Sensitivity of terrestrial water and energy budgets to CO2-physiological forcing: an investigation using an offline land model

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Abstract
Increasing concentrations of atmospheric carbon dioxide (CO2) influence climate by suppressing canopy transpiration in addition to its well-known greenhouse gas effect. The decrease in plant transpiration is due to changes in plant physiology (reduced opening of plant stomata). Here, we quantify such changes in water flux for various levels of CO2 concentrations using the National Center for Atmospheric Research’s (NCAR) Community Land Model. We find that photosynthesis saturates after 800 ppmv (parts per million, by volume) in this model. However, unlike photosynthesis, canopy transpiration continues to decline at about 5.1% per 100 ppmv increase in CO2 levels. We also find that the associated reduction in latent heat flux is primarily compensated by increased sensible heat flux. The continued decline in canopy transpiration and subsequent increase in sensible heat flux at elevated CO2 levels implies that incremental warming associated with the physiological effect of CO2 will not abate at higher CO2 concentrations, indicating important consequences for the global water and carbon cycles from anthropogenic CO2 emissions.

Keywords: CO2-physiological effect, CO2-fertilization, canopy transpiration, water cycle, runoff, climate change

1. Introduction
The increased concentration of CO2 in the atmosphere is projected to influence the global climate by its effect on plant physiology, in addition to its radiative (‘greenhouse gas’) effect. Plant stomata open less widely under augmented CO2 concentrations, leading to a reduction in plant transpiration (Collatz et al 1992, Sellers et al 1996). Evapotranspiration (which is the sum of canopy evaporation, canopy transpiration, and soil evaporation) from vegetation is hence decreased, causing changes in atmospheric temperature, water vapour content and cloud dynamics. Another important effect of this decreased evapotranspiration is on the water cycle on land: more water is left on the land surface which causes increased runoff and soil moisture content. This driver of climate change, commonly known as ‘CO2-physiological forcing’, has been detected in both field experiments (Hungate et al 2002, Long et al 2006) and climate modelling studies (Sellers et al 1996, Betts et al 2007, Doutriaux-Boucher et al 2009).
A recent study (Cao et al 2010) using the Community Land Model (CLM3.5) coupled to the Community Atmosphere Model (CAM3.5) found that the diminished evapotranspiration from the continents as a result of CO₂-physiological forcing would increase runoff by 8.4 ± 0.6% for a doubling of atmospheric CO₂, compared to an increase in runoff by 5.2 ± 0.6% as a result of CO₂-radiative forcing. Indeed, Gedney et al (2006) reported that the CO₂-physiological effect can be inferred from observational records of continental runoff (of around 0.4 kg m⁻² yr⁻¹).

The motives for this study are twofold. (1) To investigate the sensitivity of the physiological effect to various levels of atmospheric CO₂. An important question is how changes in canopy transpiration scale with atmospheric CO₂ concentrations and whether the change in canopy transpiration tends to saturate at higher levels of CO₂ concentrations. We will also examine the manifestation of such effects on a global scale. (2) To investigate the changes in the surface energy budget caused by the decrease in evapotranspiration associated with CO₂-physiological forcing. A decrease in evapotranspiration should be accompanied by increases in surface sensible and radiative fluxes. How is this increase distributed among these two fluxes? It is challenging to isolate these components in a coupled atmosphere–land model due to feedbacks. Therefore, we use an offline version of CLM3.5 wherein the atmospheric forcing is fixed.

We examine the quantitative global effects of CO₂-physiological forcing using observed climate data to drive the land surface model CLM3.5. We perform multiple simulations under various prescribed CO₂ concentrations to investigate this effect as function of CO₂ levels. The primary objective of this study is to understand land surface response to changes in plant physiology (that is, decreased opening of stomata). Potential changes in leaf area index and vegetation distribution (caused by increased CO₂ concentrations) are not modelled; they are kept constant.

2. The model

We used CLM3.5 for our experiments in this study (Oleson et al 2008). Biophysical processes simulated by the model include solar and longwave radiation interactions with vegetation canopy and soil, momentum and turbulent fluxes from canopy and soil, heat transfer in soil and snow, hydrology of canopy, soil, and snow, and stomatal physiology and photosynthesis. Vegetation cover in CLM3.5 is represented by 16 plant functional types (PFTs) which differ in their ecological and hydrological characteristics. The model was forced with a 50 yr period (1950–99) forcing dataset derived by combining observation-based analyses of monthly precipitation and surface air temperature (Qian et al 2006).

3. Model experiments

Inputs to the model such as the initial conditions dataset, the surface dataset and the plant functional type physiological constants were all set from the input dataset associated with the distribution of CLM3.5. The land model is run with two forcing components: (1) 50 yr climatic data (from 1950–99) as described in Qian et al (2006): this dataset has three-hourly surface air temperature, precipitation, surface pressure, boundary layer wind and surface solar radiation at T62 (1.875°) resolution. When forced by this dataset, CLM3.5 reproduces many aspects of the long term mean annual cycle, interannual and decadal variations, and trends of streamflow for many large rivers (Qian et al 2006); (2) a prescribed constant level of atmospheric CO₂ concentration for each simulation. We have performed eight 50 yr runs with the same climate forcing but varying CO₂ concentrations: 100, 200, 280, 400, 600, 800, 1000, 1200 ppmv. These values were chosen for the following reasons: (1) a CO₂ concentration of 100 ppmv represents the lowest value for which important processes are well represented in the model; (2) the value of 1000 ppmv is probably the upper limit that may be reached by the end of this century. Six other values were chosen, five between this range and one outside. We consider the first 10 yr of a run as a ‘spin-up’ period and use a simulated state over the last 40 yr (1960–99) for our analysis. We inferred from a time series analysis of the 40 yr period that all relevant variables have reached a quasi-equilibrium state (drift in photosynthesis is on the order of 4.2 × 10⁻⁴ μmol m⁻² s⁻¹ yr⁻¹).

4. Results

Figure 1 shows the dependence of key variables on CO₂ levels averaged over the last 40 yr of the 50 yr simulations. There is an increase of around 9.5% in shaded stomatal resistance when CO₂ increases from 100 to 1200 ppmv, while it is around 4.5% in the case of sunlit stomatal resistance. The photosynthesis rate monotonically increases with increase in CO₂ concentrations. For the CO₂ range considered in this study, it increases from approximately 1.4 μmol m⁻² s⁻¹ for 100 ppmv to 4.5 μmol m⁻² s⁻¹ for 1200 ppmv. However, the increase is modest (about 25%) when CO₂ is doubled from present day values of 400–800 ppmv. It can also be seen that the rate of increase slows down for higher values of CO₂ concentrations. This suggests a saturation effect of photosynthesis with respect to CO₂, as discussed in the literature (Dang et al 1998). Saturation can also arise from nutrient limitations. The simulated behaviour of photosynthesis is basically due to the formulation in the model (Oleson et al 2008) which is based on observational studies.

The decrease in canopy transpiration and evapotranspiration for elevated levels of CO₂ (Bonan 2008) can be seen in figure 1. Both decrease monotonically for CO₂ concentrations in the range of 100–1200 ppmv. It is also seen that, unlike photosynthesis, the rate of decline is sustained even at higher CO₂ concentrations for these two important fluxes. We performed linear regressions on canopy transpiration and evapotranspiration for CO₂ concentration in the range of 100–1200 ppmv to get the rate of decrease of these fluxes for CO₂ concentration increases projected for the future. We find that they decrease at the rate of 0.032 and 0.023 mm day⁻¹ respectively (1755.01 and 1300.91 km³ of water per year, summed globally) for every 100 ppmv increase in CO₂ concentration. This corresponds to a sustained
Figure 1. Variation of sunlit leaf stomatal resistance, shaded leaf stomatal resistance, photosynthesis rate, canopy transpiration, evapotranspiration and total runoff (sum of surface runoff and sub-surface drainage) with increasing levels of CO₂ concentration. These are values averaged over the last 40 yr (1960–99) of the simulation. The red vertical bars indicate the uncertainty estimate of ±1 temporal standard deviation.

The decline of as much as 5.1% in canopy transpiration and 1.41% in evapotranspiration for every 100 ppmv increase of CO₂ concentration.

Robustness of the formulation of stomatal conductance. According to Oleson et al (2008), in CLM3.5, leaf stomatal conductance (gs, µmol H₂O m⁻² s⁻¹, inverse of canopy transpiration) is related to leaf photosynthesis (A, µmol CO₂ m⁻² s⁻¹) for all vegetation by the relation:

\[ g_s = m \frac{A e_{ps} P_{atm}}{e_s c_s e_i} + b \]  (1)

where \( m \) is a plant functional type dependent empirical parameter (Collatz et al 1991), \( e_s \) is the vapour pressure at the leaf surface (in pascals, Pa), \( P_{atm} \) is the atmospheric pressure (Pa), \( c_s \) is the CO₂ concentration at the leaf surface, \( e_i \) is the saturation vapour pressure (Pa) inside the leaf at the vegetation temperature, and \( b = 2000 \) µmol m⁻² s⁻¹) is a typical minimum leaf conductance. Equation (1) has been empirically well validated for many plant types and for CO₂ concentrations as low as 100 ppmv and as high as 1000 ppmv (Ball 1988, Morison and Gifford 1983). Prior to that and since then, over 30 models for stomatal conductance have been developed and validated against field studies, as outlined in an excellent recent survey by Damour et al (2010). It is found that equation (1) (Ball 1988) is one of the most commonly used models of \( g_s \), and is quite robust, giving a ‘very practical and accurate prediction of \( g_s \) under variable environment’, and ‘may also be extrapolated at field or forest stand level’ (Damour et al 2010). Further, a more recent observational study by Stockli et al (2008) compares site level data from FLUXNET sites to CLM 3.5 simulations and shows good agreement between simulated latent and sensible heat fluxes and observations.

Thus, the regional patterns projected by equation (1) for canopy transpiration and related fluxes (associated with such scaling of CO₂ levels) would also be reasonable and, hence, we believe that a more realistic spatial pattern of the scaling of canopy transpiration for a range of atmospheric CO₂ concentration can be arrived at by using a contemporary land model such as CLM3.5 (considering that there are other processes involved). Previous modelling studies on CO₂-physiological effects on climate have focused on a doubling of CO₂ levels (Betts et al 2007, Cao et al 2009, 2010). So as to allow a comparison with past studies, we compare the 400 and 800 ppmv simulations here (table 1). On a global mean basis, the rate of photosynthesis increases by 0.84 ±
800 ppmv (increases in leaf and soil temperature lead to an increase in the heat flux, which is the main cause for the surface warming simulated by 0.168×10−3 W m−2). We see an increase in the total runoff of 0.01 mm day−1, which remains unchanged in our simulations and water is conserved, as shown. It can be seen that for changes from 600 to 800 ppmv in CO2, the increase comes from the drainage component, which increases by more than 12%.

Table 1 shows that there is no change in the net surface energy budget when CO2 is increased from 400 to 800 ppmv. This is expected because we have performed quasi-equilibrium simulations and hence there is no storage of surface energy. Since solar radiative forcing and surface air temperature are prescribed in our experiments, we anticipate small changes in radiative components and hence changes in evapotranspiration should be compensated by changes in sensible heat fluxes. We note that this is indeed the case: the decrease in evapotranspiration (3.04±0.00 W m−2) is compensated mostly by an increase in sensible heat flux (2.74±0.01 W m−2) which increases by about 10%. This increase in sensible heat flux is the main cause for the surface warming simulated in earlier studies (e.g. Cao et al 2010). We find that slight increases in leaf and soil temperature lead to an increase of 0.33 W m−2 in surface wave emissions (table 1). A small increase in absorbed solar radiation has also been simulated, which is likely to enhance leaf surface temperature due to lower evapotranspiration which results in higher soil moisture content.

The spatial pattern of change in some key variables for a doubling of CO2 concentration can be seen in figure 2. We see that both sunlit and shaded stomatal resistance increase significantly in many parts of the world. Further, our experiments show that the shaded stomatal resistance has a more pronounced increase than sunlit stomatal resistance which is opposite to what was found in Cao et al (2009) who used an earlier version of the model (CLM3.0). This change in sunlit versus shaded resistance is related to changes in the canopy photosynthesis and transpiration formulations from CLM3.0 to CLM3.5 (Lawrence and Chase 2009). Photosynthesis increases significantly for most areas of the globe, especially in parts of Eurasia, the Congo and Amazon basins, and South-East Asia. Meanwhile, the canopy transpiration decreases significantly in most parts of the world. The cause for significant decrease is the simulated increase in sunlit and shaded stomatal resistance. There is no significant change in canopy evaporation, but there are some areas with significant increases in ground evaporation. The net effect is an overall decrease in evapotranspiration (7.4%, for the global average), as shown by earlier studies (Sellers et al 1996, Betts et al 2007, Doutriaux-Boucher et al 2009). Also, the changes in evapotranspiration are significant for about 11.5% of the land area around the globe. This reduction in the water flux from the land to the atmosphere causes an increase in total runoff, by as much as 12% (when globally averaged). Here, total runoff is the sum of surface runoff (streams, rivers, etc) and sub-surface drainage. Runoff increases significantly mostly in the vegetated parts of the world: parts of Eurasia such as South-East Asia, Amazon basin, the Congo basin and northern parts of the North American continent. But, in general, the overall change in runoff is not significant.

In figure 3, global scaling of photosynthesis and canopy transpiration for varying levels of CO2 concentrations is shown. It can be seen that for changes from 600 to 800 ppmv and 800 to 1000 ppmv, the change in photosynthesis is minimal (i.e. it has saturated), and is significant in very few places. On the other hand, it can be seen that canopy transpiration
Figure 2. Maps of annual mean percentage changes in sunlit stomatal resistance, shaded stomatal resistance, photosynthesis, canopy transpiration, canopy evaporation, ground evaporation, evapotranspiration and total runoff for a doubling of atmospheric CO2 concentration levels (from 400 to 800 ppmv). These changes are calculated from the last 40 yr results of 50 yr simulations. Hatched areas are regions where changes are not statistically significant. Significance is determined at the 99% confidence level using the standard student t-test. Values in parentheses (at the top of figure) indicate the percentage change in the global mean of the variable taken from table 1.

continues to significantly decline all over the globe (and especially in the densely vegetated areas such as the Amazon and the Congo basin) even at these high levels of CO2 concentrations.

5. Discussion

In this letter, we have quantified the effects of increasing levels of CO2 on plant physiology and its subsequent effects on water and energy fluxes. Additional effects on these fluxes are expected due to changes in leaf area index and vegetation structure but these effects depend strongly on the strength of vegetation feedback and the timescales involved (Betts et al 2007, Bala et al 2005). The increase in surface runoff we obtain for a doubling of CO2 (7.81 ± 1.59%) is in agreement with other similar recent projections: e.g. Cao et al (2010) report an increase in runoff by 8.4 ± 0.6% for a doubling of CO2 levels. Betts et al (2007) find a runoff increase of 6% due to CO2-physiological forcing relative to pre-industrial levels. Further, these two studies show that this increase is comparable to the runoff increase purely due to radiative
Figure 3. Global scaling of photosynthesis and canopy transpiration for varying levels of CO$_2$ concentrations. For instance, ‘400–200’ denotes the percentage change in the variable for an increase in CO$_2$ concentrations from 200 to 400 ppmv. These changes are calculated from the last 40 yr results of 50 yr simulations. Hatched areas are regions where changes are not statistically significant. Significance is determined at the 99% confidence level using the standard student $t$-test. For changes from 600 to 800 ppmv and 800 to 1000 ppmv, the change in photosynthesis is minimal (i.e. it has saturated). However, canopy transpiration continues to decline all over the globe for these increases in CO$_2$ concentrations.

effects (which is 5.2 $\pm$ 0.6% and 11 $\pm$ 6%, respectively, in their studies). Our projections of the relative increases in surface runoff (7.81 $\pm$ 1.59%) and drainage (12.52 $\pm$ 1.93%) will have implications for irrigated agriculture.

Since we use an offline land model, decreases in evapotranspiration fluxes are accompanied by increases in sensible heat flux of the same magnitude. Changes in surface radiative fluxes are smaller before any feedback between the atmosphere and land could amplify their changes. The changes in sensible heat fluxes have the same magnitude as those of latent heat fluxes even when the feedback between land surface and atmosphere is included (Cao et al 2010). This result suggests that land cover change (e.g. deforestation and forest degradation) and land use change (urbanization, irrigation) that alters the evapotranspiration fluxes will have associated changes in surface sensible heat fluxes of similar magnitude but opposite sign. Some indication of this increased sensible heat for surface warming is given in a recent work (Bala et al 2007) that analysed model simulated tropical deforestation. Tropical deforestation (which reduces local evapotranspiration) in that study leads to a global warming by about 0.7 °C. Two more important consequences of a decrease in evapotranspiration are discussed in Cao et al (2010): Regional relative humidity decreases by as much as 7% and regional low-cloudiness by 4%. Such changes can have significant feedback effects on regional weather and climate. The significance of this result to the global warming potential concept has also been discussed in Cao et al (2010): the importance of CO$_2$ relative to non-CO$_2$ greenhouse gases increases by about 10% when the physiological effect is considered.

We find that change in latent and sensible heat fluxes are the driving forces of climate change when there is a change in water flux from land to atmosphere. Another trend we find is the behaviour of evapotranspiration and sensible heat at high levels of CO$_2$ concentrations. Here, unlike photosynthesis (which tends to saturate), evapotranspiration continues to decline (globally, by 1305.45 km$^3$ of water per year for every 100 ppmv CO$_2$ increase) accompanied by an increase in sensible heat. This implies that the rate of global temperature increase by the CO$_2$-physiological effect will remain undiminished at higher levels of CO$_2$.

A recent observational study has shown that evapotranspiration over land has decreased since 1998–2008 (Jung et al 2010) and it demonstrates that soil moisture limitations are the main cause for the decline. Since the simulated evapotranspiration change due to CO$_2$-physiological effect is only about 1.41% for 100 ppm increase in CO$_2$, we believe that long term observational data on evapotranspiration would be crucial to directly assess the CO$_2$-physiological effect on evapotranspiration. There is also currently uncertainty in the indirect evidence for increased runoff due to the CO$_2$-physiological effect: while Labat et al (2004) find that the global runoff has increased in recent decades, Dai et al (2009) show that the global runoff has decreased from 1948–2004. Gedney et al (2006) attribute the CO$_2$-physiological effect to the increase found in Labat et al (2004) and
Dai et al (2009) attribute precipitation decrease to their observation of decreased runoff. Therefore, as of now, there is no consensus on the observational evidence for the CO$_2$-physiological effect on the global scale. Further work is needed in this direction including observational and modelling studies on plant physiology and realistic simulations of the surface hydrological cycle.

This study is conducted using an offline land surface model. In reality both CO$_2$-radiative and the physiological effect operate on the climate system and changes in atmospheric and oceanic processes would feedback on the terrestrial response. The modelling of stomatal response to increasing atmospheric CO$_2$ and environmental variables is a challenge. The simulated response of plant stomata here is based on the semi-empirical relations between stomatal conductance and environmental variables (Collatz et al 1991). The semi-empirical stomatal response model is also used in other global climate modelling studies that found significant effects of CO$_2$-physiological forcing on global climate (e.g. Betts et al 2007, Boucher et al 2009, Cao et al 2010). Recently, alternative models have been developed that simulate stomatal adaptations based on the optimization of carbon gain under the constraint of a cost of water loss (e.g. Konrad et al 2008, Katul et al 2010, De Boer et al 2011). De Boer et al (2011), using an optimization model of stomatal adaptation forced by prescribed environmental conditions, predicts that a doubling of today’s CO$_2$ concentration will decrease the annual transpiration flux from subtropical vegetation in Florida by an amount that is approximately 50% of the current total evapotranspiration in that region. However, the conclusions and modelling approach were challenged by Miglietta et al (2011). Certainly, the appropriate treatment of stomatal conductance and scaling it up to the level of regional and global transpiration merits further studies.

Uncertainties exist in the modelled effect of CO$_2$-physiological forcing on global climate, in particular the land hydrology. Gedney et al (2006) reported that the suppression of plant transpiration due to CO$_2$-induced stomatal closure is a big contributor to the increased trend of global runoff in recent decades. On the contrary, Dai et al (2009), using a combination of observed historical monthly streamflow and CLM3 simulations, found that the CO$_2$-physiological forcing has a small effect on the historical change in runoff compared to the effect of climatic forcing. However, we note that the model used in the study of Dai et al (2009), CLM3.0, has an unrealistic partitioning of plant transpiration in the control simulation, which suppresses the modelled response of transpiration to increasing atmospheric CO$_2$ (Cao et al 2009). In a study that reported a recent decline in the global land evapotranspiration (Jung et al 2010) it was suggested that the CO$_2$-physiological effect does not have a measurable influence on the global land evapotranspiration. These contradictory results emphasize the urgent need to better understand the stomatal response and its interactions with climate feedback.

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