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Sensitivity and uncertainty of modelled terrestrial net primary productivity to doubled CO_2 and associated climate change for a relatively large perturbed physics ensemble

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ABSTRACT

Net primary productivity (NPP) is often modelled explicitly in general circulation models (GCMs) utilising process models that may include plant photosynthesis, respiration, allocation of photosynthates, phenology, mortality and competition between plant functional types. It is an important measure for understanding the role of terrestrial vegetation in the global carbon cycle, and useful for gaining insights into the large-scale, integrated effects of climate and atmospheric changes on potential plant productivity and associated impacts, i.e. food security and carbon cycle feedbacks. However, there are simplifications and uncertainties in GCM projections of future climate change, as well as further uncertainties involved in modelling the associated terrestrial vegetation responses. In particular, it is important to highlight that many GCM simulations, including the ones used in this study, do not model nutrient limitation, even though primary plant nutrients, e.g. nitrogen and phosphorus, are key limiting factors on plant productivity.

Here, we examine sensitivities and uncertainties in large(global)-scale modelled NPP to climate and atmospheric carbon dioxide concentration [CO_2], utilising a relatively large perturbed physics ensemble (PPE) of simulations generated from the HadSM3 GCM under equilibrium doubling of pre-industrial atmospheric [CO_2]. We also exploit the ensemble design to highlight the relative importance of two, often opposing, forcings on NPP: (i) plant physiological responses to CO_2, termed 'Phys'; and (ii) plant responses to physical drivers of climate, termed 'Rad'. It is important to note that this is a sensitivity study that provides useful guidance on the relative importance of the Rad and Phys drivers and their uncertainties. The results cannot be considered quantitatively realistic, particularly because the equilibrium experimental design and lack of nutrient limitation in the model are important limitations that prevent such interpretation.

We find that doubled [CO_2] and associated climate changes ultimately increase potential global average NPP by 57%, from 0.293 $kg\,cm^{-2}\,yr^{-1}$ (~36 $PgCyr^{-1}$) to 0.460 $kg\,cm^{-2}\,yr^{-1}$ (~57 $PgCyr^{-1}$). Spatially, the largest decreases (~−0.45 $kg\,cm^{-2}\,yr^{-1}$) occur across the north-east of South America in association with the largest decreases in precipitation. The largest increases (up to ~0.75 $kg\,cm^{-2}\,yr^{-1}$) occur across tropical Africa and Indonesia, where NPP is already high, and both temperature and precipitation increase under doubled [CO_2]. In most regions where NPP shows an increase the changes are significantly larger than the ensemble standard deviation, indicating that increases in global NPP under doubled [CO_2] are reasonably robust. However, in some regions, particularly north-eastern South America and Central America, where NPP decreases are projected, the standard deviation across the ensemble is larger than the average NPP change, indicating that even the sign of the NPP sensitivity to doubled [CO_2] and climate is uncertain. These uncertainties are shown to be highly dependent on the relative sensitivities of NPP to the Phys and Rad forcings.

1. Introduction

General circulation models (GCMs) provide our main means of integrating the current understanding of all components of the global climate system in order to assess the potential impacts of future climate changes. Many GCMs now go beyond the modelling

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of atmospheric and oceanic components of the physical climate system including, for example, terrestrial vegetation and carbon cycle components (Cramer and Field, 1999). However, results from these have shown sometimes large differences in the magnitude and even sign of the carbon cycle responses to climate change (Cox et al., 2000, 2004; Berthelot et al., 2002, 2005; Betts, 2004; Dufresne et al., 2002; Friedlingstein et al., 2003; Jones et al., 2003; Zeng et al., 2004; Crucifix et al., 2005).

Uncertainties in vegetation and carbon cycle responses to climate change reflect hugely different implications for food supply (Rosenzweig and Parry, 1994; Tubiello et al., 2002; Parry et al., 2004; Challinor et al., 2005), forestry and carbon cycle feedbacks (Cox et al., 2000). Quantifying and understanding these uncertainties are an important research focus for improving climate change projections and their interactions with the global carbon cycle (Friedlingstein et al., 2006; Booth et al., 2009; Gregory et al., 2009).

Much of the existing research assessing uncertainties in GCM projections has compared climate output from small ensembles of runs, either involving the same GCM with different initial conditions (e.g. Hennessy et al., 1997; Giorgi and Francisco, 2000; Palmer and Räisänen, 2002) or different GCMs which vary in their initial conditions, structural setup and/or parameterisations (e.g. Cubasch et al., 1994; Kharin and Zwiers, 2000; Meehl et al., 2000; Covey et al., 2003; Meehl and Tebaldi, 2004; Berthelot et al., 2005). Larger perturbed physics ensembles (PPEs) have also, more recently, been developed to quantify the uncertainties in GCM projections that arise from assigning specific values to uncertain model parameters (Allen and Stainforth, 2002; Collins et al., 2006; Murphy et al., 2004; Stainforth et al., 2004; Barnett et al., 2005). Such parameterisations are one of the major uncertainties in GCM simulations, and by perturbing key parameters it is possible to systematically explore the uncertainties that they introduce within the context of a single GCM framework. Significant further effort is required to process the output of these perturbed physics ensembles to provide estimates of the probability distribution functions of future climate variables (e.g. Collins, 2007; Murphy et al., 2007; Sexton et al., in press, 2011). Nevertheless, an investigation of the average response and ensemble spread, as is presented here, gives a useful leading-order estimate of average changes and sensitivities relative to their uncertainties.

Net primary productivity (NPP) provides an indicative measure of the integrated effects of climate and climate changes on vegetation. In this study, we utilise a 224 member PPE to examine the large-scale sensitivity of terrestrial NPP to a doubling of pre-industrial atmospheric [CO_2] and associated climate changes. The standard deviation across the ensemble members is used to assess uncertainties in NPP due to the model parameterisations. The global and regional robustness of average NPP changes are assessed relative to these uncertainties. As one of the perturbed parameters in the ensemble is a logical switch which controls whether the direct plant physiological response to atmospheric [CO_2], often known as the ‘fertilisation effect’, is active or not, we are also able to separate the relative NPP sensitivities and uncertainties into those associated with radiatively forced climate change, termed “Rad” (for radiative), and those associated with direct plant physiological responses to [CO_2] changes, termed “Phys” (for physiological). A similar approach to that adopted in Betts et al. (2007).

2. Methods

2.1. The global circulation model

All model runs were generated using the Met Office Hadley Centre's, HadSM3, GCM (see Webb et al., 2006). HadSM3 is the computationally efficient, mixed layer-, q-flux- or slab-ocean version of the third generation Met Office Hadley Centre GCM, HadCM3 (Gordon et al., 2000), which consists of a fully-dynamic atmospheric GCM, HadAM3 (Pope et al., 2000), coupled to a 50 m mixed layer ocean model. It is configured to a regular horizontal grid resolution of 2.5° latitude by 3.75° longitude, has 19 vertical levels, and is run on a 30 min time-step.

While HadSM3 retains the full atmospheric complexity of HadCM3, the simplified ocean model does not include explicit ocean dynamics, such as ocean circulation and associated biogeochemical feedbacks to the atmosphere. Instead, spatial and seasonal variations in ocean heat transport are prescribed (Hewitt and Mitchell, 1997) following a calibration phase in which the model is relaxed to the observed seasonally varying SSTs. Although no variations in the prescribed horizontal heat transports are possible under climate change, SSTs can vary as a result of changes and variability in surface fluxes. The use of a slab model facilitates the assessment of equilibrium changes and allows us to perform a relatively large number of simulations with perturbed values of parameters.

Land surface processes are modelled interactively within HadSM3 using the Met Office Surface Exchange Scheme (MOSES) (Cox et al., 1999). Exchanges of carbon and water vapour by photosynthesis and stomatal conductance are simulated by leaf-level physiological models for C_3 and C_4 plants (Collatz et al., 1991, 1992) and scaled-up to canopy exchanges using leaf area index, which follows a prescribed seasonal cycle. Soil respiration rate is assumed to double with every 10 °C temperature increase ($Q_{10} = 2$) (Raich and Schlesinger, 1992), and a prescribed observation field describes the terrestrial vegetation distribution, which remains constant in future simulations (Wilson and Henderson-Sellers, 1985). NPP is calculated as the net of photosynthesis minus autotrophic respiration, and is expressed in kg cm^{-2} yr^{-1}.

2.2. Perturbed-physics ensemble

Experts were asked to select 35 GCM parameters which were considered most dominant and uncertain, and to specify their plausible range of values. These are shown in Table 1. Some of the parameters comprise a logical switch, where, for example, a process may be activated or not, while others are specified as ranges.

An ensemble of 224 different model experiments was generated by running the GCM with different combinations of the selected parameter values. For some members, just one parameter was perturbed from its standard values to the extremes of its plausible range (Murphy et al., 2004), while for other members perturbations were made to multiple parameters simultaneously and parameter values were drawn from within those ranges (Webb et al., 2006). Two simulations were made for each ensemble member, one with atmospheric [CO_2] fixed at an approximate pre-industrial concentration of 290 ppmv, and the other with a doubled [CO_2] (580 ppmv). All simulations were continued for at least 20 model years after equilibrium had been reached (Barnett et al., 2005), and the average values over these 20-year periods were used for the analyses.

One of the parameters perturbed in the ensemble is a logical switch, termed “PF”, which controls whether the direct physiological response to atmospheric [CO_2] is active or not. In this study, we make use of this switch to gain insight into the relative contributions of radiative (“Rad”) and physiological (“Phys”) forcings to the NPP response. Our ensemble of 224 members included 81 members for which PF was switched on. This is the standard parameterisation setting for PF where NPP is influenced both by the direct physiological response of plants to doubled [CO_2] and the indirect effect of [CO_2] on plants via their climatic response to radiative forcing which induces changes in physical variables such as temperature and precipitation. This sub-ensemble is termed “RadPhys”