants: A consequence of rising atmospheric CO_2?, *Annu. Rev. Plant Physiol. Plant Mol. Biol*, *48*, 609–639, doi:10.1146/annurev.arplant.48.1.609.

Eby, M., K. Zickfeld, A. Montenegro, D. Archer, K. J. Meissner, and A. J. Weaver (2009), Lifetime of anthropogenic climate change: Millennial time scales of potential CO_2 and surface temperature perturbations, *J. Clim.*, *22*(10), 2501–2511, doi:10.1175/2008JCLI2554.1.

Essery, R. L. H., M. J. Best, R. A. Betts, P. M. Cox, and C. M. Taylor (2003), Explicit representation of subgrid heterogeneity in a GCM land surface scheme, *J. Hydrometeorol.*, *4*(3), 530–543, doi:10.1175/1525-7541(2003)004<0530:EROSHI>2.0.CO;2.

Ferraro, A. J., A. J. Charlton-Perez, and E. J. Highwood (2015), Stratospheric dynamics and midlatitude jets under geoengineering with space mirrors and sulfate and titania aerosols, *J. Geophys. Res. Atmos.*, *120*, 414–429, doi:10.1002/2014JD022734.

Foley, A. M., et al. (2013), Evaluation of biospheric components in earth system models using modern and palaeo-observations: The state-of-the-art, *Biogeosciences*, *10*(i), 8305–8328, doi:10.5194/bg-10-8305-2013.

Franks, P. J., et al. (2013), Sensitivity of plants to changing atmospheric CO_2 concentration: From the geological past to the next century, *New Phytol.*, *197*(4), 1077–1094, doi:10.1111/nph.12104.

Gent, P. R., et al. (2011), The community climate system model version 4, *J. Clim.*, *24*, 4973–4991, doi:10.1175/2011JCLI4083.1.

Gerten, D. (2013), A vital link: Water and vegetation in the Anthropocene, *Hydrol. Earth Syst. Sci.*, *17*(10), 3841–3852, doi:10.5194/hess-17-3841-2013.

Giorgetta, M. A., et al. (2013), Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the coupled model intercomparison project phase 5, *J. Adv. Model. Earth Syst.*, *5*, 572–597, doi:10.1002/jame.20038.

Giorgi, F., and R. Francisco (2000), Uncertainties in regional climate change prediction: A regional analysis of ensemble simulations with the HADCM2 coupled AOGCM, *Clim. Dyn.*, *16*(2–3), 169–182, doi:10.1007/PL00013733.

Govindasamy, B. (2002), Impact of geoengineering schemes on the terrestrial biosphere, *Geophys. Res. Lett.*, *29*(22), 2061, doi:10.1029/2002GL015911.

Gruber, N., and J. N. Galloway (2008), An Earth-system perspective of the global nitrogen cycle, *Nature*, *451*(7176), 293–296, doi:10.1038/nature06592.

Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *J. Clim.*, *19*(21), 5686–5699, doi:10.1175/JCLI3990.1.

Intergovernmental Panel on Climate Change (IPCC) (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. Stocker et al., Cambridge Univ. Press, Cambridge, U. K., and New York.

Intergovernmental Panel on Climate Change (IPCC) (2014), *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, Cambridge Univ. Press, New York.

Irvine, P. J., A. Ridgwell, and D. J. Lunt (2010), Assessing the regional disparities in geoengineering impacts, *Geophys. Res. Lett.*, *37*, L18702, doi:10.1029/2010GL044447.

Irvine, P. J., et al. (2014), Key factors governing uncertainty in the response to sunshade geoengineering from a comparison of the GeoMIP ensemble and a perturbed parameter ensemble, *J. Geophys. Res. Atmos.*, *119*, 7946–7962, doi:10.1002/2013JD020716.

Jones, A., et al. (2013), The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP), *J. Geophys. Res. Atmos.*, *118*, 9743–9752, doi:10.1002/jgrd.50762.

Kalidindi, S., G. Bala, A. Modak, and K. Caldeira (2014), Modeling of solar radiation management: A comparison of simulations using reduced solar constant and stratospheric sulphate aerosols, *Clim. Dyn.*, doi:10.1007/s00382-014-2240-3.

Keenan, T. F., D. Y. Hollinger, G. Bohrer, D. Dragoni, J. W. Munger, H. P. Schmid, and A. D. Richardson (2013), Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise, *Nature*, *499*, 324–327, doi:10.1038/nature12291.

Knutti, R., D. Masson, and A. Gettelman (2013), Climate model genealogy: Generation CMIP5 and how we got there, *Geophys. Res. Lett.*, *40*, 1194–1199, doi:10.1002/grl.50256.

Kravitz, B., A. Robock, O. Boucher, H. Schmidt, K. E. Taylor, G. Stenchikov, and M. Schulz (2011), The Geoengineering Model Intercomparison Project (GeoMIP), *Atmos. Sci. Lett.*, *12*(2), 162–167, doi:10.1002/asl.316.

Kravitz, B., et al. (2013), Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP), *J. Geophys. Res. Atmos.*, *118*, 8320–8332, doi:10.1002/jgrd.50646.

Kravitz, B., et al. (2014), A multi-model assessment of regional climate disparities caused by solar geoengineering, *Environ. Res. Lett.*, *9*(7), 074013, doi:10.1088/1748-9326/9/7/074013.

Lawrence, D. M., et al. (2011), Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model, *J. Adv. Model. Earth Syst.*, *3*, doi:10.1029/2011MS000045.

Mao, J., P. E. Thornton, X. Shi, M. Zhao, and W. M. Post (2012), Remote sensing evaluation of CLM4 GPP for the period 2000–09, *J. Clim.*, *25*, 5327–5342, doi:10.1175/JCLI-D-11-00401.1.

Matthews, H. D., L. Cao, and K. Caldeira (2009), Sensitivity of ocean acidification to geoengineered climate stabilization, *Geophys. Res. Lett.*, *36*, L10706, doi:10.1029/2009GL037488.

Mercado, L. M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, and P. M. Cox (2009), Impact of changes in diffuse radiation on the global land carbon sink, *Nature*, *458*(7241), 1014–1017.

Naik, V., D. J. Wuebbles, E. H. Delucia, and J. A. Foley (2003), Influence of geoengineered climate on the terrestrial biosphere, *Environ. Manag.*, *32*(3), 373–381, doi:10.1007/s00267-003-2993-7.

Nemani, R. R., C. D. Keeling, H. Hashimoto, W. M. Jolly, S. C. Piper, C. J. Tucker, R. B. Myneni, and S. W. Running (2003), Climate-driven increases in global terrestrial net primary production from 1982 to 1999, *Science*, *300*(5625), 1560–1563, doi:10.1126/science.1082750.

Niemeier, U., H. Schmidt, K. Alterskjær, and J. E. Kristjánsson (2013), Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle, *J. Geophys. Res. Atmos.*, *118*, 11,905–11,917, doi:10.1002/2013JD020445.

Oleson, K., D. Lawrence, and B. Gordon (2010), Technical description of version 4.0 of the Community Land Model (CLM), (April).

Pitari, G., V. Aquila, B. Kravitz, A. Robock, S. Watanabe, I. Cionni, N. De Luca, G. Di Genova, E. Mancini, and S. Tilmes (2014), Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP), *J. Geophys. Res. Atmos.*, *119*, 2629–2653, doi:10.1002/2013JD020566.

Pongratz, J., D. B. Lobell, L. Cao, and K. Caldeira (2012), Crop yields in a geoengineered climate, *Nat. Clim. Change*, *2*(2), 101–105, doi:10.1038/nclimate1373.

Raczka, B. M., et al. (2013), Evaluation of continental carbon cycle simulations with North American flux tower observations, *Ecol. Monogr.*, *83*(4), 531–556, doi:10.1890/12-0893.1.

Raddatz, T. J., C. H. Reick, W. Knorr, J. Kattge, E. Roeckner, R. Schnur, K.-G. Schnitzler, P. Wetzel, and J. Jungclaus (2007), Will the tropical land biosphere dominate the climate-carbon cycle feedback during the twenty-first century?, *Clim. Dyn.*, *29*(6), 565–574, doi:10.1007/s00382-007-0247-8.

Rasch, P. J., S. Tilmes, R. P. Turco, A. Robock, L. Oman, C.-C. Chen, G. L. Stenchikov, and R. R. Garcia (2008), An overview of geoengineering of climate using stratospheric sulphate aerosols, *Philos. Trans. A. Math. Phys. Eng. Sci.*, *366*(1882), 4007–4037, doi:10.1098/rsta.2008.0131.

Ricke, K. L., M. G. Morgan, and M. R. Allen (2010), Regional climate response to solar-radiation management, *Nat. Geosci.*, *3*(8), 537–541, doi:10.1038/ngeo915.

Schmidt, G. A., et al. (2006), Present-day atmospheric simulations using GISS ModelE: Comparison to in situ, satellite, and reanalysis data, *J. Clim.*, *19*, 153–192, doi:10.1175/JCLI3612.1.

Schmidt, H., et al. (2012), Solar irradiance reduction to counteract radiative forcing from a quadrupling of CO2: Climate responses simulated by four Earth system models, *Earth Syst. Dynam.*, *3*(1), 63–78, doi:10.5194/esd-3-63-2012.

Takata, K., S. Emori, and T. Watanabe (2003), Development of the minimal advanced treatments of surface interaction and runoff, *Global Planet. Change*, *38*(1–2), 209–222, doi:10.1016/S0921-8181(03)00030-4.

Taylor, K., R. Stouffer, and G. Meehl (2009), A summary of the CMIP5 experiment design, *WCRP, Submitt.*, *2009*(January 2011), 1–33.

The Royal Society (2009), Geoengineering the climate.

Thornton, P. E., S. C. Doney, K. Lindsay, J. K. Moore, N. Mahowald, J. T. Randerson, I. Fung, J.-F. Lamarque, J. J. Feddema, and Y.-H. Lee (2009), Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: Results from an atmosphere-ocean general circulation model, *Biogeosciences*, *6*(10), 2099–2120, doi:10.5194/bg-6-2099-2009.

Tian, B., E. J. Fetzer, B. H. Kahn, J. Teixeira, E. Manning, and T. Hearty (2013), Evaluating CMIP5 models using AIRS tropospheric air temperature and specific humidity climatology, *J. Geophys. Res. Atmos.*, *118*, 114–134, doi:10.1029/2012JD018607.

Tilmes, S., R. R. Garcia, D. E. Kinnison, A. Gettelman, and P. J. Rasch (2009), Impact of geoengineered aerosols on the troposphere and stratosphere, *J. Geophys. Res.*, *114*, D12305, doi:10.1029/2008JD011420.

Tilmes, S., et al. (2013), The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP), *J. Geophys. Res. Atmos.*, *118*, 11,036–11,058, doi:10.1002/jgrd.50868.

Tjoelker, M. G., J. Oleksyn, and P. B. Reich (2001), Modelling respiration of vegetation: Evidence for a general temperature-dependent Q10, *Global Change Biol.*, *7*(2), 223–230, doi:10.1046/j.1365-2486.2001.00397.x.

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, *131*(612), 2961–3012, doi:10.1256/qj.04.176.

Van der Sleen, P., P. Groenendijk, M. Vlam, N. P. R. Anten, A. Boom, F. Bongers, T. L. Pons, G. Terburg, and P. A. Zuidema (2014), No growth stimulation of tropical trees by 150 years of CO2 fertilization but water-use efficiency increased, *Nat. Geosci.*, doi:10.1038/ngeo2313.

Verseghy, D. L., N. A. McFarlane, and M. Lazare (1993), Class—A Canadian land surface scheme for GCMS, II. Vegetation model and coupled runs, *Int. J. Climatol.*, *13*(4), 347–370, doi:10.1002/joc.3370130402.

Watanabe, S., et al. (2011), MIROC-ESM: model description and basic results of CMIP5-20c3m experiments, *Geosci. Model Dev. Discuss.*, *4*, 1063–1128, doi:10.5194/gmdd-4-1063-2011.

Xia, L., et al. (2014), Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP), *J. Geophys. Res. Atmos.*, *119*, 8695–8711, doi:10.1002/2013JD020630.

Zhang, Y., G. Yu, J. Yang, M. C. Wimberly, X. Zhang, J. Tao, Y. Jiang, and J. Zhu (2014), Climate-driven global changes in carbon use efficiency, *Global Ecol. Biogeogr.*, *23*(2), 144–155, doi:10.1111/geb.12086.