MIT Joint Program on the Science and Policy of Global Change

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives.

Henry D. Jacoby and Ronald G. Prinn,
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Abstract

The Terrestrial Ecosystem Model (TEM version 4.1) is applied to assess the sensitivity of net ecosystem production (NEP) of the terrestrial biosphere to transient changes in atmospheric CO_2 concentration and climate in the 21st Century. These NEP estimates provide a measure of the potential for various vegetated regions and countries to act as sinks or sources of atmospheric CO_2. We use three transient climate change predictions over the period of 1977–2100 from the MIT Integrated Global System Model for assessment of the effects of different climate changes. Global annual NEP has large interannual variations and increases over time, thus representing a growing net carbon flux from the atmosphere to the biosphere. Latitudinal distribution of total annual NEP along 0.5° resolution latitudinal bands has a significant shift from the tropics to the northern mid- and high-latitudes over time. The sums of annual NEP over the period of 1990–2100 differ substantially among the twelve economic regions of the world. The results show that temporal dynamics and spatial distribution of annual NEP are very sensitive to the magnitudes and paths of temporal changes in atmospheric CO_2 concentration and climate.

1. Introduction

Future changes in atmospheric CO_2 concentration and climate are likely to affect net primary production and 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*., 1997a) 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. 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 terrestrial ecosystems are not simulated. There are

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large uncertainties about the path and magnitude of future anthropogenic emissions of greenhouse gases around the world, because of uncertainty 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 MIT Integrated Global System Model (IGSM) for climate change, impact assessment and climate policy has been developed (Prinn *et al*., 1996, 1997; Xiao *et al*., 1997a). As shown in Figure 1, the components of the IGSM include the Anthropogenic Emission Prediction and Policy Analysis (EPPA) model (Yang *et al*., 1996); an atmospheric chemistry model (Wang *et al*., 1995), a 2-dimensional climate model (MIT 2-D L-O climate model; Yao and Stone,1987; Stone and Yao, 1987, 1990; Sokolov and Stone, 1995, 1997; Xiao *et al*., 1997a), an ocean carbon model (Prinn *et al*., 1997), 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*., 1997a) and natural emission models of N_2O and CH_4 from soils (Liu, 1996). The MIT IGSM addresses most of the major anthropogenic and natural processes involved in climate change and is also computationally efficient (Prinn *et al*., 1996, 1997; Xiao *et al*., 1997a). The EPPA model projects anthropogenic emissions of CO_2 and other greenhouse gases (*e.g*., N_2O and CH_4) in twelve 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 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*., 1996, 1997; Tian *et al*., 1997) are used to estimate carbon and nitrogen fluxes and pools of terrestrial ecosystems over time.

In this paper, we report the temporal dynamics and spatial distribution of net ecosystem production of the terrestrial biosphere under the three transient climate change scenarios in the 21st Century, which were projected by the MIT IGSM (Prinn *et al*., 1997). Net ecosystem production (NEP) is defined as the difference between net primary production (NPP) and heterotrophic respiration (R_h) and represents net carbon 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 NEP of 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 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. Annual NEP in an economic region represents its ecological capacity of 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.

2. The Terrestrial Ecosystem Model (TEM)

The TEM (Fig. 2) is a process-based ecosystem model that makes monthly estimates of important carbon and nitrogen fluxes and pool size of various terrestrial ecosystems (Raich *et al*., 1991; Melillo *et al*., 1993; McGuire *et al*., 1992, 1993, 1995, 1997; Xiao *et al*.,1997a). 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*., 1996, 1997; Tian *et al*., 1997). The water balance model of Vorosmarty *et al*. (1989) has been incorporated into version 4.1 of TEM, thus monthly fluxes of water, carbon and nitrogen are calculated simultaneously in version 4.1 of TEM. 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*., 1996, 1997) and the conterminous United States (Tian *et al*., 1997).

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

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

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):

$$R_h = k_d\, C_s\, f(M)\; e^{0.0693T} \qquad [2]$$

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 k_d 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 biological "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*., 1996, 1997; Tian *et al*., 1997). 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*., 1992; Melillo *et al*., 1993). 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.

For global extrapolation of TEM, we use spatially-explicit data sets that are organized at 0.5˚ (longitude) × 0.5˚ (latitude) spatial resolution. At this resolution, global land areas are represented by 62,483 grid cells. 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 long-term average contemporary climate, we use the Cramer and Leemans Climate database (Wolfgang Cramer, personal communication), which is a major 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 in Otto *et al*. (1997) using the percent sunshine duration in the above Cramer and Leemans data set. For elevation, we use an aggregation to 0.5˚ resolution of a global 10 minute resolution data set (NCAR/NAVY, 1984). We use the FAO/CSRC (undated) soil texture data set, which represents a digitization to 0.5˚ resolution of the Soil Map of the World (FAO/UNESCO, 1971). We use a global potential 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 these spatial data sets, there are 3,059 ice grid cells and 1,525 wetland grid cells (*e.g*., mangrove, swamp, salt marsh and flood plains).

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 a sensitivity study of the MIT Integrated Global System Model (Prinn *et al*., 1997). In the sensitivity study (Prinn *et al*., 1997), the standard parameters and assumptions in the EPPA model and the atmospheric chemistry/climate model were first used to generate the RRR (reference) projections 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 IPCC (IPCC, 1994). Then, the EPPA model projected higher and lower emissions of CO_2 and other greenhouse gases by changing labor productivity growth, non-price-induced changes in energy efficiency and non-carbon backstop technology cost. The EPPA emissions of CO_2 and other greenhouse gases were then used to drive the MIT coupled atmospheric chemistry/2-D L-O climate model. In this coupled model, coefficients for vertical ocean heat diffusion, parameters quantifying direct and indirect aerosol effects, and the model sensitivity to doubled CO_2, were changed to generate different climate change predictions for a given set of 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 sensitivity study (Prinn *et al*., 1997). Here, we use three of the seven transient climate change predictions: the RRR prediction; the HHL prediction, which has higher EPPA emissions, slower ocean heat diffusion and smaller aerosol effects, and lower model sensitivity to doubling CO_2, leading to somewhat larger changes in temperature than the RRR prediction; and the LLH prediction, which has lower EPPA emissions, 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. As can be seen in Figure 3, atmospheric CO_2 concentration and climate vary significantly among the three transient climate change predictions over the period of 1990_2100. 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 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 the three predictions. Global mean annual cloudiness decreases in the RRR and the LLH predictions but increases in the HHL prediction.

The MIT 2-D L-O climate model simulates the surface climate fields (*e.g*., surface temperature, evaporation) separately over land and ocean as a function of latitude and height. 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 MIT 2-D L-O 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," 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 L-O 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 by the contemporary monthly precipitation and monthly mean cloudiness data, respectively. The contemporary monthly mean climate data are from the Cramer and Leemans Climate database, which is mostly based on long-term average climate data for the period of 1931–1960.

We use the predicted atmospheric CO_2 concentrations and climate changes over the period of 1977–2100 to drive the transient TEM. These runs of the transient 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 MIT 2-D L-O climate and global mean atmospheric CO_2 concentration 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.*, 1997). In these three TEM simulations, we use potential 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.

4. Results and Discussion

4.1 Global Dynamics of Annual NEP

The TEM estimates that global annual NEP in 1990 is about 0.8 PgC/yr for the RRR transient climate change prediction, which is the difference between the 43.4 PgC/yr of global annual NPP and the 42.6 PgC/yr of global annual R_h in 1990. Geographically, the distribution of annual NEP in 1990 varies significantly, as shown in Figure 4. The spatial distribution of annual NEP is determined by the spatial patterns of annual NPP and annual R_h. The spatial patterns of annual NPP is highly correlated to both the spatial pattern of annual net nitrogen mineralization (NMIN) and the spatial pattern of estimated annual evapotranspiration (EET). These spatial patterns are the results of complex interactions among carbon, nitrogen and water in terrestrial ecosystems, as simulated by the TEM.

Global annual NEP increases gradually over the period of 1990–2100 and differs significantly among the three transient climate change predictions by the end of the 21st Century, as shown in Figure 5. Compared to their values in 1990, global annual NEP in 2100 increases by about 1.8 PgC/yr for the RRR, 2.6 PgC/yr for the HHL, and 0.5 PgC/yr for the LLH climate change predictions. The simulations indicate that the terrestrial biosphere will increase its uptake of atmospheric CO_2 and act as a net carbon sink between 1990–2100 under the three transient climate change predictions. The sum of global annual NEP over the period of 1990–2100, which represents the total carbon uptake by the terrestrial biosphere, is about 122.9 PgC under the LLH, 186.1 PgC under the RRR and 240.1 PgC under 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 1289.3 PgC for the LLH, 1575.3 PgC for the RRR and 1832.8 PgC for the HHL climate change predictions (Prinn *et al.*, 1997). Thus, the total carbon uptake by the terrestrial biosphere accounts for 9.5% of the total anthropogenic CO_2 emission for the LLH, 11.8% for the RRR and 13.1% for the HHL climate change predictions. The results indicate that the total CO_2 uptake by the terrestrial biosphere depends on both the magnitudes and paths of changes in atmospheric CO_2 concentrations and climate.

As shown in Figure 5, the increase of global annual NEP results from a larger increase in annual NPP than in annual R_h. Compared to their values in 1990, global annual NPP and annual R_h in 2100 increase by about 9.5 PgC/yr and 6.9 PgC/yr for the HHL, 7.9 PgC/yr and 6.1 PgC/yr for the RRR, and 4.3 PgC/yr and 3.8 PgC/yr for the LLH climate change predictions, respectively. Simultaneous interactions among carbon, nitrogen and water cycles determine the dynamics of NPP and R_h. Globally, atmospheric CO_2 concentration increases continuously over time in all the three climate change predictions (Fig. 3). In TEM, increases in CO_2 enhance water use efficiency of vegetation and result in an increase in annual NPP due to the CO_2 fertilization effect (McGuire *et al*., 1992). The CO_2 fertilization effect has been considered as a major mechanism for 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 are proportional to the increase of the atmospheric CO_2 concentration, specifically through definition of the so-called β_{NEP} functions (Keeling *et al*., 1989; Heimann *et al*., 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. The results of our study, which shows non-parallel dynamics between atmospheric CO_2 levels and global annual NEP (Figs. 3 and 5), also demonstrate the serious limitation of using a single β_{NEP} or β_{NPP} value in studies of the global carbon cycle, and indicate the importance of incorporating process-based ecosystem models into the modeling studies of the global carbon cycle.

Global annual NPP and R_h have moderate interannual variations (Fig. 5), mostly due to interannual variation of climate projected by the MIT 2-D L-O climate model (Fig. 3). Interannual variation of NEP is relatively larger, compared to interannual variation of NPP and R_h (Fig. 5). It is worthwhile to note that the interannual variation of NPP is not always in phase with the interannual variation of R_h (see the period of 1990–2010 in Fig. 5, for instance), which indicates that NPP and R_h respond differently to the interannual variations of climate. 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 Member, 1995; Xiao *et al*., 1997a). Higher temperature may increase plant photosynthesis in some ecosystems where temperature has not yet reached the optimum temperature of photosynthesis. Higher temperature also enhances plant respiration. Potential evapotranspiration (PET) increases as temperature rises, which may cause water stress to plants, consequently resulting in a decrease of NPP. 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. The difference in phases of interannual variations between NPP and R_h indicates that the NPP response to nitrogen release induced by warming plays an important role in NEP dynamics, in addition to the instantaneous NPP and R_h responses to interannual climate variation. The modeling study of Dai and Fung (1993) has suggested that interannual variation of climate in the last few decades contributes significantly to the terrestrial CO_2 sink. Based on atmospheric CO_2 observational data in 1980–1994, Keeling *et al*. (1995) suggested that warming in 1987 and 1988 during the El Niño event may have caused an increased CO_2 uptake by the terrestrial biosphere in 1989 and 1990, and cooling produced by the volcanic aerosols from the Pinatubo volcanic eruption of June 1991 might explain large terrestrial biosphere sinks of CO_2 during 1991–1993. Because the climate data in our simulations are not historical observational data, we cannot directly test the hypothesis of Keeling *et al*. (1995). The interannual variation of climate projected by the MIT 2-D L-O climate model (Fig. 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 that predicted in coupled ocean-atmosphere GCMs (Sokolov and Stone, 1997). In future work, it would be useful to examine interannual variation of climate from observations and projections by 3-D GCMs and to quantify their effects on carbon and nitrogen fluxes and storage of the terrestrial biosphere.

4.2 Latitudinal Distribution of 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, as shown in Figure 6, with large positive values in both the northern mid- to high-latitudes and the tropical regions for most years within the 1990–2100 period under the RRR climate change prediction. These large positive annual NEP values in the northern mid- to high-latitudes and the tropical regions represent two significant terrestrial carbon sinks. As shown in Figure 7, the relative magnitudes of these two terrestrial carbon sinks vary among the three transient climate change predictions, being lower in the LLH but higher in the HHL climate change predictions. Note that the latitudinal distribution of annual NEP has large interannual variations, as is apparent in Figures 6 and 7. In some years, total annual NEP in the tropical regions have negative values and represents a carbon source to the atmosphere. The results clearly indicate that the latitudinal distribution of annual NEP is very sensitive to transient changes in climate and atmospheric CO_2 concentration.

The latitudinal distribution of total annual NEP changes significantly over the period of 1990–2100 under the RRR transient climate change prediction. Total annual NEP has a substantial increase over time in the northern mid- to high- latitudes, but a smaller increase in the tropical regions. The latitudinal distribution of total annual NEP differs significantly among the three climate change predictions. Total annual NEP in the tropical regions has a slight increase in the LLH but a relatively large increase in the HHL climate change predictions. In the northern mid- to high-latitudes, the increase of total annual NEP occurs much earlier and is larger in the HHL than in the LLH climate change prediction. As shown in Table 1, the net CO_2 uptake in the tropics in all three of the climate change predictions appears to be primarily occurring in the tropical evergreen forests, while the net CO_2 uptake in the northern mid- to high-latitude appears to be largely in the boreal forests. Under the RRR climate change prediction, tropical evergreen forests accumulate about 30.3 PgC, which accounts for 16.3% of the 186.1 PgC total carbon uptake by the terrestrial biosphere in 1990–2100, while boreal forests accumulate 36.3 PgC (19.5%). 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.

Field flux studies, which measure net CO_2 exchange using the eddy correlation technique, have indicated that undisturbed tropical rainforests of the Amazon Basin are accumulating carbon (Grace *et al*., 1995). In a modeling study, Taylor and Lloyd (1992) suggested that a significant net CO_2 uptake (1 PgC/yr 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.

Field flux studies have also shown that deciduous forests in the United States are currently accumulating carbon (Wofsy *et al*., 1993; Goulden *et al*., 1996). Several inverse 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; Tan *et al*., 1990; Enting and Mansbridge, 1991; Enting *et al*., 1995; Ciais *et al*., 1995), suggest that there is a large net carbon sink in the northern hemisphere, most probably in the mid- to high-latitudes. The normalized difference vegetation index (NDVI) data from the Advanced Very High Resolution Radiometers (AVHRR) 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).

Our study shows that the latitudinal distribution of annual NPP, which is a bimodal distribution with the highest values in tropical regions and the second highest values in northern mid-latitudes, differs significantly from the latitudinal distribution of annual NEP under the RRR climate change prediction (Fig. 6). The difference in the latitudinal distributions between annual NEP and annual NPP become more significant over time over the period of 1990–2100. The difference in the latitudinal distributions between annual NPP and NEP is attributed to a latitudinal gradient in the turnover time of soil organic carbon. 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 time scales (Bird *et al*., 1996). In TEM, soil organic matter decomposes significantly faster in the tropical regions than in the high latitudes (McGuire *et al*., 1995). In some inverse modeling studies (Heimann and Keeling, 1989; Tans *et al*., 1990; Enting *et al*., 1995), a critical assumption is made that biospheric CO_2 uptake due to CO_2 fertilization has spatial patterns (*i.e*. latitudinal distribution) similar to NPP. The TEM simulation results imply that the assumption in those studies that NEP has spatial patterns similar to NPP is likely to be invalid at decadal to century time scales when both CO_2 and climate changes are taken into account. Our results again indicate the importance of incorporating process-based ecosystem models into the modeling studies of global carbon cycle.

4.3 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 sum of annual NEP over the period of 1990–2100 in an economic region represents its potential for carbon sequestration in mature terrestrial ecosystems. As shown in Table 2, of the 186.1 PgC global CO_2 uptake by the terrestrial biosphere over the period 1990–2100 under the RRR climate change prediction, relative contributions from the twelve economic regions of the world differ significantly, ranging from 0.5% (0.9 PgC) in Japan to 21.3% (39.6 PgC) 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 18.1% (33.8 PgC) of the 186.1 PgC global carbon uptake. The Other OECD Countries economic region also makes a relatively large contribution, accounting for 17.6% of the 186.1 PgC global carbon uptake. The sums of annual NEP over the period of 1990–2100 for the twelve economic regions under the RRR climate are higher than under the LLH but lower than under the HHL climate change predictions. However, relative contributions from the twelve economic regions to their global carbon uptake are similar under the three climate change predictions. Under the HHL climate change prediction, Japan accounts for 0.6% of the 240.1 PgC global carbon uptake and the Former Soviet Economic region accounts for 20.7%.

For anthropogenic sources of CO_2, the EPPA model (Yang *et al.*, 1996) in the MIT Integrated Global System Model projects substantially different CO_2 emissions from fossil fuel combustion in the twelve economic regions over the period of 1990–2100 (Table 2; also see Prinn *et al.*, 1997). Total CO_2 emissions from fossil fuel combustion over the period of 1990–2100 under the RRR scenario ranges from 37.6 PgC in Brazil to 332.6 PgC 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 regions. Under the RRR climate, total carbon uptake by mature 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 PgC) in that region, 41.4% of the 95.8 PgC CO_2 emissions in the Former Soviet Union region, but only 4.7% of the 332.6 PgC CO_2 emissions in the U.S. and 1.7% of the 53.7 PgC CO_2 emissions in Japan. The ratios of the total potential CO_2 uptake by mature terrestrial ecosystems over the total CO_2 emission from fossil fuel combustion also differ substantially among the twelve economic regions under the HHL and LLH climate change predictions.

Caution should be taken in using these results in policy discussions relevant to anthropogenic CO_2 emissions and carbon taxes, since we use potential vegetation in this study and therefore, 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). 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. 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). A few modeling studies have suggested that atmospheric nitrogen deposition over the last century increased significantly both NPP and carbon storage of the terrestrial biosphere (Melillo *et al*., 1996; Townsend *et al*., 1996). In the next century, atmospheric nitrogen deposition is likely to continue to increase substantially (Galloway *et al*., 1995; Prinn *et al*., 1996), particularly in the northern mid- to high-latitudes, 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 and land cover change and atmospheric nitrogen deposition on carbon fluxes and storage of the terrestrial biosphere.

5. Conclusion

We have applied a global terrestrial biogeochemistry model to assess the transient responses of the terrestrial biosphere to three predictions of transient changes in atmospheric CO_2 concentration and climate in the 21st Century. The results have shown that global annual NEP is very sensitive to the different time-paths of changes in CO_2 and climate, and has large interannaul variations. The latitudinal distribution of annual NEP changes significantly over time. There exist two terrestrial carbon sinks along the latitude (the tropic regions and the northern mid- to high-latitudes), but the strength of these carbon sinks changes over time. The results have shown that spatial distribution and temporal dynamics of annual NEP depend on the paths of transient change in CO_2 and climate in the next century. Our study implies that inverse studies of the global carbon cycle need to include treatments of the differing spatial and temporal variations in NPP and NEP of the terrestrial biosphere and their complex relation to the CO_2 and climate changes.

This study has demonstrated that the application of the MIT Integrated Global System Model (Prinn *et al*., 1996, 1997; Xiao *et al*., 1997a) can provide very useful information on climate change and impact assessment of terrestrial biosphere. Our future work for integrated assessment of climate change will include: (1) interactive coupling of the TEM with the coupled atmospheric chemistry/climate model; (2) incorporation of the effects of atmospheric nitrogen deposition and air pollution (*e.g.*, O_3 and SO_2) on the terrestrial biosphere into the TEM; and (3) interactive coupling of the TEM with the land use and land cover change model (Xiao *et al*., 1997b). These works will further our understanding on the feedback from undisturbed natural and managed ecosystems to climate and socioeconomic dynamics.

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Table 1. The sums of annual net ecosystem produ ction (PgC) over the period of 1990–2100 among the 18 upland biomes under the three transient climate change predi ctions (RRR, HHL and LLH). These values represent the net changes in total carbon storage of land ecosystems in the 18 biomes.

Vegetation type	number of grid cells	area ($10^6 km^2$)	RRR (PgC)	RRR (%)	HHL (PgC)	HHL (%)	LLH (PgC)	LLH (%)
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	

Table 2. The sums of annual net ecosystem production (PgC) and CO_2 emissions from fossil fuel combustion over the period of 1990–2100 in the twelve economic regions of the world under the three climate change predictions (RRR, HHL and LLH). These values represent the net changes in total carbon storage of land ecosystems in the twelve economic regions of the world.

	sums of annual net ecosystem production (NEP)						CO_2 emissions from fossil fuels		
	RRR		HHL		LLH		RRR	HHL	LLH
EPPA economic regions	(PgC)	(%)	(PgC)	(%)	(PgC)	(%)	(PgC)	(PgC)	(PgC)
USA	15.6	8.4	20.9	8.7	8.6	7.0	332.6	382.8	217.6
Japan	0.9	0.5	1.4	0.6	0.3	0.3	53.7	64.3	46
India	3.3	1.8	4.4	1.8	2.1	1.7	122	144.5	104
China	13.6	7.3	19.0	7.9	6.9	5.6	235.2	283.1	196.3
Brazil	12.3	6.6	15.6	6.5	8.7	7.1	37.6	36.8	39.9
European Economic Communi	6.9	3.7	9.2	3.8	3.7	3.0	131.8	164.2	102.2
Eastern European Countries	2.8	1.5	3.5	1.5	1.5	1.2	66.2	79.1	49.6
Dynamic Asia Economies	1.4	0.7	1.9	0.8	0.8	0.6	48.4	64.1	35.6
Other OECD Countries	32.7	17.6	41.0	17.1	22.9	18.7	78.1	88.5	67.2
Former Soviet Union	39.6	21.3	49.6	20.7	27.7	22.6	95.8	123.5	74.7
Energy Exporting Countries	23.1	12.4	29.6	12.3	16.0	13.1	219	244.3	184.2
The Rest of the World	33.8	18.1	44.0	18.3	23.4	19.0	129.2	121.8	136.3
Globe	186.1		240.1		122.9		1549.6	1797	1253.6

Figure 1. A schematic diagram illustrating the framework and components of the MIT Integrated Global System Model for assessment of climate change. 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.

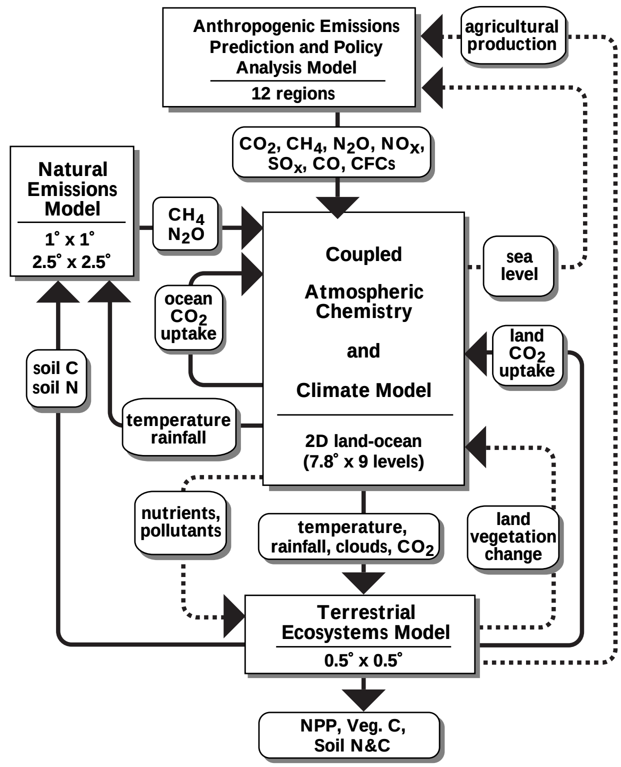
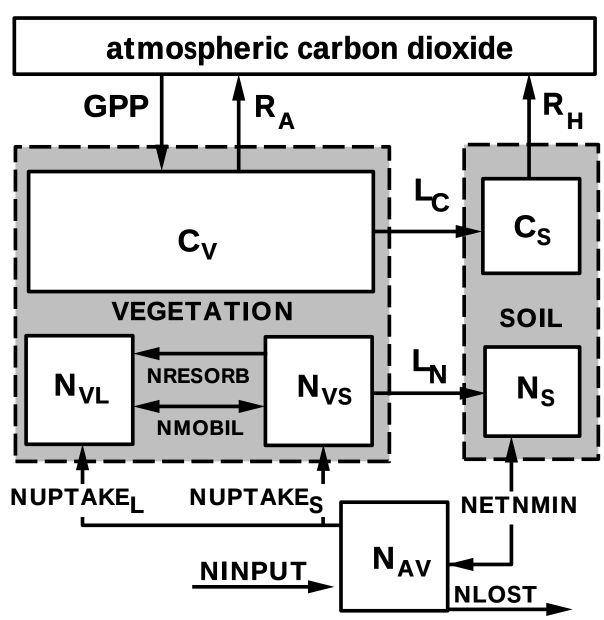


Figure 2. The Terrestrial Ecosystem Model (TEM). The state variables are: carbon in vegetation (C_V); structural nitrogen in vegetation (N_{VS}); labile nitrogen in vegetation (N_{VL}); organic carbon in soils and detritus (C_S); organic nitrogen in soils and detritus (N_S); and available soil inorganic nitrogen (N_{AV}). Arrows show carbon and nitrogen fluxes: GPP, gross primary productivity; R_A, autotrophicrespiration; 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.



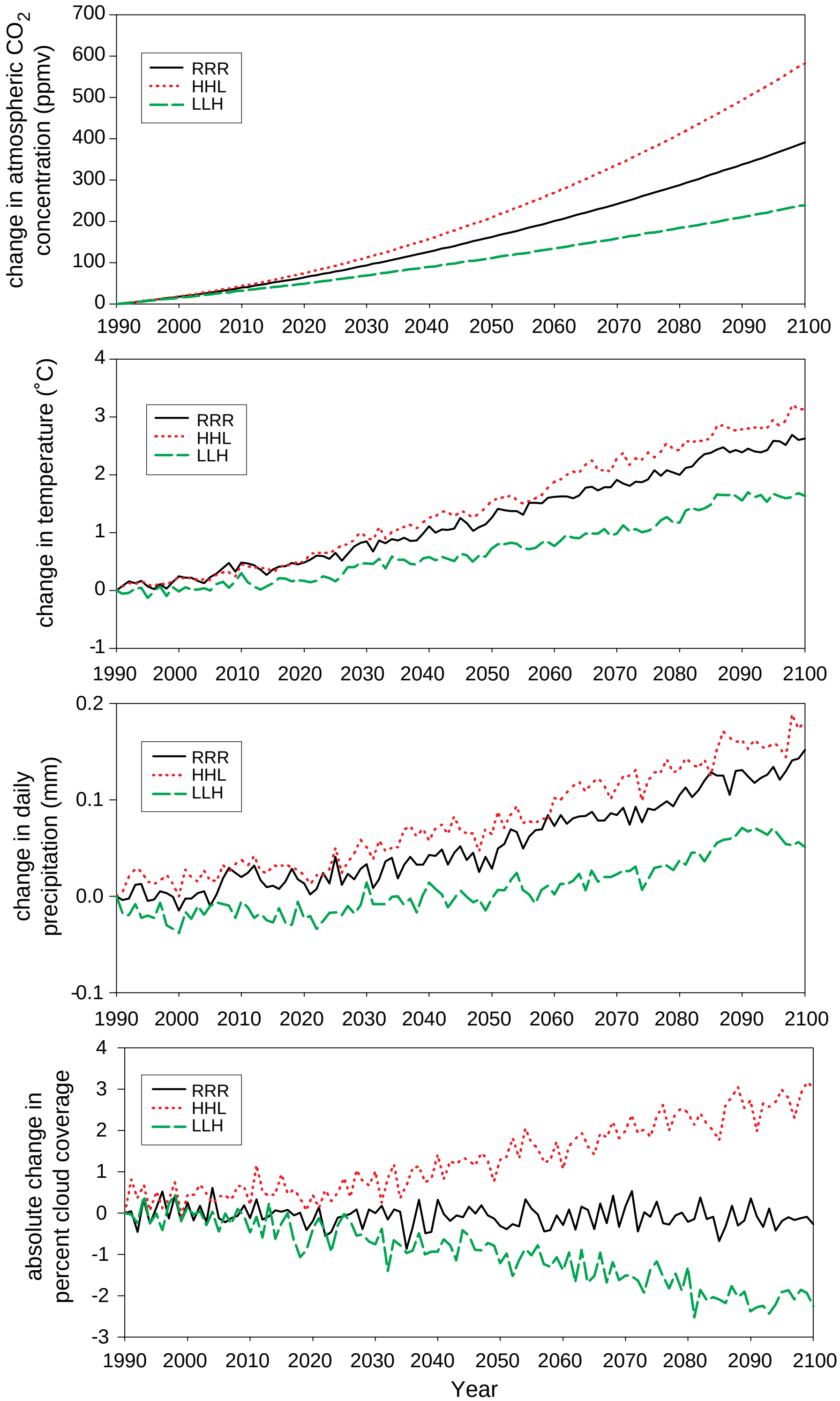


Figure 3. Transient changes (from 1990 values) in global mean annual atmospheric CO_2 concentration, global mean annual temperature, global mean daily precipitation and global mean annual cloudiness (%) over the period of 1990–2100, projected by the coupled 2-D atmospheric chemistry/L-O climate model in the MIT Integrated Global System Model (see Fig. 1, also Prinn *et al.*, 1997).

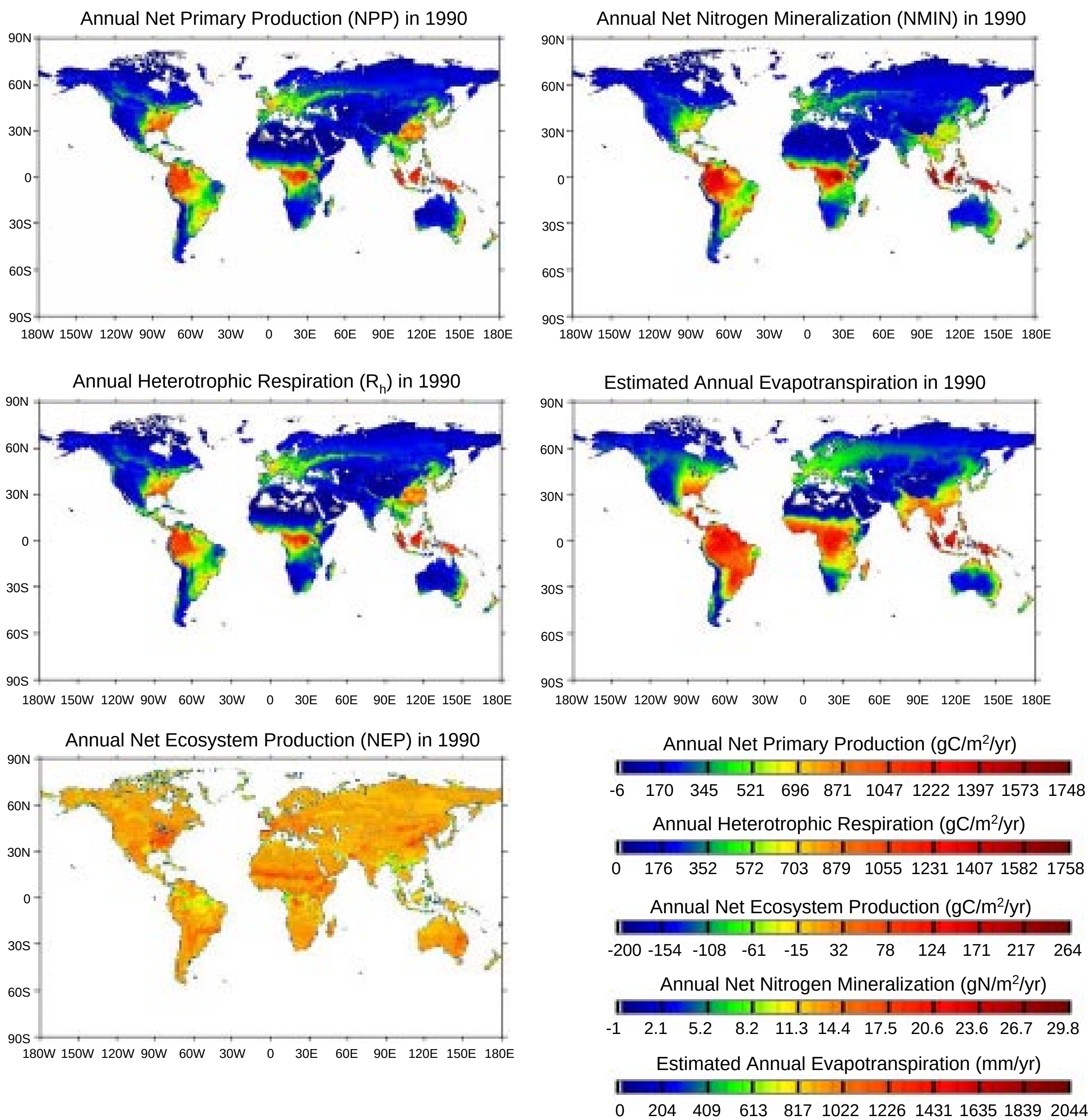


Figure 4. Spatial distributions of annual net primary production (NPP), heterotrophic respiration (R_h), net ecosystem production (NEP), net nitrogen mineralization (NMIN) and estimated evapotranspiration (EET) in 1990, as estimated by the Terrestrial Ecosystem Model (TEM, version 4.1) under the RRR transient climate change prediction.

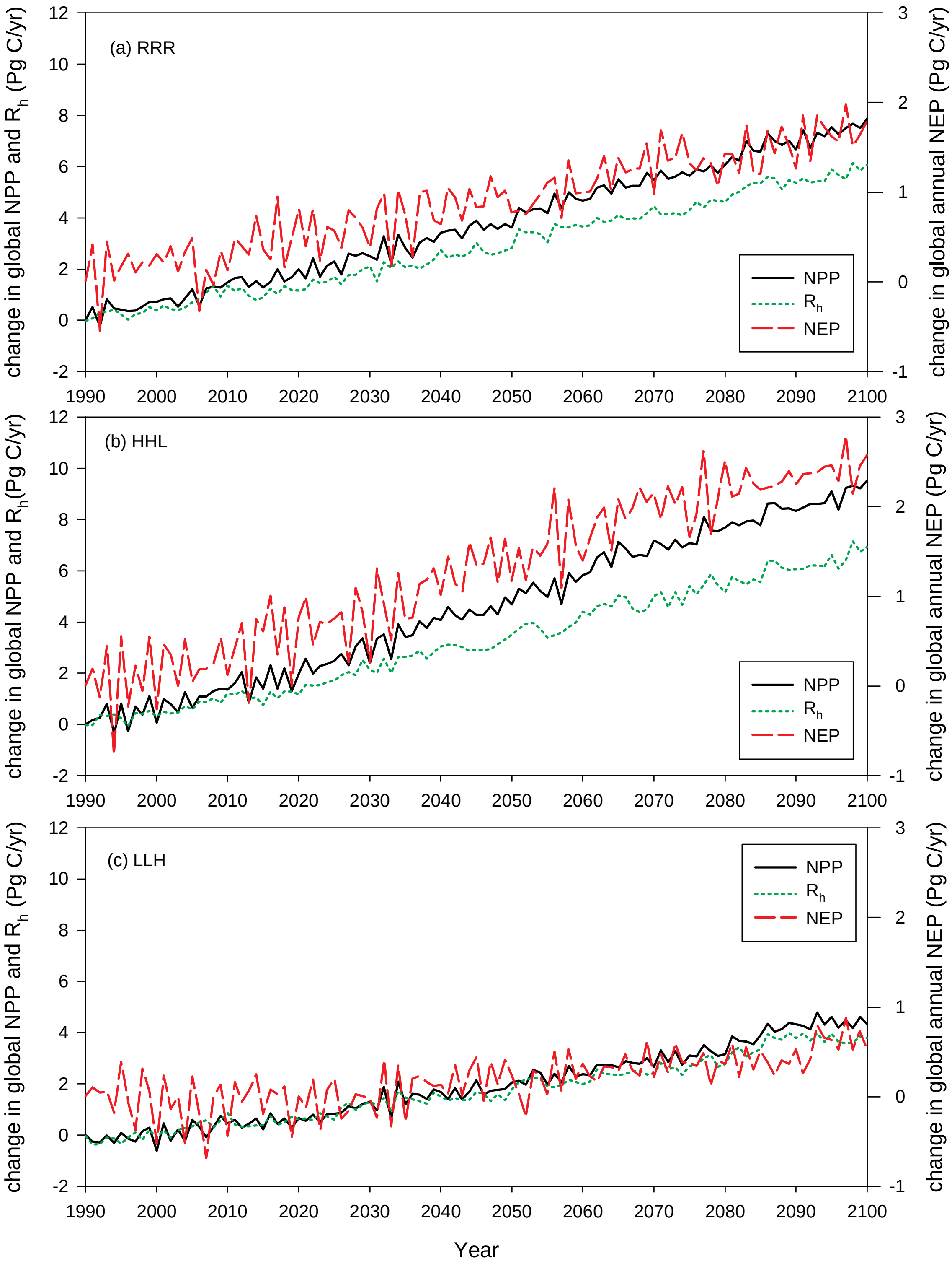


Figure 5. Projected changes (from 1990 global annual values) in global annual net ecosystem production (NEP), annual net primary production (NPP) and annual heterotrophic respiration (R_h) over the period of 1990–2100 under the RRR, HHL and LLH transient climate change predictions.

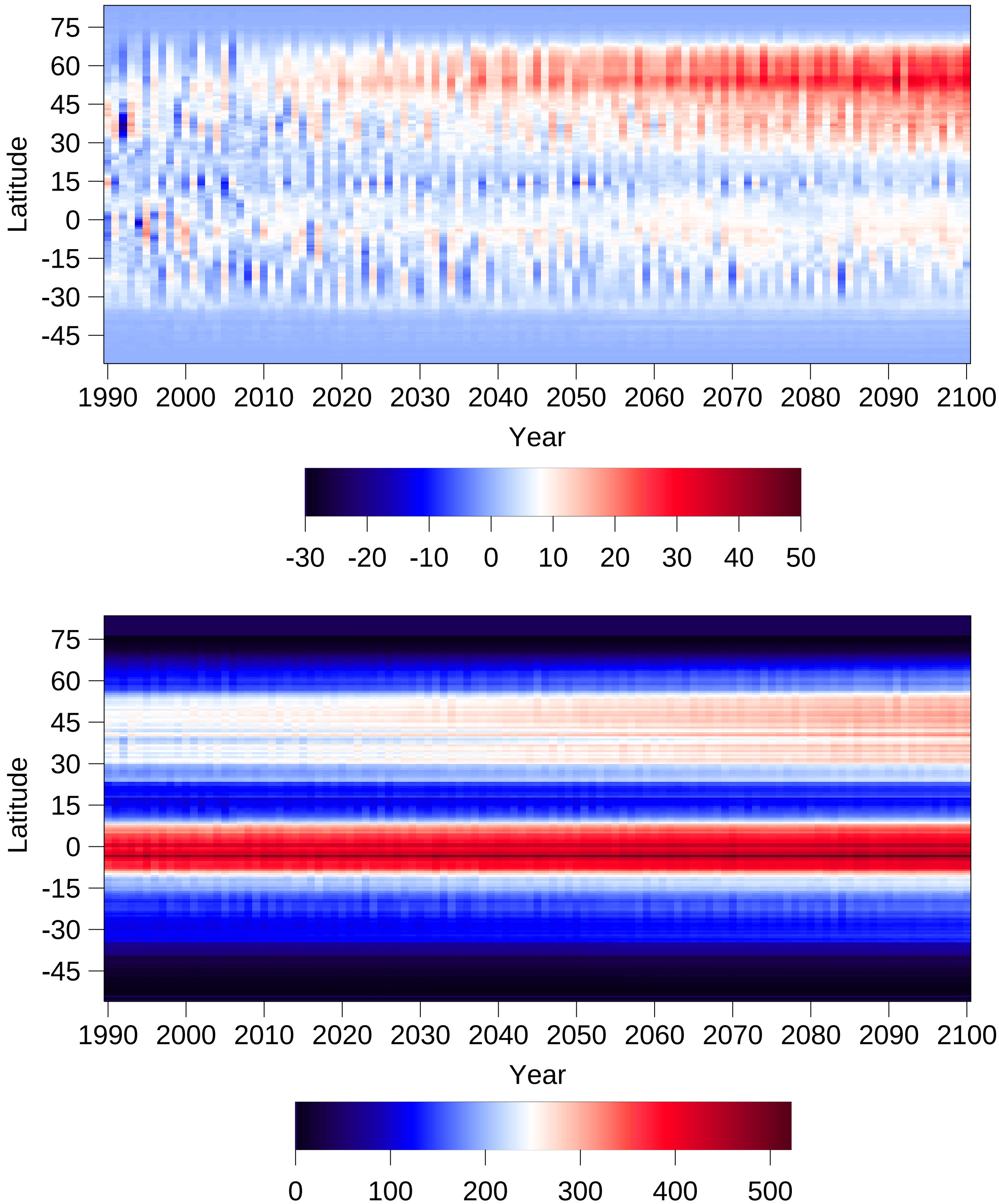


Figure 6. Latitudinal distributions of total annual net ecosystem production (NEP, TgC/yr; upper panel) and net primary production (NPP, TgC/yr; lower panel) along 0.5˚-resolution latitudinal bands over the period of 1990–2100 under the RRR transient climate change prediction.

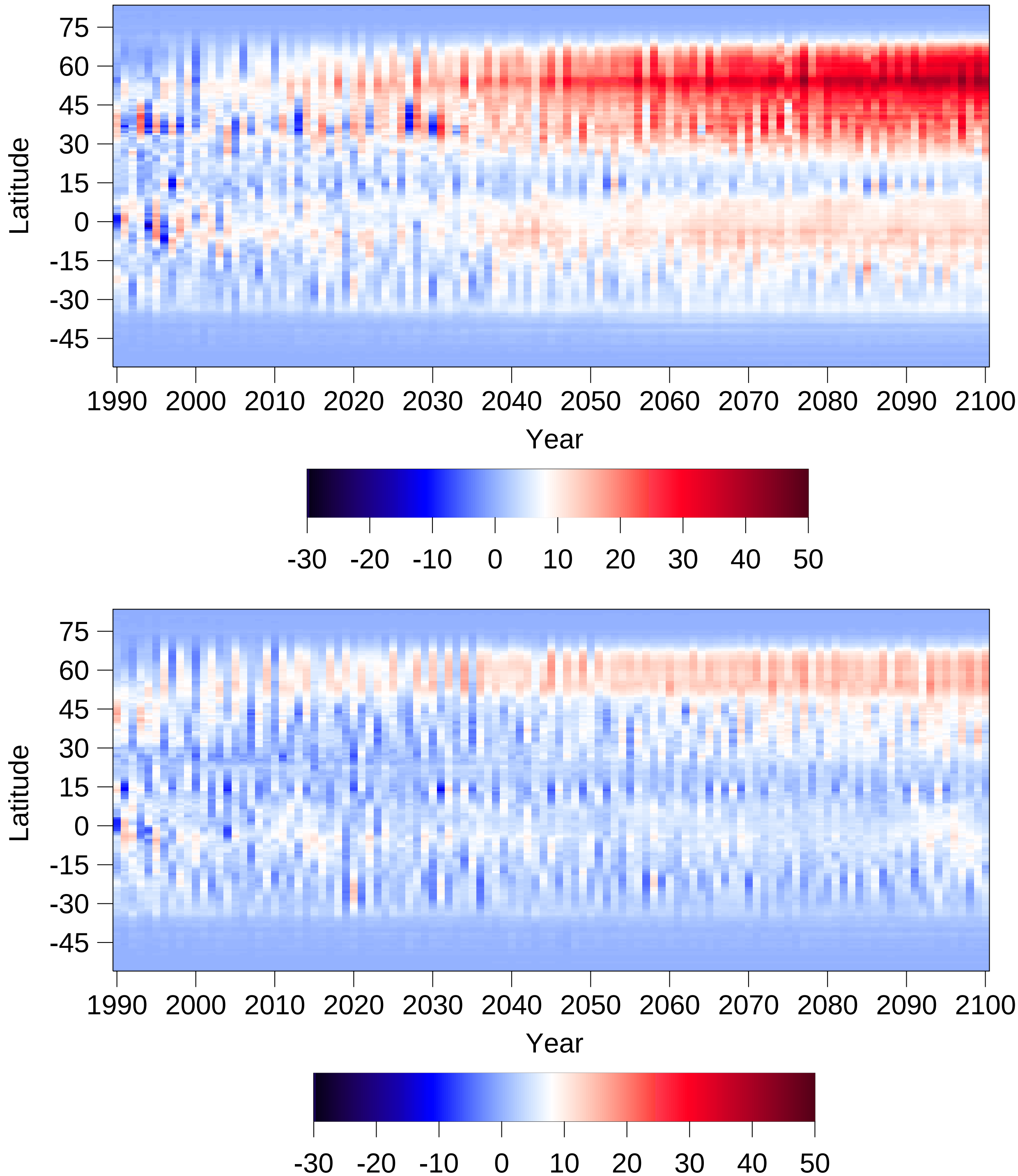


Figure 7. Latitudinal distributions of total annual net ecosystem production (NEP, TgC/yr) along 0.5°-resolution latitudinal bands over the period of 1990–2100 under the HHL (upper panel) and LLH (lower panel) transient climate change predictions.