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Evidence for carbon dioxide and moisture interactions from the leaf cell up to global scales: Perspective on human-caused climate change

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Abstract

It is of utmost interest to further understand the mechanisms behind the potential interactions or synergies between the greenhouse gases (GHG) forcing(s), particularly as represented by CO_2, and water processes and through different climatic scales down to the leaf scale. Toward this goal, the factor separation methodology introduced by Stein and Alpert [Stein U. and Alpert, P. 1993. Factor separation in numerical simulations, J. Atmos. Sci., 50, 2107–2115.] that allows an explicit separation of atmospheric synergies among different factors, is employed. Three independent experiments carried out recently by the present authors, are reported here, all strongly suggest the existence of a significant CO_2–water synergy in all the involved scales. The experiments employed a very wide range of up-to-date atmospheric models that complement the physics currently introduced in most Global Circulation Models (GCMs) for global climate change prediction.

Three modeling experiments that go from the small/micro scale (leaf scale and soil moisture) to mesoscale (land-use change and CO_2 effects) and to global scale (greenhouse gases and cloudiness) all show that synergies between water and CO_2 are essential in predicting carbon assimilation, minimum daily temperature and the global Earth temperature, respectively. The study also highlights the importance of including the physics associated with carbon–water synergy which is mostly unresolved in global climate models suggesting that significant carbon–water interactions are not incorporated or at least well parameterized in current climate models. Hence, there is a need for integrative climate models. As shown in earlier studies, the climate involves physical, chemical and biological processes. To only include a subset of these processes limits the skill of local, regional and global models to simulate the real climate system.

In addition, our results provide explicit determination of the direct and the interactive effect of the CO_2 response on the terrestrial biosphere response. There is also an implicit scale interactive effect that can be deduced from the multiscale effects discussed in the three examples. Processes at each scale-leaf, regional and global will all synergistically contribute to increase the feedbacks — which can decrease or increase the overall system's uncertainty depending on specific case/setup and needs to be examined in future coupled, multiscale studies.

Keywords: factor separation; biosphere atmospheric interactions; scale interactions; carbon-dioxide assimilation; land-use changes; coupled carbon–water processes; elevated CO_2

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1. Introduction

It is widely believed that cloud and water processes dominate climate model errors. For instance, the ability of the General Circulation Models (GCMs) to describe accurately the transport of water vapor into the upper troposphere by well-developed clouds is a central point in the debate on the ability of GCMs to simulate the atmospheric warming due to the radiative effect of the doubling of CO_2 (Lindzen, 1990). This study addresses the ability of GCMs to faithfully simulate the interactive effects of CO_2 and water processes, which we will refer to here as "CO_2–water interaction", or equivalently, "CO_2–water synergy". Synergy indicates a result which is contributed solely by the joint action of two or more factors. In addition, particularly these CO_2–water synergies may emerge at different spatial scales. GCMs rely on a relatively coarse grid-interval of the order of 100-km, which necessitates making gross assumptions about smaller-scale processes often simplified via physical parameterizations, and this makes it difficult to identify synergistic effects that are due to processes at different scales.

The complex nonlinear interactions among the different components of the climate system have been recently emphasized. This synergy has been summarized in National Research Council (2005), as well as in review papers (e.g. Pielke, 2001; Pitman, 2003). For instance, Fig. 1-1 in the National Research Council report, schematically overviews the interrelationship. Similarly, meta-analysis studies of measurements involving doubling of CO_2 conditions (e.g. Curtis and Wang, 1998) consistently suggest that there are many interactive variables that can modulate the effect associated with the doubling of CO_2, which needs to be extracted and quantified.

It is therefore of utmost interest to further understand the mechanisms behind the potential synergies between the greenhouse gases (GHG) forcing(s) and the water processes and particularly through the different scales down to the leaf scale. Towards this goal, we employ a factor separation methodology (Stein and Alpert, 1993), that allows separating the contributions of several factors to a specific model result, as well as all the synergic (i.e., interactive) contributions. For *n* factors, the method requires 2n experiments or simulations in which all possible combinations for switching on/off factors, are performed. For instance, in the case of two factors being investigated, four simulations are required in order to obtain four contributions as follows: two pure (or direct) contributions for each factor, one double synergy and a fourth contribution independent of the two factors. Section 4 (3rd example) provides the equations for a case of two factors. The method was applied for better understanding of lee-cyclogenesis mechanisms with four factors, i.e., 16 simulations including triple interactions and even one quadruple synergy (Alpert et al., 1995, 1996). The method was also applied to many other studies including, oceanic modeling (Deleersnijder et al., 1995) paleoclimate forcings (Berger et al., 1993); air-pollution (Guan and Reuter, 1996), flood events (Ramis et al., 1998), and urban landscape induced mesoscale convection initiation (Niyogi et al., in press-b).

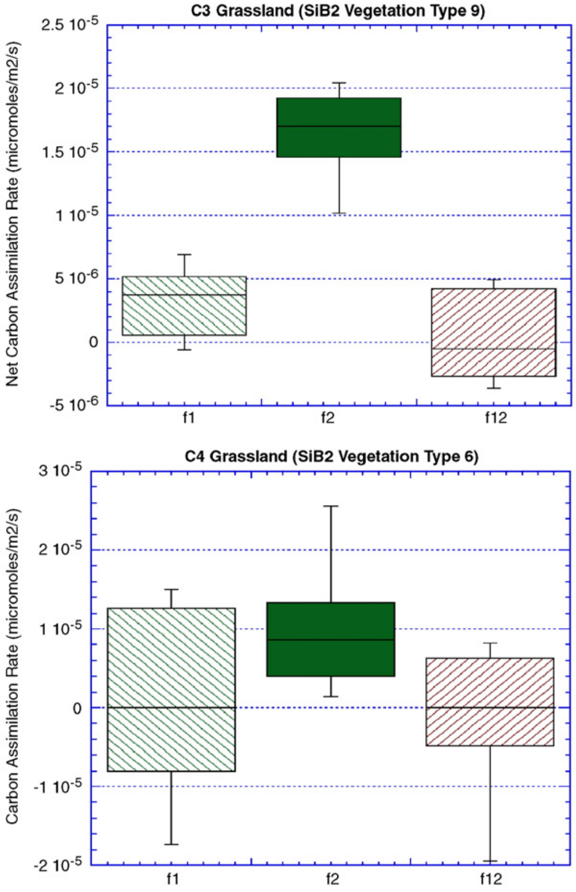

Fig. 1. Box plots summarizing the factor separation results for carbon assimilation rates, for C3 and C4 grasslands (over Great Plains corresponding to 1989 growing season during a field experiment). The functions $\hat{f}1$, $\hat{f}2$ *and* $\hat{f}12$ refer, respectively, to the separated contributions due to the pure effect of CO_2 doubling; pure effect of soil moisture availability, and the soil moisture/CO_2 change synergy, Niyogi (2000). The domain spread of the results is indicated. Notice, that in the figure $\hat{f}1$, $\hat{f}2$ *and* $\hat{f}12$ are denoted without the ^ symbol. But it should be clarified that the symbols without this ^ symbol in the text (as in Stein and Alpert, 1993), refer to the experiments' results, not to the separated contributions.

We report here, for the first time jointly, on three independent experiments carried out recently by the present authors, which all strongly suggest the existence of a significant CO_2–water synergy in all the involved scales. The experiments employed a wide range of up-to-date atmospheric models that complement the physics currently introduced in the GCMs in global climate change prediction. The three experiments go from the small canopy scale to mesoscale and global scale, respectively.

In the first example, at the canopy scale, a high-resolution 1D atmospheric model dynamically coupled with a prognostic soil moisture/soil temperature scheme with a photosynthesis-based vegetation/stomatal resistance submodel, was employed (Niyogi and Xue, 2006-this issue). Factor separation results show that the CO_2–soil moisture synergy contributes as much as the CO_2 contribution for the net carbon assimilation. In a second example (Eastman et al., 2001), the effects of landscape change and biological responses to elevated CO_2 on minimum surface temperatures are examined using a coupled plant and a meteorological model with a horizontal grid of 50 km. Finally, in a third example at the global scale, factor separation for the globally-averaged surface temperature reveals a large cloud and GHG synergy.

2. First example: biosphere–atmosphere interactions coupled with CO_2 and soil moisture changes

It was shown that the biological effect of the CO_2 change is interactively linked with soil moisture availability for two different vegetation types. A 1D atmospheric boundary layer model dynamically coupled with a prognostic soil moisture/soil temperature scheme with photosynthesis-based vegetation/stomatal resistance submodel was used in this study. The model was a column model with stretched log linear grid with lowest layer at 10 m and typically increasing at 30 m interval. The model was also integrated using meteorology fields supplied by a mesoscale model with inner horizontal grid intervals at 5 km for some cases. Further details can be found in Niyogi (2000) and Niyogi and Xue (2006-this issue). The photosynthesis-conductance model is similar to the Collatz–Farquhar photosynthesis–transpiration model described in Collatz et al. (1991) for C3, and Collatz et al. (1992) for C4; and the Ball–Berry stomatal conductance scheme (Ball et al., 1987). The model has been modified following Calvet (2000) to account for soil moisture stress, and is fully coupled within a land surface model with prognostic soil moisture, and soil temperature variations.

The photosynthesis-conductance model has been validated against grasslands, crops, and forest based biophysical measurements (and reported in Niyogi, 2000; Niyogi and Raman, 2001; Niyogi et al., 2003, 2004). Further, the coupled modeling system has been robust in simulating complex multiscale interactions in coupled weather forecast models as described in Holt et al. (2006) and Niyogi et al. (in press-a,-b).

Study objective was to analyze the biological effects of CO_2 doubling, under high as well as limiting, i.e., drought-like, soil moisture conditions, for C3 vs. C4 grassland, which differ in their photosynthetic pathways and water use efficiency. The four experiments performed included combinations of present day CO_2 (340 ppm), and limiting soil moisture (f_0), for doubling of CO_2 concentrations (f_1), and soil moisture under nonlimiting conditions (f_2), and resulting synergistic interactions (f_{12}).

Results are consistent with observations that CO_2 and soil moisture related effects are important for both the C3 and C4 grassland carbon assimilation (Fig. 1). While each biome type responded differently to the prescribed changes in soil moisture and CO_2 changes, for each case the soil moisture–CO_2 interaction term was significant. Fig. 1 shows that although the interaction terms are around zero their range of values, is significant.

3. Second example: role of land-use change and the radiative and biological effect of CO_2 on the climate

To assess the relative sensitivity of land-use change and the physical and biological effects of CO_2 on the climate system, a suite of sensitivity experiments were performed for a particular growing season (1989) over the central Great Plains of the United States. The most significant land use change since pre-settlement was the conversion of the tall grass prairie to agriculture. The change has almost completely eliminated this vegetation type. Lesser, but still significant conversion of the short grass prairie to agriculture also occurred and is represented in the model landscapes. A regional coupled model (RAMS-GEMTM, Eastman et al., 2001) was applied in which the lateral atmospheric boundary conditions were identical between experiments. The RAMS model used was validated against observations in this study, as reported in Eastman et al. (2001), and in numerous other investigations (e.g., see the recent summaries by Pielke et al., 1992, and Cotton et al., 2003). The model run had a horizontal grid interval in the fine grid of 50 km.

The vertical grid was 100 m near the surface which then slowly increased to 1.5 km near the model top. There were 20 points in the vertical with 26 × 30 in the horizontal (the fine grid). It should be noted that the land use change involves soil water effects, but it also includes leaf surface area and albedo.

The domain-growing season-averaged deviations from the control experiment (f_0) due to land-use change (f_1), the radiative effect of CO_2 (f_2), the biophysical/biogeochemical effect of CO_2 (f_3), and the subset of interaction experiments (f_{12}, f_{23}, f_{13}, and f_{123}) for the minimum temperature are presented in Fig. 2. We find is that the largest effect, of 0.26 C was due to the biophysical/biogeochemical effect of CO_2.,f_3, larger than the radiative effect of CO_2,f_2, with a value of 0.10 C. While this result does not imply that the radiative effect of CO_2 is not important on longer time scales, it does indicate there should be heightened concern regarding the biological feedback of vegetation into the climate system.

In addition, the interactive terms, while relatively small, are still often as large as the radiative effect of doubled CO_2 alone. For example, the interaction of land-cover change and the biological effect of CO_2 have a similar effect on domain-averaged minimum temperature to that of the radiative effect of doubled CO_2 (Fig. 2). The reason that the minimum temperatures are affected as much by land-cover change and the biological effect of elevated CO_2 is that a greater amount of water vapor is transpired into the atmosphere during the daytime due to greater leaf area and hence greater transpiring area. Therefore, at night the added water vapor reduces the long-wave loss of heat to space (i.e., a larger “greenhouse effect”). Thus stomatal closure in response to elevated CO_2 is more than compensated for by larger leaf area with this particular land use change. Its magnitude is as large as that due to the radiative effect of the added CO_2.

4. Third example: roles of clouds, GHG and their interaction in global warming

Houghton (1997, Table 5.1, p.76) presents simple one-dimensional model estimates of global average temperature changes due to effects of the greenhouse gases and the clouds (Fig. 3).

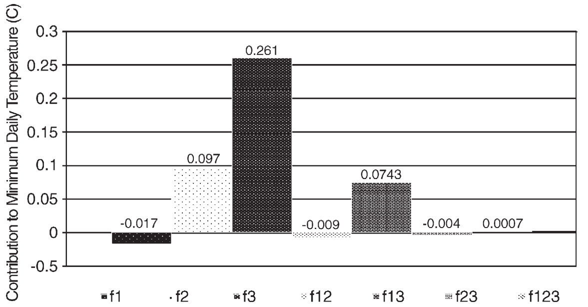

Fig. 2. The domain-growing season-averaged factor-separated contributions due to land-use change ($\hat{f}\,1$), the radiative effect of CO_2 ($\hat{f}\,2$), the biophysical/biogeochemical effect of CO_2 ($\hat{f}\,3$), and the synergy (interaction) terms ($\hat{f}_{12}$, $\hat{f}_{23}$, $\hat{f}_{13}$, and $\hat{f}_{123}$) for the minimum temperature. Notice, that in the figure the factor-separated contributions are denoted without the ^ symbol.

The departures in °C from the current average global surface temperature of 15 °C are calculated based on four on/off model experiments in which the ‘off’ experiment represents the situation without GHG and no clouds, and the ‘on’ for the present full GHG and cloud climate simulation. The possible four experiments and the resulting ΔT (°C) are summarized by:

GHG	Clouds	ΔT (°C)	Factor separation Terminology
Off	Off	−21	f_O
On	On	0	f_{CG}
Off	On	−32	f_C
On	Off	4	f_G

It is suggested that the role of clouds and GHG cannot be interpreted without the isolation of the cloud and GHG synergy. This can be performed by adopting the factor separation approach (Stein and Alpert, 1993). Following this method, the four contributions to the current global surface temperature of 15 °C, i.e., $\Delta T=0$ °C can be separated to *cloud only* ($\hat{f}_C$), *GHG only* ($\hat{f}_G$), cloud and GHG synergy ($\hat{f}_{CG}$) and due to other factors independent of C and/or GHG ($\hat{f}_O$) (Fig. 3). They are given respectively by:

$$\hat{f}_C = f_C - f_O = -32-(-21) = -11$$

$$\hat{f}_G = f_G - f_O = 4-(-21) = 25$$

$$\hat{f}_{CG} = f_{CG} - (f_C + f_G) + f_O = +7$$

$$\hat{f}_O = -21$$

The sum of all four contributions yields the present climate $\Delta T=0$ °C. The conclusions, however, are interesting. First, the *cloud only* contribution is negative (−11 °C) but when the positive synergy of clouds with the GHG are also accounted for, then the negative feedback of clouds drops to −4 °C only. Second, the ‘GHG only’ contribution is strongly positive +25 °C. Hence, the balanced global surface temperature of −6 °C for the atmosphere *without* GHG and *without clouds* i.e., experiment f_O is increased towards our current value of 15 °C primarily by the GHG (+25°) and by their synergy with clouds (+7°). The negative contribution of *clouds only* (−11°) brings the result back to 15 °C.

These results give only the correct interpretation for the results of the model atmosphere and its associated physical parameterizations. When the model physics is modified/improved to better represent the real atmosphere, the

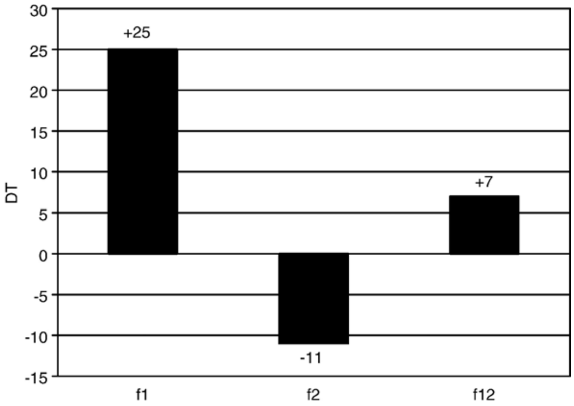

Fig. 3. The contributions to the current global surface temperature of 15 °C, i.e. $\Delta T=0$ °C, can be separated to, *GHG only* ($\hat{f}_G$)$-f_1$ in the figure, *cloud only* ($\hat{f}_C$)$-f_2$ in the figure and the cloud and GHG synergy ($\hat{f}_{CG}$)$-f_{12}$ in the figure. The $\hat{f}_O=-21$ contribution has to be added to get the current climate value of $\Delta T=0$ °C.

aforementioned results will probably change in accordance with the corresponding changes in the GHG and new cloud parameterizations. In particular, as also indicated by J. H. Houghton (personal communication), there is a large uncertainty in the value of −32 °C (widely quoted as the size of the natural greenhouse effect) for the anomaly of the Earth temperature without GHG but with clouds.

5. Summary and discussion

The need for integrative climate models is a major conclusion of our paper. As shown in the National Research Council (2005) and IGBP (2004) books, also in Pitman's (2003) review, climate involves physical, chemical and biological processes. To only include a subset of these processes limits the skill of local, regional and global models to simulate the real climate system.

Three modeling experiments that go from the canopy scale (for different vegetation types) to mesoscale (land-use change and CO_2 effects on daily minimum temperature) and to global scale (greenhouse gases and cloudiness in a global climate model), all show that synergies between water and CO_2 are essential in predicting carbon assimilation, minimum daily temperature or the global Earth temperature. Most of the physical processes involved in these interactions, such as cloud formation, turbulent fluxes and radiative flux divergences, are often not well resolved in global climate models, suggesting that significant carbon–water interactions are not captured in current climate models.

In the first example, in the canopy-scale, a high-resolution 1D atmospheric model dynamically coupled with a prognostic soil moisture/soil temperature scheme with a photosynthesis based vegetation/stomatal resistance submodel, was employed. Factor separation results show that the CO_2–soil moisture synergy contributes as much as the CO_2 contribution for the net carbon assimilation. In a second example, the effects of CO_2 and landscape change are examined using a coupled plant and a meteorological model with a horizontal grid of 50 km. Here, we choose to show the significant contribution of the synergy between the land-use change and the biological effects of CO_2 on minimum surface temperatures. In the last example, factor separation for the globally-averaged surface temperature reveals a large cloud and GHG synergy.

The results indicate that (a) resolving the direct and interactive synergies associated with the input variable changes are useful measures for assessing the effects due to CO_2 changes; (b) both C3 and C4 vegetation will be significantly affected by the CO_2 changes; and the impact on C4 vegetation could in fact depend on the soil moisture availability; (c) studies linking CO_2 effects in a sensitivity-type analysis both in observational as well as numerical experiments should explicitly resolve the synergies. Changes in soil moisture from drought or high soil moisture availability can enhance, or completely balance, or even reverse the biological effects associated with CO_2 doubling by itself, and therefore need to be considered in any future assessment. Often, despite dramatic leaf level impacts due to climate changes, the natural ecosystem tends to buffer and does not show a dramatic response. Our analysis suggests that the synergies between the biotic and abiotic changes tend to have a first order effect causing synergistic response for carbon sequestration. This has potential implications in terms of scaling the information from measurements to the modeling studies as well as to develop uncertainty estimates for the system response.

Some implications of our results are: (i) the presence of a coupled feedback from canopy scale to the regional to the global scales between the different terrestrial-biosphere components, and (ii) the presence of both scale-up and scale-down feedback pathways of the terrestrial-biosphere interactions from leaf to the global scales, as they impact the interactions. A related impact of this is the propagation of uncertainty from the leaf scale to regional and global scales and the feedback of the global and regional weather and climate on the leaf scale response (as illustrated for example in Alapaty et al., 1997; Niyogi et al., 1999).

An interesting question following this study is what interactive effects may be common to all of the scales or does the magnitude of the effect seem to change in a predictable way with scale. It seems from the obtained results that the need to include radiative and biogeochemical effects of added CO_2 on vegetation and soil processes is essential at all spatial scales. Individual plants respond to their immediate environment, while when aggregated, vegetation significantly affects regional and even global climate. Hence, the need to assess both water and carbon processes simultaneously in observations and in models is one conclusion of the examples presented here.

In addition, our results provide explicit determination of the direct and the interactive effect of the CO_2 response on the terrestrial biosphere response. We show that stomatal responses to elevated CO_2 affect the level of evapotranspiration, which affects local climate and cloud cover, which then affect global climate; radiative effects of CO_2 influence all scales, such plant physiological responses to temperature, and the water holding capacity of the atmosphere. What is the propagation of the uncertainty or feedback from one scale to the other is still not known. This study suggests that processes at each scale-canopy, regional and global will all synergistically contribute to increase the feedbacks, which can decrease or increase the overall system's uncertainty depending on the specific case/setup and needs to be examined in future coupled, multiscale studies.

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