Carbon dioxide induced stomatal closure increases radiative forcing via a rapid reduction in low cloud

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[1] We performed an ensemble of twelve five-year experiments using a coupled climate-carbon-cycle model with scenarios of prescribed atmospheric carbon dioxide concentration; CO_2 was instantaneously doubled or quadrupled at the start of the experiments. Within these five years, climate feedback is not significantly influenced by the effects of climate change on the carbon system. However, rapid changes take place, within much less than a year, due to the physiological effect of CO_2 on plant stomatal conductance, leading to adjustment in the shortwave cloud radiative effect over land, due to a reduction in low cloud cover. This causes a 10% enhancement to the radiative forcing due to CO_2, which leads to an increase in the equilibrium warming of 0.4 and 0.7 K for doubling and quadrupling. The implications for calibration of energy-balance models are discussed. **Citation:** Doutriaux-Boucher, M., M. J. Webb, J. M. Gregory, and O. Boucher (2009), Carbon dioxide induced stomatal closure increases radiative forcing via a rapid reduction in low cloud, *Geophys. Res. Lett.*, *36*, L02703, doi:10.1029/2008GL036273.

1. Introduction

[2] Differing cloud feedbacks continue to be the primary cause of inter-model differences in the global mean temperature response to a doubling of CO_2 in ocean-atmosphere climate models (or climate sensitivity) [*Bony et al.*, 2006]. Recent studies [*Gregory and Webb*, 2008; *Andrews and Forster*, 2008; *Williams et al.*, 2008] have shown that a substantial fraction of this spread can be attributed to fast responses of clouds to the radiative increasing CO_2 concentrations. *Gregory and Webb* [2008] developed a statistical regression technique to diagnose these fast responses (hereafter referred to as adjustments) which are independent of cloud feedbacks associated with increases in near-surface temperatures. These may be considered as an additional component of the CO_2 radiative forcing (over and above the instantaneous CO_2 forcing [*Shine et al.*, 1990]) analogous to stratospheric adjustment [*Shine et al.*, 1995] and indirect aerosol forcing [*Forster et al.*, 2007]. Separating forcing and feedback terms properly in climate models is crucial because these are needed to calibrate the energy balance models used to interpolate between various socio-economic scenarios in IPCC assessments [e.g., *Meehl et al.*, 2007]. The rate of warming is sensitive to the partitioning between forcing and feedback terms [*Gregory and Webb*, 2008].

[3] The new generation of climate models, known as Earth System models, includes a fully coupled carbon cycle, which is responsible for a range of climate feedbacks [*Cox et al.*, 2000; *Friedlingstein et al.*, 2006]. The CO_2 concentration affects the stomatal aperture of plants and consequently the evapotranspiration flux, an effect known as the CO_2 physiological forcing [*Sellers et al.*, 1996, 1997; *Betts et al.*, 1997]. *Boucher et al.* [2008] and *Joshi et al.* [2008] showed that this effect can have a significant impact on a model's climate sensitivity. This effect is still poorly understood, however, and it has an unknown impact on radiative forcing and on feedbacks dependent on global-mean temperature.

[4] Here we use a climate model to demonstrate the utility of a new experimental framework for assessing the impact of the carbon cycle and the CO_2 physiological forcing on the climate sensitivity, separating rapid cloud adjustment and cloud feedback. The approach is to apply an ensemble variant of the *Gregory et al.* [2004] method to a coupled climate carbon model forced with prescribed atmospheric CO_2 concentrations, with and without the CO_2 physiological forcing. We also examine how these different effects scale with the CO_2 concentration in 2xCO2 and 4xCO2 experiments.

2. Experimental Design

[5] We use the HadCM3LC version of the Met Office Unified Model System (MetUM), which features a carbon cycle and dynamic vegetation model fully coupled to the HadCM3 ocean-atmosphere model. The reader is referred to *Cox et al.* [1999, 2000, and references therein] for a description of the model as well as to the auxiliary material provided.[1] However, for this study, the atmospheric concentration of carbon dioxide is prescribed and the carbon fluxes between the atmosphere, the land and the ocean are pure diagnostics. A control simulation (CONTROL) has been run for 20 years at equilibrium under $1 \times CO_2$ condition (286 ppmv). We follow the experimental setup of *Gregory et al.* [2004] whereby the atmospheric concentration of CO_2 is suddenly doubled (2xCO2_FULL) or quadrupled (4xCO2_FULL) so that the climate system is taken out of equilibrium. In order to increase the signal-to-noise ratio in these experiments we performed a set of twelve 5-year integrations in each case with initial states taken from the control simulation. Because we do not want the model response to be contaminated by the seasonal cycle, the twelve perturbed experiments start from initial states a month apart from each other in the control simula-

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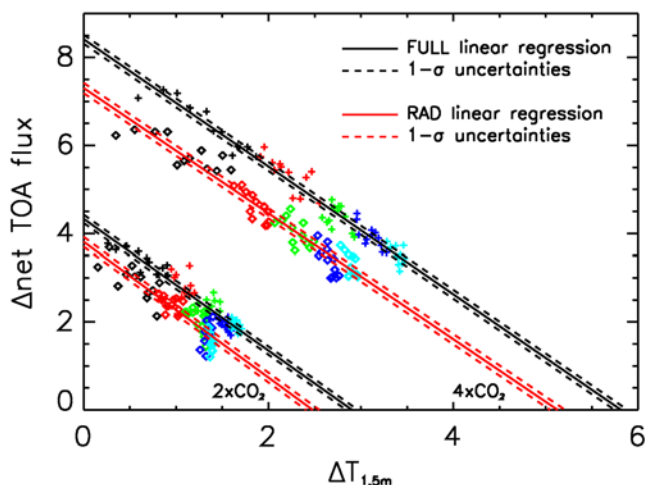[2]Department of Meteorology, University of Reading, Reading, UK.

Figure 1. Scatter plot of the global-mean response (the difference with the control experiment) in net downward TOA flux (Wm^{-2}) as a function of the global-mean response in near-surface temperature (K) for the 2xCO$_2$_FULL, 2xCO$_2$_RAD, 4xCO$_2$_FULL and 4xCO$_2$_RAD experiments. The plus and diamond symbols are for the FULL and the RAD experiments, respectively. Each symbol represents an average across the 12-member (in order to sample the annual cycle) ensemble, at monthly resolution and with successive years in different colors (black, red, green, dark blue, and light blue for years 1 to 5, respectively).

tion (from 1st January to 1st December). The results are presented as averages over the 12 experiments of the ensemble so that each monthly ensemble average fully samples the annual cycle. For instance the month-1 ensemble average includes the first January from the experiment initialised at 1st January, the first February from the experiment initialised at 1st February and so on. The 2xCO$_2$_RAD and 4xCO$_2$_RAD experiments are like the FULL experiments but with only the radiation seeing the perturbed CO$_2$ concentration, and plants seeing the unperturbed CO$_2$ concentration (this kind of experiment is called "uncoupled" by *Friedlingstein et al.* [2006]). This makes a grand total of 12 × 2 × 2 or 48 perturbed simulations of 5 years each in addition to the control experiment.

3. Results

[6] We plot the response (the difference with the control) in net downward top-of-atmosphere (TOA) flux as a function of the response in global mean near-surface temperature (1.5 m above surface) using averages calculated as described above from the 2xCO$_2$_FULL, 2xCO$_2$_RAD, 4xCO$_2$_FULL and 4xCO$_2$_RAD experiments (Figure 1). *Gregory et al.* [2004] showed that on such plots the radiative forcing and the climate feedback parameter can be diagnosed as the *y*-axis intercept and the slope of a linear regression, respectively. As the climate system responds to the initial perturbation and moves towards a new equilibrium, the surface temperature increases and the TOA flux imbalance reduces to zero. We use the *Gregory et al.* [2004]

definition of the radiative forcing throughout the rest of the study rather than the usual IPCC definition [*Shine et al.*, 1995; *Forster et al.*, 2007]. It is important to note that the radiative forcing diagnosed in this way includes "fast" responses, such as cloud adjustment associated with the CO$_2$ forcing [*Gregory and Webb*, 2008; *Andrews and Forster*, 2008]. The values from the Gregory plots are listed in Table 1 for the 2xCO$_2$_FULL, 2xCO$_2$_RAD, 4xCO$_2$_FULL and 4xCO$_2$_RAD experiments along with their 1-σ uncertainties.

[7] The radiative forcing for the 2xCO$_2$_RAD and 4xCO$_4$_RAD experiments is found to be 3.81 ± 0.11 and 7.30 ± 0.12 Wm^{-2}, respectively, in line with previous studies. The climate feedback parameter is consistent in 2xCO$_2$_RAD and in 4xCO$_4$_RAD (1.54 ± 0.10 versus 1.42 ± 0.05 $Wm^{-2}K^{-1}$), and also between FULL and RAD experiments (2xCO$_2$_FULL and 4xCO$_2$_FULL values are 1.49 ± 0.07 and 1.44 ± 0.04, respectively). This suggests that in this model, the CO$_2$ physiological forcing has no impact on global feedbacks on the 5-year timescale we examine. While carbon-cycle-climate feedbacks are expected to materialise on various timescales, they do not appear as differences between FULL and RAD, at least on the 5-year timescale and in a global-mean sense. However, in the FULL experiments, there is an extra component to the radiative forcing of 0.5 and 1.1 Wm^{-2} due to the CO$_2$ physiological forcing under 2xCO$_2$ and 4xCO$_2$, respectively. Between 10% and 20% of the near-surface temperature response appears to be due to the CO$_2$ physiological forcing in the HadCM3LC model. The CO$_2$ physiological forcing also affects vegetation and runoff in a way that is not reflected in the CO$_2$ radiative forcing.

[8] Furthermore Figure 1 shows that with the ensemble average the linear relationship between TOA fluxes and near-surface temperature response holds on timescales shorter than a year. The ensemble is needed to demonstrate this with statistical significance, which could not be shown in previous studies, that considered annual means only [e.g., *Gregory et al.*, 2004; *Gregory and Webb*, 2008]. It suggests that the fast responses, both physical and physiological, take place within a month or two (Dong et al., Understanding land-sea warming contrast in response to increasing green-

Table 1. Forcing and Feedback Parameter, With Corresponding 1-σ Uncertainties, Obtained From Linear Regression of the Global-Mean Change in Net Downward TOA Flux Against Global-Mean Change in Surface Temperature

Experiment		Forcing (Wm^{-2})	Feedback Parameter ($Wm^{-2}K^{-1}$)	Equilibrium Surface Temperature Change (K)
2xCO$_2$_FULL	12 × 5 yrs	4.33 ± 0.09	1.49 ± 0.07	2.90
2xCO$_2$_RAD	12 × 5 yrs	3.81 ± 0.11	1.54 ± 0.10	2.47
4xCO$_2$_FULL	12 × 5 yrs	8.41 ± 0.10	1.44 ± 0.04	5.82
4xCO$_2$_RAD	12 × 5 yrs	7.31 ± 0.12	1.42 ± 0.05	5.13
HadCM3[a]	2xCO$_2$	3.9 ± 0.2	1.26 ± 0.09	3.0
HadCM3[a]	4xCO$_2$	7.5 ± 0.3	1.19 ± 0.07	–

[a]From *Gregory et al.* [2004]. Note that HadCM3 and HadCM3L are not the same model.
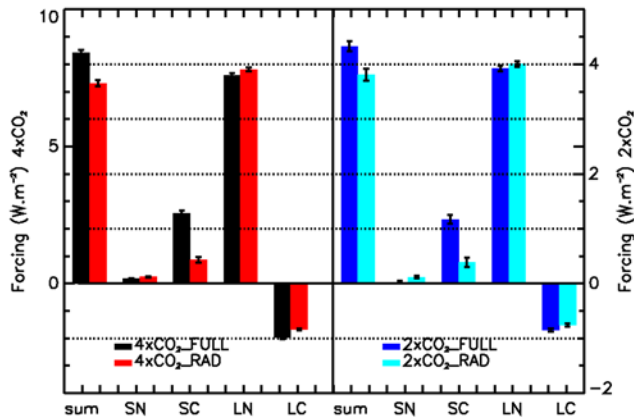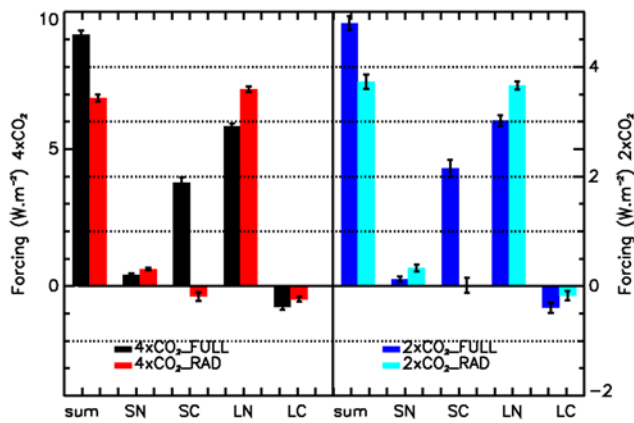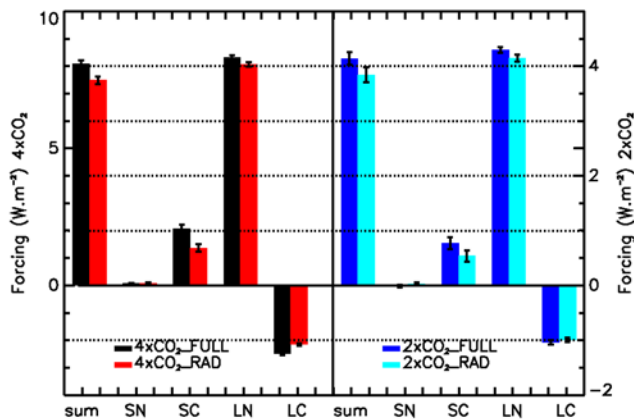
Figure 2. Different components of the (a) global-averaged, (b) land-averaged and (c) ocean-averaged forcing evaluated using the regression method of *Gregory and Webb* [2008] for the (left) 4xCO$_2$ and (right) 2xCO$_2$ experiments. The forcing is split in its shortwave (*S*) and longwave (*L*) components for non-cloudy (*N*) and cloudy (*C*) sky. Numbers are reported for the fully coupled (FULL) and radiation only (RAD) experiments.

house gases. Part I: Transient adjustment, submitted to *Journal of Climate*, 2008).

[9] Having the ensemble runs starting at different points in the year allows us to look at the month-to-month difference in the forcing or the feedback parameter. To do so we have performed our regression on individual members of the ensemble. The uncertainties are greater but in the 4xCO$_2$_FULL experiment there is a distinct seasonal cycle in the forcing as a function of the initial state month, with larger forcings for months April to June, which correspond to the growing season in Northern Hemisphere (for the 4xCO$_2$_FULL experiment the forcing varies from 7.5 to 9.1 ± 0.4 Wm^{-2}). There is no such seasonal cycle in the forcing for the 4xCO$_2$_RAD experiment (not shown). We have also performed our regression using only January (or February,...) months from the 12-member ensemble. There is also some evidence of a seasonal cycle for the forcing in the FULL experiment which is weaker in the RAD experiments. In contrast no evidence of a seasonal cycle was found for the feedback parameter. These conclusions demonstrate the advantage of sampling the annual cycle, compared with the use of annual means.

[10] We consider a number of hypotheses to explain the enhanced radiative forcing in the FULL experiments compared to the RAD experiments. One is that changing leaf area index on short timescales affects the radiative balance through changes in surface albedo. We test this hypothesis by decomposing the forcing term into longwave (LW), shortwave (SW), cloudy and non-cloudy components as those of *Gregory and Webb* [2008]. We reject this hypothesis because regression of intercepts of SW clear sky radiation (SN term in Figure 2) does not show differences large enough to explain the total. We can also rule out different responses from the dynamic vegetation on similar grounds; in any case responses in dynamic vegetation would not be expected on such short timescale.

[11] Our remaining hypothesis is that increasing the CO$_2$ instantaneously reduces the evapotranspiration at the surface through stomatal closure [*Joshi et al.*, 2008; Dong et al., submitted manuscript, 2008]. This causes a reduction in low-level cloudiness through a drying and/or warming of the boundary layer, adding to the cloud adjustment component of the CO$_2$ radiative forcing. Figure 2a shows the stronger difference in forcing is caused by the SW cloud component although this is slightly offset by opposite changes in the LW terms. Further decomposition of the forcing into a land and ocean average shows that most but not all of the change in the SW cloud component occurs over land. The LW compensation occurs over land in clear sky and both over land and ocean in cloudy sky.

[12] Examination of the geographical distribution of these forcing terms (calculated by regressing the response in the local fluxes against the response in the global mean near-surface temperature) shows that the SW cloud effect originates from high latitude forests (boreal, and temperate forest in North America and Europe) and the Amazon forest region (Figure 3, bottom right-hand plot). Regional distributions of the surface latent heat flux and cloud fraction (extrapolated for ΔT = 0) show substantial reductions over land in the fully forced (FULL) experiment that are not seen in the radiatively forced (RAD) experiment (Figure 3). These results therefore support our hypothesis, that CO$_2$ induced
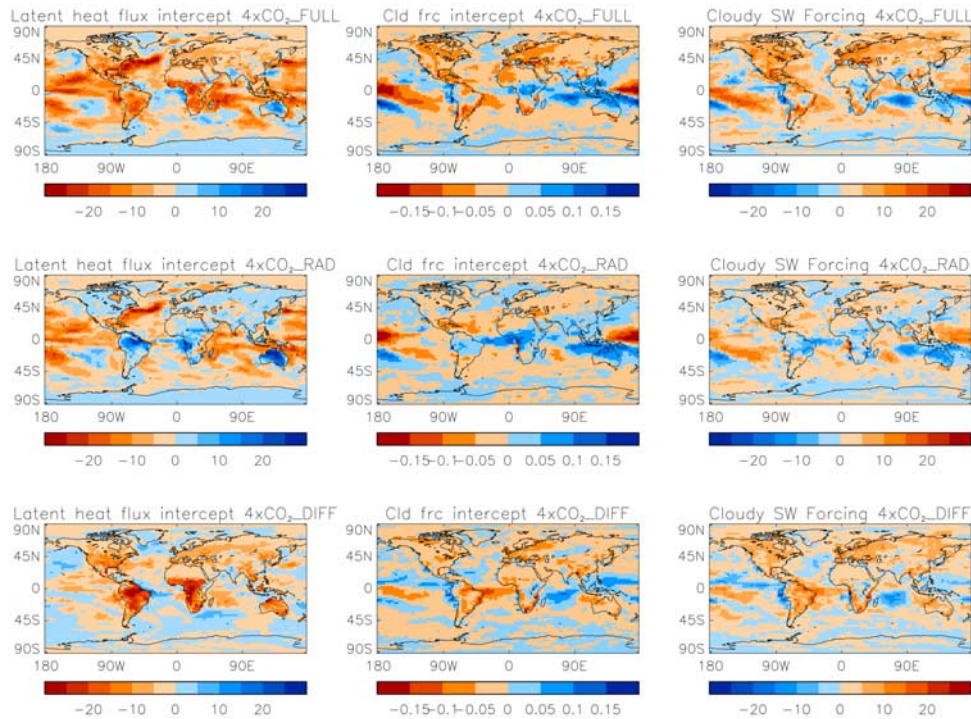
Figure 3. Spatial distribution of intercepts of the local regression against global mean near-surface temperature response for the responses in surface latent heat flux (Wm^{-2}), the cloud fraction (%) and the shortwave cloud radiative forcing (Wm^{-2}) for the fully coupled (FULL) and radiation only (RAD) experiments. The last row shows the difference between the FULL and RAD experiments.

stomatal closure increases the radiative forcing via a rapid reduction in low cloud cover.

4. Discussion and Conclusion

[13] The physiological forcing induced by doubling/quadrupling CO_2 increases the CO_2 radiative forcing in HadCM3LC by reducing the evapotranspiration and consequently low level cloud cover over the Amazon and mid and high latitude forests. We estimate that the impact of this is to increase the equilibrium warming by 0.4 K and 0.7 K (or 16% and 13%) for doubling and quadrupling CO_2, respectively. The extra radiative forcing associated with the CO_2 physiological forcing is 0.5 and 1.1 Wm^{-2}. Since the overall climate feedback parameter is hardly affected by the physiological response, it would be straightforward to incorporate this effect in energy-balance models by making an adjustment to the CO_2 forcing. It should be noted that adjusted radiative forcing cannot be diagnosed adequately from experiments with time-varying forcing, such as the Coupled Model Intercomparison Project (CMIP) scenario of 1% CO_2 increase because the adjusted forcing and temperature response are co-varying. Consequently, instantaneous step-changes in CO_2 will be useful to diagnose these effects in a wider range of models. Our methodology could also be applied to diagnose evapotranspiration driven components of the radiative forcing other than CO_2, for example those associated with changes in land use.

[14] One may wonder if the impact of the physiological forcing on the adjusted radiative forcing scales logarithmically with the CO_2 concentration, as it is the case for the instantaneous CO_2 radiative forcing [Shine et al., 1990].

The ratio of physiological forcing quadrupling/doubling is 2.1 ± 0.7. This ratio of about 2 is consistent with a logarithmic dependence, but a wider range of concentrations should be tested to determine the relationship. This would be a necessary step for prescribing the adjusted CO_2 forcing for arbitrary scenarios.

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