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Transient climate change and net ecosystem production of the terrestrial biosphere

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Abstract. In this sensitivity study, we have applied the Terrestrial Ecosystem Model ((TEM) version 4.1) to examine the responses of terrestrial ecosystems to transient changes in atmospheric CO_2 concentration and climate in the 21st century at the scales of the globe, biomes, latitudinal gradient, and economic regions. Three predictions of transient change in climate and atmospheric CO_2 concentration in the 21st century from the Integrated Global System Model developed at Massachusetts Institute of Technology were used. The TEM estimates a global annual net ecosystem production (NEP) of about 0.8 Pg C yr^{-1} in 1990. Global annual NEP in 2100 increases by about 2.6 Pg C yr^{-1} for the HHL (higher CO_2 emissions and temperature increases), 1.8 Pg C yr^{-1} for the RRR (reference CO_2 emissions and temperature increases), and 0.5 Pg C yr^{-1} for the LLH (lower CO_2 emissions and temperature increases) climate change predictions. The boreal and tropical evergreen forests account for a large portion of the increased global annual NEP. Latitudinal distribution of total annual NEP along 0.5°-resolution latitudinal bands shifts significantly from the tropics to the northern middle and high latitudes over time. The potential CO_2 uptake over the period of 1990-2100 differs substantially among the 12 economic regions of the world. As we used potential mature natural vegetation in the global extrapolation of TEM, these NEP estimates represent the potential CO_2 uptake or the upper bound for long-term carbon sequestration by the terrestrial biosphere. This sensitivity study shows that the temporal dynamics and spatial distribution of carbon, nitrogen, and water fluxes of terrestrial ecosystems are very sensitive to the magnitudes and paths of transient changes in atmospheric CO_2 concentration and climate in the 21st century.

1. Introduction

Future changes in atmospheric CO_2 concentration and climate are likely to affect net primary production and the carbon storage of terrestrial ecosystems [*Gates*, 1985; *Houghton and Woodwell*, 1989; *Melillo et al.*, 1990; *Jenkinson et al.*, 1991]. A number of modeling studies have applied ecosystem models to examine the equilibrium responses of net primary production and carbon storage of the terrestrial biosphere to elevated atmospheric CO_2 concentration and the doubled CO_2 equilibrium climate changes predicted by atmospheric general circulation models at the scales of the globe [*Melillo et al.*, 1993; *Parton et al.*, 1995; *Xiao et al.*, 1997] and the conterminous United States [*VEMAP Members*, 1995; *Schimel et al.*, 1997]. The results from the above equilibrium studies have shown that net primary production and carbon storage of terrestrial ecosystems are substantially affected by the changes in atmospheric CO_2 concentration and climate. In the above equilibrium studies, vegetation structure and distribution are assumed to remain constant [*Melillo et al.*, 1993; *Parton et al.*, 1995; *Xiao et al.*, 1997] or to change to a new equilibrium condition in a single step [*VEMAP Members*, 1995]. These equilibrium studies, however, are significantly limited in their usefulness to climate policy and decision making because the time paths of changes in CO_2 and climate are not taken into account, and consequently, the transient responses of carbon and nitrogen dynamics of terrestrial ecosystems are not simulated. Transient changes in vegetation structure and distribution will also influence the transient responses of ecosystem physiology to climate change and the interaction between the land biosphere and the atmosphere. There are large uncertainties about the path and magnitude of future anthropogenic emissions of greenhouse gases around the world because of uncertainties in population dynamics, economic growth, technological development, and other factors [*Wigley et al.*, 1996]. A significant number of transient climate change simulations associated with different anthropogenic emissions of greenhouse gases need to be conducted in order to quantify uncertainties and impacts of global climate change that are relevant to climate policy [*Jacoby and Prinn*, 1994].

Recently, the Integrated Global System Model (IGSM) has been developed to address major issues in climate change, impact assessment, and climate policy [*Prinn et al.*, 1998; also *Xiao et al.*, 1997]. At this stage of development, the IGSM includes six component models (Figure 1): the Anthropogenic Emission Prediction and Policy Analysis (EPPA) model [*Yang et al.*, 1996]; an atmospheric chemistry model [*Wang et al.*, 1995, 1998], a two-dimensional (2-D) land-ocean climate model [*Yao and Stone*, 1987; *Stone and Yao*, 1987, 1990; *Sokolov and Stone*, 1995, 1998; *Xiao*

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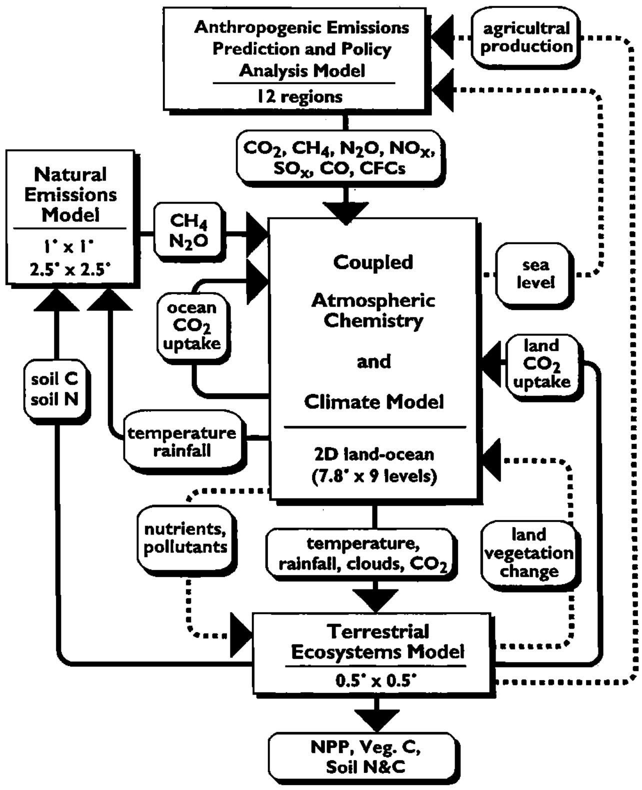

Figure 1. A schematic diagram illustrating the framework and components of the Integrated Global System Model for assessment of climate change, which is developed at Massachusetts Institute of Technology. The linkages and feedbacks between the component models that are currently included or under development for future inclusion are shown as solid and dashed lines, respectively.

et al., 1997], an ocean carbon model [*Prinn et al.*, 1998], a global terrestrial biogeochemistry model (the Terrestrial Ecosystems Model) [*Raich et al.*, 1991; *Melillo et al.*, 1993; *McGuire et al.*, 1992, 1993, 1995, 1997; *Xiao et al.*, 1997], and natural emission models of N_2O and CH_4 from soils [*Liu*, 1996]. The IGSM addresses most of the major anthropogenic and natural processes involved in climate change and is also computationally efficient [*Prinn et al.*, 1998; *Xiao et al.*, 1997]. The EPPA model projects anthropogenic emissions of CO_2 and other greenhouse gases (e.g., N_2O and CH_4) in 12 economic regions of the world over time. The projected anthropogenic and natural emissions of greenhouse gases are then used in the coupled atmospheric chemistry/climate model [*Wang et al.*, 1998] to predict the evolution of concentrations of chemical species in the atmosphere and their radiative forcing on climate systems. The projected transient changes in climate and atmospheric CO_2 level are used to drive the Terrestrial Ecosystem Model (TEM). Version 4.1 of TEM [*Melillo et al.*, 1996; *Prinn et al.*, 1998; *H. Tian* et al., The sensitivity of terrestrial carbon storage to historical atmospheric CO_2 and climate variability in the United States, submitted to *Tellus*, 1998, (hereinafter referred to as Tian et al., submitted manuscript, 1998)] is used to calculate carbon and nitrogen fluxes and pools of terrestrial ecosystems over time. In the current version of the IGSM, information of spatial and temporal dynamics of net CO_2 exchange estimated by the TEM is not used to modify inputs of CO_2 to the combined atmospheric chemistry/climate model [*Wang et al.*, 1998]. In addition, the effects of transient changes in atmospheric nutrient (e.g., nitrogen) deposition, air pollution (e.g., SO_2 and O_3), vegetation structure and distribution, and land use, and land cover on terrestrial ecosystems are not considered in this version of the IGSM (Figure 1). All these factors have large uncertainties and may affect significantly the global carbon cycle.

In this paper, we report a detailed sensitivity analysis of TEM in the three transient climate change scenarios in the 21st century, which were projected by the IGSM [*Prinn et al.*, 1998]. We focus on the temporal dynamics and spatial distribution of annual net ecosystem production (NEP) of the terrestrial biosphere. Annual NEP is defined as the difference between annual net primary production (NPP) and annual heterotrophic respiration (R_h) and represents net CO_2 exchange between the terrestrial biosphere and the atmosphere. Positive annual NEP indicates that the terrestrial biosphere is a carbon sink (net CO_2 flux from the atmosphere to the biosphere), while negative annual NEP indicates that the terrestrial biosphere is a carbon source (net CO_2 flux from the biosphere to the atmosphere). The temporal dynamics and spatial distribution of annual NEP across the terrestrial biosphere play an important role in the global carbon cycle and may have significant implications for discussions of greenhouse gas emissions and climate policies. Our objective in this study is to determine to what extent transient changes in atmospheric CO_2 concentration and climate in the 21st century could affect the temporal dynamics and spatial distribution of annual NEP of the terrestrial biosphere. We examine specifically the spatial distribution and temporal dynamics of annual NEP at the scales of the globe, latitudinal bands, biomes, and the economic regions. The data analysis at the latitudinal scale will facilitate our future effort in fully coupling the 2-D land-ocean climate model, which generates a latitudinal gradient of climate change, and the TEM in the IGSM framework. Annual NEP in an economic region represents its ecological capacity for CO_2 sequestration. In climate policy and negotiations relevant to anthropogenic CO_2 emissions and carbon taxes, it is necessary to quantify the sinks and sources of CO_2 in various economic regions of the world. As the IGSM is also used as a tool for climate policy analysis, our analysis about the magnitudes of CO_2 uptake by terrestrial ecosystems relative to anthropogenic CO_2 sources in economic regions provides a linkage between terrestrial ecosystems and regional economies.

2. Terrestrial Ecosystem Model (TEM)

The TEM (Figure 2) is a process-based ecosystem model that makes monthly estimates of important carbon and nitrogen fluxes and the pool size of various terrestrial ecosystems [*Raich et al.*, 1991; *Melillo et al.*, 1993; *McGuire et al.*, 1992, 1993, 1995, 1997; *Xiao et al.*, 1997]. In this study, we use version 4.1 of TEM, which can calculate carbon fluxes in either transient mode or equilibrium mode [*Melillo et al.*, 1996; *Prinn et al.*, 1998; *Tian, et al.*, submitted manuscript, 1998]. The water balance model of *Vorosmarty et al.* [1989] has been incorporated into version 4.1 of TEM so that monthly fluxes of water, carbon, and nitrogen are calculated simultaneously. Version 4.1 of TEM has been used to investigate the effects of the historical transient changes in CO_2 and climate on terrestrial carbon fluxes and storage at the scales of the globe [*Melillo et al.*, 1996; *Prinn et al.*, 1998] and the conterminous United States (*Tian, et al.*, submitted manuscript, 1998).

In this study, we focus on net ecosystem production (NEP), which represents net CO_2 exchange between the terrestrial bio-

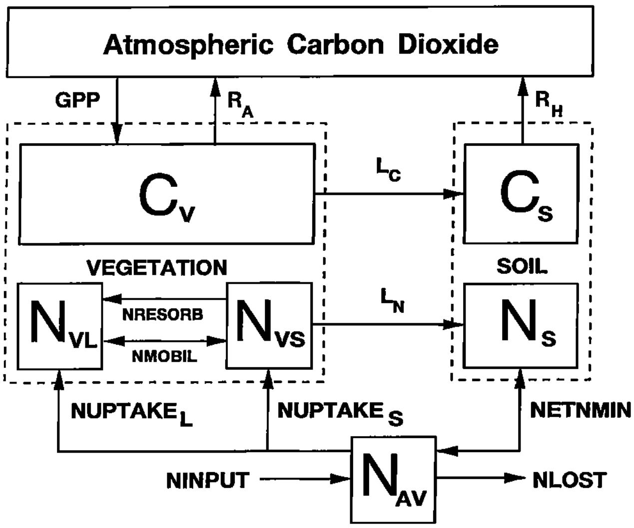

Figure 2. The Terrestrial Ecosystem Model (TEM). The state variables are carbon in vegetation (C_V); structural nitrogen in vegetation (N_{VS}); labile nitrogen in vegetation (N_{VL}); organic carbon in soils and detritus (C_S); organic nitrogen in soils and detritus (N_S); and available soil inorganic nitrogen (N_{AV}). Arrows show carbon and nitrogen fluxes: GPP, gross primary productivity; R_A, autotrophic respiration; R_h, heterotrophic respiration; L_C, litterfall carbon; L_N, litterfall nitrogen; $NUPTAKE_S$, N uptake into the structural N pool of the vegetation; $NUPTAKE_L$, N uptake into the labile N pool of the vegetation; NRESORB, N resorption from dying tissue into the labile N pool of the vegetation; NMOBIL, N mobilized between the structural and labile N pools of the vegetation; NETNMIN, net N mineralization of soil organic N; NINPUT, N inputs from the outside of the ecosystem; and NLOST, N loss from the ecosystem.

sphere and the atmosphere. The NEP flux is calculated as the difference between net primary production (NPP) and heterotrophic respiration (R_h). In TEM, the NPP flux is calculated as the difference between gross primary production (GPP) and plant respiration (R_A). The monthly R_A flux, which includes both maintenance respiration and construction respiration, is calculated as a function of temperature and vegetation carbon. The GPP flux is calculated at each monthly time step as follows [*Raich et al.*, 1991]:

$$GPP = C_{max} f(PAR) f(LEAF) f(T) f(CO_2, H_2O) f(NA) \quad (1)$$

where C_{max} is the maximum rate of C assimilation, PAR is photosynthetically active radiation, LEAF is leaf area relative to maximum annual leaf area (phenology), T is temperature, CO_2 is atmospheric CO_2 concentration, H_2O is water availability, and NA is nitrogen availability [*Raich et al.*, 1991; *McGuire et al.*, 1992, 1993].

In TEM, the R_h flux represents decomposition of all organic matter in an ecosystem and is calculated at monthly time step as follows [*Raich et al.*, 1991; *McGuire et al.*, 1995, 1997]:

$$R_h = k_d \, Cs \, f(M) \exp^{0.0693T} \quad (2)$$

where k_d is the heterotrophic respiration rate at 0°C, C_s is carbon storage in soils, M is mean volumetric soil moisture, and T is mean monthly air temperature. The parameter kd is modeled as a power function of the carbon and nitrogen ratio of litterfall, so that changes in litter quality associated with changes in vegetation nitrogen concentration are implemented in TEM [*McGuire et al.*, 1997]. The TEM defines a reactive soil organic carbon pool (C_s) that excludes biologically "inert" soil organic matter in both version 4.0 [*VEMAP Members*, 1995; *Pan et al.*, 1996; *McGuire et al.*, 1997; *Xiao et al.*, 1996, 1997] and version 4.1 [*Melillo et al.*, 1996; *Prinn et al.*, 1998; *Tian, et al.*, submitted manuscript, 1998]. Soil organic carbon increases with litterfall which depends on vegetation biomass. Changes in heterotrophic respiration (R_h) depend directly on changes in temperature and precipitation. Changes in CO_2 indirectly influence R_h by affecting the pool size of soil organic matter through litterfall inputs. Higher CO_2 levels may increase water use efficiency of vegetation, resulting in an increase of NPP and eventually more litterfall input to soils [*McGuire et al.*, 1993, 1997; *Melillo et al.*, 1993; *Pan et al.*, 1998]. Cloudiness also indirectly affects R_h through soil moisture. In TEM, cloudiness is used to calculate the fluxes of net solar radiation and photosynthetically active radiation (PAR) that reaches the vegetation canopy. In the water balance submodel [*Vorosmarty et al.*, 1989], the monthly flux of potential evapotranspiration (PET) is calculated as a function of monthly mean air temperature and solar radiation [*Jensen and Haise*, 1963]. An increase in PET may result in a decrease in soil moisture.

The application of TEM to a grid cell requires the use of data describing monthly climate (precipitation, mean temperature, and mean cloudiness), soil texture (proportion of sand, silt, and clay), elevation, and vegetation types [*Pan et al.*, 1996]. Soil texture and vegetation types are used to define the soil- and vegetation-specific parameters for a grid cell. For global extrapolation of TEM, we use spatially explicit data sets that are organized at a 0.5° (longitude) × 0.5° (latitude) spatial resolution. At this resolution, global land areas are represented by 62,483 grid cells. We use a global potential natural vegetation data set at 0.5° resolution, which is developed from a number of sources [see *Melillo et al.*, 1993]. The natural vegetation classification has 18 upland vegetation types and 13 floodplain and wetland vegetation types [*Melillo et al.*, 1993]. Out of the 62,483 land grid cells in the spatial data set, there are 3059 ice grid cells and 1525 floodplain and wetland (e.g., mangrove, swamp, and salt marsh) grid cells. For long-term average contemporary climate, we use the Cramer and Leemans Climate database (W. Cramer, personal communication, 1995), which is an update of the Leemans and Cramer climate database [*Leemans and Cramer*, 1991] and is developed using records of about 18,000 weather stations over the globe. The data for solar radiation was calculated with the algorithms described by R.D. Otto et al. (Static and dynamic input data of terrestrial biogeochemical models, submitted to *Global Biogeochemical Cycles*, 1997) using the percent sunshine duration in the Cramer and Leemans data set. For elevation, we use an aggregation to 0.5° resolution of a global 10-min resolution data set [*National Center for Atmospheric Research (NCAR)/NAVY*, 1984]. We use the soil texture data set that is based on digitization of the soil map of the world from the Food and Agriculture Organization (FAO) – United Nations Educational, Scientific, and Cultural Organization (UNESCO) [1971].

3. Transient Climate Change Scenarios

To assess the sensitivity of net CO_2 exchange between the terrestrial biosphere and the atmosphere to future climate change, we used transient climate change predictions for the period of 1977-2100 from the sensitivity study of the IGSM [*Prinn et al.*, 1998]. In the IGSM sensitivity study [*Prinn et al.*, 1998], the standard parameters and assumptions in the EPPA model and the combined atmospheric chemistry/climate model were first used to generate the reference (RRR) projection of changes in anthropogenic emissions of greenhouse gases and climate. Anthropogenic emissions of CO_2 projected by the EPPA model in the RRR projection are similar to the CO_2 emissions of the IS92a scenario of the *Intergovernmental Panel on Climate Change* (IPCC) [1995]. Then, the EPPA model projected higher and lower emissions of CO_2 and other greenhouse gases by changing labor productivity growth, changes in energy efficiency not induced by price, and cost of noncarbon backstop technologies (e.g., nuclear, solar, and hydropower technologies). The anthropogenic emissions of CO_2 and other greenhouse gases from the EPPA model were then used to drive the coupled atmospheric chemistry/2-D land-ocean climate model [*Wang et al.*, 1998]. In this coupled chemistry/climate model, vertical ocean heat diffusion coefficients, parameters quantifying direct and indirect aerosol effects, and the climate model sensitivity to doubled CO_2 were changed to generate different climate change predictions for a given set of anthropogenic emissions of CO_2 and other greenhouse gases from the EPPA model. Overall, seven transient climate change predictions over the period of 1977-2100 were generated in the IGSM sensitivity study [*Prinn et al.*, 1998]. In assessing the sensitivity of TEM to transient change in climate and CO_2 level, we used three (RRR, HHL, and LLH) of the seven transient climate change predictions. The RRR prediction is generated by using the standard or "reference" set of parameters and assumptions in the IGSM. The HHL prediction has higher CO_2 emissions from the EPPA model, slower ocean heat diffusion and smaller aerosol effects, and lower climate model sensitivity to doubling CO_2, leading to somewhat larger changes in temperature than the RRR prediction. The LLH prediction has lower CO_2 emissions from the EPPA model, faster ocean heat diffusion and larger aerosol effects, and higher model sensitivity to doubling CO_2, leading to somewhat smaller changes in temperature than the RRR prediction (Figure 3, see also Prinn et al., 1998 for more details). Globally, atmospheric CO_2 concentration and climate vary significantly among the three transient climate change predictions over the period of 1990 - 2100 (Figure 3). Atmospheric CO_2 concentration is 354 ppmv in 1990 and is projected to reach about 745 ppmv in the RRR, 936 ppmv in the HHL, and 592 ppmv in the LLH predictions in 2100. Compared to its value in 1990, global annual mean temperature in 2100 increases by about 2.6°C for the RRR, 3.1°C for the HHL, and 1.6°C for the LLH predictions. Global daily precipitation increases slightly over time for all three predictions (Figure 3). Global mean annual cloudiness decreases in the RRR and the LLH predictions but increases in the HHL prediction (Figure 3).

The 2-D land-ocean climate model simulates the surface climate fields (e.g., surface temperature and evaporation) separately over land and ocean as a function of latitude and height [*Sokolov and Stone*, 1998]. It has 23 latitude bands, corresponding to a resolution of 7.826°, and nine vertical layers. Both CO_2 and climate outputs in the 23 latitudinal bands from the coupled atmospheric chemistry/2-D land-ocean climate model were first linearly interpolated to 0.5°-resolution latitudinal bands, and the interpolated values were then applied to all the grid cells within a 0.5° latitudinal band. In generating "future climate," our procedure is to overlay the projected changes in climate on the contemporary mean climate, similar to our earlier work [*Xiao et al.*, 1997]. The contemporary monthly mean climate data are from the Cramer and Leemans Climate database, which represents the long-term average climate for the period of 1931-1960. We first calculated absolute differences in monthly mean temperature and ratios in monthly precipitation and monthly mean cloudiness over the period of 1977-2100, using the simulated climate data for 1931-1960 from the MIT 2-D land-ocean climate model as the baseline values. Then, we added the absolute differences in monthly mean temperature over the period of 1977-2100 to the contemporary monthly mean temperature data and multiplied the ratios in monthly precipitation and monthly mean cloudiness over the period of 1977-2100 to the contemporary monthly precipitation and monthly mean cloudiness data, respectively. In our procedure, a limitation exists in extending zonal mean climate data, particularly zonal mean precipitation data, for generating the above data sets of climate change [*Xiao et al.*, 1997], therefore, we contained our analysis of TEM results to large scales, for example, the globe, biome, latitudinal bands, and economic regions.

We use the predicted changes in atmospheric CO_2 concentrations and climate over the period of 1977-2100 to drive the transient TEM. These transient runs of the TEM are initiated using nonequilibrium conditions of carbon, nitrogen, and water fluxes and storage in December 1976, which were derived from a TEM simulation driven by the simulated climate data from the 2-D land-ocean climate and global mean atmospheric CO_2 concentration data from ice cores and direct observations over the period of 1850-1976. In this paper, we choose the base year to be 1990 and report the results of TEM simulations from 1990 to 2100, since policy discussions in the Framework Convention on Climate Change usually reference CO_2 emission reductions to 1990 [*Prinn et al.*, 1998]. In these three TEM simulations, we use potential mature natural vegetation [Melillo et al., 1993], and thus the effects of land use and land cover changes on NEP estimates are not taken into consideration. These NEP estimates represent the potential for net CO_2 exchange of natural terrestrial ecosystems under perturbation of transient changes in climate and atmospheric CO_2 concentration.

4. Results

4.1. Dynamics of Global Annual NEP

The TEM estimates that global annual NEP in 1990 is about 0.8 Pg C yr^{-1} for the RRR transient climate change prediction, which is the difference between the 43.4 Pg C yr^{-1} of global annual NPP and the 42.6 Pg C yr^{-1} of global annual R_h in 1990. Annual NEP in 1990 varies significantly across the globe (Plate 1). The spatial distribution of annual NEP is determined by the spatial patterns of annual NPP and annual R_h (Plate 1). Annual NPP and R_h are high in the tropical regions but low in the high latitudes and desert. The spatial pattern of annual NPP is highly correlated to the spatial pattern of annual net nitrogen mineralization (NMIN) and the spatial pattern of estimated annual evapotranspiration (EET). Although we have not used the observational climate data in 1990 in this study, the large spatial variations of annual NPP, R_h, NEP, NMIN, and EET (Plate 1) illustrate the complex interactions among carbon, nitrogen, and water in various terrestrial ecosystems across the globe, as simulated by the TEM.

For all three climate change predictions, global annual NEP increases gradually over the period of 1990-2100 and represents a

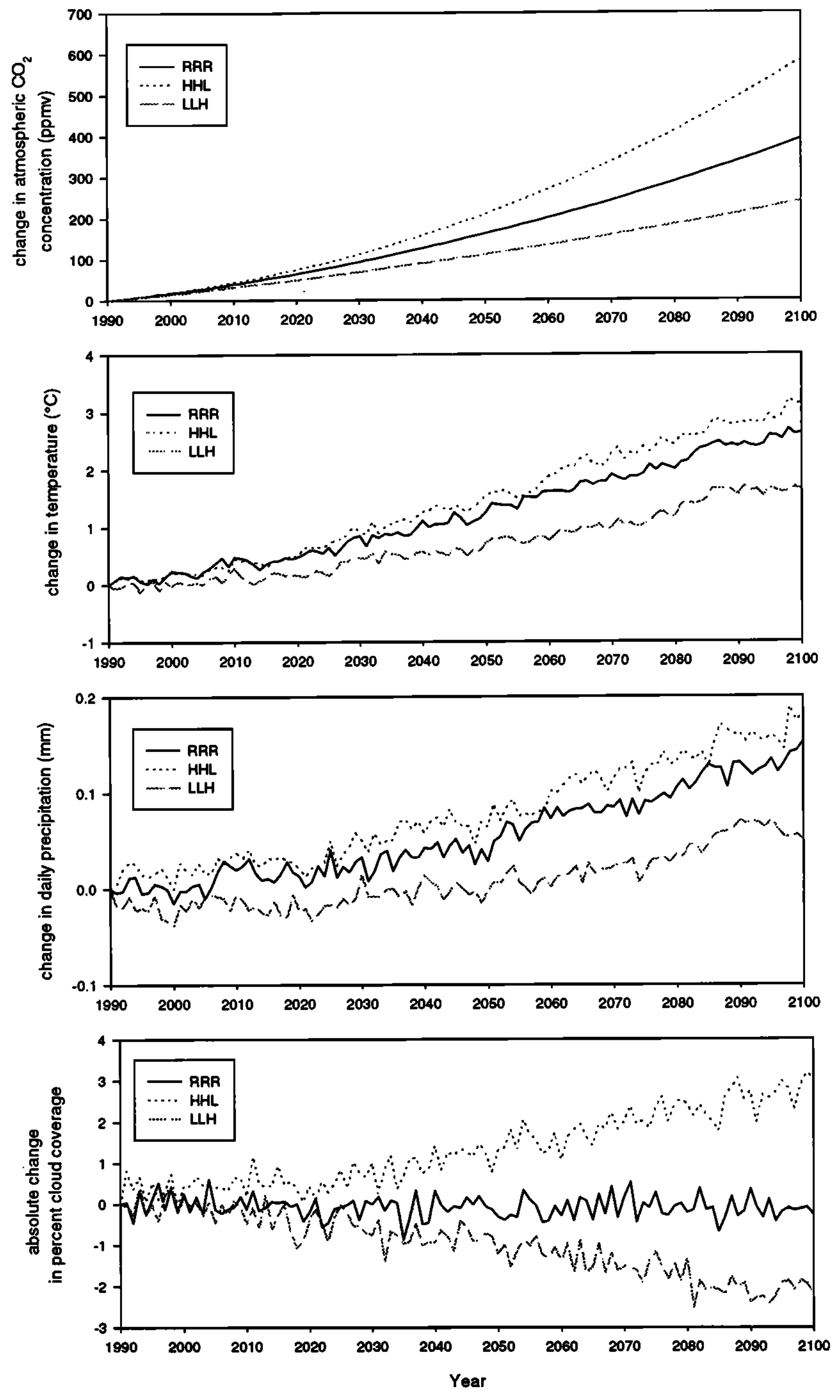

Figure 3. Transient changes in global mean annual atmospheric CO_2 concentration, global mean annual temperature, global mean daily precipitation and global mean annual percent cloudiness over the period of 1990-2100, projected by the coupled two-dimensional atmospheric chemistry/land-ocean climate model in the MIT Integrated Global System Model (see Figure 1 and *Prinn et al.*, 1998). The graph is presented using their values in 1990 as the reference.

growing net CO_2 flux from the atmosphere to the terrestrial biosphere, that is, a potential terrestrial carbon sink. The increases of global annual NEP result from a larger increase in annual NPP than in annual R_h (Figure 4). By the end of the 21st century, increases in global annual NPP and R_h differ significantly among the three transient climate change predictions (Figure 4). Compared to their values in 1990, global annual NPP and annual R_h in 2100 increase by about 9.5 Pg C yr^{-1} and 6.9 Pg C yr^{-1} for the HHL, 7.9 Pg C yr^{-1} and 6.1 Pg C yr^{-1} for the RRR, and 4.3 Pg C yr^{-1} and 3.8 Pg C yr^{-1} for the LLH climate change predictions, respectively (Figure 4). As a result, global annual NEP in 2100 is about 2.6 Pg C yr^{-1} higher for the HHL, 1.8 Pg C yr^{-1} higher for the RRR, and 0.5 Pg C yr^{-1} higher for the LLH climate change predictions than its values in 1990. The TEM simulations indicate that the terrestrial

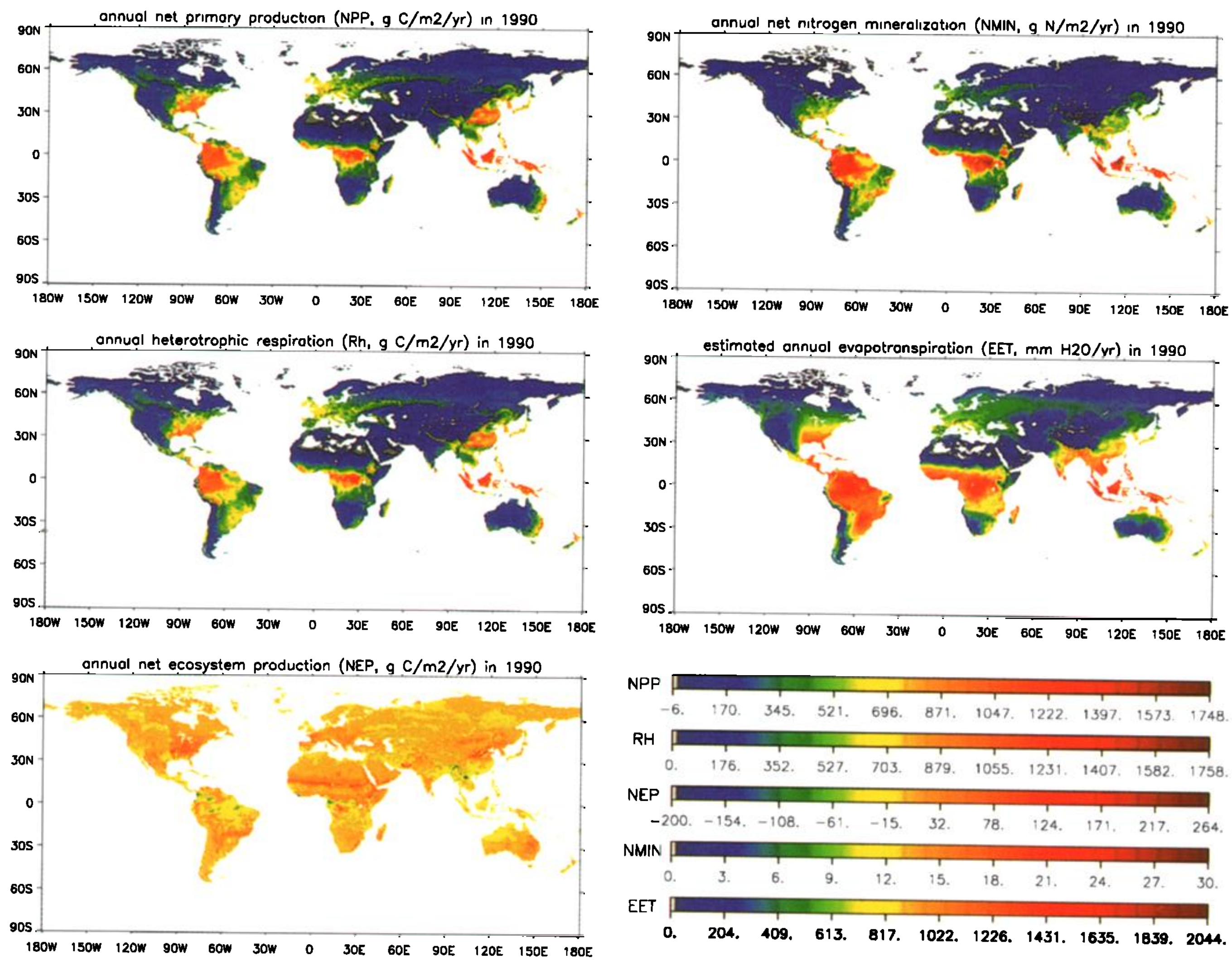

Plate 1. Spatial distributions of annual net primary production (NPP), heterotrophic respiration (R_h), net ecosystem production (NEP), net nitrogen mineralization (NMIN), and estimated evapotranspiration (EET) in 1990, as estimated by the Terrestrial Ecosystem Model ((TEM), version 4.1) in the RRR transient climate change prediction. We also calculated the linear Pearson correlation coefficient between annual NPP and annual NMIN and annual EET. For 59424 grid cells (57899 grid cells of upland biomes and 1525 grid cells of wetlands) that have TEM estimates of carbon, nitrogen, and water fluxes, the spatial linear Pearson correlation coefficient *r* is about 0 92 between annual NPP and annual NMIN and is about 0 84 between annual NPP and annual EET

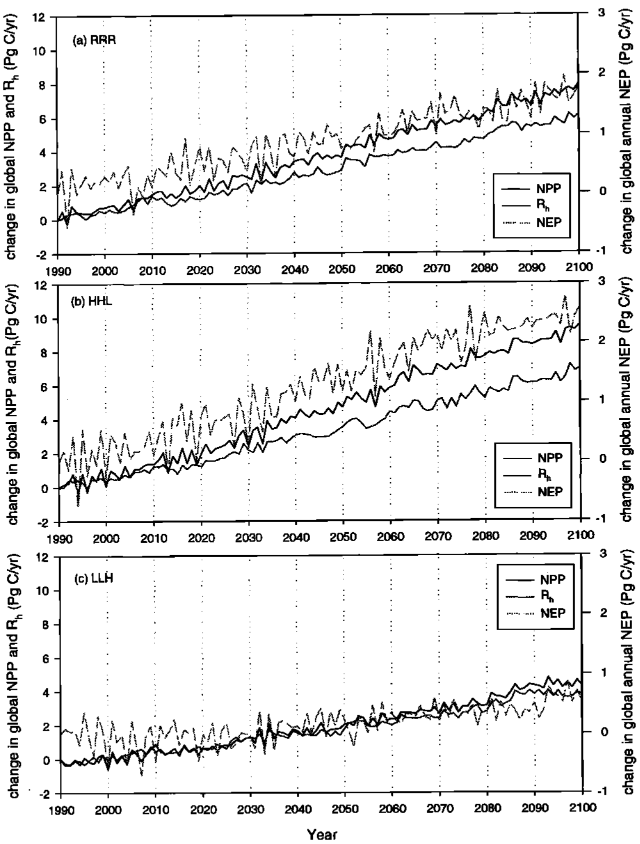

Figure 4. Projected changes in global annual net ecosystem production (NEP), annual net primary production (NPP), and annual heterotrophic respiration (R_h) over the period of 1990-2100 in the RRR, HHL, and LLH transient climate change predictions. We use the global annual NPP, R_h, and NEP in 1990 as the reference.

biosphere is likely to increase its uptake of atmospheric CO_2 and act as a net carbon sink between 1990 and 2100 in the three transient climate change predictions.

The potential total CO_2 uptake by the terrestrial biosphere, which is calculated as the sum of global annual NEP over the period of 1990-2100, is about 122.9 Pg C in the LLH, 186.1 Pg C in the RRR, and 240.1 Pg C in the HHL transient climate change predictions. According to projections of the EPPA model, total anthropogenic CO_2 emission (fossil fuel combustion plus deforestation) in the period of 1990-2100 is 1253.6 Pg C for the LLH, 1549.6 Pg C for the RRR, and 1797.0 Pg C for the HHL climate change predictions [*Prinn et al.*, 1998]. Thus the total carbon uptake by the terrestrial biosphere accounts for 9.8% of the total anthropogenic CO_2 emission for the LLH, 12.0% for the RRR, and 13.4% for the HHL climate change predictions. Note that the above global NEP estimates by the TEM model are the potential effects of mature natural vegetation. As contemporary and future land use and land cover changes are not taken into account in these TEM simulations, these NEP estimates do not represent actual terrestrial carbon sinks, rather they represent the tendency of natural terrestrial ecosystems to accumulate carbon in the projected changes in atmospheric CO_2 concentration and climate.

4.2. Dynamics of Annual NEP for 18 Biomes

The contribution of various biomes to the potential total CO_2 uptake of the terrestrial biosphere over the period of 1990-2100 differs substantially (Table 1). In the RRR climate change prediction, boreal forests accumulate 36.3 Pg C over the period of 1990-2100, which accounts for 19.5% of the 186.1 Pg C total carbon uptake by the terrestrial biosphere in 1990-2100. Tropical evergreen forests accumulate about 30.3 Pg C, accounting for 16.3%. Desert has the least amount of carbon accumulation over the period of 1990-2100 (only 2.0 Pg C or 1.1%). Similarly, for the

Table 1. Total CO_2 Uptake Over the Period of 1990-2100 by the 18 Upland Biomes Under the Three Transient Climate Change Projections

			RRR		HHL		LLH	
Vegetation Type	Grid Cells	Area, 10^6 km^2	C, Pg	C, %	C, Pg	C, %	C, Pg	C, %
Polar desert/alpine tundra	3,580	5.3	3.9	2.1	5.1	2.1	2.4	2.0
Wet/moist tundra	4,212	5.2	6.4	3.4	8.0	3.3	4.9	4.0
Boreal woodland	4,545	6.5	13.8	7.4	16.5	6.9	10.5	8.5
Boreal forest	7,578	12.5	36.3	19.5	44.2	18.4	25.6	20.8
Temperate coniferous forest	1,127	2.5	5.6	3.0	6.6	2.7	3.8	3.1
Desert	4,170	11.6	2.0	1.1	2.6	1.1	1.5	1.2
Arid shrubland	5,784	14.7	8.2	4.4	10.6	4.4	6.0	4.9
Short grassland	2,072	4.7	3.1	1.7	4.4	1.9	2.0	1.6
Tall grassland	1,567	3.6	2.5	1.4	3.6	1.5	1.7	1.3
Temperate savanna	2,921	6.8	10.5	5.7	14.6	6.1	6.0	4.9
Temperate mixed forest	2,320	5.2	12.7	6.8	17.2	7.2	5.8	4.7
Temperate deciduous forest	1,666	3.7	10.9	5.9	16.2	6.7	4.9	4.0
Temperate broadleaf evergreen forest	1,268	3.3	7.7	4.2	10.2	4.2	4.6	3.7
Mediterranean shrubland	575	1.5	2.5	1.3	3.3	1.4	1.8	1.5
Tropical savanna	4,666	13.9	12.5	6.7	16.4	6.8	8.5	6.9
Xeromorphic forest	2,387	6.9	10.5	5.7	13.8	5.8	7.5	6.1
Tropical deciduous forest	1,606	4.7	6.5	3.5	8.5	3.5	4.4	3.6
Tropical evergreen forest	5,855	17.8	30.3	16.3	38.4	16.0	21.1	17.2
Globe	57,899	130.3	186.1		240.1		122.9	

The percentage contributions of each biome to the global CO_2 uptake are calculated. The three climate change projections are as follows: RRR, reference CO_2 emissions and temperature increases; HHL, higher CO_2 emission and temperature increase; and LLH, lower CO_2 emissions and temperature increases.

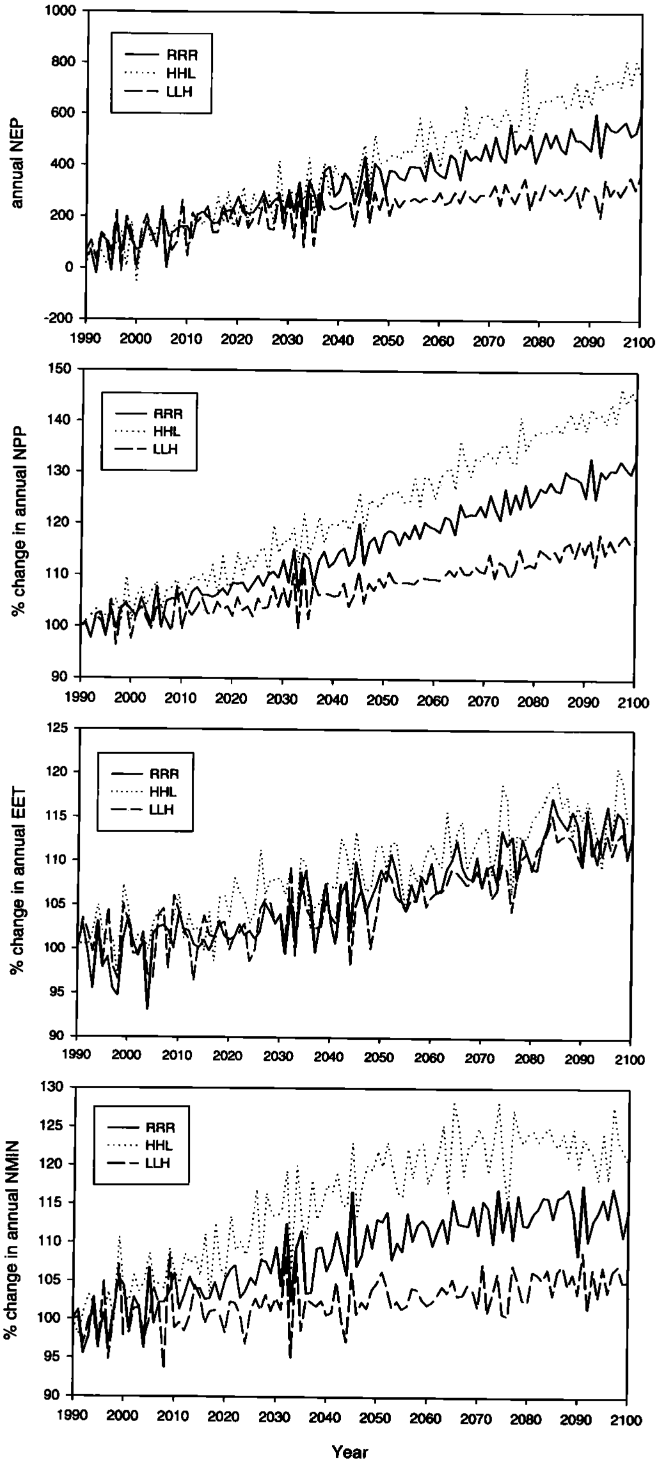

Figure 5. Temporal changes in annual net ecosystem production (NEP) (10^{12} g C yr^{-1}), net primary production (NPP), net nitrogen mineralization (NMIN), and estimated evapotranspiration (EET) of boreal forests over the period of 1990-2100. We used annual NPP, NMIN, and EET in 1990 as the reference in calculating the percent change of annual NPP, NMIN, and EET.

HHL and LLH climate change predictions, boreal forests and tropical evergreen forests have the largest contributions to the total CO_2 uptake of the terrestrial biosphere over the period of 1990-2100 (Table 1). The results suggest that boreal forests and tropical evergreen forests play a dominant role in carbon sequestration over the period of 1990-2100.

The large increases in annual NEP of the northern high-latitudinal biomes are attributed to the large increases in annual NPP. As shown in Figure 5, annual NPP of boreal forests in 2100 is about 33% higher than its value in 1990 in the RRR climate change prediction. The NPP increases of boreal forests are clearly determined by the large increases in annual NMIN and annual EET (Figure 5). For boreal forests in the RRR prediction, the temporal linear Pearson correlation coefficient r is about 0.93 between annual NPP and annual NMIN but is about 0.91 between annual NPP and annual EET. In TEM, NPP is affected by climate (temperature, moisture, and solar radiation) and nitrogen availability [*Melillo et al.*, 1993; *McGuire et al.*, 1995, 1997; *VEMAP Members*, 1995; *Xiao et al.* 1997]. Higher temperature may increase plant photosynthesis in some ecosystems where temperature has not yet reached the optimum temperature of photosynthesis. Decomposition of soil organic matter (R_h in TEM) increases under higher temperature and soil moisture, and as a result, more mineralized nitrogen is released for plant uptake, which may increase NPP. According to the results from the 2-D land-ocean climate model, temperature increases in the high latitudes in the RRR prediction are about 1°-2°C lower than the HHL prediction but are 2°-3°C higher than the LLH prediction by the end of 21st century [*Prinn et al.*, 1998]. The larger temperature increases in the HHL prediction result in larger increases in annual NMIN and annual EET, compared to the RRR and LLH predictions (Figure 5).

In tropical evergreen forests, annual NEP fluctuates substantially and increases only slightly over the period of 1990-2100 (Figure 6). Annual NEP is mostly higher in the HHL prediction than in the RRR prediction; however, increases of annual NPP are slightly higher in the RRR prediction than in the HHL prediction. This is largely attributed to larger increases in annual hetrotrophic respiration (R_h) in the RRR prediction than in the HHL prediction (note NEP = NPP – R_h). Figure 6 shows that while annual NPP of tropical forests increases over the period of 1990-2100, annual NMIN declines in all three climate predictions. Annual NMIN has the largest decline in the HHL prediction, being 14.5% lower than its 1990 value in 2100. In TEM, the nitrogen limitation of NPP is generally much weaker in tropical evergreen forests than in temperate and boreal forests [*McGuire et al.*, 1992; *Melillo et al.*, 1993]. Annual EET is also lower in the HHL prediction than in the RRR and LLH predictions (Figure 6), mostly owing to the fact that there is an increase (about 2%) of cloud coverage in the tropics in the HHL prediction but a decrease of cloud coverage in the tropics in the RRR (about 1%) and LLH (about 1-2%) predictions [*Prinn et al.*, 1998]. Higher cloud coverage in the HHL prediction results in a reduction in total solar radiation and photosynthetically active radiation (PAR) that reaches vegetation canopy. The water balance model [*Vorosmarty et al.*, 1989] in the TEM is sensitive to changes in cloudiness [*Pan et al.*, 1996; *Xiao et al.*, 1996]. In TEM, increases in atmospheric CO_2 concentration also enhance water use efficiency of vegetation and result in an increase in annual NPP due to the CO_2 fertilization effect [*McGuire et al.*, 1993, 1997; *Melillo et al.*, 1993; *Pan et al.*, 1998]. Atmospheric CO_2 concentration increases continuously over time in all the three climate change predictions but is much higher in the HHL prediction than in the RRR and LLH predictions (Figure 3). Therefore the TEM estimates that tropical evergreen forests are able to incorporate a substantial proportion of elevated CO_2 into NPP in the HHL prediction.

4.3. Latitudinal Distribution of Potential Annual NEP

Total annual NEP along 0.5°-resolution latitudinal bands, which is the sum of annual NEP of all land grid cells within a 0.5°-resolution latitudinal band, has a bimodal distribution with the large positive values in both the northern middle to high latitudes and the tropical regions for most years within the 1990-2100 period in the RRR climate change prediction (Plate 2). These large positive annual NEP values in the northern middle to high latitudes and the tropical regions represent potentially two significant terrestrial carbon sinks.

The latitudinal distribution of total annual NEP changes significantly over the period of 1990-2100 in the RRR transient climate change prediction (Plate 2). Total annual NEP has a substantial increase over time in the northern middle to high latitudes, which is caused by large increases in annual NPP (Plate 3) but relatively small increases in annual R_h (not shown here, but it could be inferred from NEP and NPP dynamics in Plates 2 and Plate 3, respectively, as NPP - R_h = NEP). As NPP of boreal ecosystems and tundra ecosystems in the northern high latitudes are primarily limited by low temperature and low-nitrogen availability because of the slow turnover rate of soil organic matter, projected large temperature increases in the northern high-latitudes [*Prinn et al.*, 1998] result in higher plant photosynthesis and faster decomposition rates of soil organic matter in these high-latitudinal biomes, which, in turn, release more inorganic N available for plant uptake. In the tropical regions, however, the increases in annual NPP (Plate 3) are only slightly larger than the increases in annual R_h, which results in smaller increases in annual NEP over time (Plate 2). In TEM, soil organic matter decomposes significantly faster in the tropical regions than in the high latitudes [*McGuire et al.*, 1995]. The residence time of soil organic carbon in high-latitude soils is much longer than that in tropical forest soils, and therefore high-latitude soils have the capacity to act as a carbon sink on decadal timescales [*Bird et al.*, 1996].

The latitudinal distribution of total annual NEP differs significantly among the three climate change predictions (Plate 2). Total annual NEP in the tropical regions has a slight increase in the LLH prediction but has a relatively large increase in the HHL climate change prediction. In the northern middle to high latitudes, the increase of total annual NEP occurs much earlier and is larger in the HHL than in the LLH climate change predictions (Plate 2). In all three of the climate change predictions, the net CO_2 uptake in the tropics appears to be primarily occurring in the tropical evergreen forests, while the net CO_2 uptake in the northern middle to high latitudes appears to be largely in the boreal forests (Table 1). The results indicate that the temporal dynamics of latitudinal distribution of annual NEP are also sensitive to the magnitudes and paths of changes in climate and atmospheric CO_2 concentration.

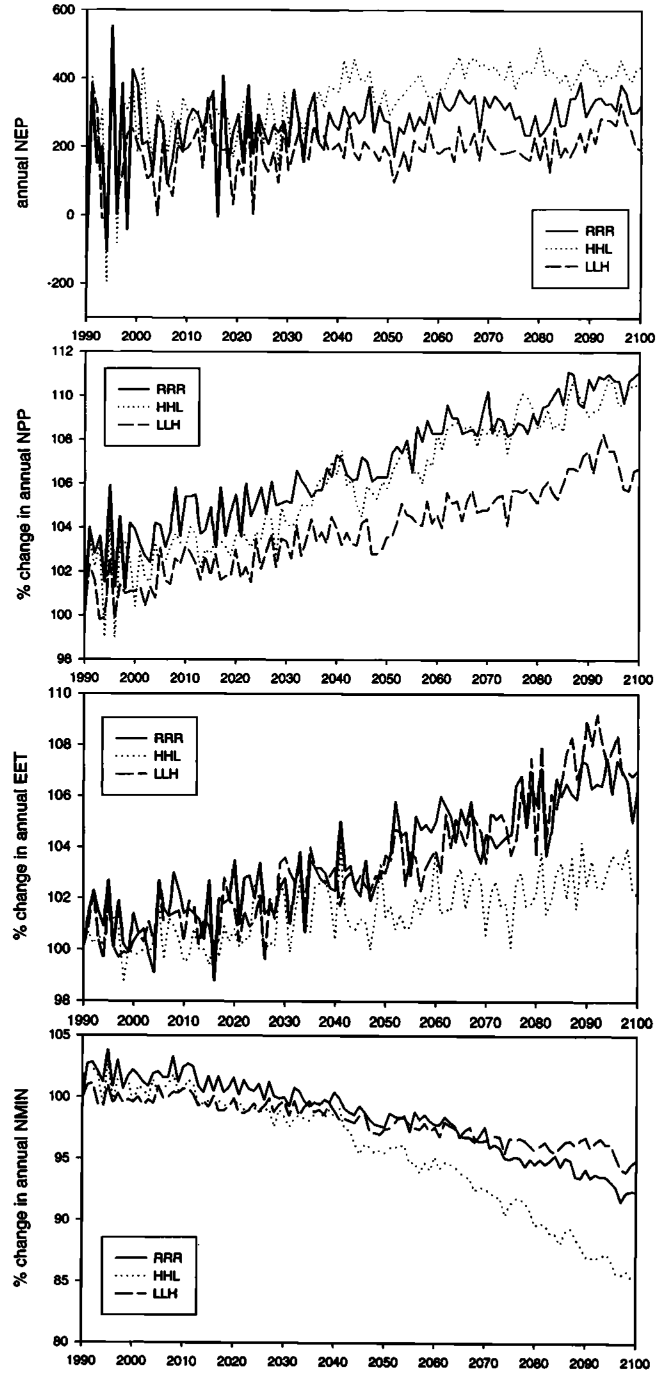

Figure 6. Temporal changes in annual net ecosystem production (NEP) (10^{12} g C yr^{-1}), net primary production (NPP), net nitrogen mineralization (NMIN), and estimated evapotranspiration (EET) of tropical evergreen forests over the period of 1990-2100. We used annual NPP, NMIN, and EET in 1990 as the reference in calculating the percent change of annual NPP, NMIN, and EET.

4.4. Sinks and Sources of CO_2 Among the Economic Regions of the World

Aggregation of NEP responses to transient changes in atmospheric CO_2 concentration and climate over the 12 economic regions of the world defined in the EPPA model can, for example, provide an important linkage between terrestrial ecosystems and the economy, which may have significant implications for climate policy and decision making. The total CO_2 uptake in an economic region, which is calculated as the sum of annual NEP over the period of 1990-2100 in an economic region, represents its potential for carbon sequestration in mature natural terrestrial ecosystems. Of the 186.1 Pg C "potential" global CO_2 uptake by the terrestrial biosphere over the period 1990-2100 in the RRR climate change prediction, relative contributions from the 12 economic regions of the world differ significantly (Table 2), ranging from 0.5% (0.9 Pg

Table 2. Total CO_2 Uptake by Terrestrial Ecosystems and Total Anthropogenic CO_2 Emission Over the Period of 1990-2100 in the 12 Economic Regions of the World Under the Three Transient Climate Change Projections

Economic Regions	Total CO_2 Uptake by Terrestrial Ecosystems						Total Anthropogenic CO_2 Emission					
	RRR		HHL		LLH		RRR		HHL		LLH	
	C, Pg	C, %	C, Pg	C, %	C, Pg	C, %	C, Pg	C, %	C, Pg	C, %	C, Pg	C, %
United States of America	15.6	8.4	20.9	8.7	8.6	7.0	332.6	21.5	382.8	21.3	217.6	17.4
Japan	0.9	0.5	1.4	0.6	0.3	0.2	53.7	3.5	64.3	3.6	46.0	3.7
India	3.3	1.8	4.4	1.8	2.1	1.7	122.0	7.9	144.5	8.0	104.0	8.3
China	13.6	7.3	19.0	7.9	6.9	5.6	235.2	15.2	283.1	15.8	196.3	15.7
Brazil	12.3	6.6	15.6	6.5	8.7	7.1	37.6	2.4	36.8	2.0	39.9	3.2
European economic community	6.9	3.7	9.2	3.8	3.7	3.0	131.8	8.5	164.2	9.1	102.2	8.2
Eastern European countries	2.8	1.5	3.5	1.5	1.5	1.2	66.2	4.3	79.1	4.4	49.6	4.0
Dynamic Asian countries	1.4	0.8	1.9	0.8	0.8	0.7	48.4	3.1	64.1	3.6	35.6	2.8
Other OECD countries	32.7	17.6	41.0	17.1	22.9	18.6	78.1	5.0	88.5	4.9	67.2	5.4
Former Soviet Union	39.6	21.3	49.6	20.7	27.7	22.5	95.8	6.2	123.5	6.9	74.7	6.0
Energy-exporting countries	23.1	12.4	29.6	12.3	16.0	13.0	219.0	14.1	244.3	13.6	184.2	14.7
Rest of the world	33.8	18.2	44.0	18.3	23.4	19.0	129.2	8.3	121.8	6.8	136.3	10.9
Globe	186.1		240.1		122.9		1549.6		1797.0		1253.6	

The percentage contributions of each economic region to the global CO_2 uptake or global CO_2 emissions are also calculated. The three climate change projections are as follows: RRR, reference CO_2 emissions and temperature increases; HHL, higher CO_2 emission and temperature increase; and LLH, lower CO_2 emissions and temperature increases.

C) in Japan to 21.3% (39.6 Pg C) in the "former Soviet Union" economic region. The "rest of world" economic region ranks the second largest in net CO_2 uptake, accounting for about 18.2% (33.8 Pg C) of the 186.1 Pg C global carbon uptake. The "other Organization for Economic Cooperative Development (OECD) countries" economic region also makes a relatively large contribution, accounting for 17.6% of the 186.1 Pg C global carbon uptake. The total CO_2 uptakes over the period of 1990-2100 for the 12 economic regions in the RRR climate are higher than in the LLH but are lower than in the HHL climate change predictions (Table 2). However, relative contributions from the 12 economic regions to their global carbon uptake are similar in the three climate change predictions. For example, in the HHL climate change prediction, Japan accounts for 0.6% of the 240.1 Pg C global carbon uptake, and the "former Soviet Union" economic region accounts for 20.7%.

For anthropogenic sources of CO_2, the EPPA model [*Yang et al.*, 1996] in the IGSM projects substantially different CO_2 emissions from fossil fuel combustion in the 12 economic regions over the period of 1990-2100 (Table 2) (also see *Prinn et al.*, 1998). Total CO_2 emissions from fossil fuel combustion over the period of 1990-2100 in the RRR scenario ranges from 37.6 Pg C in Brazil to 332.6 Pg C in the United States. The ratio of the total potential CO_2 uptake to the total CO_2 emissions from fossil fuel combustion in an economic region is a useful index to measure relative sizes of potential sinks and sources of CO_2 by economic regions. In the RRR climate, total carbon uptake by mature natural terrestrial ecosystems in the "other OECD countries" economic region accounts for 41.9% of the total CO_2 emission from fossil fuel combustion (78.1 Pg C) in that region, 41.4% of the 95.8 Pg C CO_2 emissions in the former Soviet Union economic region but only 4.7% of the 332.6 Pg C CO_2 emissions in the United States and 1.7% of the 53.7 Pg C CO_2 emissions in Japan (Table 2). The ratios of the total potential CO_2 uptake by mature natural terrestrial ecosystems over the total CO_2 emission from fossil fuel combustion also differ substantially among the 12 economic regions in the HHL and LLH climate change predictions.

Temporal dynamics of annual NEP differs substantially among the 12 economic regions. The former Soviet Union economic region and the other OECD countries economic regions (including Canada) have the largest increases in annual NEP over the period of 1990-2100 (Figure 7), mostly because of the large increases in annual NPP in these two economic regions (Figure 8). Boreal forest in Russia accounts for about two thirds of the global boreal forests (more than 12 million km^2), and Canada also has a large area of boreal forests. The "energy exporting countries" and the "rest of world" economic regions include mostly tropical countries where tropical forests dominate, and therefore their annual NEP fluctuates substantially (see Figure 6 for annual NEP in tropical evergreen forests). The TEM results also show that the temporal dynamics of annual NEP and NPP over the period of 1990-2100 vary significantly among the three climate change predictions (Figure 7 and 8). Again, we want to point out that these NEP estimates represent the potential carbon sequestration by mature natural ecosystems in each of economic regions, as we have not taken land use and land cover change into consideration.

5. Discussion

In this study, we have applied a global terrestrial biogeochemistry model (the Terrestrial Ecosystem Model, version 4.1) to assess the sensitivity of the terrestrial biosphere to three predictions of transient changes in atmospheric CO_2 concentration and climate in the 21st century as projected by the IGSM model [*Prinn et al.*, 1998]. The TEM estimate of global annual NEP in 1990 (0.8 Pg C yr^{-1}) is comparable to the result of an earlier modeling study [*Kindermann et al.*, 1996], which used the Frankfurt Biosphere Model and temperature and precipitation anomalies for the period of 1980-1993 and estimated a global annual NEP of 1.08 Pg C yr^{-1} in 1990. The TEM results have shown that the net CO_2 exchange by the terrestrial biosphere is sensitive to the magnitudes and paths of changes in atmospheric CO_2 concentrations and climate over the period of 1990-2100 across the spatial scales of the globe, biomes, latitudinal bands, and

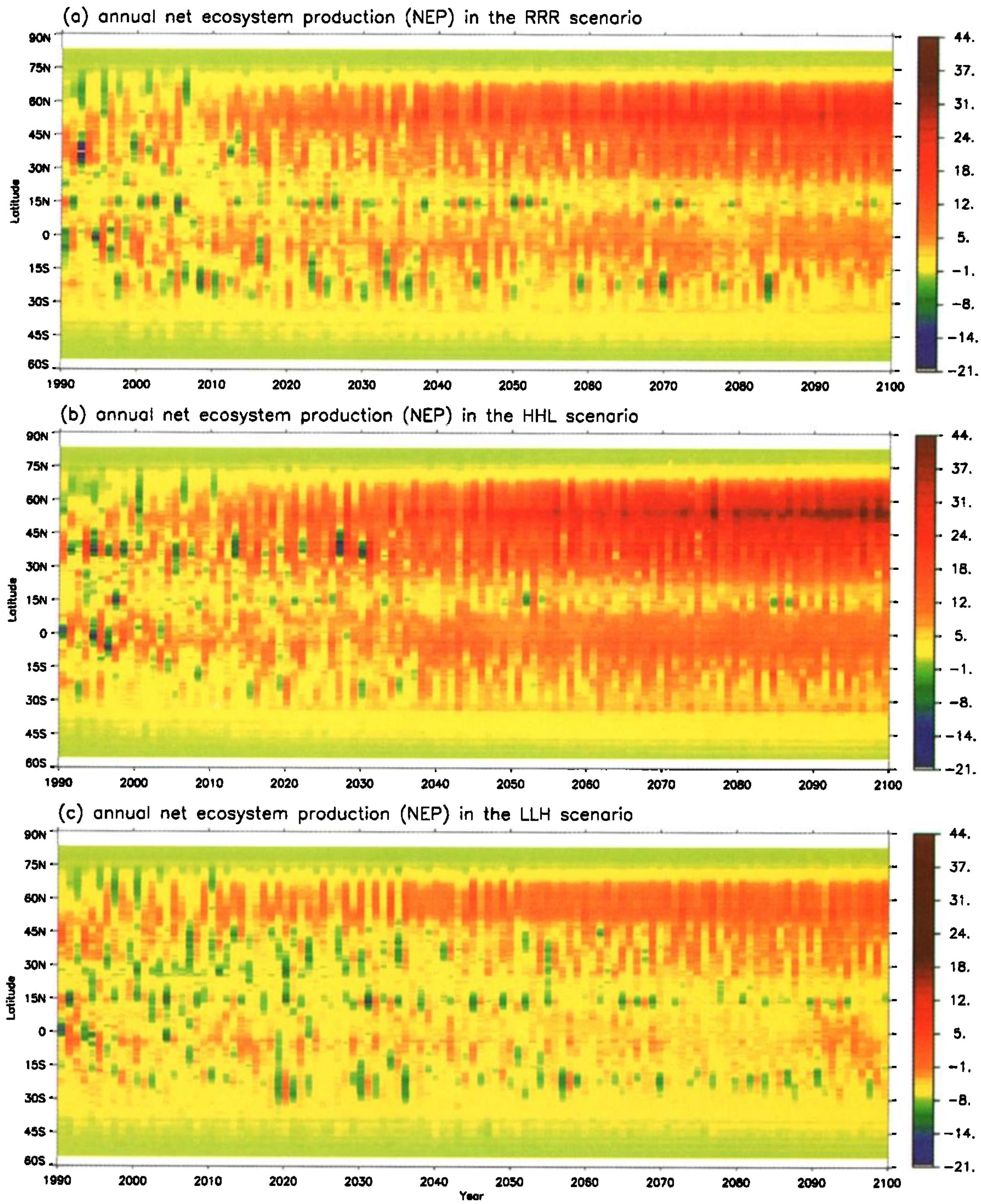

Plate 2. Latitudinal distributions of annual net ecosystem production (NEP) (10^{12} g C yr^{-1}) along 0.5°-resolution latitudinal bands over the period of 1990-2100 in the RRR, HHL, and LLH transient climate change predictions.

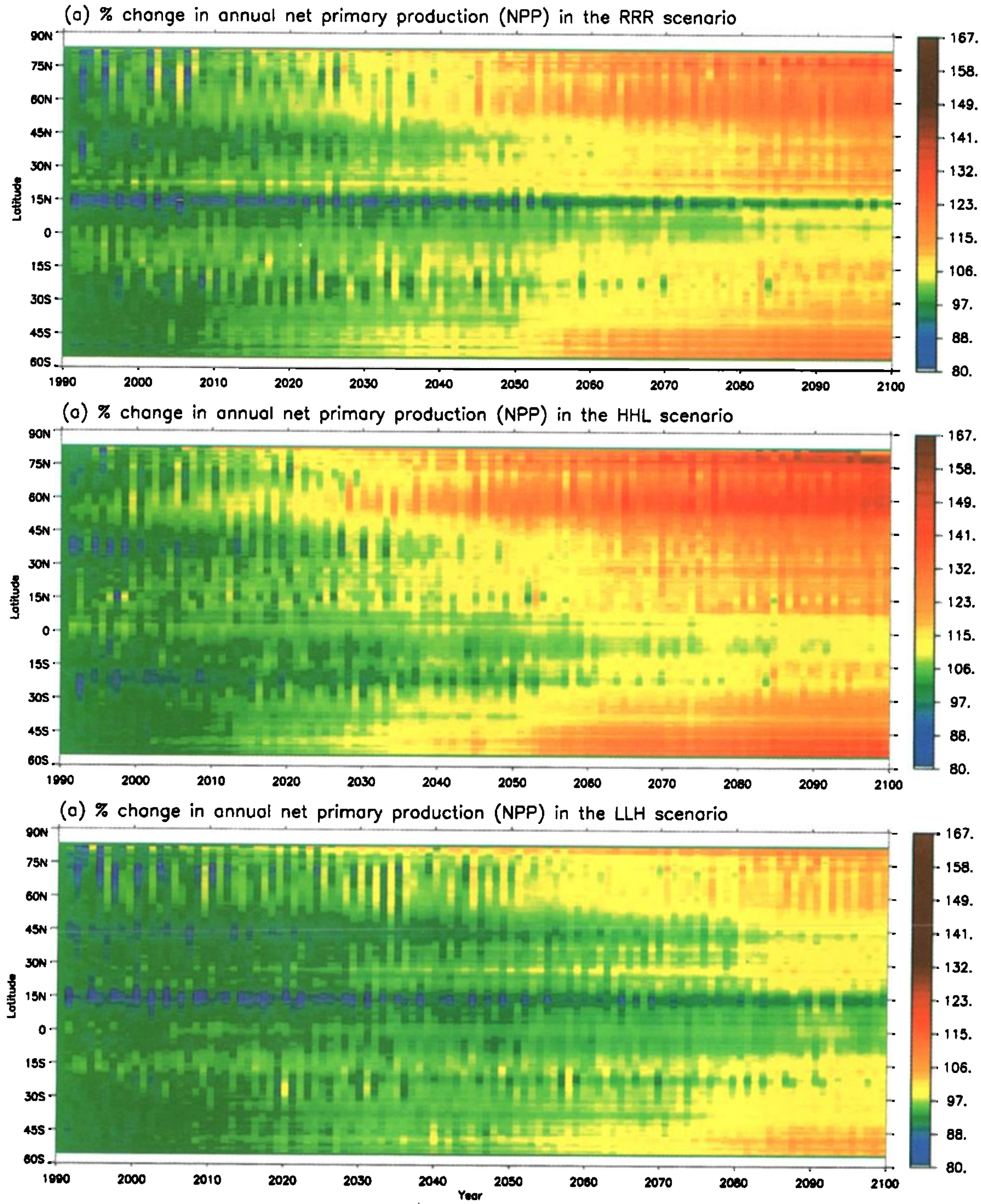

Plate 3. Percent changes of annual net primary production (NPP) along 0.5°-resolution latitudinal bands over the period of 1990-2100 in the RRR, HHL, and LLH transient climate change predictions. We used annual NPP in 1990 as the reference in calculating the percent change of annual NPP.

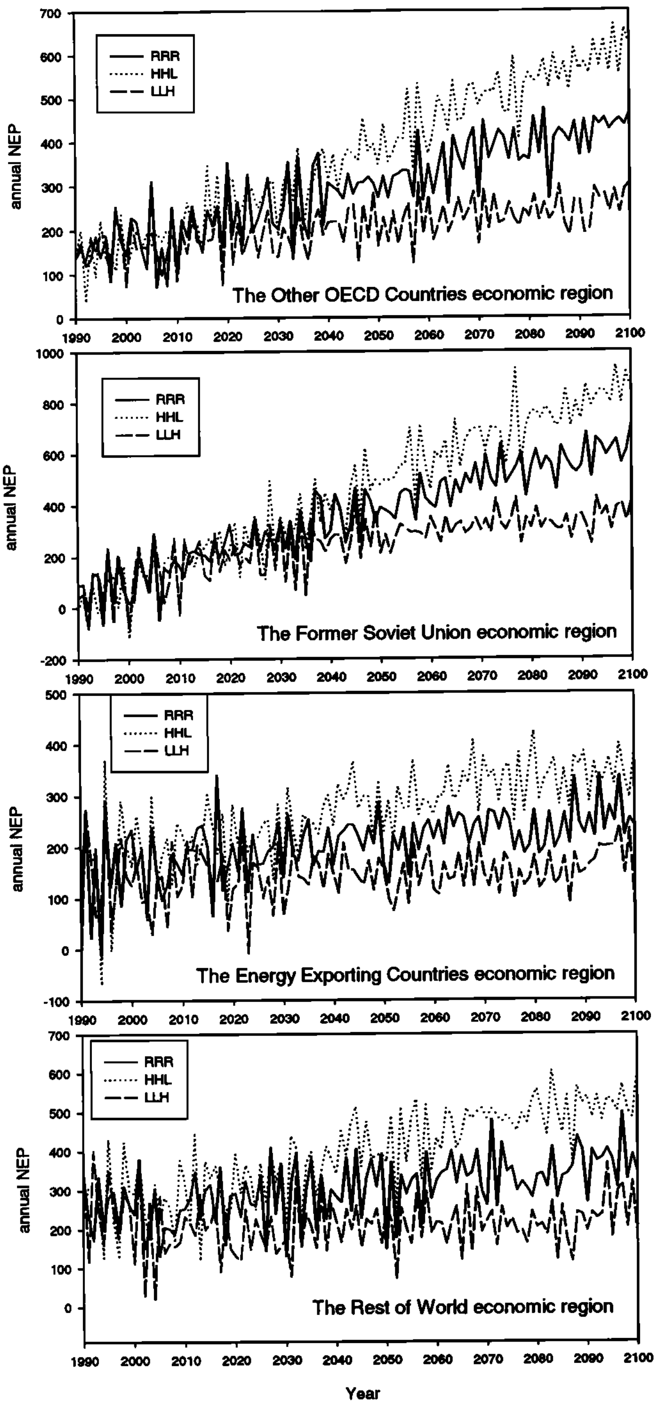

Figure 7. Temporal dynamics of annual net ecosystem production (NEP) (10^{12} g C yr^{-1}) among the four economic regions of the world over the period of 1990-2100 in the RRR, HHL, and LLH climate change predictions.

economic regions. Future studies that use various scenarios of stabilization of atmospheric CO_2 concentration to drive TEM are needed to quantify the relative role of paths and magnitudes in changes in climate and atmospheric CO_2 concentration.

The CO_2 fertilization effect has been considered as a major mechanism in accounting for the "missing" carbon sink, when calculating the global carbon budget for the 1980s [*IPCC*, 1990, 1992; *Friedlingstein et al.*, 1995]. A number of modeling studies of the global carbon budget and CO_2 fertilization effect have assumed that the relative increase of NPP or NEP is proportional to the increase of the atmospheric CO_2 concentration, specifically through definition of the so-called β_{NEP} functions [*Keeling et al.*, 1989;

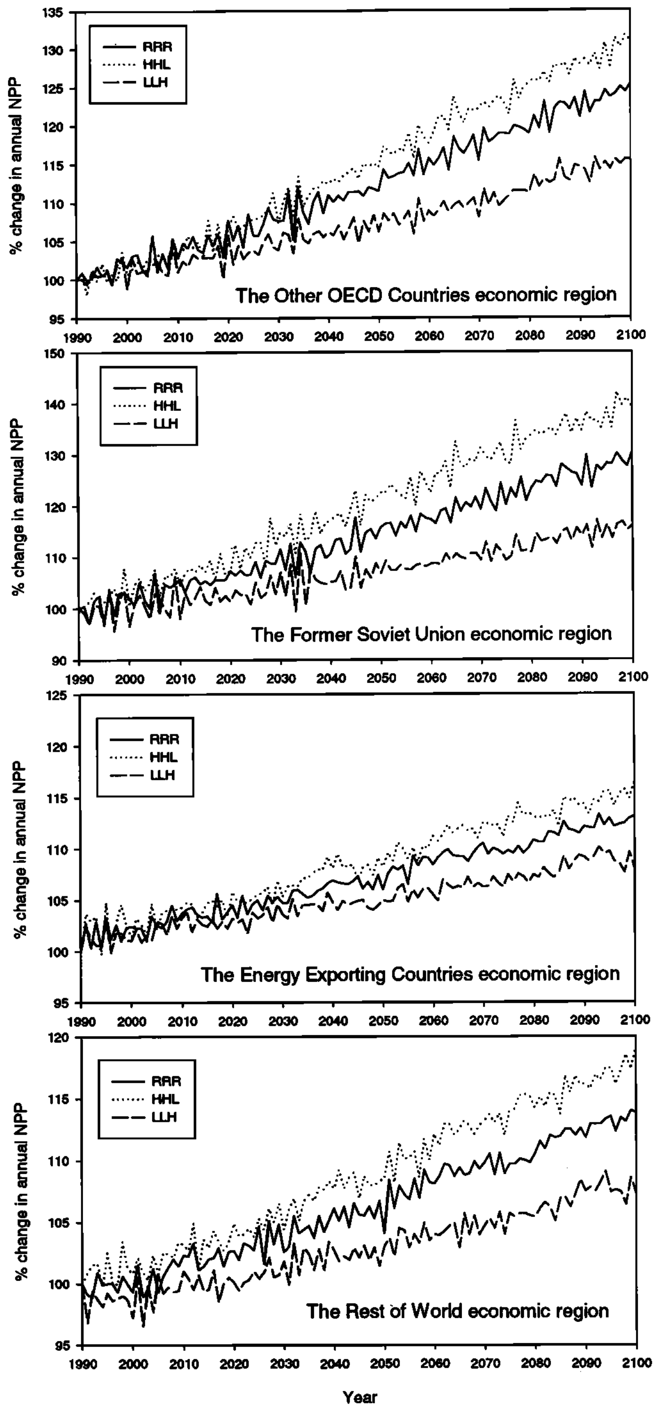

Figure 8. Temporal changes in annual net primary production (NPP) among the four economic regions of the world over the period of 1990-2100 in the RRR, HHL, and LLH climate change predictions. We used annual NPP in 1990 as the reference in calculating the percent change of annual NPP.

Heimann and Keeling, 1989] or β_{NPP} functions [*Goudriaan and Ketner*, 1984; *Esser*, 1987; *Polglase and Wang*, 1992; *Friedlingstein et al.*, 1995]; for example, in the approach using β_{NPP} the change in NPP is given by $\Delta NPP = NPP_o \times [\beta_{NPP} \times (C_t - C_o)/C_o]$. The β_{NEP} or β_{NPP} would presumably change over time and over space because of abiotic environmental constraints, specifically nutrients and climate [*Friedlingstein et al.*, 1995], and acclimation of plants. Some modeling studies [*Heimann and Keeling*, 1989; *Tans et al.*, 1990; *Enting et al.*, 1995] have also made a critical assumption that biospheric CO_2 uptake due to CO_2 fertilization has similar spatial patterns (e.g., latitudinal distribution) as NPP. In these transient simulations of TEM, the latitudinal distribution of annual NPP has kept a bimodal distribution with the highest NPP values in tropical regions and the second highest NPP values in northern midlatitudes over the period of 1990-2100 [see also *Prinn et al.*, 1998], similar to the latitudinal distribution of annual NPP in steady states [*Xiao et al.*, 1997]. Annual NEP is higher in the tropical regions than in the northern middle to high latitudes in early simulation period, but is higher in the northern middle to high latitudes than in the tropic regions in late simulation period (Plate 2). The results of our study demonstrate the limitation of using a single β_{NEP} or β_{NPP} value in studies of the global carbon cycle and indicate the importance of incorporating multiple pool and turnover-time process-based ecosystem models into the modeling studies of the global carbon cycle at decadal to century timescales when changes in atmospheric CO_2 concentration and climate are taken into account.

The effects of interannual variation of climate in the last decades on terrestrial carbon fluxes have been investigated by a number of observational studies, for example, analysis of atmospheric CO_2 concentration data over the period of 1980-1994 [*Keeling et al.*, 1995], and modeling studies [*Dai and Fung*, 1993; *Schimel et al.*, 1996; *Kindermann et al.*, 1996]. *Thompson et al.* [1996] has examined the effects of temperature and precipitation anomalies from 1880 to 1990 on carbon exchange of the terrestrial biosphere. All these studies have suggested that large interannual variation of climate has resulted in a sizable terrestrial carbon sink. The modeling study of *Dai and Fung* [1993] includes the assumption that the effects of temperature and precipitation anomalies on the terrestrial carbon exchange are instantaneous and have no time-lagged effects. However, observational time series studies [*Keeling et al.*, 1995; *Braswell et al.*, 1997] and other modeling studies [*Schimel et al.*, 1997] have suggested the existence of time-lagged effects of climate anomalies on net carbon exchange of the terrestrial biosphere. The time-lagged effects are attributed to the NPP response to nutrient releases induced by climate anomalies not to the instantaneous physiological NPP and R_h responses to interannual climate variation [*Schimel et al.*, 1997]. In our study, global annual NPP and R_h have moderate interannual variations over the period of 1990-2100 (Figure 4), mostly because of interannual variation of climate projected by the MIT 2-D land-ocean climate model (Figure 3). The interannual variation of NPP is not always in phase with the interannual variation of R_h (e.g., see the period of 1990-2010 in Figure 4). The latitudinal distribution of annual NEP has large interannual variations (Plate 2). In some years, the tropical regions has negative annual NEP values, representing a carbon source to the atmosphere (Plate 2). Note that the interannual variation of climate projected by the MIT 2-D land-ocean climate model (Figure 3) is much smaller than the observed interannual variation of climate in the last few decades [see *Dai and Fung*, 1993] and is about half of interannual climate variation predicted in coupled ocean-atmosphere general circulation models (GCMs) [*Sokolov and Stone*, 1998]. Therefore these TEM simulations may underestimate the effects of interannual variation of climate on carbon fluxes of terrestrial ecosystems in the period of 1990-2100. In future work, it would be useful to examine the effects of interannual variations of climate projected by 3-D GCMs on carbon and nitrogen dynamics of the terrestrial biosphere.

The TEM simulation results suggest the possibility of two large terrestrial carbon sinks in the period of 1990-2100, that is, one carbon sink in northern middle to high latitudes and the other carbon sink in the tropical region. In a modeling study, *Taylor and Lloyd* [1992] suggested that a significant net CO_2 uptake (1 Pg C yr^{-1} carbon sink) may be occurring in tropical rainforests. The carbon sink in the tropical regions may compensate for some of the CO_2 emissions from land use and land cover changes (e.g., deforestation) that are occurring in the tropical regions [*Houghton*, 1996]. In a study that deduces global and hemispheric CO_2 sinks from changes in atmospheric O_2 concentration [*Keeling et al.*, 1996], the results imply that tropical ecosystems were not a strong net source or sink for CO_2 over the period of 1991-1994. Several other modeling studies, which infer CO_2 source and sink distribution from the observed concentration of atmospheric CO_2 and a knowledge of spatial and seasonal variations in fossil fuel emissions [*Keeling et al.*, 1989; *Heimann and Keeling*, 1989; *Taylor*, 1989; *Tans et al.*, 1990; *Enting and Mansbridge*, 1991; *Enting et al.*, 1995; *Ciais et al.*, 1995], also suggest that there is a large net carbon sink in the northern hemisphere, most probably in the middle latitudes to high latitudes. The normalized difference vegetation index data from the advanced very high resolution radiometers of the NOAA meteorological satellite have shown a large increase in plant growth in the northern high latitudes (mainly in 45°N to 70°N) from 1981-1991 [*Myneni et al.*, 1997]. A number of field flux studies [*Grace et al.*, 1995; *Wofsy et al.*, 1993; *Goulden et al.*, 1996, 1998] have measured net CO_2 exchange between various ecosystems and the atmosphere using eddy correlation technique. The field CO_2 flux data have been used to test process-based ecosystem models [*Kimball et al.*, 1997]. Our ongoing effort in incorporating the field CO_2 flux data for calibration and testing of TEM will significantly improve our modeling capacity to estimate how sensitive various terrestrial ecosystems respond to transient changes in climate and atmospheric CO_2 concentration.

Caution should be taken in using these NEP results in policy discussions relevant to anthropogenic CO_2 emissions and carbon taxes, since we use potential mature natural vegetation in this study. These NEP estimates represent the potential CO_2 uptake by the terrestrial biosphere or the upper bound for long-term carbon sequestration. We have not taken into consideration the management of agriculture and forests for mitigation of CO_2 emissions [*Cole et al.*, 1996; *Brown et al.*, 1996] as well as land use and land cover change [*Houghton*, 1996]. Quantification of actual land sinks or sources of CO_2 requires additional studies that include land cover and land use changes, nitrogen deposition, and air pollution, as well as feedbacks between the biosphere and the atmosphere. Industrial activities and fertilizer application for intensive agriculture have significantly altered the global nitrogen cycle and resulted in substantial increases in atmospheric nitrogen deposition [*Melillo*, 1995; *Galloway et al.*, 1995; *Townsend et al.*, 1996]. A few modeling studies have suggested that atmospheric nitrogen deposition over the last century increased both NPP and carbon storage of the terrestrial biosphere [*Melillo et al.*, 1996; *Townsend et al.*, 1998] significantly. In the next century, atmospheric nitrogen deposition is likely to continue to increase substantially in the world [*Galloway et al.*, 1995; *Prinn et al.*, 1996] and thus will significantly affect carbon fluxes and storage of the terrestrial biosphere. The study presented here provides a basis and methodology for future investigation of the impacts of land use/cover change and atmospheric nitrogen deposition on carbon fluxes and storage of the terrestrial biosphere. Our ongoing efforts in coupling interactively the TEM with the atmospheric chemistry/climate model [*Wang et al.*, 1998] and developing and incorporating the dynamic vegetation-ecosystem model and the land use and land cover model (*X. Xiao et al.*, Transient climate change and potential croplands of the world in the 21st century, submitted to *Ambio,* 1998) into the IGSM [*Prinn et al.*, 1998] will substantially enhance applications of the TEM and the IGSM in addressing critical issues in climate change science and policy.

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