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Influence of Geoengineered Climate on the Terrestrial Biosphere

VAISHALI NAIK
DONALD J. WUEBBLES*
Department of Atmospheric Sciences
University of Illinois
105 S. Gregory Avenue
Urbana, Illinois 61801 USA

EVAN H. DELUCIA
Department of Plant Biology
University of Illinois
505 S. Goodwin Avenue
Urbana, Illinois 61801 USA

JONATHAN A. FOLEY
Center for Sustainability and the Global Environment (SAGE)
Gaylord Nelson Institute for Environmental Studies
University of Wisconsin
1710 University Avenue
Madison, Wisconsin 53726 USA

ABSTRACT / Various geoengineering schemes have been proposed to counteract anthropogenically induced climate change. In a previous study, it was suggested that a 1.8% reduction in solar radiation incident on the Earth's surface could noticeably reduce regional and seasonal climate change from increased atmospheric carbon dioxide (CO_2). However, the response of the terrestrial biosphere to reduced solar radiation in a CO_2-rich climate was not investigated. In this study, we hypothesized that a reduction in incident solar radiation in a Doubled CO_2 atmosphere will diminish the net primary productivity (NPP) of terrestrial ecosystems, potentially accelerating the accumulation of CO_2 in the atmosphere. We used a dynamic global ecosystem model, the Integrated Biosphere Simulator (IBIS), to investigate this hypothesis in an unperturbed climatology. While this simplified modeling framework effectively separated the influence of CO_2 and sunlight on the terrestrial biosphere, it did not consider the complex feedbacks within the Earth's climate system. Our analysis indicated that compared to a Doubled CO_2 scenario, reduction in incident solar radiation by 1.8% in a double CO_2 world will have negligible impact on the NPP of terrestrial ecosystems. There were, however, spatial variations in the response of NPP-engineered solar radiation. While productivity decreased by less than 2% in the tropical and boreal forests as hypothesized, it increased by a similar percentage in the temperate deciduous forests and grasslands. This increase in productivity was attributed to a ~1% reduction in evapotranspiration in the Geoengineered scenario relative to the Doubled CO_2 scenario. Our initial hypothesis was rejected because of unanticipated effects of engineered solar radiation on the hydrologic cycle. However, any geoengineering approaches that reduce incident solar radiation need to be thoroughly analyzed in view of the implications on ecosystem productivity and the hydrologic cycle.

The increasing concern about the effects of human activities on the global climate change has led to various "geoengineering" schemes to reduce the levels of human-induced warming (Keith 2000). One proposal involves the reduction of incoming solar radiation by placing reflectors or scatterers in the stratosphere or in orbit between the Earth and Sun (Early 1989, Flannery and others 1997, Teller and others 1997) to negate the radiative forcing caused by increased atmospheric carbon dioxide (CO_2). Recently, Govindasamy and Caldeira (2000) used the standard configuration of NCAR Community Climate Model (CCM3) to investigate the decrease in solar luminosity required to balance the increased radiative forcing from Doubled atmospheric CO_2 [current levels ~360 parts per million (ppm)]. They estimated that approximately a 1.8% reduction in the incident solar radiation would compensate for the radiative effects of Doubled CO_2. In their study, they only considered response of the atmosphere to geoengineering, ignoring the reaction of the terrestrial biosphere to reduced sunlight.

In terrestrial ecosystems, photosynthesis is central to plant growth and productivity and is constrained by light, water, CO_2, and soil nutrients. Each of these constraints acts differently on different plant functional types. Photosynthetically active radiation (PAR) corresponds to wavelengths from 400 to 700 nm. Only about 1% of the total energy received in sunlight is actually used for photosynthesis (Botkin and Malone 1968, Reiners 1972). As the amount of light incident on

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*Author to whom correspondence should be addressed, *email:* wuebbles@atmos.uiuc.edu leaves increases, the rate of photosynthesis increases linearly until it saturates, typically at well below the full sunlight (Luo and others 2000).

Net primary production (NPP) is the difference between photosynthesis and plant respiration and represents the annual increment of carbon in terrestrial ecosystems. It has been observed that NPP of terrestrial ecosystems is proportional to the absorbed PAR (Monteith 1972, 1977, Jarvis and Leverenz 1983, Linder 1985). Furthermore, observations (Curtis and Wang 1998, DeLucia and others 1999, Hamilton and others 2002) and modeling studies (Cao and Woodward 1998, Levis and others 2000) have shown that elevated levels of atmospheric CO_2 can stimulate photosynthesis and enhance NPP in natural terrestrial ecosystems. This CO_2 fertilization effect is known to reduce stomatal conductance resulting in enhanced water-use efficiency of many plant species (Field and others 1995). Given the relationship between photosynthesis and sunlight, an engineered reduction in incoming solar radiation may reduce NPP, potentially accelerating the accumulation of CO_2 in the atmosphere. Because of the complex interplay between atmosphere, plant productivity, and climate, it is difficult to predict the effects of an engineered reduction of sunlight on the Earth.

In this study, we investigated the response of net primary production and evapotranspiration of terrestrial ecosystems to a geoengineered reduction in solar luminosity, using a dynamic global vegetation model that effectively separates the influence of CO_2 and sunlight on the terrestrial biosphere under constant climatology. This simplified modeling framework, however, did not represent the many feedbacks within the Earth's climate system as characterized in complex, coupled climate–carbon cycle models. We performed equilibrium simulations and did not consider the transient effects of increasing CO_2 on net ecosystem carbon fluxes in this study.

Model and Simulations

We investigated the influence of geoengineered climate on the biosphere using the Integrated Biosphere Simulator (IBIS), developed at the University of Wisconsin (Foley and others 1996, Kucharik and others 2000). IBIS is a dynamic global vegetation model (DGVM) that simulates the transient changes in vegetation composition and structure in response to environmental changes. Furthermore, IBIS simulates land surface processes, canopy physiology, vegetation phenology and dynamics, and terrestrial carbon balance in a single integrated configuration. It has been evaluated against measurements on both global (Kucharik and others 2000) and regional (Delire and Foley 1999, Lenters and others 2000) scales and has been extensively used in recent studies of the global carbon cycle (Delire and others 2003, Levis and others 2000).

Initially, IBIS was run for 300 years driven to an equilibrium state by a monthly climatological data set of temperature, precipitation, relative humidity, and cloudiness from 1961 to 1995. The climate data set was compiled by New and others (1999). The model was run at a resolution of 2° longitude by 2° latitude. The simulation was initialized by an "observed" potential vegetation map (Ramankutty and Foley 1999) and run with a constant atmospheric CO_2 concentration of 360 ppm. Using the equilibrium state created by this initial model simulation, we performed five model experiments to study the impact of geoengineering on terrestrial ecosystems: (1) "Control", or present-day simulation, with an atmospheric CO_2 concentration of 360 ppm and solar constant of 1370 W/m^2; (2) "Solar", with the same CO_2 concentration as control but the solar constant reduced by 1.8%; (3) "Doubled " CO_2 with a CO_2 concentration of 720 ppm and the same solar constant as the control; (4) "Geoengineered", with Doubled CO_2 and the solar constant reduced by 1.8%; and (5) "Geoengineered with no feedback", which is the same as "Geoengineered" but with no water stress feedback (explained later). For all the five experiments, IBIS was run for 100 years extending beyond the initial base simulation, driven by observed mean climatological data (New and others 1999) to arrive at a near equilibrium state. The impact of climate change on terrestrial biospheric productivity, which may be particularly important for the Doubled CO_2 case, was not considered in this study. Furthermore, one might argue that for the geoengineered cases IBIS should be driven by geoengineered climate variables. However, Govindasamy and Caldeira (2000) have shown that geoengineering may compensate for the radiative forcing caused by Doubled atmospheric CO_2 and may cause the geoengineered world to have a climate similar to the current climate. Since the objective of our study was to evaluate the effects of geoengineering on the terrestrial biosphere, it was appropriate to use the current climate attributes to drive the model. Vegetation cover was allowed to respond to elevated CO_2 in the experiments. Greenland and Antarctica were not included in the model domain of this study. We averaged results from the last 15 years of each simulation to perform comparisons. The differences in ecosystem attributes described below were found to be statistically significant when compared against the model's internal variability.

Table 1. Globally averaged ecosystem attributes with standard deviations for five simulations[a]

Ecosystem attributes	Control	Solar	Doubled CO_2	Geoengineered	Geoengineered with no feedback
Net primary productivity (Gt C/yr)	62.1 ± 0.3	62.38 ± 0.3 (+0.4%)	101.1 ± 0.5 (+63%)	101.2 ± 0.5 (+0.1%)	98.8 ± 0.5 (−2.3%)
Biomass (Gt C)	684.6 ± 0.2	688.4 ± 0.2 (0.5%)	1135.4 ± 3.0 (+66%)	1137.1 ± 3.0 (+0.1%)	1108.9 ± 2.8 (−2.3%)
Leaf area index (m^2/m^2)	3.3 ± 0.01	3.3 ± 0.01 (+0.2%)	4.6 ± 0.02 (+41%)	4.6 ± 0.02 (−0.2%)	4.5 ± 0.02 (−2%)
Soil carbon content (Gt C)	1601.5 ± 0.2	1610.0 ± 0.4 (+0.5%)	1977.3 ± 9.7 (+23%)	1984.8 ± 9.9 (+0.4%)	1955.9 ± 9.2 (−1.1%)
Actual evapotranspiration (mm/yr)	513.7 ± 1.2	509.0 ± 1.2 (−0.9%)	505.9 ± 1.2 (−1.5%)	500.9 ± 1.2 (−0.9%)	504.6 ± 1.2 (−0.2%)

[a] Control, with CO_2 concentration of 360 ppm and Solar constant of 1370 W/m^2; Solar, with CO_2 concentration of 360 ppm and Solar constant reduced by 1.8%; Doubled CO_2, with CO_2 concentration of 720 ppm and Solar constant of 1370 W/m^2; Geoengineered, with Doubled CO_2 and Solar constant reduced by 1.8%; and Geoengineered with no feedback, with Doubled CO_2 and PAR reduced by 1.8% instead of the Solar constant. Standard deviations were calculated from annual variation using 15-year output data for each simulation. The values in parentheses are the percentage difference in the attributes for the Solar and Doubled CO_2 simulations relative to Control (columns 3 and 4) and for the Geoengineered and Geoengineered with no feedback simulations relative to Doubled CO_2 (columns 5 and 6).

Results

Global average ecosystem attributes for the five simulations are shown in Table 1. Comparison of Solar and Doubled CO_2 simulations with Control showed that elevated CO_2 had a greater impact on the NPP of terrestrial ecosystems as compared to reduced sunlight. Global NPP for the Doubled CO_2 case increased by 63% compared to the Control. In contrast, the change in NPP for the Solar case relative to Control was negligible (Table 1). While in agreement with Levis and others (2000), this increase in NPP in response to Doubled CO_2 should be regarded as an upper limit for CO_2 fertilization, as mineral nutrient limitations (for example, availability of nitrogen) on photosynthesis and plant growth were not considered in this study. Biomass, leaf area index (LAI), and soil carbon content for the Doubled CO_2 simulation also increased significantly relative to the Control. The overall evapotranspiration for Doubled CO_2 decreased (~1.5%) compared to the Control as a result of lower stomatal conductance in a CO_2-rich atmosphere (Table 1).

The difference in global NPP between the Geoengineered and Doubled CO_2 simulations was negligible (Table 1), that is, geoengineering had no significant impact on the productivity of terrestrial ecosystems. There were, however, regional differences in NPP for Geoengineered simulation relative to the Doubled CO_2 case (Figure 1). There was a 2% or smaller reduction in NPP for tropical evergreen (Amazon basin, central Africa and Indonesian archipelago) and boreal forests, while it increased by a similar percentage for temperate deciduous forests and grasslands. The percentage difference in NPP appeared to be high in some drier and sparsely vegetated regions such as the Sahara desert because the productivity over these regions was extremely low to begin with (less than 30 g $C/m^2/yr$). This regional increase in NPP for the Geoengineered simulation relative to Doubled CO_2 was attributed to lowered water stress in the Geoengineered simulation. Water stress was alleviated by reduced evapotranspiration (soil water evaporation and transpiration from leaves) resulting in increased soil moisture (Figure 2), canopy photosynthesis (data not shown), and plant productivity. This was particularly true for ecosystems where water limitation played a stronger role in determining the productivity (e.g., grasslands, temperate deciduous forests).

The increase in zonally averaged NPP for the Geoengineered compared to the Doubled CO_2 simulation was 1% – 1.5% in the mid latitudes both in the northern and southern hemispheres, while it decreased to less than 1% in the tropics and the northern high latitudes (Figure 3). Corresponding regional differences were observed in the zonally averaged evapotranspiration (Figure 4). Evapotranspiration for the Geoengineered scenario compared to Doubled CO_2 decreased more in the tropics than the midlatitudes.

To isolate the effect of reduced sunlight from the effect of reduced water stress on the terrestrial biosphere, we performed another simulation similar to the Geoengineered case but with water stress feedback turned off. For this, we reduced the incoming PAR by

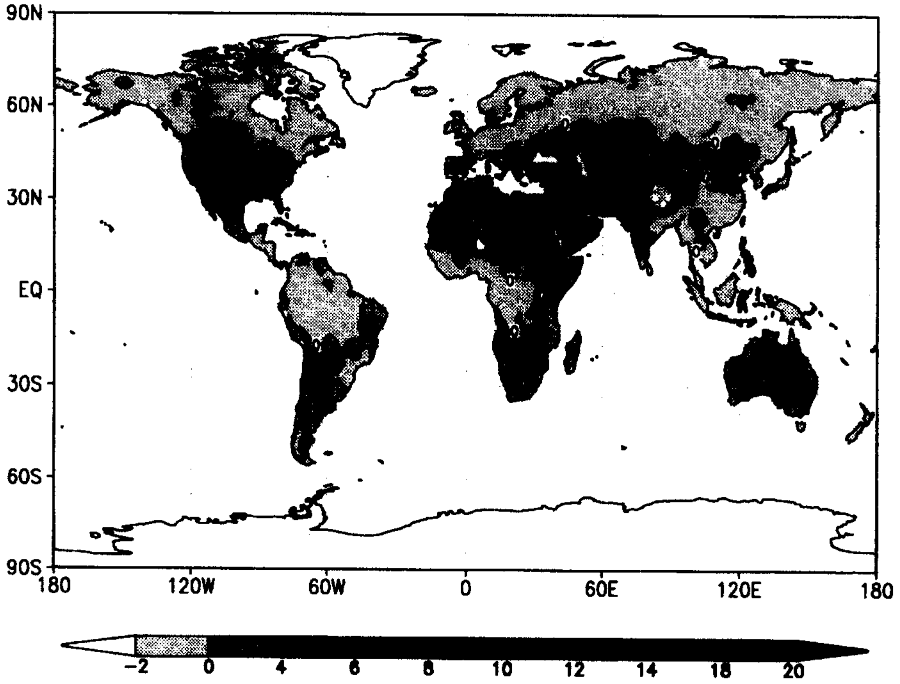

Figure 1. Percentage difference in simulated annual net primary productivity for terrestrial ecosystems for Geoengineered scenario compared to Doubled CO_2 simulation.

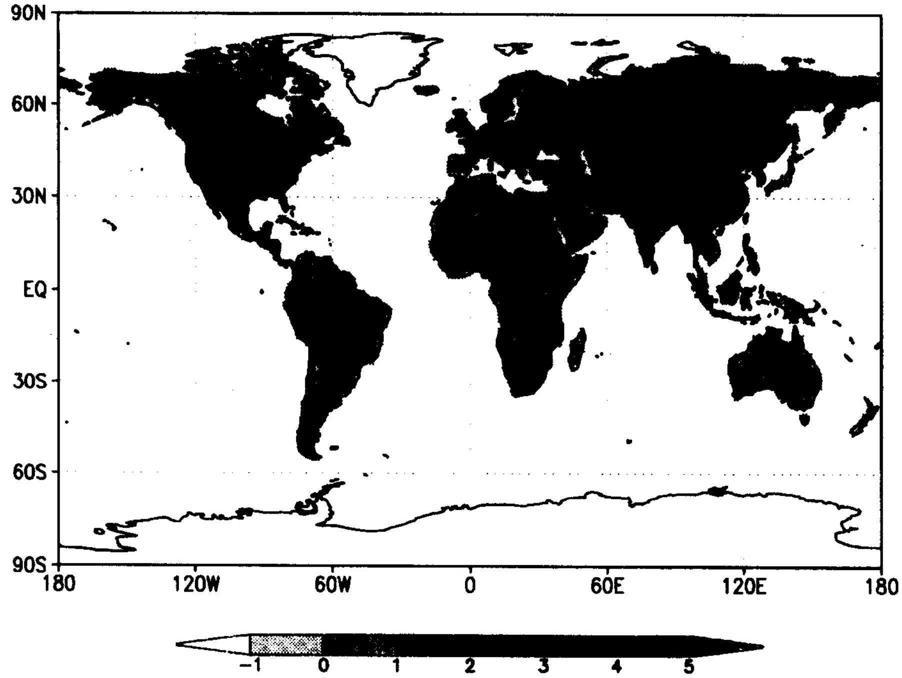

Figure 2. Percentage difference in simulated annual soil moisture for terrestrial ecosystems for Geoengineered scenario compared to Doubled CO_2 simulation.

1.8% instead of reducing the incoming Solar radiation. Since PAR is only used to calculate canopy photosynthesis in the model, its reduction had no direct effect on the simulation of water balance. However, changing PAR indirectly affected the water balance by changing canopy density.

The annual NPP for the Geoengineered with no feedback case decreased by 2.3% relative to the Doubled CO_2 scenario over the globe (Table 1). This caused a corresponding reduction in the vegetation cover as represented in the 2% reduction in LAI. Diminished vegetation cover resulted in a slight reduction

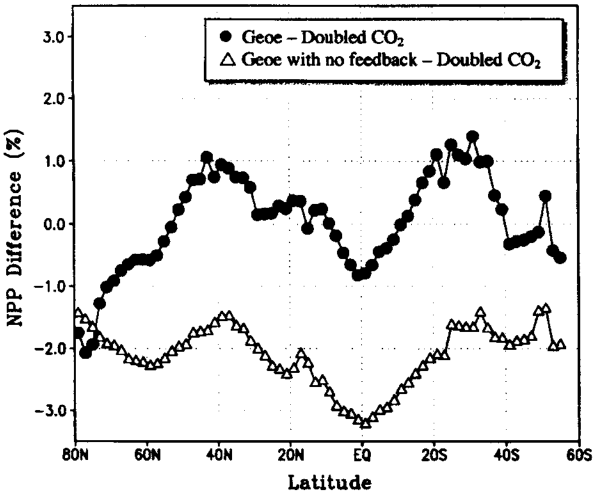

Figure 3. Percentage difference in zonally averaged net primary productivity for Geoengineered (closed circles) and Geoengineered with no feedback (open triangles) scenarios compared to Doubled CO_2 simulation.

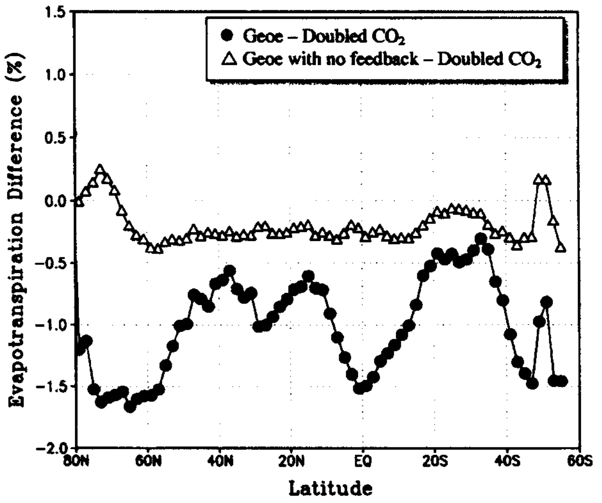

Figure 4. Percentage difference in zonally averaged evapotranspiration for Geoengineered (closed circles) and Geoengineered with no feedback (open triangles) scenarios compared to Doubled CO_2 simulation.

in evapotranspiration. The reduction in PAR lowered NPP over all vegetated regions of the Earth (Figure 5A). The decline in NPP was most pronounced in the tropical forests followed by boreal deciduous forests. With PAR not influencing soil water, lower value led to a reduction in canopy photosynthesis (data not shown).

The zonally averaged NPP decreased for all latitudes (Figure 3) for the Geoengineered with no feedback scenario compared to the Doubled CO_2 scenario. The decrease in NPP in the tropics (~2% – 3.5%) was higher than in the midlatitudes (1% – 2%). The effect of reduced PAR on the productivity was more pronounced in the tropics as compared to the midlatitudes because of higher vegetation cover. Lower PAR caused a slight decrease in LAI that indirectly reduced evapotranspiration by 0.5% over all latitudes (Figure 4) for the Geoengineered with no feedback compared to the Doubled CO_2 simulation.

To analyze the seasonal variability in the Geoengineered and Doubled CO_2 simulations, we examined the time series of monthly mean NPP for the tropics (15°S – 15°N; Figure 6A) and mid latitudes (30°N – 60°N; Figure 7A). In the tropics, the seasonality of simulated NPP was small for the three simulations, while in the mid latitudes NPP had strong seasonal amplitude corresponding to annual variation in temperature, precipitation, and incident irradiance. In the tropics, there was no change in monthly NPP for the Geoengineered case relative to the Doubled CO_2 while it declined by ~0.003 kg $C/m^2/mo$ for the Geoengineered with no feedback case compared to Doubled CO_2 (Figure 6B). In the mid-latitudes, monthly NPP for the Geoengineered case increased in the summer months relative to Doubled CO_2 whereas it decreased for the Geoengineered with no feedback case relative to Doubled CO_2 (Figure 7B). This change in NPP in response to the perturbations had strong seasonality corresponding to the annual variation in NPP in the midlatitudes.

Discussion and Conclusion

We used a dynamic vegetation model to investigate the effect of a proposed Geoengineered reduction of incoming Solar radiation on the terrestrial biosphere. Our model results demonstrated that, compared to a Doubled CO_2 scenario, reduction in incident Solar radiation by 1.8% to compensate for the radiative forcing due to double CO_2 will have negligible impact on the global annual net primary productivity of the terrestrial biosphere. There were, however, regional and seasonal differences in the change in NPP for the Geoengineered simulation relative to Doubled CO_2. Compared to Doubled CO_2, NPP for the Geoengineered simulation diminished for tropical evergreen and boreal forests while it increased for temperate deciduous forests, grasslands, and deserts. This regional variation in the change in NPP for Geoengineered simulation relative to Doubled CO_2 was attributed to the alleviation of water-stress in ecosystems where water-limitation played an important role in determining productivity. Reduced sunlight caused a reduction in evapotranspira-

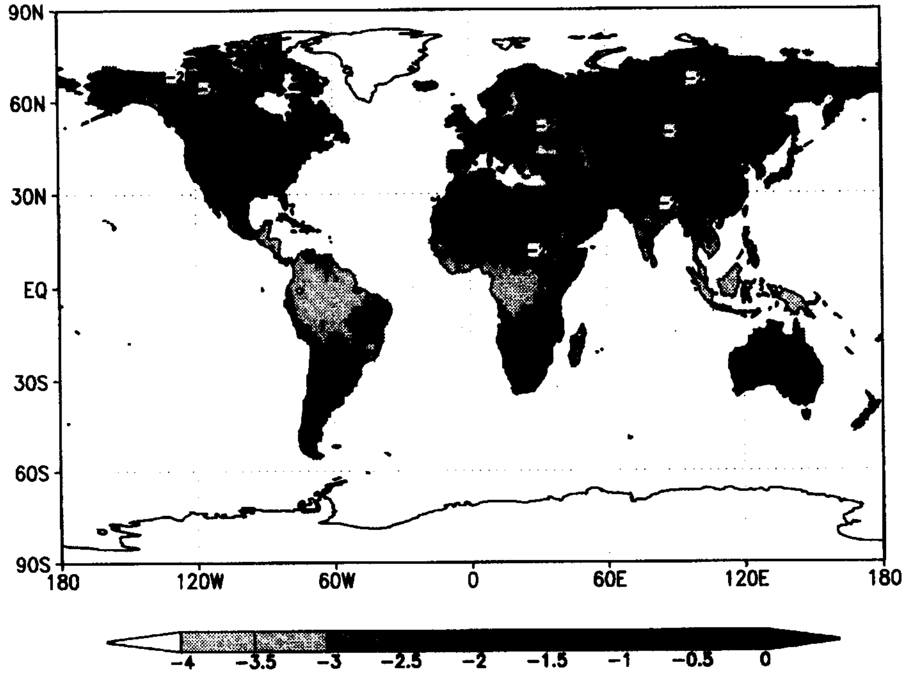

Figure 5. Percentage difference in simulated net primary productivity for terrestrial ecosystems for Geoengineered with no feedback scenario compared to Doubled CO_2 simulation.

tion resulting in enhanced soil moisture available for canopy photosynthesis. Our results are subject to verification using other DGVM and coupled climate–carbon cycle models.

Net primary productivity and terrestrial water balance for current observed climate conditions, simulated by IBIS in this study, were in reasonable agreement with observations (Foley and others 1995, Kucharik and others 2000). Although the effects of climate change as a result of increased atmospheric CO_2 were not explicitly included in this study, the simulated responses of NPP and evapotranspiration to CO_2 fertilization agreed with previous model analyses (Levis and others 2000, Cramer and others 2001). NPP increased in response to Doubled CO_2 resulting in increased vegetation cover while evapotranspiration decreased as a result of the reduction in stomatal conductance in a CO_2-rich atmosphere. We emphasize that on longer timescales this CO_2 fertilization effect may diminish in magnitude as photosynthesis saturates at high CO_2 concentrations and other limiting factors become important, such as the rate of nutrient supply from the soil. Moreover, as the climate warms, plant respiration and decomposition of soil organic matter will be enhanced, resulting in increased accumulation of CO_2 in the atmosphere (Cramer and others 2001, Malhi and others 2002).

Incident irradiance drives canopy photosynthesis and evapotranspiration (Amthor 1999), but these processes can have varying effects on productivity owing to the differences in leaf area and availability of resources. In the case of tropical and boreal evergreen forests, abundant water supply helps maintain high LAIs (Perry 1994). Dense leaf canopy leads to light competition and as light attenuates through the canopy, lower leaves become light-limited. When incoming irradiance is reduced, canopy leaves, specifically in the understory, may become increasingly light-limited, resulting in reduced productivity in the tropical and boreal ecosystems. However, in mid latitude temperate deciduous forests and grasslands, photosynthesis is water-stressed because of variation in the distribution of precipitation; consequently, these ecosystems have low NPP and LAI. The absorption of PAR is sufficiently homogenous in low leaf-area canopies, hence these ecosystems are less light-limited. For LAIs less than 4, evapotranspiration becomes uncoupled from photosynthesis because of a proportional increase in surface evaporation (Schulze and others 1994). Low incoming irradiance diminishes surface evaporation as well as transpiration, resulting in an increased availability of soil water for canopy photosynthesis. Hence, the water-limitation on productivity in temperate deciduous forests and grasslands is weakened, resulting in enhancement of NPP in these ecosystems.

The injection of aerosols into the atmosphere by volcanic eruption provides a "natural" test of the consequences of Geoengineered reduction in Solar irradi-

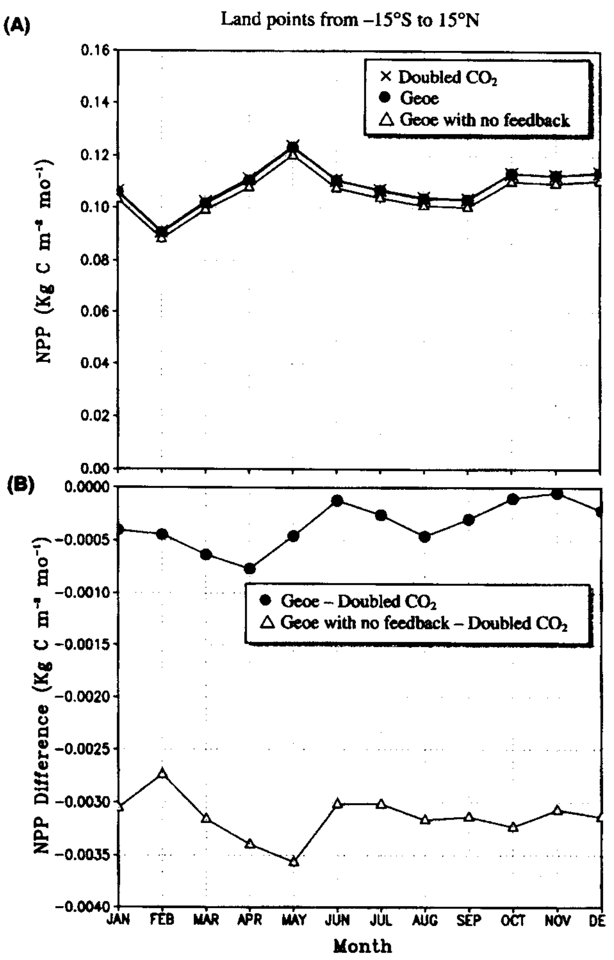

Figure 6. (A) Simulated monthly mean NPP for Doubled CO_2 (crosses), Geoengineered (closed circles) and Geoengineered with no feedback (open triangles) scenarios for the equatorial tropics (15°S–15°N), (B) the average differences in simulated monthly values of NPP for Geoengineered (closed circles) and Geoengineered with no feedback (open triangles) scenarios compared to Doubled CO_2 simulation for the equatorial tropics (15°S–15°N).

ance. Stratospheric aerosols generated by the Pinatubo eruption in 1991 lowered incoming short-wave radiation by approximately 1 W/m^2 (Lucht and others 2002), similar to the effect of placing reflectors in the stratosphere. Lucht and others (2002) concluded that following the Pinatubo eruption the steady rise in NPP in the boreal forests associated with climate warming was temporarily reversed. Leaf area index declined after the eruption, and cooling caused an imbalance in NPP and microbial respiration, resulting in the temporary reduction in the growth rate of global atmospheric CO_2. These observations are consistent with the simulated decrease in NPP for boreal forests in response to reduced Solar irradiance (Figure 1).

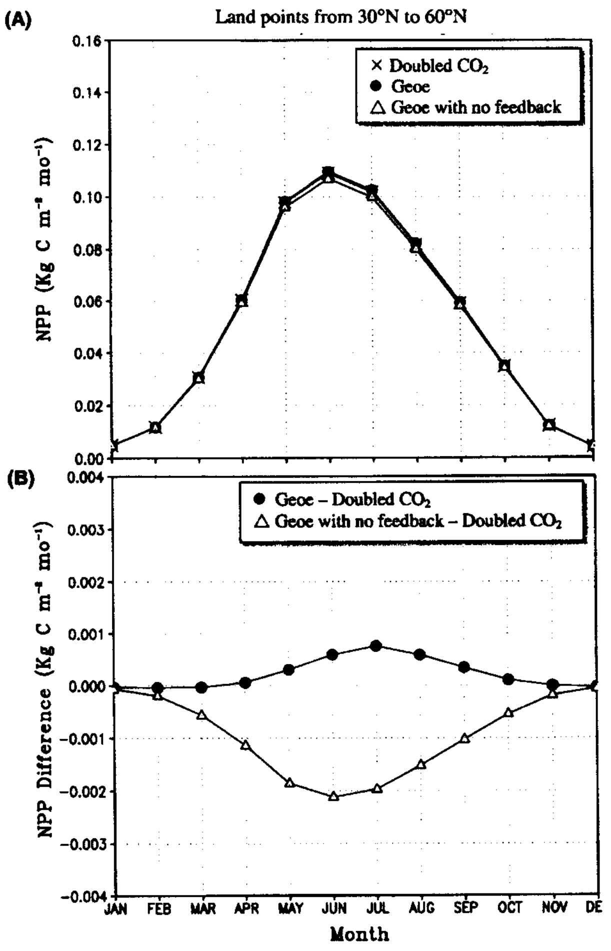

Figure 7. Same as in Figure 6A,B but for the mid-latitudes (30°N–60°N).

In addition to the evident impact of reduced irradiance on biospheric productivity, our model results also indicate implications for the hydrologic cycle. Evapotranspiration is an important factor determining the hydrologic balance and Earth's climate (Shukla and Mintz 1982). Globally, simulated evapotranspiration decreased in response to the Geoengineered reduction in Solar radiation. This reduction in evapotranspiration may amplify surface runoff in a Geoengineered world, particularly in the tropical and boreal forest ecosystems. As a consequence of increased runoff, floods may be frequent, causing soil and nutrient erosion. In many regions of the Earth, evapotranspiration contributes significantly to precipitation. For example, 25% – 50% of the rainfall in Amazon forests is derived from evapotranspiration within the basin (Eltahir and Bras 1994). Hence, diminished evapotranspiration may significantly reduce precipitation in the Amazon Basin. These effects have the potential to worsen the global CO_2-

induced climate change that we had initially set out to counteract by geoengineering Solar radiation.

The response of oceans to a Geoengineered reduction in Solar radiation was not included in our simulation, representing a significant limitation to our evaluation of the efficacy of this approach to reducing global warming. Oceans account for half of the Earth's photosynthesis (Schlesinger 1997). Net primary productivity in the marine biosphere is limited by light, nutrient availability, and temperature. Unlike the terrestrial biosphere, water stress plays no role in the marine biospheric productivity. Photosynthesis occurs in the sunlit ocean surface mixed layer known as the photic zone, and the depth of this zone depends on the intensity of Solar radiation, the optical properties of water, and the abundance of phytoplankton. With no change in other factors, a reduction in the incoming Solar radiation may reduce the depth of the photic zone, resulting in diminished phytoplankton photosynthesis and marine productivity. This may have a profound effect on the biological cycling of carbon in the oceans, potentially disrupting the partitioning of carbon between the atmosphere and the oceans in the Geoengineered scenario.

Given the reduction in NPP for tropical and boreal forests and the potential decline in global evapotranspiration, with a corresponding increase in runoff, geoengineering approaches that would reduce the Solar radiation reaching the Earth's surface need to be carefully evaluated before their implementation to reduce global warming.

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