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Environmental Consequences of Large-Scale Deployment of New Energy Systems

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FY06 LDRD Final Report

Environmental Consequences of Large-Scale Deployment of New Energy Systems

LDRD Project Tracking Code: 05-ERD-047

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Abstract

This project's scientific goal was to achieve better understanding of where land cover change may mitigate climate change, accounting for both direct climate effects as well as the impacts on the global carbon cycle. As tools for investigating this problem, several models of different complexities were used: an offline land model, a standard coupled climate model, and a model in which coupled carbon-climate interactions were explicitly represented. Results from all model simulations were qualitatively similar: climate mitigation projects involving large-scale re-growth of forests are predicted to be beneficial in mitigating future CO_2-induced global warming if these are carried out in the tropical latitudes, to be largely ineffectual if conducted in temperate latitudes, and to be counterproductive if implemented at high latitudes. Details of the quantitative differences in these predictions which are exhibited by the chosen climate models also are discussed .

Research Motivation

LDRD Project 05-ERD-047 was initially proposed as an investigation of the environmental impacts of a number of different climate-change mitigation strategies, including use of alternative energy technologies, as well as applications of carbon sequestration via re-growth of forests. However, because we attained especially interesting early insights on the latter topic, we subsequently focused exclusively on studying the climate-carbon impacts of various possible large-scale land-cover change.

Certain land management practices can potentially mitigate the expected global warming from emissions of carbon dioxide, but the climate-carbon consequences of these approaches must be better understood before they are implemented at large scale. For example, forest re-growth (or "afforestation") has been widely proposed as a means to store carbon. However, because the dark forest canopy also absorbs solar radiation, it is not clear where the cooling from carbon storage outweighs the warming effect of the dark forest surface.

In addition, the presence or absence of vegetation also greatly impacts surface evaporative fluxes which can have a substantial cooling effect locally, and perhaps also globally. Hence, widespread deforestation (such as currently practiced in the developing world) may exacerbate the anticipated climatic effects of greenhouse gas emissions. Deforestation affects the global climate both by releasing the carbon stored in the living plants and soils, and by altering the physical properties of the land surface. Deforestation therefore exerts a warming influence by 1) adding CO_2 to the atmosphere, 2) eliminating the possible increased carbon storage in trees as a result of future CO_2-fertilization and 3) decreasing evapotranspiration, especially in tropical latitudes. However, deforestation also exerts a cooling influence by 4) decreasing the surface albedo, especially in seasonally snow-covered high-latitudes. We will refer to the first two climate effects that are mediated by changes in atmospheric carbon dioxide content as "carbon-cycle effects" and refer to the other two climate effects of forests as "biophysical effects". Thus, vegetation changes produce changes in land-surface properties and atmospheric greenhouse gas concentrations, both of which can affect climate it complicated ways.

Our project has assessed the climatic effects of land-cover changes in the context of ongoing global warming induced by increasing concentrations of atmospheric carbon dioxide. In this study, we used a hierarchy of existing climate-simulation models of different complexities, and we ran model simulations that quantitatively bracket the range of possible climatic outcomes to be expected from several different large-scale land-cover changes.

We have found that the ultimate climatic impacts of land-cover changes are complicated, in that either heating or cooling of the surface may result, depending on where the vegetation changes are implemented. These results provide preliminary guidance for proposed future climate-mitigation strategies that involve land-use practices.

Research Tools, Procedures, and Results

Global climate models of different complexity were used to investigate the research problem.
The rationale was that our most complex model, which included interactions between the global carbon cycle and the climate, was very expensive to run; so we started investigating our reseearch problem with simpler climate models, in order to provide a "reality-check" on subsequent complex model simulations. Moreover, to the extent that predictions in models of different complexities would be found to agree, this would offer the possibility of using simpler models for exploratory work, and only then applying the most complex model for definitive studies. The approach we took in all our land-cover change simulations was to perform relatively extreme "thought experiments" in an attempt to bound the problem, while maximizing the experimental signal to noise ratio.

a. Offline land modeling

As an initial investigation of the direct climatic effects of land cover change (Gibbard et al. 2005), we first performed simulations without atmospheric feedbacks using version 3 of the Community Land Model (CLM3; Vertenstein et al. 2004) driven, in its offline mode with prescribed atmospheric climatologies. CLM3 allows for 15 types of vegetation with up to four vegetation types, as well as bare ground, lake, and glacier surfaces, in

each grid cell. Every vegetation type had its own leaf and stem area, root distribution, optical properties, and canopy top and bottom heights (Bonan et al., 2002).

To investigate the effects of vegetation changes in this model, we replaced the standard vegetation-type map used by CLM3 with maps containing only a single vegetation type in 100% of the occupied grid cells (without regard to where specific vegetation-types could realistically grow), while leaving the percentages of lake and glacier in each grid cell unchanged from their nominal values. We ran the CLM3 land model in offline mode, driving it by repeatedly using monthly climatologies of atmosphere data for 20 years, then discarding the first five years as a potentially nonequilibrated spin-up period, and then averaging over the last 15 years. We also performed a 20-year control run using the standard vegetation-type map supplied with the CLM3.

We found that the range of responses in surface air temperature predicted for all the different vegetation types minus that for bare ground clearly varied spatially, with the strongest responses occurring in the higher Northern Hemisphere latitudes presently occupied by boreal forest (Figure 1). In general, all vegetation types produced cooling (warming) in low (high) latitudes relative to bare-ground conditions. Surface albedo change was the dominant influence in middle and high latitudes, with vegetation producing a net warming (since snow-covered plants and trees have a much lower albedo than snow-covered bare ground).

In the Tropics, the main effect was via evapotranspiration, with vegetation producing a net cooling. Evapotranspiration removed heat from the surface more efficiently at low latitudes, partly because of the exponential relationship between temperature and saturation water vapor pressure (the Clausius-Clapeyron equation). This effect was most pronounced for trees, since there was both direct evaporation of water held in the forest canopy, and evapotranspiration of additional soil moisture brought up to the surface by the trees' deep roots. This property of forests acted to distribute much of the incoming solar energy as a latent heat of evaporation, thus cooling the surface. In tropical latitudes, this evaporative cooling effect won out over the albedo effect of a dark forest canopy, since even though more energy was absorbed, less energy was converted into sensible heating which is associated with increasing temperature.

Figure 1 shows that the 15 vegetation types can be roughly divided into two groups: open canopy (grass, shrubs), and closed canopy (trees). Note that Figure 1 does not imply an actual temperature change; instead this difference should be interpreted as the temperature tendency produced by a localized land cover change on a scale small enough to have no substantial effect on the atmosphere. (The surface temperature response to vegetation change in these offline runs is constrained by that of the atmospheric climatology.) Figure 1 suggests that to estimate the potential range of response to land cover change in a coupled model that includes both land and atmosphere effects, it suffices to consider only two types of vegetation: forest vs. grass/shrubland.

b. Coupled climate modeling

In order to consider land-atmosphere-ocean feedbacks for vegetation of different types under present climate conditions, we used a dynamical atmospheric model, Version 3 of the Community Atmosphere Model (CAM3; Collins *et al.* 2004) developed by the National Center for Atmospheric Research (NCAR) with a spatial resolution of 2.0° in latitude and 2.5° in longitude, and with 26 levels in the vertical. We also coupled the

CAM3 atmosphere to the CLM3 land model and to NCAR's simple slab ocean and thermodynamic sea ice model, thus allowing full two-way interactions to occur among vegetated land, atmosphere, ocean, and sea ice components. (The slab ocean model employed a spatially and temporally prescribed horizontal ocean heat transport and mixed layer-depth, which ensured prediction of realistic sea surface temperatures and ice distributions for the present climate.)

To achieve quasi-equilibrium among the land, slab-ocean, and atmospheric components, we ran the coupled model for 20 years, and then for an additional 30 years to collect data for analysis. We made control runs which included both the current vegetation and no vegetation (bare-soil conditions). Based on the results from our offline runs, we also ran two idealized vegetated experiments, one with global coverage by trees and the other with global grass/shrubs—referred to as "Tree World" and "Grass World", respectively. For the Tree World run, the vegetation type was specified in latitude bands, with each band assigned the most common type of tree presently at that latitude, based on current vegetation maps. A similar procedure was followed for the Grass World simulation.

For the Tree World simulation (Figure 2) the overall effect, compared to that for bare soil, was a warming of 1.6°C globally and 2.3°C for the land only. Results from the Grass World simulation indicated that the overall influence of grass vs. bare soil was a relatively small cooling effect (0.03°C globally and 0.1°C for the land only). Comparison of the Tree World and Grass World simulations with the current vegetation run indicated that the replacement of current vegetation by trees (grassland) at all latitudes would produce a global mean warming (cooling) of 1.3°C (0.38°C). A pronounced warming of 3.77°C was simulated in the Northern Hemisphere middle and high-latitude land surfaces in the Tree World simulation, a substantial amplification of the corresponding warming in the offline cases (Figure 1). This result presumably was due to the more complete representation of the climatic effects of forests where remote land-atmosphere-ocean interactions were represented.

The surface temperature difference between the Tree World simulation and the bare soil simulation (Figure 3) implies that the heating effect of forest, which was confined to latitudes poleward of 50° in the offline runs, instead extends poleward from about 20° in the coupled climate runs (compare Figures 1 and 2). Thus, the albedo effect dominated over the evapotranspiration effect from the poles to the deep Tropics in this case. It is also clear from Figure 3 that there was "downwind" heating or cooling of the oceans by the vegetated land in these fully coupled runs.

In the Tree World scenario it was not clear whether the heating effect of trees was primarily due to the presence of the boreal forest, or of mid-latitude forests. In order to investigate the effects of afforestation at mid-latitudes, we therefore ran another simulation in which the vegetation from 30-50° N was replaced by forest, with the rest of the vegetation in its current (control) configuration. The results (not shown) indicated that, without considering the climatic implications of carbon storage, the direct temperature effect of mid-latitude trees was also a warming—by 0.68°C compared to bare ground, or by 0.27°C compared to current vegetation.

c. Coupled carbon-climate modeling

Even a fully interactive standard global climate model is quite limited, from the standpoint of representing the global carbon cycle and its interactions with the climate. That is, a coupled global carbon-climate model is necessary to realistically simulate transient changes in carbon dioxide emissions and the global climatic effects of their subsequent uptake by the atmosphere, oceans, soil, and vegetation.

Such an investigative tool, the LLNL Integrated Climate and Carbon (INCCA) model, was developed by a previous LDRD-funded project (Thompson et al. 2004). The components and interactions of INCCA are shown schematically in Figure 4. The physical ocean-atmosphere model is the NCAR/DOE PCTM model (Meehl et al. 2004), which is a version of the NCAR CCM 3.2 model (Kiehl et al. 1996) coupled to the LANL POP ocean model that includes both surface currents and abyssal circulations (Maltrud et al. 1998). The atmospheric model also is coupled to a terrestrial biosphere model with dynamically varying vegetation, the Integrated Biosphere Simulator version 2 (IBIS2; Foley et al. 1996; Kucharik et. al. 2000), as well as to a prognostic ocean biogeochemistry model based on the diagnostic Ocean Carbon-cycle Model Intercomparison Project (OCMIP) Biotic protocols (Najjar and Orr 1999). The horizontal resolution of the land and atmospheric models is approximately 2.8° x 2.8° latitude-longitude, while that of the ocean model is (2/3)° x (2/3)° . The atmosphere and ocean models represent processes on 18 and 40 vertical levels, respectively.

In using the INCCA model to study the carbon-climate effects of land-cover changes, we made relatively large-scale alterations of vegetation in order to bound the problem, while maximizing the experimental signal to noise ratio. We first simulated a “Control” run in which emissions of CO_2 were fixed at their estimated pre-industrial (circa 1870) levels (Bala et al. 2005).

Next, we simulated transient carbon-climate interactions for a “Standard” experiment in which CO_2 emissions followed historically observed levels for the historical period 1870-2000, the projected SRES A2 levels of emissions (Nakicenovic 2000) for the years 2000-2100, and a logistic function for the long-range 2100-2300 period (Bala et al. 2005). This Standard simulation produced a global-mean warming of 3.2 K relative to that of the Control simulation in the year 2100, and about an 8 K global warming by year 2300 (Figure 5). Subsequent analysis of this experiment (Bala et al. 2006a) estimated that about 0.65 K of this warming was attributable to the increased albedo resulting from forests that expanded poleward while their uptake of atmospheric carbon dioxide also increased.

We subsequently applied INCCA in a series of 4 deforestation cases, each simulated in a 150-year run during the period 2000 to 2150, in which the same A2 emissions scenario as in the Standard experiment was also operative. These were the first studies ever to investigate the combined carbon-climate effects of deforestation in a fully interactive three-dimensional model incorporating complex sub-models of vegetation dynamics and terrestrial and oceanic components of the carbon-cycle.

We initially conducted a “Global” experiment which bracketed the climatic effects of an extreme case where deforestation implemented on all land surfaces. This was identical to the Standard experiment, except that plant functional types representing trees were not allowed to exist after year 2000, and thus only shrub and grass plant functional types

remained. In this Global deforestation simulation, the biomass in tree leaves and fine roots was immediately transformed to litter in year 2000, while the stem biomass changed more gradually to litter on a time scale of 10 to 50 years depending on the tree plant functional type. The total carbon released to the atmosphere from tree functional types in the simulated 21st century was 818 PgC.

In order to isolate the net effects of large-scale deforestation implemented in tropical, temperate and Northern high-latitudes, we next considered three additional simulations where deforestation was restricted to the latitude bands 20°S-20°N ("Tropical"), 20°-50° in both the Northern and Southern Hemispheres ("Temperate") and 50°-90° in the Northern Hemisphere ("Boreal"), respectively. The corresponding amounts of carbon released from trees in these latitude-band deforestation cases in the 21st century were 422, 316 and 80 PgC. Note that the sum of carbon lost from tree plant functional types in these three latitude-band simulations was equivalent to the tree carbon lost in the Global simulation.

Atmospheric CO_2 content was greater in the Global deforestation experiment by 381 ppmv, both because of the release of carbon stored in trees in the early 21st century as well as the loss of CO_2-fertilization of forested ecosystems seen in the Standard simulation (Figure 6). Despite higher atmospheric CO_2 concentrations, the global- and annual-mean temperature in the Global experiment was cooler by about 0.3 K than the Standard case. Thus, on a global-mean basis, the cooling biophysical effects of deforestation overcame the warming carbon-cycle effects.

Relative to the Standard case, the atmospheric CO_2 concentration was higher by 299, 110 and 5 ppmv in the Tropical, Temperate, and Boreal cases. The global-mean temperature differences relative to the Standard case in year 2100 in the Tropical, Temperate, and Boreal experiments, were +0.7 K, -0.04 K, and -0.8 K, respectively (Figure 6). These results imply that the combined carbon-cycle and biophysical effects from tropical, temperate, and boreal deforestation were, respectively, net cooling, near-zero temperature change, and net warming. These latitude-band experiments thus suggested that projects in the Tropics promoting afforestation are likely to slow global warming, but such efforts would offer only meager mitigation benefits when implemented in temperate regions, and they would be counterproductive (from strictly a climate standpoint) at higher latitudes.

The linear sum of the area-weighted global-mean temperature change over all the latitude-band experiments was -0.1 K in the year 2100. This value was close to the corresponding -0.3 K temperature change of the Global deforestation simulation, suggesting a near-linear behavior of the large-scale climate system, despite the many non-linear processes represented by the INCCA model. The linear sum was slightly larger than the Global average because, in the latitude-band experiments, the dynamic vegetation model allowed forests to expand into regions which were not completely deforested. Forests also have lower albedos than grasses, and thus absorb more solar radiation. The presence of trees in the latitude-band deforestation experiments and the consequent higher CO_2-fertilization caused the linear sum of CO_2 changes from the Tropical, Temperate, and Boreal experiments to be lower than that of the Global deforestation case by 67 ppmv in year 2100.

Since the linear sum of the temperature response from latitude-band deforestation experiments was approximately equal to that of the Global experiment (Figure 6), we focus here on further analysis of this global-scale deforestation simulation. The complete

removal of forests in the Global experiment resulted in an atmospheric CO_2 concentration at year 2100 that was 381 ppmv greater than in the Standard simulation (1113 versus 732 ppmv; Figure 6). In the Standard A2 scenario, 1790 PgC carbon was emitted to the atmosphere over the 21st century (Figure 7). By year 2100, the terrestrial biosphere in the Global deforestation experiment had 972 Pg less carbon than in the Standard case. About 82 % (799 PgC) of this carbon resided in the atmosphere, with the oceans taking up the remaining 18 % (173 PgC). The ocean uptake increased in the Global deforestation experiment (444 vs 271 PgC in Standard A2) because the higher concentration of atmospheric CO_2 drove an increased flux of carbon into the oceans.

The spatial distribution of climate and carbon-cycle changes in the Global simulation for the decade centered on year 2100 is shown in Figure 8A. Similar to the global-mean statistics, the linear sum (Figure 8B) of the *spatial patterns* of temperature response from the latitude-specific Boreal, Temperate, and Tropical deforestation experiments (Figures 8C, 8D, and 8E) was also approximately equal to that of the Global experiment (Figure 8A). This once again highlighted the apparent linear response of the large-scale climate system despite the presence of many non-linear processes.

The spatial pattern of temperature differences suggests that the strongest cooling in the Global deforestation was associated with the removal of boreal forests in the Northern Hemisphere high-latitudes (Figure 8A). The replacement of these forests by grasses and shrubs increased the surface albedo (brightened the surface) by as much as 0.25 (Figure 9A). This resulted in decreased absorption of surface solar radiation and cooling that exceeded 6 K in some locations, despite higher CO_2 concentrations and high-latitude amplification of CO_2-induced warming. The albedo effect therefore dominated the climate response in the Northern Hemisphere mid- and high-latitudes. The magnitude of cooling due to albedo-change would likely become smaller after 2100 as the simulated length of the snow season is reduced further.

In the Tropics, however, increases in surface albedo (Figure 9A) did not produce as much cooling, largely due to a decrease in cloud cover (Figure 9C) brought about by the reduced evapotranspiration (Figure 9B) that resulted from the removal of tropical forests. Thus, the replacement of tropical forests with grass and shrub lands brightened the surface, while the decrease of clouds tended to darken the planet. These effects nearly cancelled each other so that the planetary (top-of-atmosphere) albedo (Fig. 9D) changed little over tropical regions. This suggests that cloud feedbacks initiated by evapotranspiration changes play a major role in determining the overall climatic impact of deforestation in the Tropics.

Despite higher atmosphere CO_2 concentrations, the average annual-mean surface temperature over land in the Global deforestation experiment was cooler by 2.1 K, 1.6 K, and 0.4 K than that of the Standard experiment in the Northern Hemisphere high-latitudes (50^0N to 90^0N), mid-latitudes (20^0N to 50^0N), and tropics (20^0S to 20^0N), respectively. In contrast, the Southern Hemisphere mid-latitude (50^0S to 20^0S) land surface warmed by only 0.1 K. In the Northern Hemisphere mid- and high-latitudes, surface albedo effects dominated, resulting in decreased net surface solar absorption and cooling. In the Tropics and Southern Hemisphere mid-latitudes, the decrease of surface albedo was comparable to that in the Northern Hemisphere mid-latitudes, but the decreases in evapotranspiration and cloudiness led to increases in the surface incident and absorbed solar radiation, which tended to warm the surface. However, the net biophysical effect was still an overall

cooling, and it was larger than the warming carbon-cycle effects in the Tropics, while being only slightly smaller in the Southern Hemisphere mid-latitudes (Figure 8A).

We also investigated the annual- and seasonal-mean changes in surface albedo and evapotranspiration rates in areas covered by specific vegetation types (details not shown), indicating large albedo changes in boreal forests in the winter, and evapotranspiration changes in all tree types during summer. Because convection plays an especially important role in vertical moisture transport and cloud formation during summer, the evapotranspiration changes in this season led to a reduction in cloud cover.

Analysis of the latitude-band experiments showed large surface albedo changes in the latitudes where deforestion took place, with the largest changes in boreal regions. The albedo changes were larger in the winter hemispheres, while the evapotranspiration changes were larger in the deforested tropical and temperate regions, and in the summer hemispheres. However, planetary (top-of-atmosphere) changes in albedo were restricted to deforested boreal areas. Tropical deforestation warmed the planet everywhere, indicating that the remote warming from the carbon cycle (greenhouse) effect dominated in this case. Even though the evapotranspiration changes tended to enhance the local warming, the change in surface albedo reduced the local warming to less than the global average in the INCCA model. Temperate deforestation produced local cooling due to the dominant albedo change, but remote warming due to the carbon-cycle effect, and these effects cancelled each other in the net global average. Besides causing strong local cooling, boreal deforestation produced remote cooling everywhere, presumably via atmospheric circulation changes.

Interpretation of Research Results

The approximate global-mean warming from carbon-cycle effects and cooling from biophysical effects can be estimated from the physical model's known climate sensitivity of 2.1 K in surface temperature for a radiative forcing of 3.5 Wm^{-2} per doubling of atmospheric CO_2 concentrations. The extra radiative forcing in the Global experiment due to the excess 381 ppmv of CO_2 at year 2100 would thus produce an equilibrium carbon-cycle warming of about +1.3 K. If we further assume that the transient temperature difference of -0.3 K between the Global and Standard experiments at year 2100 (Figure 6B) remains the same when equilibrium is eventually achieved, the net cooling from biophysical effects is estimated to be about -1.6 K.

The INCCA terrestrial biosphere component model IBIS2 is known to predict higher carbon uptake with increased atmospheric CO_2 than similar models (Cramer et al. 2001). This bias would tend to accentuate the simulated difference between the atmospheric CO_2 in our deforestation simulations relative to the Standard simulation, thereby overestimating the warming carbon-cycle effects of global-scale deforestation relative to its biophysical cooling effects. With a less responsive biosphere model than IBIS2, therefore, we would expect to see even more cooling as a result of deforestation. The magnitude of the model-predicted net cooling (warming) from large-scale deforestation (afforestation) thus may be greater than what would actually be seen. Further studies with similarly complex carbon-climate models are therefore needed to confirm and better quantify the net temperature change to be expected.

Our conclusions from the experiments conducted with the INCCA carbon-climate model are consistent with inferences drawn from simulations with simpler models that we have

utilized: the climate effects of CO_2 storage in forests are offset by albedo changes at high latitudes, so that climate mitigation projects promoting large-scale afforestation projects are likely to be counterproductive in these regions.

We also find that tropical deforestation contributes to global warming via both carbon-cycle and biophysical effects (Figure 8E), supporting conclusions drawn in previous studies with simpler models. The tropical cooling seen in the Global experiment therefore implies the presence of remote effects of deforestation implemented outside the Tropics. Nonetheless, this net tropical temperature change is small, and so its sign may be sensitive to the different representations of physical processes such as cloud dynamics and surface hydrology in today's climate models.

Certain results obtained with INCCA also highlight the need to employ climate-carbon models in order to comprehensively evaluate the carbon-cycle and biophysical effects of forests on climate. For example, although the importance of time-horizon in defining tradeoffs between carbon and biophysical effects is evident (e.g. increasing ocean uptake in Figure 7), this aspect of the problem has been largely overlooked in previous assessments. Another new policy-relevant implication is that large-scale afforestation implemented in temperate latitudes may be largely ineffectual in mitigating global warming. We note, however, that results for particular forest species in specific locations might vary from the global-scale results presented here. Moreover, because carbon-cycle effects are manifested globally while biophysical effects are most strongly felt locally, a particular afforestation project could produce regional warming while cooling the remainder of the planet.

Finally, it should be emphasized that since preservation of ecosystems is a primary goal of preventing global warming, their destruction in the purported service of climate mitigation would be a perverse outcome. Hence, the cooling that could potentially arise from deforestation outside the Tropics should not necessarily be viewed as a strategy for mitigating climate change since forests are valuable environmental resources in many other respects. For example, forests provide natural habitat to plants and animals, preserve the biodiversity of natural ecosystems, produce economically valuable timber and firewood, protect watersheds through prevention of soil erosion, and indirectly prevent ocean acidification by reducing atmospheric CO_2. In planning responses to global challenges, therefore, it is important to pursue broad goals and to reject narrow criteria which may lead to environmentally harmful consequences.

Summary of Research Accomplishments

In this LDRD project, we completed a series of runs of large-scale vegetation changes in a hierarchy of global climate models of different complexity (e.g. with vegetation changes either prescribed or dynamically predicted), and we bracketed the range of climatic outcomes to be expected. Results from all model simulations are qualitatively similar: large-scale afforestation projects are predicted to be beneficial in mitigating future CO_2-induced global warming if these are carried out in the tropics, to be largely ineffectual if conducted in temperate latitudes, and to be counterproductive if implemented at high latitudes. To disseminate these results broadly in the scientific community, we presented our work at numerous professional meetings (Bala et al. 2004, 2005a, 2005b, Caldeira et al. 2005, 2006a, 2006b, Duan et al. 2005) and discussed the details as well in several peer-reviewed journal papers (Bala et al., 2005b, 2006a, 2006b, Gibbard et al. 2005). Our study provides preliminary guidance for proposed future

climate-change mitigation projects involving land-cover management, and we recommend that similar future projects be funded in order to provide more detailed strategic guidance to policy makers.

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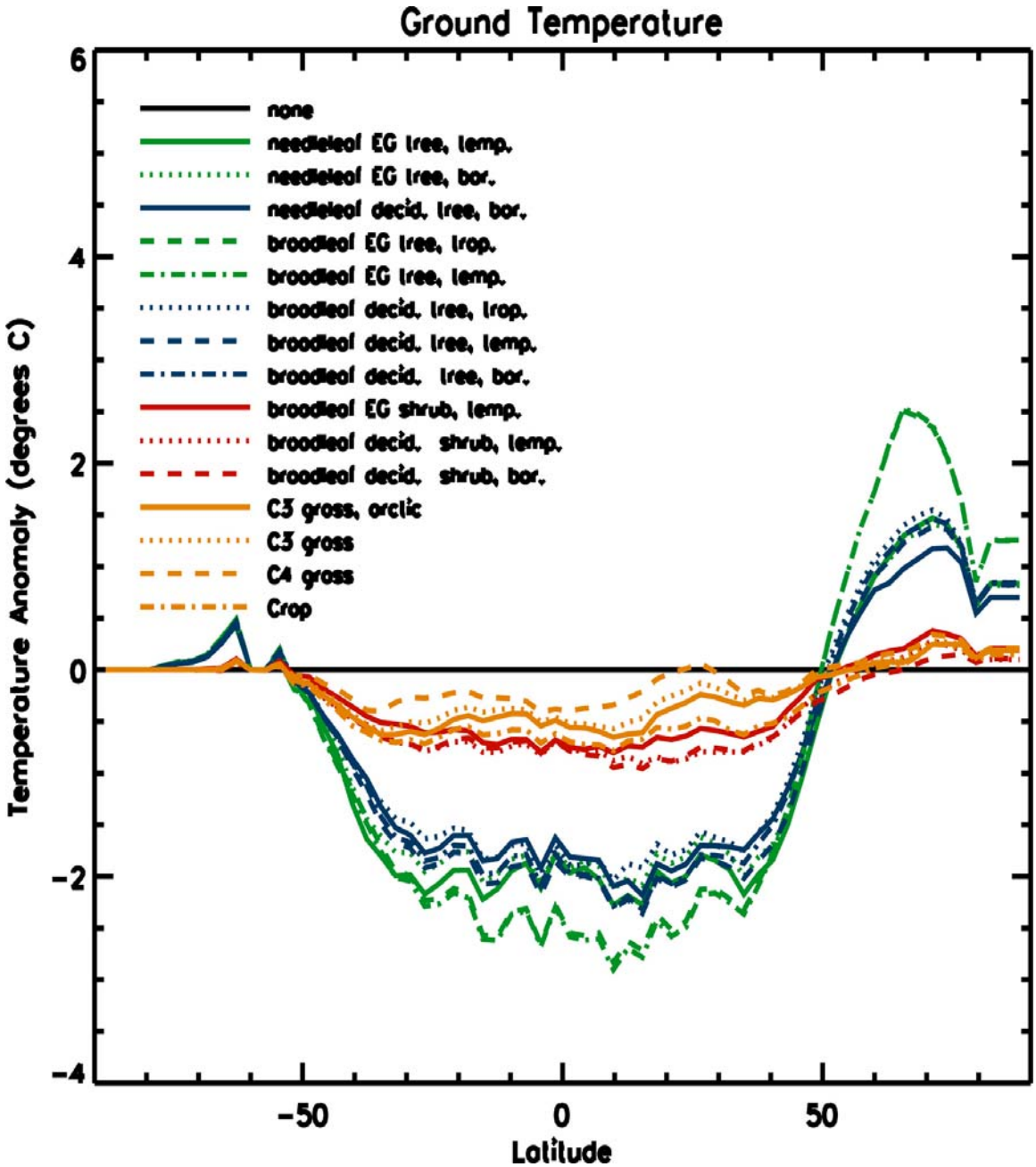


Figure 1: Change in zonal and annual mean ground temperature resulting from changes in vegetation. Green and blue lines represent forest ecosystems; orange and red lines represent grassy or bushy ecosystems. At low latitudes, forests cool despite their dark canopies because evaporatranspirative effects are more pronounced than albedo effects. At high latitudes, evaporative cooling is less effective, while the presence of fallen snow increases the albedo contrast between the forest canopy and the ground. Both of these effects lead to warming.

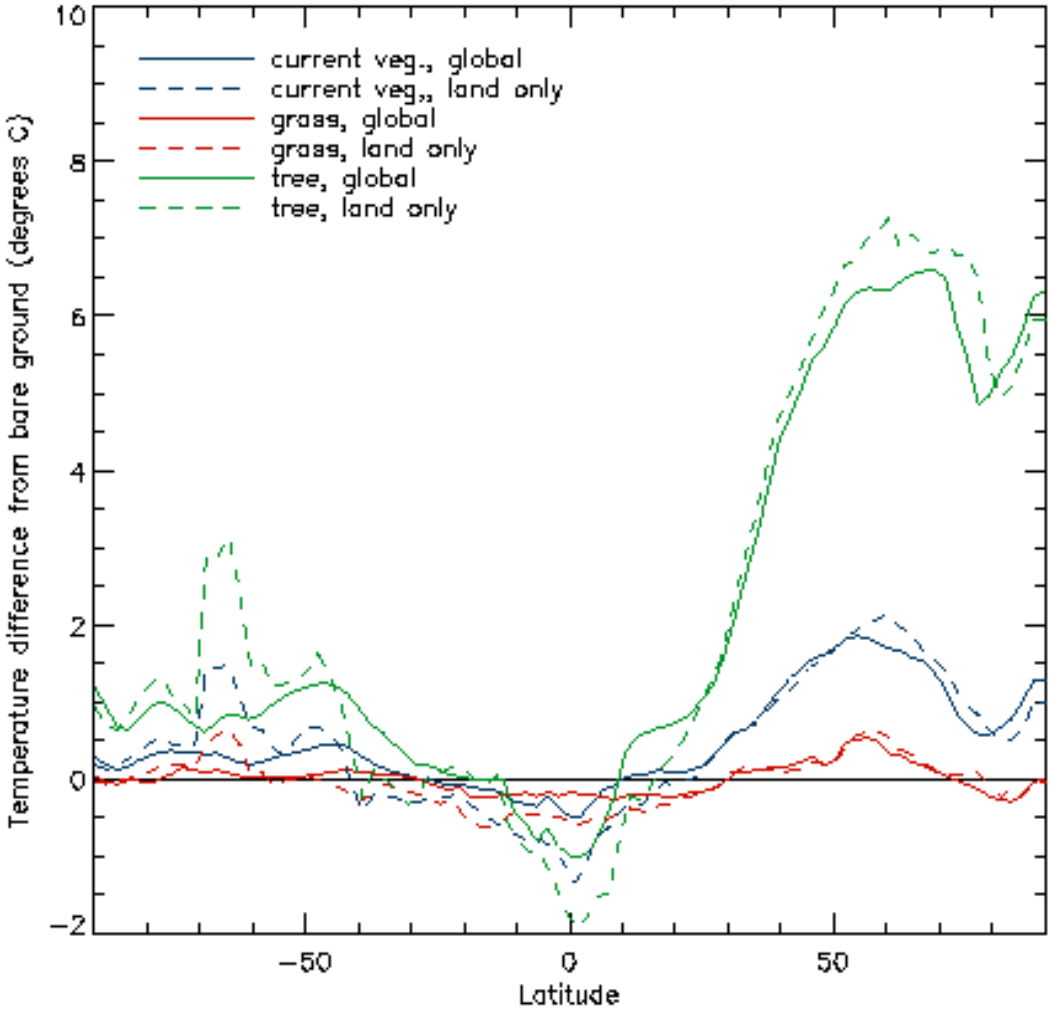


Figure 2: Zonal average temperature changes (relative to bare ground) are shown for the current distribution of vegetation and for "Tree World" and "Grass World" experiments made with a fully interactive climate model (including dynamical atmosphere, land model, and mixed-layer ocean). Note especially the amplification and latitudinal extent of the warming effects of trees in these fully interactive runs compared with those in which only the land model was driven offline by monthly atmospheric climatologies (shown in Figure 1).

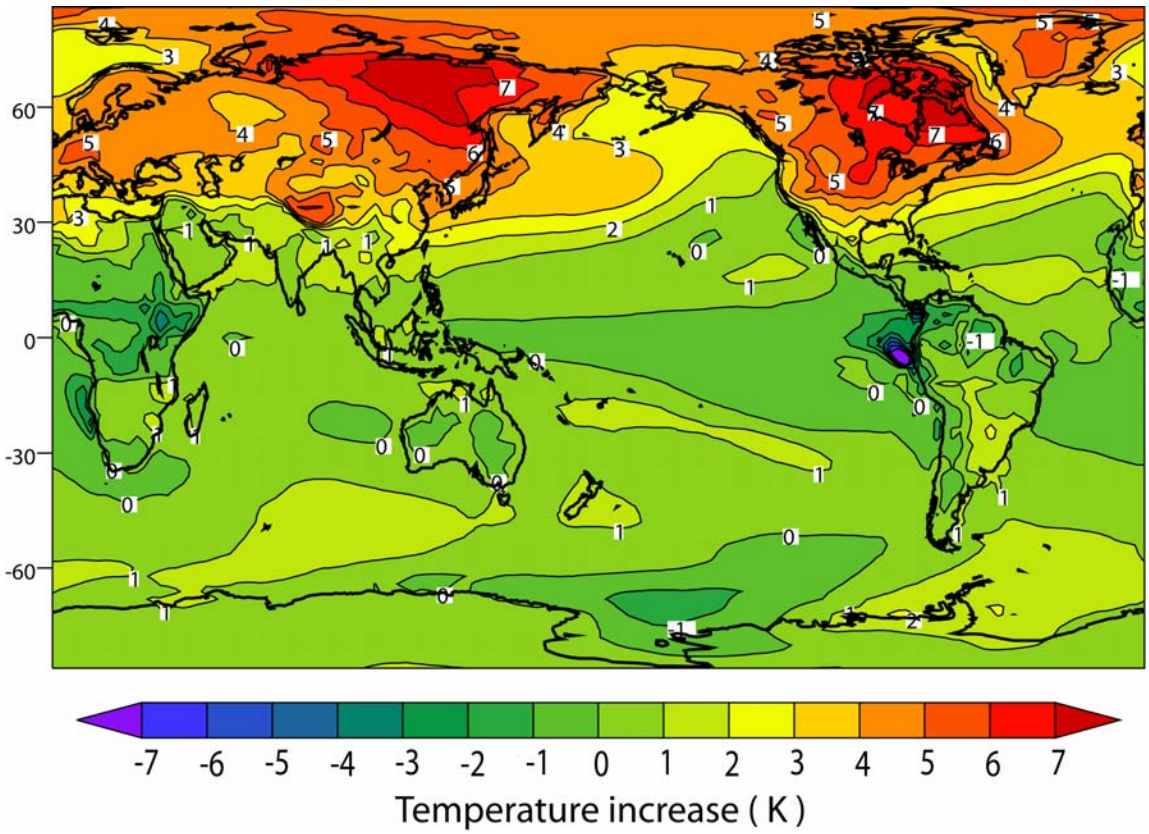


Figure 3: Map of surface air temperature changes (relative to bare ground) in the "Tree World" experiment implemented with a fully interactive climate model.

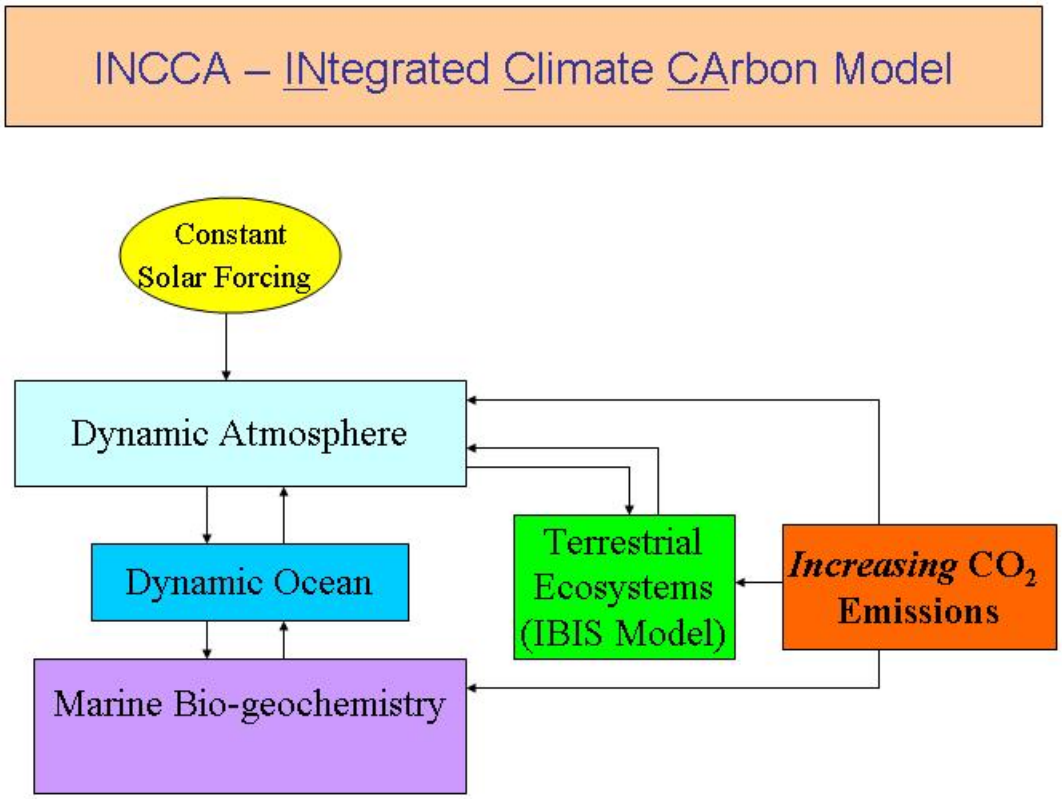


Figure 4: Schematic diagram of the INCCA coupled global carbon-climate model showing its solar and carbon-dioxide emission forcings, as well as the subcomponent atmospheric, ocean, terrestrial ecosystems, and marine bio-geochemistry models.

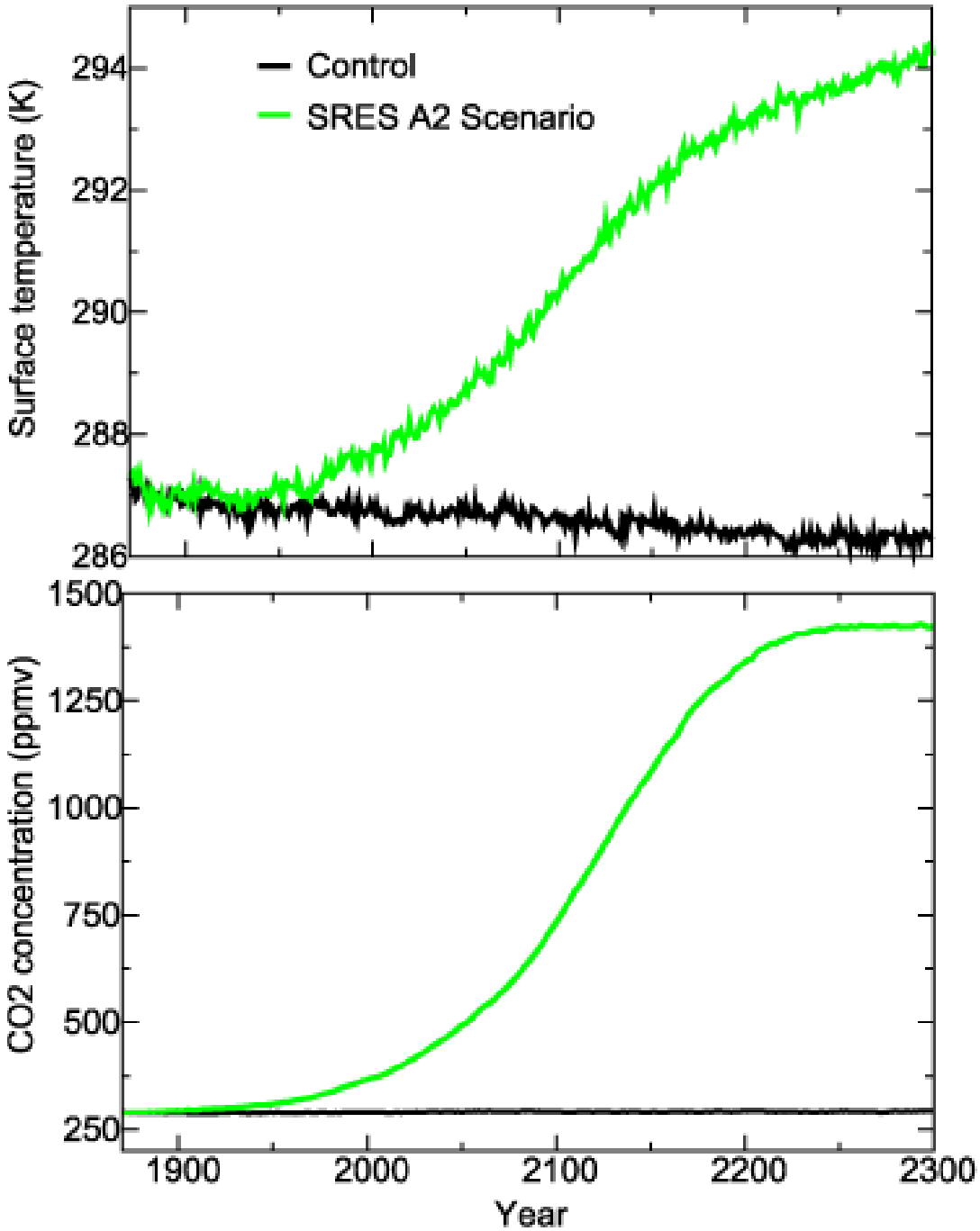


Figure 5: Global-average surface air temperature changes (top panel) and corresponding atmospheric concentrations of carbon dioxide (lower panel) simulated in a Control experiment with pre-industrial CO_2 emissions, and in a Standard global warming experiment that corresponds to an A2 CO_2-emissions scenario, where both experiments were run for simulation years 1870-2300. (Note: the slow downward temporal trend in global-average temperature in the Control is symptomatic of a slow "climate drift" that is commonly found after coupling ocean and atmosphere models that are first equilibrated separately in uncoupled mode.)

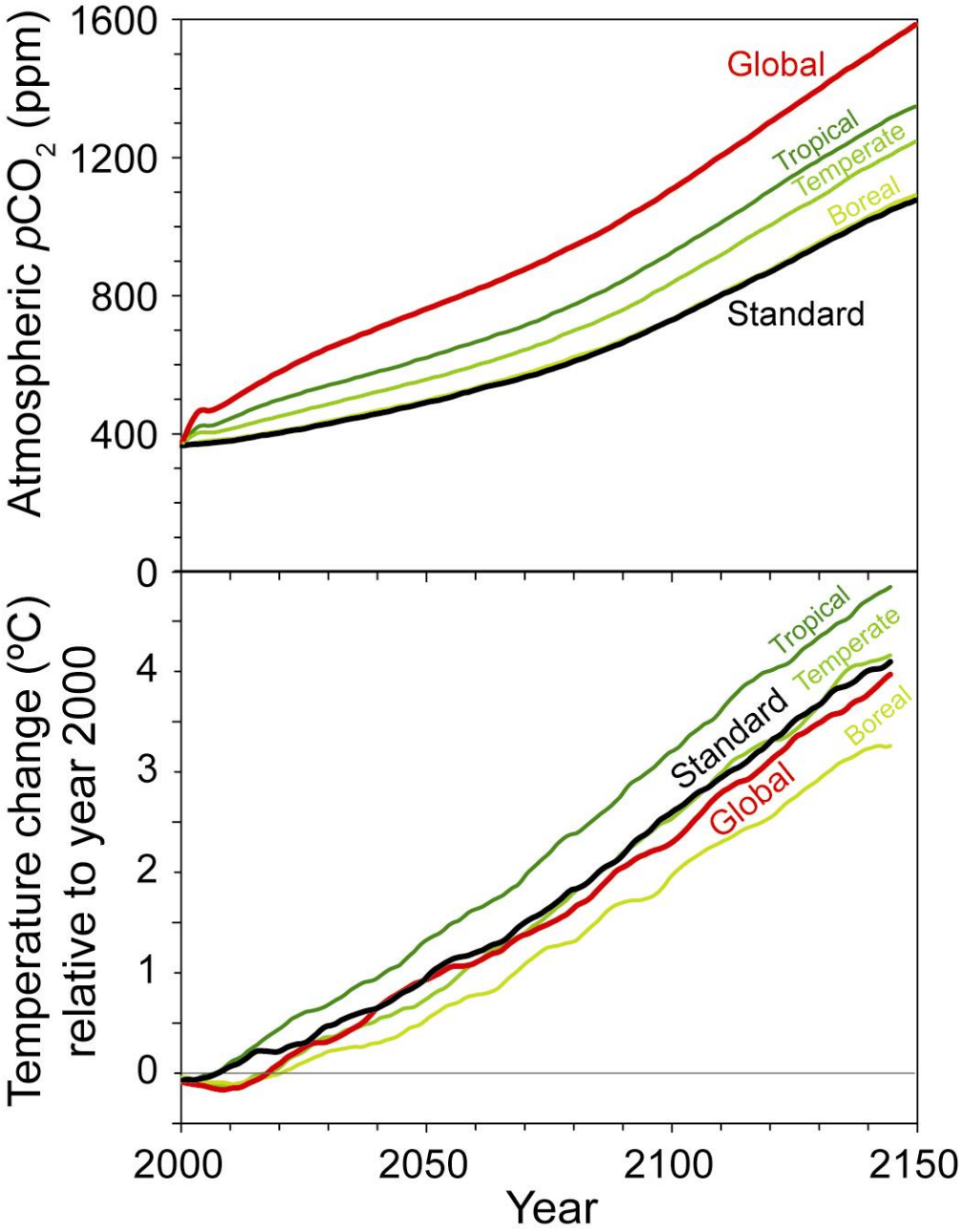


Figure 6: Simulated temporal evolution of a) atmospheric CO_2 and b) 10-year running of surface temperature change for the period 2000-2150 in the Standard and deforestation experiments. Warming effects of increased atmospheric CO_2 are more than offset by the cooling biophysical effects of global deforestation in the Global simulation, producing a cooling relative to the Standard experiment of about 0.3 K around year 2100. The combined carbon-cycle and biophysical effects from Tropical, Temperate, and Boreal deforestation are a net cooling, a near-zero temperature change, and a net warming, respectively. The sum of the temperature changes in the latitude-band experiments is approximately equal to the temperature change in the Global simulation, suggesting near-linearity.

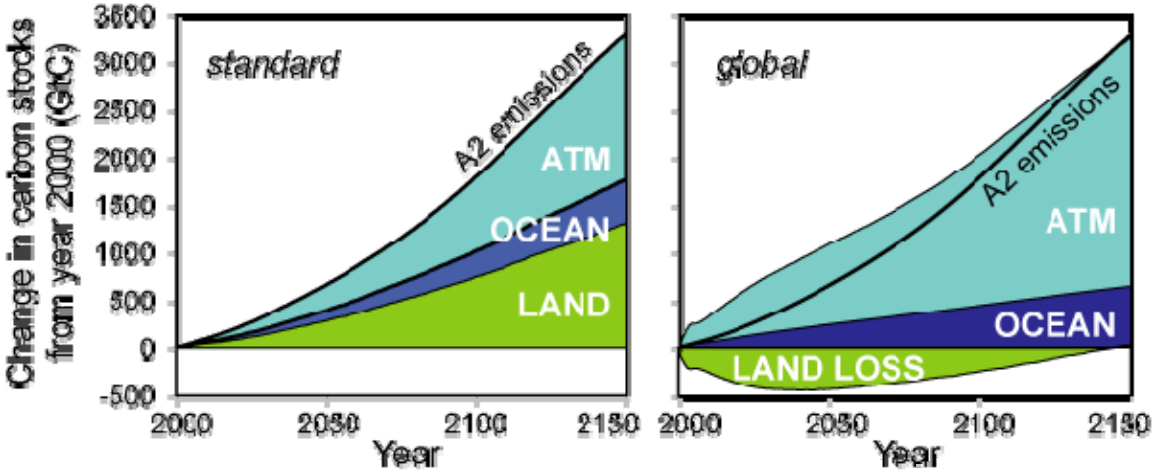
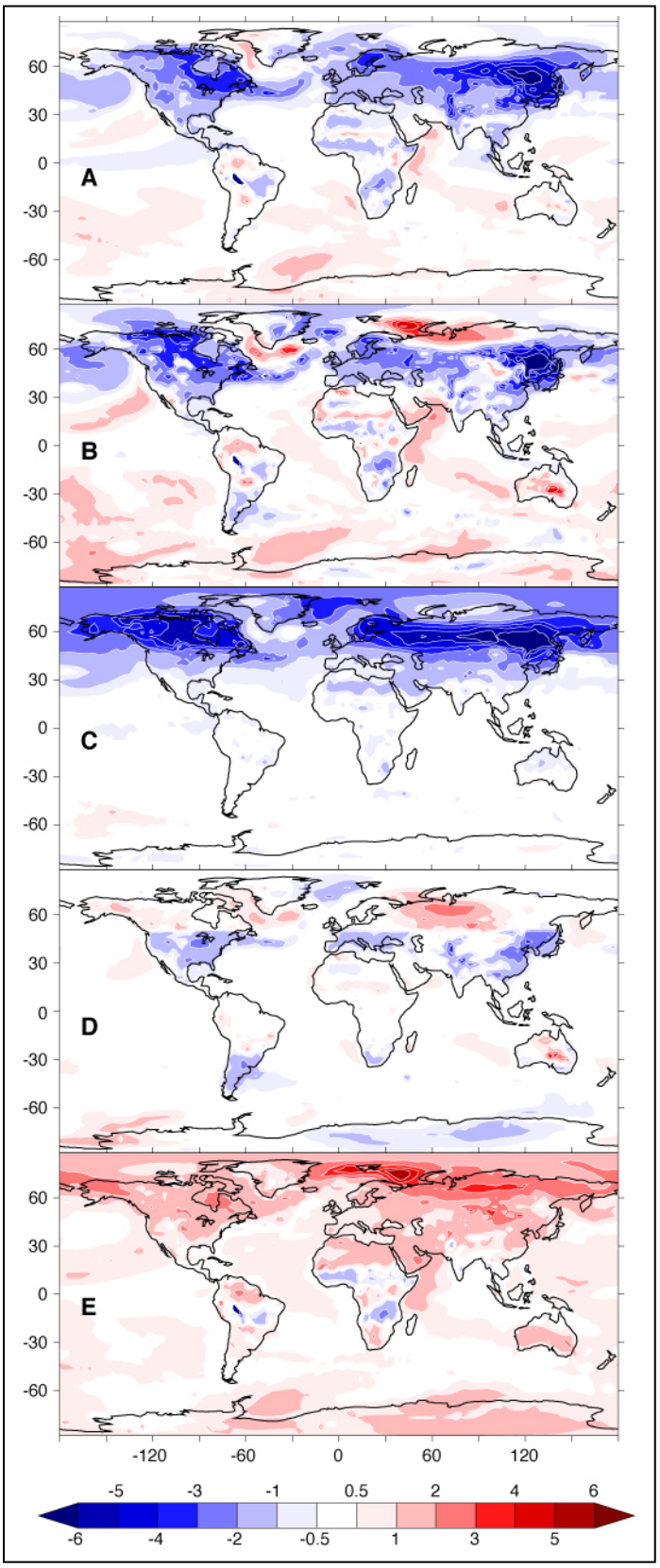


Figure 7: Simulated cumulative emissions and carbon stock changes in atmosphere, ocean, and land for the period 2000-2150 in A) Standard and B) Global experiments. In the Standard experiment, strong CO_2-fertilization results in vigorous uptake and storage of carbon by land ecosystems. In the Global experiment, land ecosystem carbon is lost to the atmosphere as a result of global deforestation. Most of this carbon is ultimately reabsorbed by grasses and shrubs growing in a warmer CO_2-fertilized climate at year 2100. Of the land ecosystem carbon in the Standard simulation that is not present in the land biosphere in the Global simulation at year 2100, about 82 % resides in the atmosphere, and the remaining 18 % in the oceans.

Figure 8: Simulated spatial surface temperature differences relative to the Standard experiment in the decade centered on year 2100 for A) Global and B) the linear sum of C) Boreal, D) Temperate, and E) Tropical deforestation experiments. Cooling biophysical effects of deforestation outweigh the warming carbon-cycle effects over most of the land surface (including tropical regions), but are most pronounced in the Northern high latitudes. Comparison of A) and B) shows the near-linear behavior of the model climate system. Cooling biophysical effects of deforestation dominate the climate response in the Boreal deforestation case C). In the Temperate deforestation case D), there are strong local cooling responses, though the global-mean response is near zero. The carbon-cycle effects of warming outweigh the biophysical effects in the Tropical deforestation case E) with slight local cooling resulting from the biophysical effects.



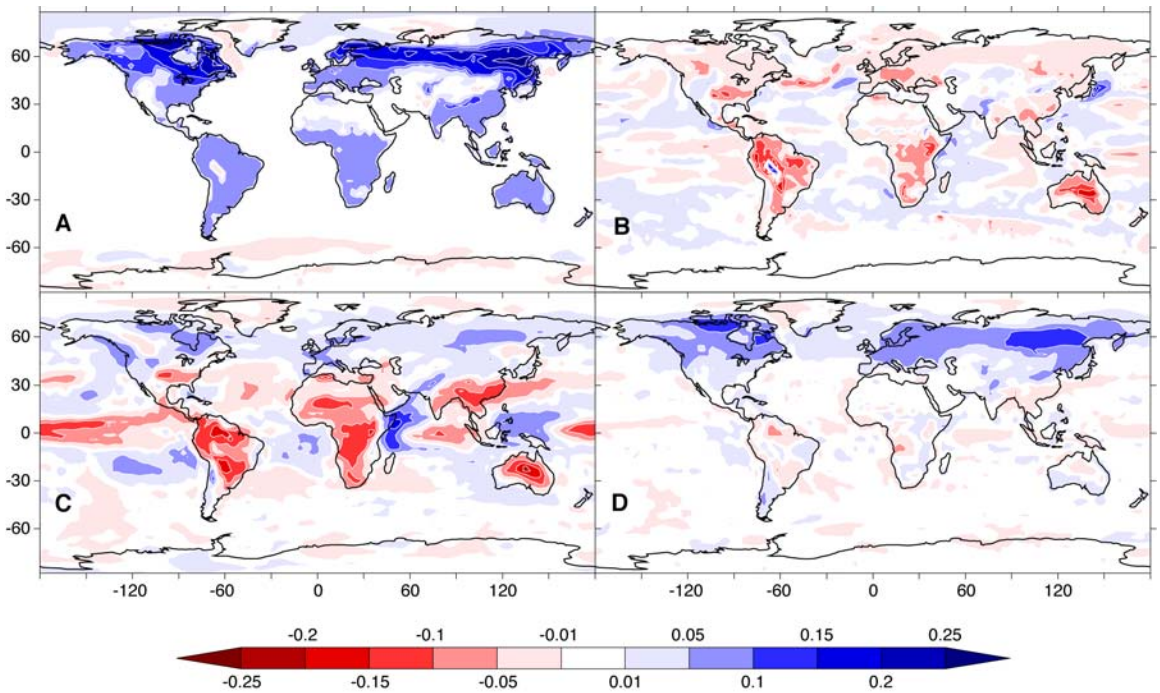


Figure 9: Simulated spatial pattern differences (Global experiment minus Standard experiment) in the decade centered on year 2100 for A) surface albedo (fraction), B) evapotranspiration (cm/day), C) cloudiness (fraction), and D) planetary albedo (fraction) differences. Albedo effects dominate the Northern Hemisphere mid- and high-latitude climate change and produce a strong cooling in the Global deforestation relative to that in the Standard experiment. In the Tropics and Southern Hemisphere land areas, the warming due to higher atmospheric CO_2 is largely offset by cooling biophysical effects, producing little net temperature change. In the Tropics also, removal of forests increases surface albedo (A) and decreases evapotranspiration (B) and cloudiness (C), thus reducing the albedo as seen from the top of the atmosphere (D), and largely offsetting the effects of the increased surface albedo.