A regional and global analysis of carbon dioxide physiological forcing and its impact on climate

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Abstract An increase in atmospheric carbon dioxide concentration has both a radiative (greenhouse) effect and a physiological effect on climate. The physiological effect forces climate as plant stomata do not open as wide under enhanced CO_2 levels and this alters the surface energy balance by reducing the evapotranspiration flux to the atmosphere, a process referred to as 'carbon dioxide physiological forcing'. Here the climate impact of the carbon dioxide physiological forcing is isolated using an ensemble of twelve 5-year experiments with the Met Office Hadley Centre HadCM3LC fully coupled atmosphere–ocean model where atmospheric carbon dioxide levels are instantaneously quadrupled and thereafter held constant. Fast responses (within a few months) to carbon dioxide physiological forcing are analyzed at a global and regional scale. Results show a strong influence of the physiological forcing on the land surface energy budget, hydrological cycle and near surface climate. For example, global precipitation rate reduces by $\sim 3\%$ with significant decreases over most land-regions, mainly from reductions to convective rainfall. This fast hydrological response is still evident after 5 years of model integration. Decreased evapotranspiration over land also leads to land surface warming and a drying of near surface air, both of which lead to significant reductions in near surface relative humidity ($\sim 6\%$) and cloud fraction ($\sim 3\%$). Patterns of fast responses consistently show that results are largest in the Amazon and central African forest, and to a lesser extent in the boreal and temperate forest. Carbon dioxide physiological forcing could be a source of uncertainty in many model predicted quantities, such as climate sensitivity, transient climate response and the hydrological sensitivity. These results highlight the importance of including biological components of the Earth system in climate change studies.

Keywords Carbon dioxide physiological forcing ·
Climate response · Hydrological cycle ·
Surface energy balance · Fast responses

1 Introduction

Carbon dioxide (CO_2) is a powerful greenhouse gas and so a change in its atmospheric concentration perturbs the Earth's radiative balance. The radiative effect of a change in atmospheric CO_2 concentration is quantified by its radiative forcing (near-instantaneous change to the Earth's planetary energy balance caused by an external factor, e.g. Forster et al. 2007). In response to a radiative forcing the Earth's global temperature changes over a multi-annual timescale in order to restore planetary energy balance, which can be amplified or dampened by various climate feedbacks (e.g. Forster et al. 2007; Randall et al. 2007). In addition to its radiative effect, a change in atmospheric CO_2 concentration directly influences plant physiology with implications for local and global climate (e.g. Field et al. 1995). Under increased CO_2 concentration plant stomata do not open as wide and this alters the surface energy balance by reducing the evapotranspiration flux to the atmosphere (e.g. Sellers et al. 1996; Betts et al. 1997; Cox et al. 1999). This CO_2 physiological effect, referred to

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as 'CO$_2$ physiological forcing', has a strong impact on surface hydrology. For example reduced evapotranspiration is expected to increase water availability at the land surface, increasing surface runoff (e.g. Gedney et al. 2006; Betts et al. 2007; Boucher et al. 2009). In addition to the impacts on surface hydrology, reduced evapotranspiration at the land surface causes land warming (e.g. Field et al. 1995; Sellers et al. 1996; Betts et al. 1997; Cox et al. 1999), which is important for understanding the land-sea warming contrast under climate change (e.g. Joshi et al. 2008; Joshi and Gregory 2008; Boucher et al. 2009; Dong et al. 2009).

In a recent study, Doutriaux-Boucher et al. (2009) investigated how the CO_2 physiological effect influenced the CO_2 radiative effect (note that here the physiological effect does not include carbon-cycle feedbacks; the atmospheric CO_2 concentration being prescribed in the simulation). They found that in response to a step change in atmospheric CO_2 concentration the physiological effect caused a rapid reduction in low level cloudiness which altered the Earth's radiative balance (i.e. a change to the radiative effect). This response occurred within a few months, much quicker than the multi-annual timescale associated with the global temperature response to the radiative effect. Furthermore, they found that global climate feedbacks that either amplify or dampen global temperature change were largely unaffected by the physiological effect. Hence in a simple forcing and response energy balance model the physiological effects of CO_2 could be included as an adjustment to the initial CO_2 radiative forcing, analogous to how the indirect and semi-direct effect of aerosols are included into the radiative forcing concept (Doutriaux-Boucher et al. (2009)).

The overall response of the climate system to an increase in atmospheric CO_2 concentration is therefore a complex mixture of different responses to both radiative and physiological effects that act on different timescales. As separating different timescale responses is important for predicting transient climate change (Gregory and Webb 2008; Williams et al. 2008; Andrews 2009) it is the purpose of this study to isolate, on a regional and global scale, other 'fast' responses that are specific to CO_2 physiological forcing. By 'fast' response we are referring to any response that comes about quickly (within a few months) due to the altered surface energy balance, as opposed to any response that comes about simply because CO_2 physiological forcing causes global temperature to change (which acts on a longer timescale due to the large heat capacity of the oceans). Section 2.2 gives further definition and an illustration of the fast response.

We examine how CO_2 physiological forcing impacts the Earth's surface energy balance and near surface climate, focusing on the hydrological cycle and local temperature response. For the first time, we look into the regional distribution of the fast response patterns. As we will show, the fast responses to CO_2 physiological forcing reveal new and important insights into climate change processes. Section 2 presents the experimental design, Sect. 3 presents the results and Sect. 4 presents the discussion and conclusions.

2 Experiments and method

2.1 Model setup

The experimental design and model runs are the same as those described by Doutriaux-Boucher et al. (2009). This involves the Hadley Centre Coupled Model version 3 (HadCM3) coupled to a dynamic vegetation model and includes a carbon cycle (see, e.g. Cox et al. 1999, for further model description). This setup is referred to as HadCM3LC. From a control simulation the atmospheric CO_2 concentration is instantaneously quadrupled and thereafter held constant ($4 \times CO_2$); an increase of this size is required to increase the signal-to-noise ratio, particularly when analyzing responses on a regional scale. The model is then run for 5 years—this is enough time to observe the transient changes that are of most interest to this study. To further increase the signal-to-noise ratio each simulation was performed 12 times, starting from initial states 1 month apart from each other in the control run (this covers the entire seasonal cycle). All results are then averaged over the 12-member ensemble so that the first monthly-mean represents the mean of the first month of each member of the ensemble and so on. The advantage of this approach is that it allows an analysis on timescales shorter than a year because the monthly-means are not affected by the seasonal cycle (Doutriaux-Boucher et al. 2009).

We isolate the impact of CO_2 physiological forcing on climate by differencing the results of two 12-member experiments; RADPHYS and RAD. RADPHYS refers to the fully coupled setup as described above, where all components 'see' the $4 \times$ CO_2. RAD is the same as RADPHYS but only the radiation scheme sees the perturbed CO_2 level, the plants continue to see $1 \times CO_2$ as in the control. Note that in Doutriaux-Boucher et al. (2009) RADPHYS is referred to as 4×CO2_FULL and RAD is referred to as 4×CO2_RAD. We also make use of another experiment, PHYS, whereby the radiation scheme sees the unperturbed level while the plants see the perturbed CO_2 level. Note that in all experiments the atmospheric CO_2 concentration is prescribed, and so carbon-cycle feedbacks that change the atmospheric CO_2 concentration are prohibited (we are only focusing on the response to the altered surface energy balance). One might think that the PHYS

experiment might be best to isolate CO_2 physiological forcing and its impact on climate because it is not contaminated by the CO_2 radiative effect (the RAD experiment), but we find that the transient change in this experiment is not large enough to isolate the fast responses to CO_2 physiological forcing (see Sect. 2.2). In summary, from a control experiment we have three forcing scenarios:
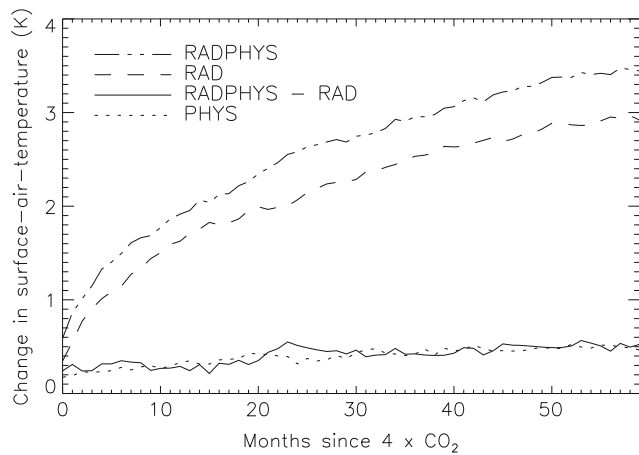
1. RADPHYS: Both the radiation scheme and plants see $4\times CO_2$

Fig. 1 Monthly-mean time series of global-mean surface air temperature change, ΔT (in K), for the first 5 years of the $4\times$ CO_2 RADPHYS, RAD and PHYS experiments. RADPHYS–RAD is the difference between the two forcing scenarios

2. RAD: The radiation scheme sees $4\times$ CO_2. The plants see $1\times$ CO_2.
3. PHYS: The radiation scheme sees $1\times$ CO_2. The plants see $4\times$ CO_2.

Figure 1 illustrates the three different experiments by showing the time-series of the monthly-mean global-mean surface-air-temperature change, ΔT. The difference between RADPHYS and RAD, agrees extremely well with the PHYS experiment. The geographical distribution of surface-air-temperature change, averaged over the fifth year of the integrations, is shown in Fig. 2. Differencing RADPHYS and RAD locally, agrees well with the PHYS experiment. We use these two figures to justify our use, globally and regionally, in differencing the results between the RADPHYS and RAD experiments to isolate the impact of CO_2 physiological forcing on climate.

2.2 Isolating the fast responses

To isolate the fast responses to CO_2 physiological forcing we use the same method as Doutriaux-Boucher et al. (2009). For constant forcing the method involves the regression of change in any variable X, that scales linearly with global-mean surface air temperature change ΔT, against ΔT during transient climate change. An illustration of the method can be seen in Sect. 3.2. The slope of the regression line gives the response of variable X to ΔT, as measured by change in variable X per Kelvin. The limit of ΔT tending to zero, the y axis intercept, gives the change in
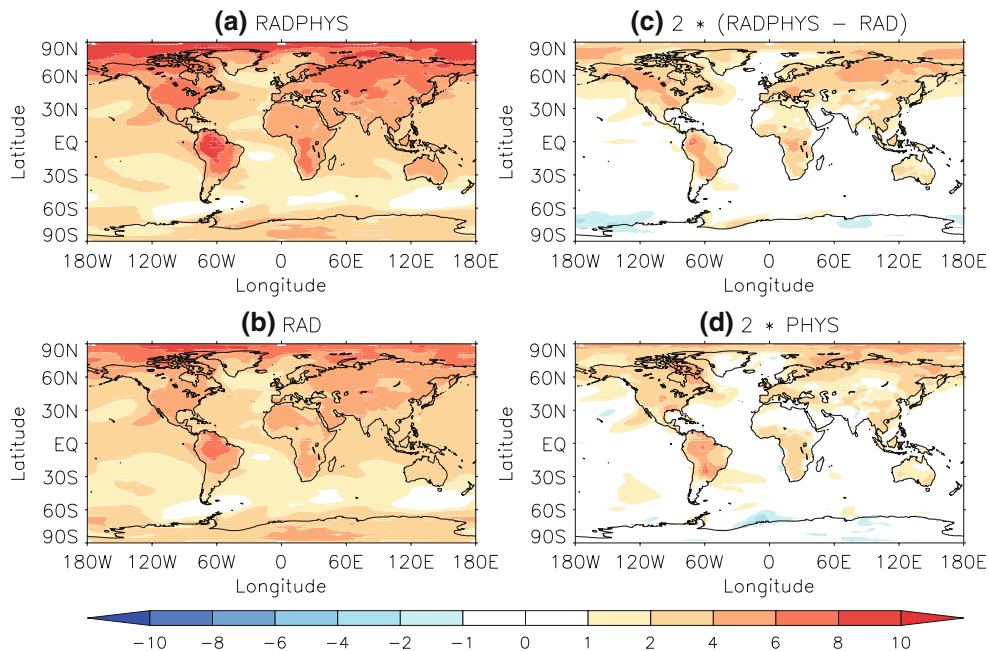

Fig. 2 Change in surface air temperature (in K) averaged over the fifth year of the $4\times$ CO_2 **a** RADPHYS, **b** RAD and **d** PHYS experiments, compared to the control run. Also shown is **c** RADPHYS–RAD. Note that **c** and **d** have been scaled by a factor of two

variable X before time has occurred for global-mean surface air temperature to respond to the forcing; this is the fast response (see Gregory et al. 2004; Gregory and Webb 2008; Andrews et al. 2009, for further details). A similar analysis can be performed with the local change in variable X to obtain the response patterns.

By differencing the fast responses diagnosed from the RAD and RADPHYS experiments we can diagnose the fast responses that are directly the result of CO$_2$ physiological forcing.

3 Results

3.1 CO$_2$ physiological forcing

Figure 3 shows the fast response patterns, diagnosed from the difference in fast responses between the RADPHYS and RAD experiments that are attributable to CO$_2$ physiological forcing. Note that all energy fluxes are defined as positive downwards, so a positive change in any energy flux represents an energy gain at the surface. The reduced stomatal opening due to the increased CO$_2$ reduces the land surface latent heat (LH) flux to the atmosphere (Fig. 3a, indicated by a positive change in LH flux). The global-mean reduction in surface LH flux to the atmosphere is ~ 2.8 Wm^{-2} (Table 1). Over land areas the average reduction is ~ 7.9 Wm^{-2}, which significantly dries the near surface air, shown by the large reductions in 1.5 m specific humidity over most land regions (Fig. 3b; Table 1). The reduced evaporative cooling also increases land temperatures (see Sect. 3.3). This can also be seen in Fig. 3e because the upwards surface longwave (LW) flux is a function of surface temperature. Figure 3e shows an increase in upward LW flux to the atmosphere over most land regions, which follows from an increase in surface land temperature. The drying and warming of the boundary layer leads to large reductions in near surface relative humidity, which are almost entirely restricted to land regions (Fig. 3c; Table 1). Over land the near surface relative humidity is reduced by $\sim 6.2\%$ on average, compared to only $\sim 0.04\%$ over the ocean (Table 1).

The fast responses are largest in the southern hemisphere land regions, particularly the Amazon and central African forests. The responses however are still widespread over almost all land regions, other 'hot spots' include the temperate and boreal forests of the mid to high latitudes (Fig. 3).

Some of the changes in atmospheric variables will impact the surface radiation budget. For example there are large reductions in net absorbed surface LW radiation (Fig. 3d), partly due to changes in surface upward radiation (Fig. 3e), as previously described, but there are also

Fig. 3 Geographical distribution of fast responses caused by CO$_2$ ▶ physiological forcing. They are diagnosed from the differences in fast response patterns in the RADPHYS and RAD experiments. To use one scale the specific humidity and the precipitation rate have been scaled by a factor of 10^4 and 10, respectively. All energy fluxes are defined as positive downwards. Results that are not statistically different from zero at the $1 - \sigma$ level are also shown as *white*

changes in surface downwelling radiation (Table 1). The atmospheric warming by itself would increase the amount of downwelling LW radiation at the surface, but the surface downwelling radiation is actually reduced (Table 1). In clear skies the change in global-mean downwelling surface LW radiation is ~ -1.6 Wm^{-2} (Table 1). This suggests that the reduced atmospheric water-vapour content reduces the greenhouse effect sufficiently enough to outweigh the small increase in downwelling LW radiation that results from atmospheric warming.

Doutriaux-Boucher et al. (2009) showed that low level cloud cover reduced in response to CO$_2$ physiological forcing. This is supported by Fig. 3f where reductions in cloud fraction are present over almost all land areas (land-mean cloud fraction change is $\sim -2.9\%$, Table 1). As cloud fraction depends on relative humidity, it is not surprising to see such changes in cloud given the large reductions in relative humidity already discussed. Changes in cloud fraction have a significant impact on the surface radiation budget because clouds reflect shortwave (SW) radiation and have a greenhouse effect. Changes in surface SW radiation and LW radiation have been separated into clear-sky and cloud radiative effect (CRE) (Table 1), where CRE is determined from the difference between all-sky and clear-sky. Changes in the surface downwelling LW and SW CRE are consistent with reduced cloud cover, which would tend to decrease the amount of downwelling LW CRE (seen in Table 1) and increase the amount of downwelling SW CRE (also seen in Table 1). The SW radiation budget is in fact dominated by this term; change in downwelling SW CRE over land-areas is ~ 5.7 Wm^{-2} on average compared to ~ 0.7 Wm^{-2} in clear-sky (Table 1).

3.2 Impact on precipitation

Figure 4 shows the change in global-mean precipitation rate (in %) as a function of ΔT for the 5 year integrations of the RADPHYS and RAD experiments. The slope of the regression line measures the percentage change in global precipitation rate per degree of ΔT, referred to as the 'differential hydrological sensitivity' (Andrews et al. 2009; Bala et al. 2009). Figure 4 suggests a considerable hydrological response to CO$_2$ physiological forcing. The precipitation response to ΔT (gradient of slopes in Fig. 4) is similar between the RADPHYS and RAD experiments
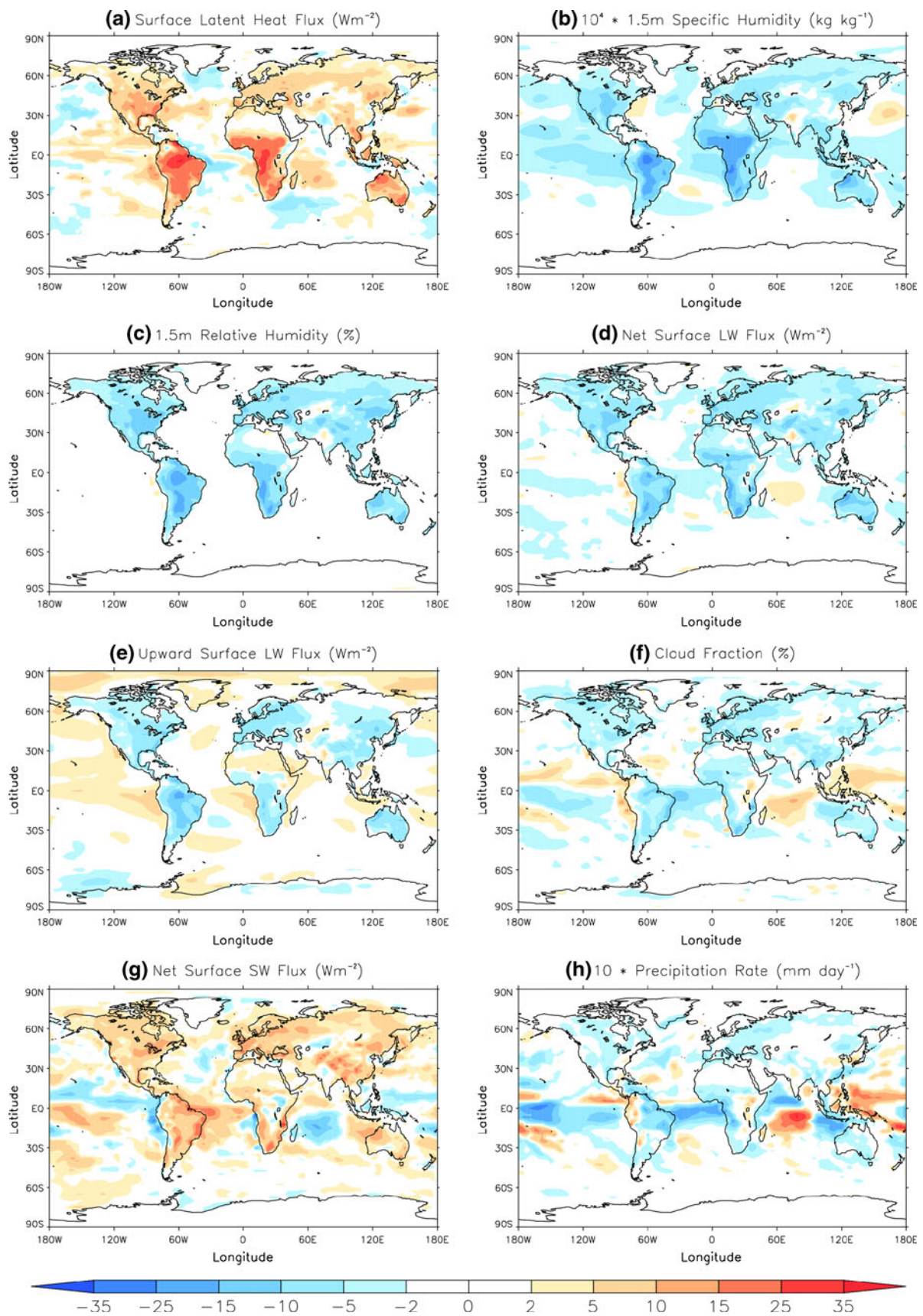
Table 1 Fast responses to CO_2 physiological forcing (see Sect. 2.2)

Fast response in	Land-mean	Ocean-mean	Global-mean
Surface latent heat flux (W m^{-2})	7.85 ± 0.24	0.75 ± 0.20	2.81 ± 0.15
Net surface LW radiation (W m^{-2})	-5.73 ± 0.24	-0.82 ± 0.09	-2.24 ± 0.08
Upward surface LW radiation (W m^{-2})	-3.34 ± 0.18	1.15 ± 0.08	-0.15 ± 0.05
Downward surface LW radiation clear-sky (W m^{-2})	-0.78 ± 0.25	-1.96 ± 0.13	-1.62 ± 0.10
Downward surface LW cloud radiative effect (W m^{-2})	-1.60 ± 0.07	-0.01 ± 0.05	-0.47 ± 0.04
Net surface SW radiation (W m^{-2})	5.24 ± 0.29	1.11 ± 0.23	2.31 ± 0.16
Downward surface SW radiation clear-sky (W m^{-2})	0.68 ± 0.07	0.38 ± 0.03	0.47 ± 0.03
Downward surface SW cloud radiative effect (W m^{-2})	5.71 ± 0.30	0.81 ± 0.23	2.23 ± 0.16
1.5 m specific humidity (g kg^{-1})	-0.64 ± 0.03	-0.18 ± 0.02	-0.31 ± 0.01
1.5 m relative humidity (%)	-6.16 ± 0.17	-0.04 ± 0.03	-1.81 ± 0.05
Precipitation rate (mm day^{-1})	-0.16 ± 0.02	-0.07 ± 0.01	-0.10 ± 0.01
Convective rainfall (mm day^{-1})	-0.11 ± 0.02	-0.06 ± 0.01	-0.07 ± 0.01
Large-scale rainfall (mm day^{-1})	-0.05 ± 0.01	-0.01 ± 0.01	-0.02 ± 0.01
Cloud fraction (%)	-2.87 ± 0.21	-0.31 ± 0.12	-1.05 ± 0.09

Numbers are determined from the differences in fast responses in the RADPHYS and RAD experiments. All energy fluxes are defined as positive downwards. Errors are $1 - \sigma$ uncertainties based on the regressions
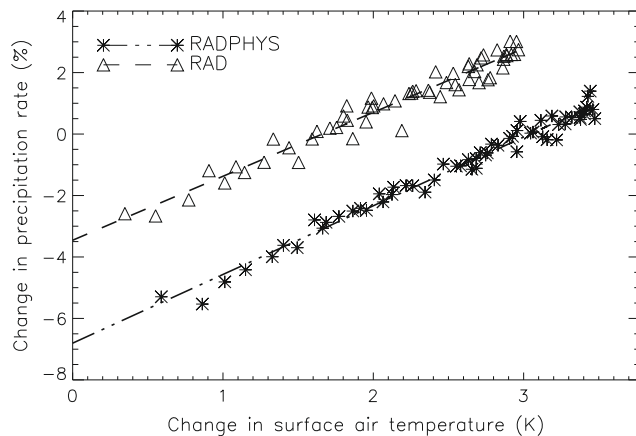

Fig. 4 Change in global-mean precipitation rate (in %) as a function of global-mean surface air temperature change (in K) for the first 5 years of the RADPHYS and RAD experiments. *Lines* are regressions and the *symbols* are monthly-means. Fast responses are diagnosed from the y axis intercepts, where $\Delta T = 0$

Table 2 Fast response in global-mean precipitation rate (in %) caused by the forcing and the response to ΔT (in % K^{-1}), referred to as the differential hydrological sensitivity, in the RADPHYS and RAD experiments

Coupling	Fast precipitation response (%)	Differential hydrological sensitivity (% K^{-1})
$4\times$ CO_2 RADPHYS	-6.80 ± 0.12	2.23 ± 0.04
$4\times$ CO_2 RAD	-3.45 ± 0.14	2.08 ± 0.06

Numbers are diagnosed from the intercepts and gradients of Fig. 4. Errors are $1 - \sigma$ uncertainties from the regressions

(see Table 2) and is in line with other estimates and models (see Lambert and Webb 2008; Andrews et al. 2009). Hence CO_2 physiological forcing has little impact on the response of precipitation to ΔT (at least on the 5 year timescale considered here). However the fast response (Fig. 4, y axis intercepts) shows significant differences between the RADPHYS and RAD experiments. In the RAD experiment there is an initial reduction to global precipitation rate of $\sim 3.5\%$ (Table 2) before it subsequently increases with positive ΔT. This is the result of conserving of the tropospheric heat budget (see, e.g. Allen and Ingram 2002; Yang et al. 2003; Andrews et al. 2009). In the RADPHYS experiment the fast response gives an initial reduction that

is almost double this value (Table 2; Fig. 4), CO_2 physiological forcing therefore significantly reduces the global precipitation rate. If the fast response of precipitation to CO_2 physiological forcing varies between models then this could be a large source of uncertainty in model-predicted hydrological cycle change.

The geographical distribution of the fast precipitation response to CO_2 physiological forcing is shown in Fig. 3h (note that the results in the figure have been scaled by a factor of 10). Over the ocean, precipitation reductions are somewhat compensated for by regions of increases, giving an ocean-mean change in precipitation rate of -0.07 mm day^{-1} (Table 1). Over land regions precipitation rate is reduced in most areas (Fig. 3h), leading to a larger average reduction over land areas of ~ 0.16 mm day^{-1} (Table 1). The reduction is mostly composed of changes to convective rainfall, though there is a smaller contribution from large-scale rainfall (Table 1). Hence we conclude that as a fast response to CO_2 physiological forcing, significant reductions to precipitation rates occur over land.

This conclusion is in contrast to Betts et al. (2007) who used an ensemble of HadSM3 (the mixed-layer ocean version of HadCM3) experiments, created by varying certain key model parameters, to investigate the hydrological response to CO_2 physiological forcing. They divided their ensemble into two sub-ensembles, one with and without CO_2 physiological effects, and found that in response to CO_2 doubling, the ensemble with CO_2 physiological effects had a slightly greater precipitation change. Betts et al. (2007) did not sample the different choices in model parameters equally between the two sub-ensembles, and so it is possible that their results are an artifact of this. In addition any initial precipitation change (the fast response) may have been somewhat masked by the larger overall precipitation response to ΔT (see next paragraph), as they did not isolate the fast response. Therefore it is difficult to conclude if this discrepancy is a real difference in model responses between HadCM3LC and HadSM3 or an artifact of the experimental setup. Note that Boucher et al. (2009) described a similar discrepancy.

Previous studies have looked at how CO_2 physiological forcing influences precipitation and most report little or no change (e.g. Boucher et al. 2009; Cao et al. 2009). We believe our results of significant changes are consistent with previous studies for two reasons. (a) Precipitation change is highly variable and so the 12-member ensembles are required to deduce significant changes between the RADPHYS and RAD experiments (as seen clearly in Fig. 4). For example Fig. 5 shows the monthly-mean time-series of land-mean precipitation change in the RADPHYS and RAD experiments, as well as the difference between the two. Even with the 12-member ensembles there is significant variability in the time-series. Versions of Figs. 4 and 5, using only one-member of the ensembles (like most
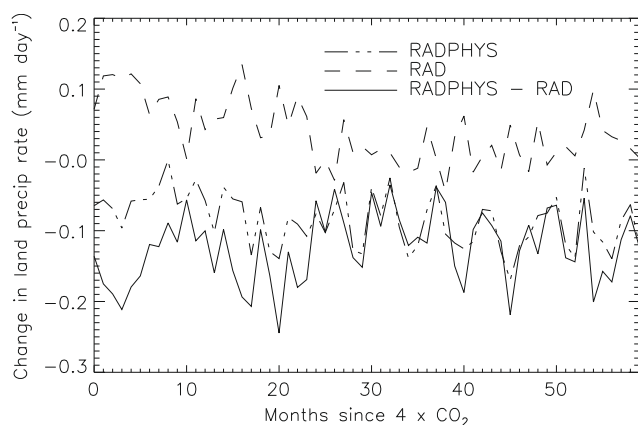

Fig. 5 Monthly-mean time series of the change in land-mean precipitation rate (in mm day⁻¹) for the first 5 years of the $4\times$ CO₂ RADPHYS and RAD experiments. RADPHYS–RAD is the difference between the two forcing scenarios

previous studies) show such a large variability that a statistically significant difference between the two experiments could not be made (not shown). (b) Most studies have run their models to equilibrium before looking at the precipitation change—this could mask the initial reduction. For example CO_2 physiological forcing causes a small amount of global warming (see Sect. 3.3), which itself will increase the precipitation rate (e.g. Lambert and Webb 2008). The equilibrium precipitation change is the result of both the fast response to the CO_2 physiological forcing and this response to ΔT. As ΔT is larger in the RADPHYS experiment than RAD (see Sect. 3.3) the overall precipitation response to ΔT will also be larger. Hence the initial reduction to precipitation rate could be masked by the larger overall response to ΔT. However, it is unlikely that this effect is large enough to completely mask the initial reduction. For example extrapolating the RADPHYS line of Fig. 4 to equal the precipitation change in the RAD experiment would require an additional ΔT of ~ 1.5 K.

3.3 Impact on surface temperature

Reduced evapotranspiration at the Earth's land surface due to CO_2 physiological forcing causes land temperatures to warm (e.g. Field et al. 1995; Sellers et al. 1996; Betts et al. 1997; Cox et al. 1999). This is seen in Figs. 1 and 2. Figure 1 shows that by the end of the fifth year CO_2 physiological forcing is responsible for an increase of nearly 0.5 K (of the order $\sim 18\%$ of the CO_2 radiative effect) in global-mean surface-air-temperature. Figure 2c, d shows the geographical pattern of this change averaged over the fifth year (note that they have been scaled by a factor of two in the figure for clarity). They confirm that the regions of largest warming are mostly confined to land areas. This warming explains a part of the land/sea warming contrast under climate change (see Joshi et al. 2008; Joshi and Gregory 2008; Boucher et al. 2009; Dong et al. 2009).

In line with the previous sections we isolate the fast response in land temperature to CO_2 physiological forcing. Andrews et al. (2009) found that regressing land-mean temperature change against sea-mean temperature change provided a linear fit with the gradient representing the 'differential land/sea warming contrast' (in analogy with the differential hydrological sensitivity) and the y-axis intercept (the land-mean temperature change) representing any initial land-mean temperature change that occurred before sea-mean temperature responded to the forcing. Figure 6 shows such a regression for the RADPHYS and RAD experiments. Land-mean temperature change scales linearly with sea-mean temperature change (Fig. 6), suggesting the differential land/sea warming contrast is constant under climate change forced by a constant forcing.
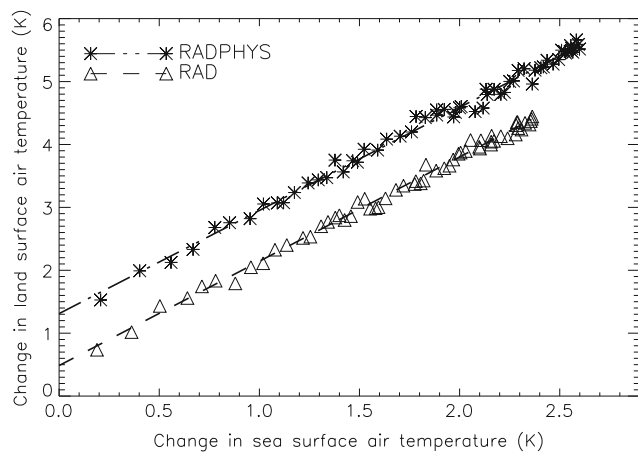
Fig. 6 Change in land-mean surface air temperature (in K) as a function of sea-mean surface air temperature change (in K) for the first 5 years of the RADPHYS and RAD experiments. *Lines* are regressions and the *symbols* are monthly-means

Table 3 Fast response in land-mean surface air temperature (in K), which occurred in the limit of sea-mean surface air temperature change tending to zero, and the differential land/sea warming contrast in the RADPHYS and RAD experiments

Coupling	Fast land temperature response (K)	Differential land/sea warming ratio
$4\times CO_2$ RADPHYS	1.31 ± 0.03	1.64 ± 0.02
$4\times CO_2$ RAD	0.49 ± 0.03	1.66 ± 0.02

Numbers are diagnosed from the intercepts and gradients of Fig. 6. Errors are $1 - \sigma$ uncertainties from the regressions

Table 3 shows this ratio to be ~ 1.65 in both RADPHYS and RAD experiments, which is high compared to other climate models (see Andrews et al. 2009). However, the initial land warming values, the y-axis intercepts, are significantly different between RADPHYS and RAD (Table 3). Land temperatures rapidly warm, before sea-mean temperature change, on average by ~ 1.3 K in the RADPHYS experiment compared to only ~ 0.5 K in the RAD experiment. CO_2 physiological forcing is therefore responsible for a rapid warming of the land surface of ~ 0.8 K.

From a global perspective it is also worth noting that CO_2 physiological forcing influences the rate of change in ΔT. For example, from Fig. 1 it is clear that the rate of change in ΔT must be larger in the RADPHYS experiment compared to the RAD experiment, possibly because the initial land warming is greater for the RADPHYS experiment (which presumably spreads out over the oceans on a longer time period), but also because the radiative forcing is larger due to the CO_2 physiological forcing (Doutriaux-

Boucher et al. 2009). CO_2 physiological forcing could be a source of uncertainty in transient climate response.

4 Discussion and conclusions

An increase in atmospheric CO_2 concentration has both a radiative (greenhouse) and physiological effect on climate. The physiological effect forces climate through altering the surface energy balance due to plant stomata opening less widely under enhanced CO_2 levels, this process is referred to as 'CO_2 physiological forcing'. Doutriaux-Boucher et al. (2009) showed that CO_2 physiological forcing altered the Earth's radiative balance through a rapid reduction in low level cloudiness. As this response occurred much quicker than the timescale associated with the CO_2 radiative (greenhouse) global warming it could be incorporated into the radiative forcing concept as an adjustment to the initial CO_2 radiative forcing (Doutriaux-Boucher et al. 2009). The climate response to a change in CO_2 concentration is therefore complex; there are different responses acting on different timescales due to both radiative and physiological effects. Isolating the fast responses is important for predicting transient climate change (Gregory and Webb 2008; Williams et al. 2008; Andrews 2009) and also has implications to geoengineering (Bala et al. 2009).

In this study further 'fast' responses to CO_2 physiological forcing beyond low-level cloud were investigated at a regional and global scale. Results showed that in addition to reduced low-level cloudiness, CO_2 physiological forcing caused a reduction in the land surface latent heat flux to the atmosphere, which in turn dried and warmed the boundary layer leading to large reductions in relative humidity, precipitation rate and specific humidity over land. Regions of largest changes included the Amazon and central African forests, but significant changes were also found in the boreal and temperate forests. Reduced cloud cover and atmospheric water-vapour fed back onto the land surface radiation budget, which increased the amount of SW radiation and decreased the amount of LW radiation absorbed by the surface.

After 5 years of model integration CO_2 physiological forcing caused an increase in global-mean surface-air-temperature that was $\sim 18\%$ of the global mean temperature change from the CO_2 radiative effect acting alone. This highlights the strong influence of biological components of the Earth system on the more physical drivers of climate change. This additional global warming will cause the climate to change, on top of the fast responses already described. For example precipitation rate increases with positive global temperature change (e.g. Lambert and Webb 2008). Hence the initial reduction to the precipitation rate will be somewhat masked by the subsequent

increase due to positive global temperature change. In addition to the fact that the precipitation rate is highly variable and so 12-member ensembles are required to improve the statistics, this may explain why previous studies that analyzed the perturbed steady state found it difficult to diagnose any impact on precipitation. Our results highlight the utility of using ensemble results and analyzing the transient change.

In addition to reduced stomatal conductance, increased CO$_2$ levels are expected to increase leaf area index (e.g. Betts et al. 1997; Kergoat et al. 2002), which could offset the reduced stomatal conductance, but will also impact climate through changed surface albedo. Furthermore vegetation dynamics also responds to increased CO$_2$ levels (e.g. Bala et al. 2006; O'Ishi et al. 2009); for example Bala et al. (2006) showed that enhanced CO$_2$ levels lead to an expansion of boreal forests which reduced surface albedo. However, neither of these responses is expected to arise on the short timescale considered by this study (Doutriaux-Boucher et al. 2009).

We re-emphasize the findings of Boucher et al. (2009), that the responses to CO$_2$ physiological forcing will not occur under non-CO$_2$ forcings and so questions the applicability of using CO$_2$ as the baseline for climate efficacies. As the exact magnitude of CO$_2$-induced stomatal closure is still poorly defined, analysis of other models would help identify which of the responses described here are robust and so whether CO$_2$ physiological forcing is a source of uncertainty in model predicted quantities, such as climate sensitivity and transient climate response. This would be especially useful given that we have found significant precipitation responses to CO$_2$ physiological forcing for the first time. For example Cao et al. (2009) investigated the impact of CO$_2$ physiological forcing and found less of an impact than in model studies using the MOSES scheme such as in this study. However they believe this might be due to unrealistic partitioning of evapotranspiration in their model. Hence, given the upcoming Coupled Model Inter-comparison Project phase 5 (CMIP5), we suggest that analysis of the climate response to CO$_2$ physiological forcing in other models would be a useful step to identify sources of uncertainty in multi-model ensemble results.

References

Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrological cycle. Nature 419:224–232. doi:10.1038/nature01092

Andrews T (2009) Forcing and response in simulated 20th and 21st century surface energy and precipitation trends. J Geophys Res 114:D17110. doi:10.1029/2009JD011749

Andrews T, Forster PM, Gregory JM (2009) A surface energy perspective on climate change. J Climate 22:2557–2570. doi:10.1175/2008JCLI2759.1

Bala G, Caldeira K, Miran A, Wickett M, Delire C, Phillips TJ (2006) Biogeophysical effects of CO$_2$ fertilization on global climate. Tellus 58B:620–627. doi:10.1111/j.1600-0889.2006.00210.x

Bala G, Caldeira K, Nemani R (2009) Fast versus slow response in climate change: implications for the global hydrological cycle. Clim Dyn. doi:10.1007/s00382-009-0583-y

Betts RA, Cox PM, Lee SE, Woodward FI (1997) Contrasting physiological and structural vegetation feedbacks in climate change simulations. Nature 387:796–799

Betts RA, Boucher O, Collins M, Cox PM, Fallon PD, Gedney N, Hemming DL, Huntingford C, Jones CD, Sexton DMH, Webb MJ (2007) Projected increase in continental runoff due to plant responses to increasing carbon dioxide. Nature 448:1037–1042. doi:10.1038/nature06045

Boucher O, Jones A, Betts RA (2009) Climate response to the physiological impact of carbon dioxide on plants in the Met Office Unified Model HadCM3. Clim Dyn 32:237–249. doi:10.1007/s00382-008-0459-6

Cao L, Bala G, Caldeira K, Nemani R, Ban-Weiss G (2009) Climate response to physiological forcing of carbon dioxide simulated by the coupled Community Atmosphere Model (CAM3.1) and Community Land Model (CLM3.0). Geophys Res Lett 36:L10402. doi:10.1029/2009GL037724

Cox PM, Betts RA, Bunton CB, Essery RLH, Rowntree PR, Smith J (1999) The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. Clim Dyn 15:183–203

Dong B, Gregory JM, Sutton RT (2009) Understanding land-sea warming contrast in response to increasing greenhouse gases. Part I: Transient adjustment. J Climate 22:3079–3097. doi:10.1175/2009JCLI2652.1

Doutriaux-Boucher M, Webb MJ, Gregory JM, Boucher O (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

Field CB, Jackson RB, Mooney HA (1995) Stomatal responses to increased CO$_2$: implications from the plant to the global scale. Plant Cell Environ 18:1214–1225

Forster P et al (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S et al (eds) Climate change 2007: the physical science basis contribution of working group 1 to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 131–234

Gedney N, Cox PM, Betts RA, Boucher O, Huntingford C, Stott PA (2006) Detection of a direct carbon dioxide effect in continental river runoff records. Nature 439:835–838. doi:10.1038/nature04504

Gregory JM, Webb M (2008) Tropospheric adjustment induces a cloud component in CO$_2$ forcing. J Clim 21:58–71

Gregory JM et al (2004) A new method for diagnosing radiative forcing and climate sensitivity. Geophys Res Lett 31:L03205. doi:10.1029/2003GL018747

Joshi M, Gregory J (2008) Dependence of the land-sea contrast in surface climate response on the nature of the forcing. Geophys Res Lett 35:L24802. doi:10.1029/2008GL036234

Joshi MM, Gregory JM, Webb MJ, Sexton DMH, Johns TC (2008) Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. Clim Dyn 30:455–465. doi:10.1007/s00382-007-0306-1

Kergoat L, Lafont S, Douville H, Berthelot B, Dedieu G, Planton S, Royer J-F (2002) Impact of doubled CO_2 on global-scale leaf area index and evapotranspiration: Conflicting stomatal conductance and LAI responses. J Geophys Res 107(D24):4808. doi: 10.1029/2001JD001245

Lambert FH, Webb MJ (2008) Dependence of global mean precipitation on surface temperature. Geophys Res Lett 35:L16706. doi:10.1029/2008GL034838

O'Ishi R, Abe-Ouchi A, Prentice IC, Sitch S (2009) Vegetation dynamics and plant CO_2 responses as positive feedbacks in a greenhouse world. Geophys Res Lett 36:L11306. doi: 10.1029/2009GL038217

Randall DA et al (2007) Climate models and their evaluation. In: Solomon S et al (eds) Climate change 2007: the physical science basis contribution of working group 1 to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 591–662

Sellers PJ, Bounoua L, Collatz GJ, Randall DA, Dazlich DA, Los SO, Berry JA, Fung I, Tucker CJ, Field CB, Jensen TG (1996) Comparison of radiative and physiological effect of doubled atmospheric CO_2 on climate. Science 271:1402–1406. doi: 10.1126/science.271.5254.1402

Williams KD, Ingram WJ, Gregory JM (2008) Time variation of effective climate sensitivity in GCMs. J Clim 21:5076–5090. doi:10.1175/2008JCLI2371.1

Yang F, Kumar A, Schlesinger ME, Wang W (2003) Intensity of hydrological cycles in warmer climates. J Clim 16:2419–2423