Quantifying the negative feedback of vegetation to greenhouse warming: A modeling approach

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[1] Several climate models indicate that in a 2 × CO_2 environment, temperature and precipitation would increase and runoff would increase faster than precipitation. These models, however, did not allow the vegetation to increase its leaf density as a response to the physiological effects of increased CO_2 and consequent changes in climate. Other assessments included these interactions but did not account for the vegetation down-regulation to reduce plant's photosynthetic activity and as such resulted in a weak vegetation negative response. When we combine these interactions in climate simulations with 2 × CO_2, the associated increase in precipitation contributes primarily to increase evapotranspiration rather than surface runoff, consistent with observations, and results in an additional cooling effect not fully accounted for in previous simulations with elevated CO_2. By accelerating the water cycle, this feedback slows but does not alleviate the projected warming, reducing the land surface warming by 0.6°C. Compared to previous studies, these results imply that long term negative feedback from CO_2-induced increases in vegetation density could reduce temperature following a stabilization of CO_2 concentration. **Citation:** Bounoua, L., F. G. Hall, P. J. Sellers, A. Kumar, G. J. Collatz, C. J. Tucker, and M. L. Imhoff (2010), Quantifying the negative feedback of vegetation to greenhouse warming: A modeling approach, *Geophys. Res. Lett.*, *37*, L23701, doi:10.1029/2010GL045338.

1. Introduction

[2] A compilation of results from climate models of varying complexity indicates that in a 2 × CO_2 environment, temperature would increase between 2 and 4.5°C, and rainfall would increase in most regions except the Mediterranean, the southwestern part of the United States, South Africa and Southwest Asia [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. Results from these models also indicate that compared to their respective baselines, the global mean surface runoff would increase faster (8.9%) than precipitation (5%) [*Nohara et al.*, 2006]. These assessments, however, did not allow vegetation leaf area index (LAI) to increase with CO_2 and subsequent changes in climate. Increase in LAI affects photosynthesis, evapotranspiration, surface albedo and surface roughness, all of which feedback on climate.

[3] Projected increases in global temperature and land precipitation are supported by observations [*IPCC*, 2007; *Wentz et al.*, 2007]. An increase in land precipitation could also increase soil moisture; and where vegetation growth has been previously water-limited, LAI will increase. Where this happens, evapotranspiration will also increase, leading to a slower rate of atmospheric warming than that projected in the absence of vegetation feedback. Hence, including this feedback in climate simulations with elevated-CO_2 may reduce the projected warming [*Betts et al.*, 1997].

[4] Observational studies based on long-term records show consistent trends between vegetation and precipitation increase over the Sahel [*Anyamba and Tucker*, 2005] and relate the increase in vegetation density over North America to change in temperature [*Neigh et al.*, 2008]. Figure 1 shows observational evidence of the quasi-linear relationship between continental-scale vegetation density [*Tucker et al.*, 2005] and the precipitation minus runoff [*U.S. Geological Survey*, 2007] over the common period of 1982–1995.

[5] Consistent with observations, modeling studies [*Piao et al.*, 2006] indicate that increases in atmospheric CO_2, temperature and precipitation account for 49%, 31%, and 13% of the increase in growing season LAI, respectively. They also show that in cold Siberian regions, vegetation growth is associated with temperature increase, while in central North America it is primarily due to increase in precipitation. These modeling studies suggest that the rate of change of LAI with temperature accelerates with increasing soil moisture, but slows down, and even becomes negative, as the mean temperature increases, implying that the current greening trend may weaken or even disappear under continued warming.

[6] Since the pioneering work of *Dickinson and Wilson* [1986] and *Sellers et al.* [1986] several models incorporated interactive vegetation. However, these interactive vegetation models are still characterized by large uncertainties and significant divergences in their results [*Friedlingstein et al.*, 2006]. Previous work by *Betts et al.* [1997] and *Levis et al.* [2000] simulated large scale vegetation feedbacks on elevated CO_2-climate by allowing the vegetation to increase its LAI as a response to the physiological effects of increased CO_2 and consequent changes in climate. Both of these studies used interactive vegetation-climate models; however neither considered down-regulation as a possible mechanism to reduce plant's photosynthetic activity under 2 × CO_2. Under elevated CO_2 plants exhibit some down-regulation characterized by a reduction in the initial CO_2-enhanced rates of photosynthesis that result from a gradual decrease in the activity and/or amount of Rubisco -Vmax [*Leakey et al.*,

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2009]. Down-regulation reduces the canopy conductance beyond the reduction caused by the radiative and physiological effects simulated in previous and our own RP-scenarios [*Sellers et al.*, 1996], leading thus to increased water availability which is diverted, as an additional effect, to increase LAI beyond increases caused by climate changes and CO_2-induced water use efficiency.

[7] Our work bears resemblance to the studies of *Betts et al.* [1997] and *Levis et al.* [2000]; however it differs from them in the modeling approach:

[8] 1. As an alternative to interactive vegetation-climate we consider a controlled vegetation-climate interaction approach to quantify the negative feedback of vegetation to greenhouse warming.

[9] 2. We use a unique methodology that simultaneously accounts for down-regulation of vegetation physiology under 2 × CO_2 and simulates growth in leaf density constrained by global satellite observations, only where vegetation is observed to exist and only where it was previously water limited.

[10] 3. We do not allow vegetation to migrate in these simulations.

[11] We postulate that the excess photosynthetic capacity and the additional water available following down-regulation would stimulate vegetation growth much more than previously suggested. This feedback results in a stronger vegetation response and may have implications for climate.

2. Method

[12] We investigated the implication of this feedback for projected changes in carbon, precipitation, temperature and runoff associated with 2 × CO_2 in a global climate model. We used a version of the Colorado State University coupled land- ocean-climate model [*Randall et al.*, 1996] with the Simple Biosphere model (SiB2) [*Sellers et al.*, 1996] to describe land biophysical exchanges.

[13] We compared three plausible future vegetation-climate interaction scenarios, two of which build on our previous work [*Sellers et al.*, 1996; *Bounoua et al.*, 1999]. The first scenario was a baseline 2 × CO_2 simulation (**RP**) in which both the radiative forcing and the vegetation physiology operate under 2 × CO_2 (700 ppm). In the second scenario, we investigated the additional effect of physiological down-regulation (**RPV**) on the water, energy and carbon budgets under 2 × CO_2. Down-regulation was prescribed in the 2 × CO_2 environment by requiring the physiological model to maintain photosynthesis rates consistent with a 1 × CO_2 (350 ppm) atmosphere [*Sellers et al.*, 1996]. This is achieved by reducing the initial CO_2-enhanced rates of

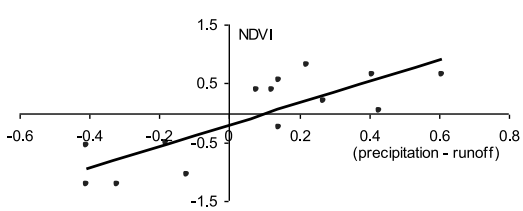

Figure 1. Annual NDVI anomalies from the (1982–2002) mean and observed precipitation minus runoff from the (1982–1995) mean, over the continental U.S. for 1982–1995 period.

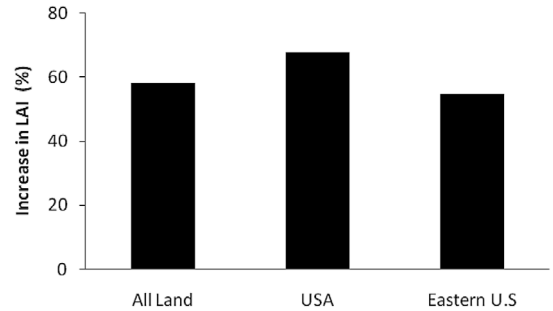

Figure 2. LAI increase for the RPVB-Control. Eastern U.S region is defined east of the Mississippi.

photosynthesis through the maximum Rubisco capacity – Vmax, which leads to an increase in the vegetation's water use efficiency and a relative decrease in evapotranspiration. Since the study of *Sellers et al.* [1996], other researchers have examined the effect of CO_2-induced stomatal closure on the hydrological cycle and have reported similar results [*Gedney et al.*, 2006; *Betts et al.*, 2007].

[14] In the third scenario (**RPVB**), we allow the vegetation to increase its foliage as a response to CO_2 fertilization [*Betts et al.*, 1997; *Levis et al.*, 2000] and water availability (Figure 2). The RPVB simulation was identical to the RPV simulation; however down-regulation led to increased water availability which was diverted to increasing LAI. Additionally, we used the reduction in Vmax from the RPV-case to increase LAI such that total Vmax within each grid cell approached that of the RP-case (Text S1 of the auxiliary material).[1] In SiB2, increases in LAI not only affect the carbon uptake, transpiration and interception rates, but also alter surface albedo and roughness and so affect the exchanges of carbon, energy, water and momentum at the land-atmosphere interface. Furthermore, the model's vegetation physiological growing season is controlled by low-temperature stress levels below which photosynthesis is inhibited. As temperatures increase with CO_2, these stress levels become less severe earlier during the onset of vegetation greening and later during the dormancy phase, increasing thus the length of the growing season.

[15] The three simulations start with 2 × CO_2 corresponding to a stabilization level, and are run long enough to equilibrium. In the real world, the actual timing of when 2 × CO_2 could be reached depends on different factors, including emission scenarios.

3. Results and Discussion

[16] All simulations started from the same initial conditions and are carried out 30 years forward. RP, RPV and RPVB were compared to a **C**ontrol simulation (**C**) using 350 ppm for both the radiative and physiological modules of the coupled model. All results are averages from the last 10 years of each simulation.

[17] In line with *Bonan* [1997] and *Levis et al.* [2000], in the RPVB-case the largest albedo decreases of 6% and 7% occurred over the continents, north of 57.6°N, during winter and spring respectively, due to the masking of snow by

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL045338.

Table 1. Carbon Uptake (Pg/yr): Control (C) and Differences From the Control

	C	RP-C	RPV-C	RPVB-C
All Land	124.80	44.60	13.40	44.45
Continental USA	11.17	4.90	1.75	6.88
Eastern USA	7.23	3.13	1.32	3.92

denser vegetation. On an annual basis, albedo decreased 5% in these latitudes. This is a significant reduction considering that in the RPVB-case the vegetation was not allowed to migrate with climate change; however it is smaller than the change simulated by *Levis et al.* [2000] where vegetation increased in extent and density. Globally and annually averaged, the albedo effect was relatively small and was dominated by the evaporative effect for an overall net cooling, in agreement with *Betts et al.* [1997].

[18] Compared to the control, the RP-case produced a carbon uptake increase of 44.6 Pg (1Pg = 10^{15}g). This increase was reduced in the RPV-scenario where the carbon uptake was only 13.4 Pg more than the control (C). As expected, the increase in LAI simulated in the RPVB-case led to a carbon uptake increase close to that simulated under the RP-scenario and is well within the constraints of nitrogen availability reported by *Hungate* [2003]. This highlights the competing effects of down-regulation and increased LAI on photosynthesis since both the RP and RPVB-cases operated under 2 × CO_2. Compared to RP, the RPVB-simulation resulted in 40% more carbon uptake over the continental U.S while it increased by only 25% over the less water-limited forested area of the eastern U.S, east of the Mississippi (Table 1). This increase in the net carbon uptake is also associated with an increase in evapotranspiration and a cooling of the atmosphere (Figure 3).

[19] The RPVB vegetation-climate feedback led to a projected warming much less than previously simulated due to the increase in evapotranspiration. Globally, the RP-case temperature increased 1.94°C, at the lower end of the 2.0 to 4.5°C range projected by the IPCC [*IPCC*, 2007] while in

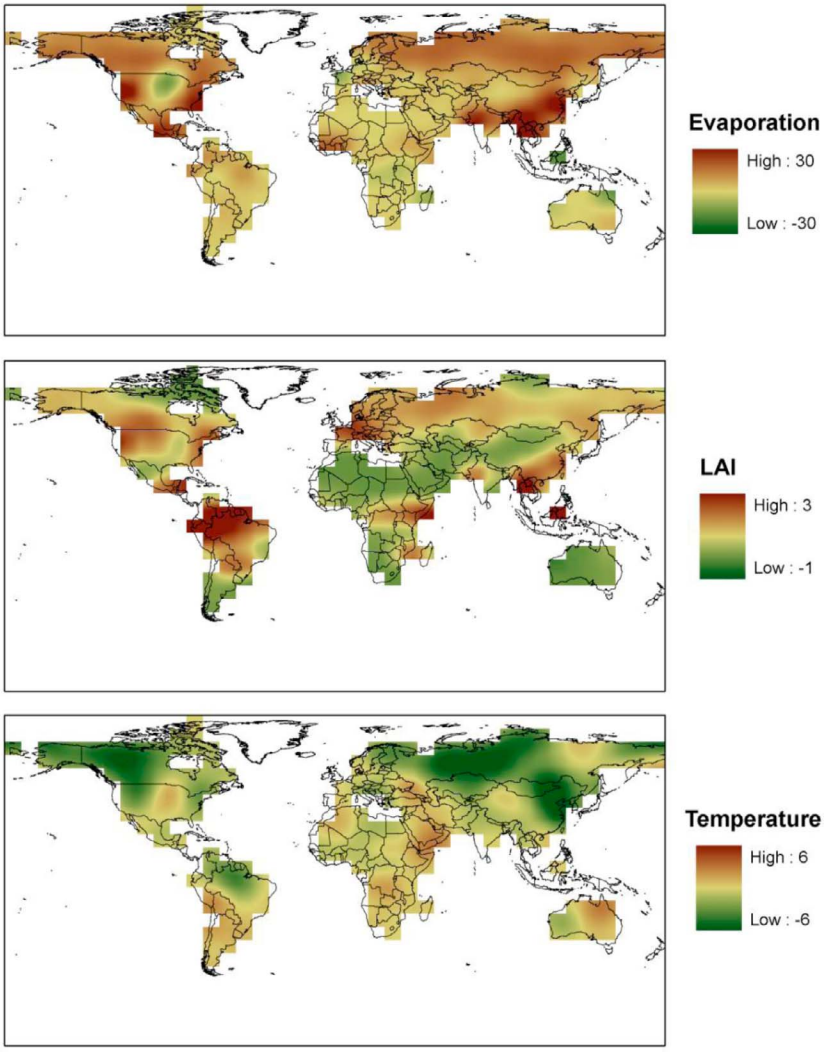

Figure 3. Annual differences of (top) canopy evaporation (Wm^{-2}), (middle) leaf area index (m^2m^{-2}) and (low) surface temperature (°C) between the RPVB and RPV cases (RPVB-RPV). Differences are obtained from averages from last 10-years of simulations at 7.2° × 9° and smoothed for plotting purpose.

Table 2. Surface Temperature (°C): Control (C) and Differences From the Control

	C	RP-C	RPV-C	RPVB-C
Global	18.53[a]	1.94[a]	1.84[a]	1.68[a]
All Land	19.55[a]	2.80[a]	2.67[a]	2.23[a]
Eastern USA	19.93[a]	2.92[a]	2.67[a]	1.38[a]

[a]Significant at 95% (T-test).

Table 3a. Precipitation (mm.day^{-1}): Control (C) and Relative Differences From to the Control (%)[a]

	C	RP-C	RPV-C	RPVB-C
Global	2.88	4.7(0.135)[b]	3.9(0.110)[b]	4.2(0.120)[b]
All Land	2.75	6.4(0.175)[b]	3.0(0.082)[b]	4.3(0.119)[b]
Eastern USA	2.36	31.2(0.735)[b]	10.4(0.246)[b]	35.7(0.843)[b]

[a]Values in parenthesis are absolute differences from the control.
[b]Significant at 95% (T-test).

the RPVB-case it increased only 1.68°C (Table 2) suggesting a reduction in global warming of 0.26°C compared to the conventional RP-case. Over land, where vegetation is expected to have a larger impact, the results are even more striking; the RPVB temperature increased only 2.23°C compared to the control; that is a cooling of about 0.57°C compared to the RP-case and 0.44°C below the RPV-case. Over the Eastern U.S forested regions, however, the increase in vegetation reduced the warming to about 1.54°C cooler than the RP-case.

[20] A comparison of our results to previous work reveals two important conclusions. First, in the RPVB-simulation, the LAI effect reduced the temperature by 0.26°C compared to 0.1°C by *Betts et al.* [1997] and no significant changes by *Levis et al.* [2000]. This is a direct consequence of down-regulation which reduced canopy conductance beyond the radiative and physiological effects of increased CO_2 and required more LAI to reproduce the RP-case carbon assimilation. This resulted in additional cooling effect not accounted for in previous 2 × CO_2 simulations. Furthermore, this cooling occurs in a model with low climate sensitivity to radiative forcing. Indeed, our results suggest a global warming of 1.94°C in the RP-case versus 4.5°C by *Betts et al.* [1997] and 2.6°C by *Levis et al.* [2000]. Therefore if the vegetation effects were to scale linearly with CO_2-induced radiative warming, the current work suggests that negative feedbacks on warming from increases in LAI could be stronger than previously suggested.

[21] Secondly and most importantly, there is recognition that even if CO_2 concentration could be stabilized, much of the warming is yet to be realized. In transient simulations [e.g., *Betts et al.*, 2007], as CO_2 rises stomata respond almost instantaneously but LAI takes a long time to grow, so the warming effect of stomatal closure can take a long time to be offset by the cooling effect of increased LAI. On the other hand, equilibrium simulations, such as the one used in this study and those of *Betts et al.* [1997] and *Levis et al.* [2000], assume an equilibrium vegetation response in which the LAI is fully grown and at equilibrium with 2 × CO_2 climate. This suggests that while increased LAI may not slow global warming significantly in the near term, its long term negative feedback could potentially reduce temperatures following a stabilization of CO_2 concentration. These results indicate that the vegetation could partially reduce the greenhouse warming projections and that the influence is more pronounced in forest-dominated regions.

[22] The control globally-averaged precipitation was 2.88 mm.day^{-1}; slightly greater than the observed 2.74 mm.day^{-1} [*Nohara et al.*, 2006].

[23] The additional vegetation-climate feedback (RPVB-case) had important impacts on the hydrological cycle (Tables 3a and 3b). In sharp contrast to results from *Nohara et al.* [2006] and *Betts et al.* [2007] and to our own RP and RPV-results, in the RPVB-case the overland increase in runoff (4.0%) was smaller than that of precipitation (4.3%). Over the Eastern U.S, the RPVB-case modeled precipitation increase is larger than increase in runoff (Tables 3a and 3b). These runoff trends are in line with those from *Jackson et al.* [2005] which show decreases in stream flow following the early stage of forest regrowth. Similar to the results of *Nohara et al.* [2006], in the conventional RP-case the relative increase in runoff is larger than that of precipitation. These trends are even more amplified in the RPV-case where the runoff increased by 6.7% and the precipitation increased only by 3%. These results suggest that when vegetation is allowed to increase its leaf density in response to CO_2 fertilization and climate, the associated increase in precipitation generated by the increase in CO_2 contributes primarily to increase evapotranspiration rather than surface runoff.

[24] Because we constrain increases in LAI to the existence of vegetation and water availability, our treatment of the response of LAI to increased CO_2 may be on the conservative side. Furthermore, the actual increase in LAI could be larger than that allowed in the RPVB-case if vegetation was allowed to extend, thus leading to a stronger cooling effect. However, the results presented here indicate that changes in the state of vegetation may already be playing a role in the continental water, energy and carbon budgets as atmospheric CO_2 increases.

4. Conclusion

[25] As an additional feedback to water availability caused by CO_2-induced water use efficiency and changes in climate, we postulate that the excess photosynthetic capacity following down-regulation of the vegetation physiological activity would stimulate vegetation growth much more than previously simulated. When we include these feedbacks in climate simulations with 2 × CO_2, the associated increase in precipitation contributes primarily to increase evapotranspiration rather than surface runoff. This results in an additional cooling effect not fully accounted for in previous elevated CO_2 climate simulations. These effects slow but do not alleviate the projected atmospheric warming by accelerating the recycling of water between the land and atmosphere, reducing the warming by about 0.3°C globally and 0.6°C over land. These results suggest a stronger negative

Table 3b. Same as Table 3a Except for Surface Runoff (mm.day^{-1})

	C	RP-C	RPV-C	RPVB-C
All Land	1.15	9.8(0.113)[a]	6.7(0.077)[a]	4.0(0.046)[a]
Eastern USA	1.6	35.4(0.567)	10.9(0.174)[a]	34.6(0.554)[a]

[a]Significant at 95% (T-test).

feedback on warming from increases in LAI than previously suggested. In sharp contrast to previous studies, the feedback also results in precipitation and runoff trends that are consistent with observations [*Jackson et al.*, 2005]. Globally, precipitation increased faster than runoff, especially in forested areas. Most importantly, results from this study suggest that long term negative feedbacks from increases in LAI could act to reduce temperature for years following a stabilization of atmospheric CO_2 concentration.

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References

Anyamba, A., and C. J. Tucker (2005), Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003, *J. Arid Environ.*, *63*, 596–614, doi:10.1016/j.jaridenv.2005.03.007.

Betts, R., P. M. Cox, S. E. Lee, and F. I. Woodward (1997), Contrasting physiological and structural vegetation feedbacks in climate change simulations, *Nature*, *387*, 796–799, doi:10.1038/42924.

Betts, R., et al. (2007), Projected increase in continental runoff due to plant responses to increasing carbon dioxide, *Nature*, *448*, 1037–1041, doi:10.1038/nature06045.

Bonan, G. B. (1997), Effects of land use on the climate of the United States, *Clim. Change*, *37*, 449–486, doi:10.1023/A:1005305708775.

Bounoua, L., et al. (1999), Interactions between vegetation and climate: Radiative and physiological effects of doubled atmospheric CO_2, *J. Clim.*, *12*, 309–324, doi:10.1175/1520-0442(1999)012<0309:IBVACR>2.0.CO;2.

Dickinson, R. E., and M. F. Wilson (1986), Biosphere–Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model, *NCAR Tech. Note NCAR/TN275+STR*, 69 pp., Natl. Cent. for Atmos. Res., Boulder, Colo.

Friedlingstein, P., et al. (2006), Climate–carbon cycle feedback analysis: Results from the C4MIP model intercomparison, *J. Clim.*, *19*, 3337–3353, doi:10.1175/JCLI3800.1.

Gedney, N., et al. (2006), Detection of a direct carbon dioxide effect in continental river runoff records, *Nature*, *439*, 835–838, doi:10.1038/nature04504.

Hungate, B. A. (2003), Nitrogen and climate change, *Science*, *302*, 1512–1513, doi:10.1126/science.1091390.

Intergovernmental Panel on Climate Change (IPCC) (2007), Summary for policymakers, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 1–18, Cambridge Univ. Press, Cambridge, U. K.

Jackson, R. B., et al. (2005), Trading water for carbon with biological carbon sequestration, *Science*, *310*, 1944–1947, doi:10.1126/science.1119282.

Leakey, A. D. B., et al. (2009), Elevated CO_2 Effects on plant carbon, nitrogen and water relations: Six important lessons from FACE, *J. Exp. Bot.*, *60*(10), 2859–2876, doi:10.1093/jxb/erp096.

Levis, S., J. A. Foley, and D. Pollard (2000), Large-scale vegetation feedbacks on a doubled CO_2 climate, *J. Clim.*, *13*, 1313–1325, doi:10.1175/1520-0442(2000)013<1313:LSVFOA>2.0.CO;2.

Neigh, S. R. C., C. J. Tucker, and J. R. G. Townshend (2008), North American vegetation dynamics observed with multi-resolution satellite data, *Remote Sens. Environ.*, *112*, 1749–1772, doi:10.1016/j.rse.2007.08.018.

Nohara, D., A. Kitoh, M. Hosaka, and T. Oki (2006), Impact of climate change on river discharge projected by multimodel ensemble, *J. Hydrometeorol.*, *7*, 1076–1089, doi:10.1175/JHM531.1.

Piao, S., P. Friedlingstein, P. Ciais, L. Zhou, and A. Chen (2006), Effect of climate and CO_2 changes on the greening of the Northern Hemisphere over the past two decades, *Geophys. Res. Lett.*, *33*, L23402, doi:10.1029/2006GL028205.

Randall, D. A., et al. (1996), A revised land surface parameterization (SiB_2) for GCMs. Part III: The greening of the Colorado State University General Circulation Model, *J. Clim.*, *9*, 738–763, doi:10.1175/1520-0442(1996)009<0738:ARLSPF>2.0.CO;2.

Sellers, P. J., Y. Mintz, Y. C. Sud, and A. Dalcher (1986), A simple biosphere model (SiB) for use within general circulation models, *J. Atmos. Sci.*, *43*, 505–531, doi:10.1175/1520-0469(1986)043<0505:ASBMFU>2.0.CO;2.

Sellers, P. J., et al. (1996), Comparison of radiative and physiological effects of doubled CO_2 on climate, *Science*, *271*, 1402–1406, doi:10.1126/science.271.5254.1402.

Tucker, C. J., et al. (2005), An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data, *Int. J. Remote Sens.*, *26*, 4485–4498, doi:10.1080/01431160500168686.

U.S. Geological Survey (2007), WaterWatch, U.S. Geol. Surv., Reston, Va. (Available at http://water.usgs.gov/waterwatch/)

Wentz, F. J., L. Ricciardulli, K. Hilburn, and C. Mears (2007), How much more rain will global warming bring?, *Science*, *317*, 233–235, doi:10.1126/science.1140746.

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