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Regional pattern and interannual variations in global terrestrial carbon uptake in response to changes in climate and atmospheric CO_2

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ABSTRACT

Atmospheric measurements indicate that the terrestrial carbon sink increased substantially from the 1980s to the 1990s, but which factors and regions were responsible for the increase are not well identified yet. Using process- and remote sensing-based ecosystem models, we show that changes in climate and atmospheric CO_2 in the period 1981–2000 enhanced net ecosystem production (NEP) and caused major geographical changes in the global distribution of NEP. In the 1980s the Americas accounted for almost all of the global NEP, but in the 1990s NEP in Eurasia and Africa became higher than that of the Americas. The year-to-year variation in global NEP was up to 2.5 Pg C (1 Pg = 10^{15} g), in which 1.4 Pg C was attributable to the El Niño Southern Oscillation cycle (ENSO). NEP clearly decreased in El Niño and increased in La Niña in South America and Africa, but the response in North America and Eurasia was mixed. The estimated NEP increases accounted for only 30% of the global terrestrial carbon sink but can explain almost all of the increase from the 1980s to the 1990s. Because a large part of the increase in NEP was driven by the long-term trend of climate and atmospheric CO_2, the increase in the global terrestrial carbon sink from the 1980s to the 1990s was a continuation of the trend since the middle of the twentieth century, rather than merely a consequence of short-time climate variability.

1. Introduction

Terrestrial ecosystems are taking up 2–4 Pg C per year, accounting for 20–30% of annual total anthropogenic CO_2 emission of 7–8 Pg C into the atmosphere (Prentice et al., 2001). The Kyoto Protocol considers some terrestrial carbon sinks in its legally binding framework for stabilizing atmospheric greenhouse gas concentrations (IGBP, 1998) and so information on changes in the terrestrial carbon sink in space and time is a fundamental requirement for effective implementation of the Protocol. At this time, however, there are large uncertainties in the size and geographical distribution of the terrestrial carbon sink and in our understanding of the mechanisms underlying it (Schimel et al., 2001; Prentice et al., 2001).

Atmospheric measurement and inverse modelling indicate that the terrestrial carbon sink increased substantially from the 1980s to the 1990s (Schimel et al., 2001; Gurney et al., 2002; Houghton, 2003), but which factors and regions were responsible for the changes are not well known. Recent studies suggest the presence of a large terrestrial carbon sink in the tropics as well as in the north (Malhi and Grace, 2000), and a dynamic distribution between North America and Eurasia (Schimel et al., 2001; Gurney et al., 2002). Factors that may cause the increasing terrestrial carbon uptake include the response of terrestrial ecosystems to CO_2 fertilization, nutrient deposition, climatic variation and the effects of changes in land use (forest regrowth, afforestation, and agricultural abandonment).

Some studies have linked the increase in the terrestrial carbon sink to climate variation (Lucht et al., 2002; Nemani et al., 2002; Cao et al., 2002); however, the effects of this on the regional and interannual patterns of the terrestrial carbon sink have not been adequately quantified. Some studies using remote sensing data have suggested that global warming enhances terrestrial carbon uptake by stimulating plant growth in the north (Lucht et al., 2002; Myneni et al., 2001), but warming may also undermine the carbon sink by reducing plant growth in dry regions and by stimulating soil carbon decomposition (Rustad and Norby, 2002). A comprehensive analysis of the impacts of climate change on the full carbon cycle of ecosystems is essential for quantifying and

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understanding regional and interannual patterns in the terrestrial carbon sink.

The global climate has undergone unusual changes in the last two decades. For example, temperature increased by the largest magnitude to reach the highest value in the instrumental record, and increases in precipitation in the north contrasted with substantial decreases in subtropical regions in the 1980s (Folland et al., 2001). The El Niño Southern Oscillation (ENSO) cycle—one of the most important drivers of interannual global climate variability—has changed, with more frequent, persistent and intense El Niño than La Niña: the 1997/98 El Niño was the strongest and the 1990–1995 El Niño was the longest in the twentieth century (Folland et al., 2001; Kerr, 1999). The signature of the ENSO cycle in interannual variations of atmospheric CO_2 concentration has been detected (Schimel et al., 2001; Prentice et al., 2001), but quantitative relationships between these variations in different regions have yet to be determined. Here we present an investigation of the impacts of climate variability and atmospheric CO_2 on terrestrial ecosystem carbon fluxes and net uptake in various continents from 1981 to 2000 using a process-based biogeochemical model and a remote sensing-based vegetation productivity model.

2. Models and data

2.1. The CEVSA model

We used the CEVSA (Carbon Exchanges in the Vegetation–Soil–Atmosphere system) model (Cao and Woodward, 1998; Cao et al., 2002), forced by observed variations in climate and atmospheric CO_2, to quantify changes in net primary production (NPP), soil heterotrophic respiration (HR) and net ecosystem production (NEP) from 1981 to 1998. CEVSA simulates ecosystem energy transfers, water, carbon and nitrogen cycles and their relationships with environmental conditions. The modelling strategies are briefly described in the following sections.

2.1.1. Plant net primary productivity. CEVSA calculates rates of plant photosynthesis, stomatal conductance and autotrophic respiration and determines NPP as a difference between the whole-plant gross photosynthesis and autotrophic respiration (Woodward et al., 1995; Cao and Woodward, 1998). In the model the plant canopy is divided into layers, each of which has a unit of leaf area index (LAI), for which rates of CO_2 assimilation, respiration and stomatal conductance are calculated separately. LAI is determined based on an assumption that the carbon fixed in photosynthesis is allocated to leaves in a manner that maximizes the net carbon assimilation of the whole canopy that can be sustained by both the water and nitrogen supply.

2.1.2. Vegetation carbon turnover and litter production. CEVSA calculates the carbon allocation among leaves, stems and roots based on leaf mesophyll resistance to CO_2 assimilation and stomatal resistance to water loss. The carbon allocated to various plant organs is given a mean residence time with a statistical distribution that varies depending on the functional type of the plant. The carbon storage in various plant organs and litter production are estimated based on the carbon allocation, autotrophic respiration, residence time and mortality. The seasonality of litter production is determined according to the phenology of the functional type of the plant.

2.1.3. Soil carbon turnover and net ecosystem production. CEVSA divides soil organic matter into surface litter, root litter, microbes and slow and passive carbon pools. All carbon transformations and decomposition in these pools are treated as first-order rate reactions and each of them has a specific decay rate that is adjusted according to temperature, soil moisture, nitrogen availability, soil texture and litter quality. Nitrogen transformations between these pools follow carbon flows and are equal to the product of the carbon flux and the nitrogen/carbon ratio of the pool that receives the carbon. HR is determined as the sum of gaseous carbon releases by microbial decomposition. The difference between NPP and HR, defined as NEP, represents the net changes in the carbon storage of vegetation and soils. If there are no disturbances such as fires, clearance of vegetation or harvest, NEP indicates the net ecosystem carbon uptake or release.

2.1.4. Data sources and model runs. The climate data that were used to run CEVSA include monthly mean values of temperature, precipitation, water vapour pressure, frequency of wet days, diurnal temperature range and duration of sunshine with a spatial resolution of 0.5 ° (New et al., 2001). Monthly atmospheric CO_2 concentrations were obtained from the Scripps Institution of Oceanography air sampling network (Keeling and Whorf, 2002). The current vegetation distribution was obtained from a 1 km global land cover map based on satellite remote sensing (Hansen et al., 2000), and its change in the period studied was not considered. The croplands were considered as natural grasslands, and the effect of nitrogen deposition on the carbon cycle of the ecosystem was not accounted for in the study. The information on soil properties was derived from the FAO-IIASA-ISRIC global soil data set (Batjes et al., 1997). Using the climate, vegetation and soil data, we first ran CEVSA with the average climate for the period 1951–2000 until an ecological equilibrium was reached, and then made simulations from January 1951 to December 1998 with transient changes in climate and atmospheric CO_2. Only the modelling results from 1981 to 2000 were used in this study; the run from 1951 to 1980 was to establish realistic initial pool sizes of carbon and water for the period 1981–2000.

2.2. GLO-PEM

We also estimated 10-day NPP from 1981–2000 using the GLObal Production Efficiency Model (GLO-PEM) that uses data almost entirely from remote sensing, including both the normalized difference vegetation index (NDVI) and meteorological variables (Prince and Goward, 1995; Cao et al., 2004), providing an independent means of evaluating the NPP estimate of CEVSA. GLO-PEM consists of linked components that describe processes of canopy radiation absorption, utilization and autotrophic respiration:

$$NPP = \Sigma_t[(S_t N_t)\varepsilon_g - R]$$

where S_t is the incident photosynthetically active radiation (PAR) in time t, N_t is the fraction of incident PAR absorbed by the vegetation canopy (Fapar) calculated as a linear function of NDVI, ε_g is the light utilization efficiency of the absorbed PAR by vegetation in terms of gross primary production limited by temperature, water vapour pressure deficit and soil moisture and R is autotrophic respiration calculated as a function of standing aboveground biomass, air temperature and photosynthetic rate.

GLO-PEM was driven with the Pathfinder AVHRR Land (PAL) data at resolutions of 8 km and 10 days derived from channels 1, 2, 4 and 5 of the AVHRR sensors aboard the NOAA-7, 9, 11 and 14 satellites (Agbu and James, 1994). While the effects of Rayleigh scattering and ozone were corrected in producing the Pathfinder data sets, cloud screening was carried out in GLO-PEM, and the orbital drift both within and between the satellite platforms on the thermal bands were also corrected (Goetz et al., 2000; Cao et al., 2004). The incident PAR was obtained from the International Satellite Cloud Climatology Project (Frouin and Pinker, 1995). The precipitation data were derived from Global Precipitation Climatology Program data sets, inferred from infrared and microwave satellites (Huffman and Bolvin, 2000).

3. Results and discussion

3.1. Geographical pattern and temporal variability

The estimated global annual variations in NPP and HR during the period 1981–1998 caused by changes in climate and atmospheric CO_2 using CEVSA had ranges of 4.48 Pg C and 3.50 Pg C. Consequently, global annual NEP varied between −0.64 and 1.68 Pg C with a mean value of 0.73 Pg C. The mean annual NEP for the period was 0.28 Pg C for northern latitudes (>20 °N) and 0.44 Pg C for tropical latitudes (20 °N–20 °S), and it was 0.41 Pg C for Eurasia, Africa and Australia and 0.32 Pg C for the Americas. From the 1980s to the 1990s, global annual NPP increased by 3.5% with a range from 1.9% in South America to 6.0% in Africa (Table 1). The northern and tropical latitudes accounted for 38% and 62%, respectively, of the increases in NPP. The estimated interannual variation in NPP using the process-based

Table 1. Annual mean temperature (T) and precipitation (PPT), and the estimated net primary productivity (NPP), soil heterotrophic respiration (HR), litter production and net ecosystem production (NEP) in various regions using the process-based CEVSA model

	T[a] (°C)	PPT[a] (%)	NPP (Pg C)	Litter (Pg C)	HR (Pg C)	NEP (Pg C)
North America						
1981–1990	0.30	3.2	6.23	6.09	6.15	0.08
1991–1998	0.53	4.6	6.48	6.31	6.22	0.25
Change	0.23	1.4	0.25	0.22	0.08	0.17
Eurasia						
1981–1990	0.43	0.6	12.03	11.90	12.02	0.01
1991–1998	0.64	1.9	12.44	12.22	12.18	0.26
Change	0.21	1.3	0.41	0.32	0.16	0.25
South America						
1981–1990	0.21	0.1	14.14	13.91	13.95	0.19
1991–1998	0.44	−0.1	14.41	14.08	14.08	0.33
Change	0.22	−0.2	0.27	0.17	0.13	0.14
Africa						
1981–1990	0.18	−3.1	11.57	11.45	11.57	0.00
1991–1998	0.39	−1.0	12.28	11.92	11.84	0.44
Change	0.21	2.1	0.71	0.47	0.27	0.44
Asia Pacific						
1981–1990	0.31	−0.9	7.38	7.28	7.41	−0.03
1991–1998	0.46	−0.5	7.56	7.38	7.49	0.07
Change	0.15	0.4	0.18	0.10	0.08	0.10
Globe						
1981–1990	0.30	−0.2	51.35	50.63	51.10	0.25
1991–1998	0.51	0.7	53.17	51.91	51.81	1.36
Change	0.21	0.9	1.82	1.28	0.71	1.11

[a]The temperature and precipitation are the anomaly relative to the mean values for vegetated land in the twentieth century using the data from New et al. (2001).

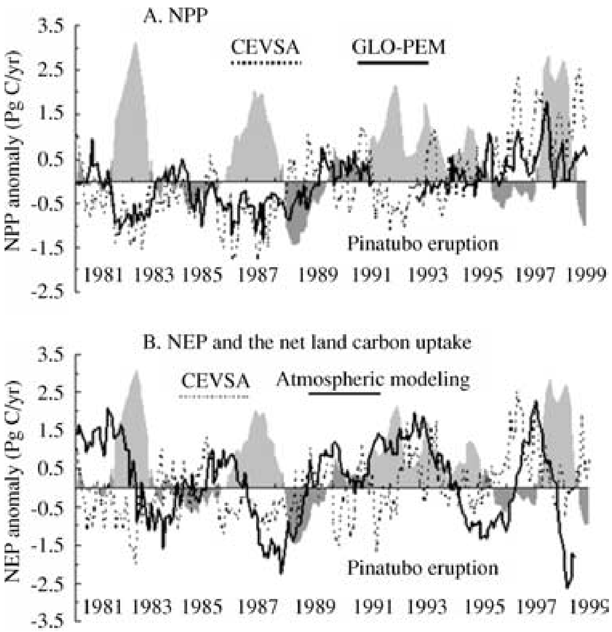

Fig. 1. Estimated interannual anomalies in monthly NPP and NEP using the process-based CEVSA and in NPP using remote sensing-based GLO-PEM. The net land uptake (represented by positive values) was derived from atmospheric inverse modelling (Bousquet et al., 2000). The GLO-PEM estimate of NPP for June 1991–June 1992 was omitted because the aerosols from the Pinatubo eruption prevented effective satellite monitoring. The shaded area with positive values indicates El Niño seasons and that with negative values indicates La Niña seasons (Wolter and Timlin, 1998).

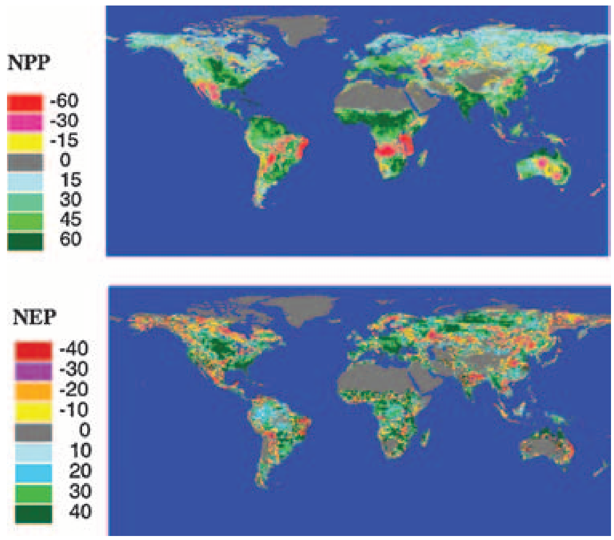

Fig. 2. Estimated changes in annual NPP (g C m^{-2}) using the remote sensing-based GLO-PEM and in NEP (g C m^{-2}) using the process-based CEVSA from the 1980s to the 1990s. NEP increased strongly in Africa, Eurasia and eastern North America but decreased in some regions in northern high latitudes and dry central Asia in response to warming.

CEVSA agreed with the remote sensing-based GLO-PEM results ($R^2 = 0.62$, $p < 0.01$, Fig. 1). The regional patterns of the changes in NPP (Table 1) also agreed with the remote sensing-based estimate (Fig. 2, Cao et al., 2004).

Global annual HR estimated with CEVSA increased by 1.4% from the 1980s to the 1990s, less than the increase in NPP. Therefore, the decadal mean annual NEP increased by 1.11 Pg C (Table 1), to which the northern and tropical latitudes contributed 40% and 60%, respectively. The geographical distribution of NEP shifted from western to eastern longitudes: in the 1980s almost all of the global NEP originated from the Americas, but in the 1990s 52% was from Africa and Eurasia. The mean annual NEP of South America was the highest among the continents but did not increase much as in other continents; thus the contribution to the global NEP decreased from 76% of in the 1980s to 13% in the 1990s. Except for the early 1980s, the interannual variations estimated using CEVSA were similar to that derived from atmospheric inverse modelling (Bousquet et al., 2000) (Fig. 1). For 1982 and 1983 when a strong El Niño occurred (Fig. 1), CEVSA estimated net carbon releases, contrasting with substantial carbon uptake inferred from atmospheric inverse modelling (Fig. 1) that was based on few atmospheric measurement data for the period (Bousquet et al., 2000).

3.2. *Effects of climatic factors and atmospheric CO_2*

Global terrestrial temperature increased by 0.21 °C from the 1980s to the 1990s, and this alone increased HR more than NPP and hence reduced global annual NEP by 0.35 Pg C (Fig. 3). In the north, the warming increased NPP less than HR because the stimulation to plant growth was limited by the correlated water stress (Barber et al., 2000) and the higher sensitivity of soil microbial activity than photosynthesis to warming (Rustad and Norby, 2002). In the tropics, the warming reduced NPP and increased HR and so reduced NEP (Fig. 3). Although the sensitivity of HR decreases at higher temperatures (Luo et al., 2001), increases in HR with warming are apparent in field observation (Rustad and Norby, 2002) and its effect is presaged by the decline in soil organic carbon with decreasing latitude (Post et al., 1982). The CEVSA model that was used in the present study considers the decreasing sensitivity of HR at higher temperature: the mean value of Q_{10} (the relative increase of HR with an increase of temperature by 10 °C) decreases from about 2.5 at temperatures below 20 °C to 1.5 at temperatures higher 20 °C (Cao and Woodward, 1998).

Combined changes in temperature and precipitation increased global NEP significantly (Fig. 3), because precipitation increases in North America, Eurasia and Africa (Table 1) enhanced NPP and moderated the stimulation of the warming to HR (Fig. 3). An upward trend of soil moisture and increased rates of hydrological cycling were observed in Europe (Robock et al., 2000) and North America (Groisman et al., 2001) in the 1990s. Among the continents, Africa had the largest increase in precipitation as it was recovering from the severe drought of the

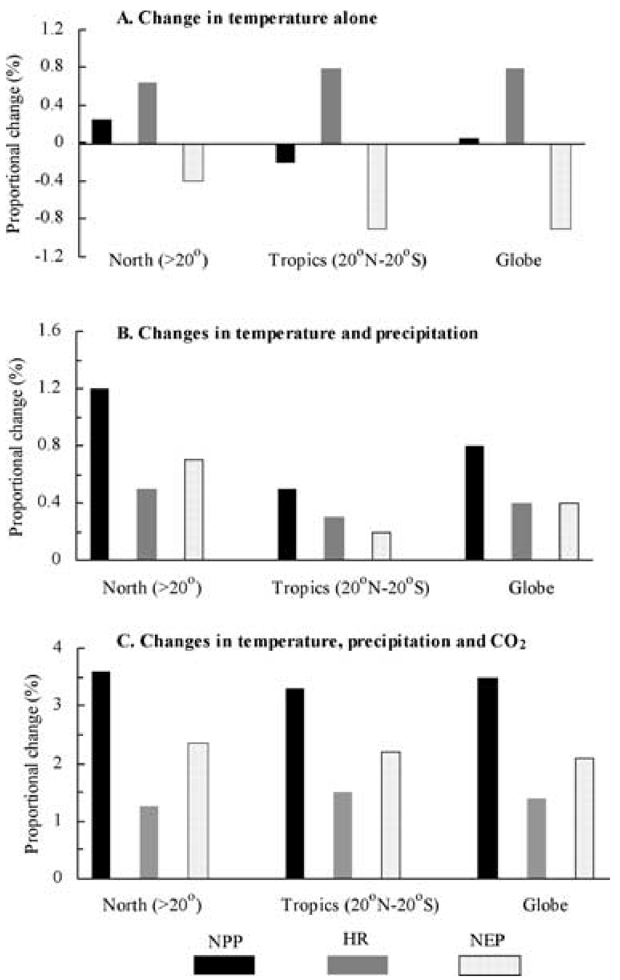

Fig. 3. The CEVSA estimates of changes in NPP, HR and NEP from the 1980s to the1990s under different climate change scenarios: (A) temperature change alone, (B) changes in temperature and precipitation, and (C) changes in temperature, precipitation and atmospheric CO_2.

1980s (Nicholson et al., 2001). In contrast, precipitation in South America decreased and increased only a little in Asia Pacific, so NPP and NEP in these regions increased slightly (Table 1).

Increases in atmospheric CO_2 (by 28 ppmv from 1981 to 1998) produced further increases in NPP and NEP (Fig. 3). The CO_2 fertilization effect is particularly strong in the tropics, compensating for the negative effect of warming on NPP (Fig. 3). The elevated CO_2, warming and precipitation increases interact positively to enhance NPP and NEP. The response of photosynthetic biochemical reactions to increases in atmospheric CO_2 is greater in warmer conditions (DeLucia et al., 1999; Körner, 2000), so the CO_2 fertilization effect will increase with warming in cool regions and be high in warm environments. Increases in atmospheric CO_2 can also enhance NPP by reducing stomatal conductance and increasing the efficiency of water utilization by plants (Drake et al., 1997; Körner, 2000). The increases in precipitation in the north and Africa are helpful to the realization of the CO_2 fertilization effect by alleviating warming-induced water stress. The CO_2-induced relative increases in NPP (Fig. 3) by about 2% from the 1980s to the 1990s are consistent with CO_2 enrichment experiments (Körner, 2000).

3.3. Dynamic responses to the ENSO

The ENSO cycle causes an alternation of dry and warm El Niño with wet and cool La Niña in the tropics and affects the global climate through teleconnections. The global effect of the ENSO was that NEP decreased from the average by 24% during El Niño and increased from the average by 18% during La Niña (Figs. 1 and 4). Annual global NEP in the 1982/83 and 1986/87 El Niños was lower by 1.36 Pg C and 1.03 Pg C, respectively, than the following La Niña years. NEP reached its highest value in the 1995/96 La Niña and then dropped by 32% in the following 1997/98 El Niño. The impact of the ENSO cycle on NEP was strong and consistent in South America and Africa but was mixed in North America and Eurasia (Fig. 4), where the mean NEP was not significantly different between El Niño and La Niña episodes. In the north, changes in NEP differed between individual ENSO events, for example NEP increased in the 1997/98 El Niño and decreased in the 1988/89 La Niña (Fig. 4). In 1992/93 El Niño, NEP did increase (Fig. 2) because of a large decrease in HR caused by a cooling associated with the Pinatubo eruption (Hansen et al., 1996). Other climate phenomena such as the North Atlantic Oscillation and the Pacific Decadal Oscillation affect biotic metabolism and therefore ecosystem carbon fluxes (Stenseth et al., 2002); however, our analysis did not find a consistent correlation of interannual variations in terrestrial ecosystem carbon fluxes with those climate modes at regional or global scales.

3.4. Relationships with changes in the terrestrial carbon sink

The increase in annual NEP from 0.25 Pg C in the 1980s to 1.36 Pg C in the 1990s (Table 1) is very close to the increase in the net land carbon uptake from 0.2 to 1.4 Pg yr^{-1} based on atmospheric measurements and inverse modelling (Schimel et al., 2001; Prentice et al., 2001; Gurney et al., 2002), but is higher than the estimate of the increase by Houghton (2003). Our estimated NEP increase is a result of both short-term climate fluctuation and long-term changes. The precipitation increase in the north during the period 1981–2000 (Table 1) was consistent with its increasing rate of 0.7 to 1.2% per decade since the beginning of the twentieth century, as a result of the enhancement of the hydrological cycle by global warming (Folland et al., 2001). However, the remarkable rainfall increases in Africa from the 1980s to the 1990s (Table 1) contrasted with a long-term drying trend in the tropics (Folland et al., 2001). The low NEP in the 1980s was related to the warm and dry climate at the time when the global mean temperature for the vegetated land surface

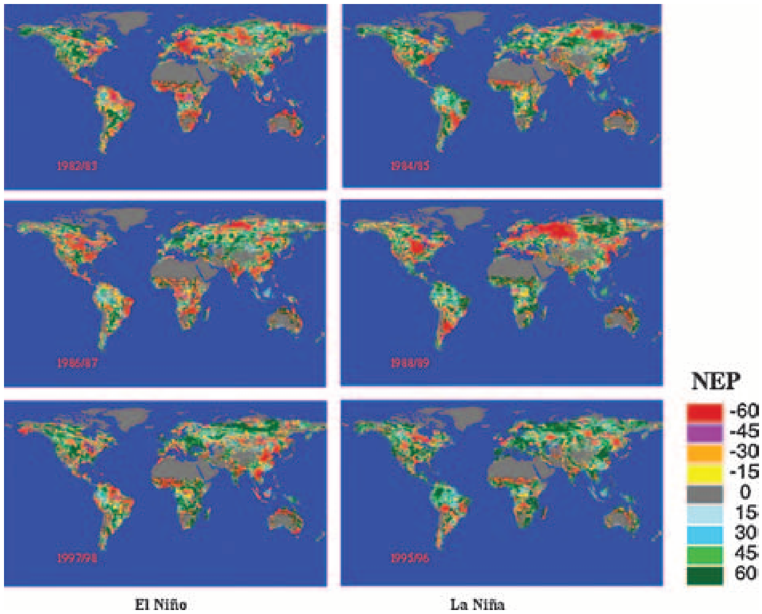

Fig. 4. The changes in the spatial pattern of net ecosystem production (NEP, g C m^{-2} yr^{-1}) in the El Niño and La Niña events, estimated with the process-based CEVSA.

increased by 0.34 °C and precipitation dropped by 1.5% from the 1970s (New et al., 2001). The 1990s were warmer but wetter; the decadal mean precipitation for the globe was the third highest, that for North America and Eurasia reached the highest level in the twentieth century (New et al., 2001) and the precipitation in Africa at the end of the 1990s had reached its pre-drought level (Nicholson et al., 2001).

4. Conclusions and discussion

During the 1980s and the 1990s changes in climate and atmospheric CO_2 caused year-to-year fluctuation of annual global NEP up to 2.3 Pg C, and an increase from 0.25 Pg C yr^{-1} in the 1980s to 1.36 Pg C yr^{-1} in the 1990s. The NEP increases were smaller in northern than in tropical latitudes and were larger in western than in eastern longitudes: Eurasia and Africa had near to zero mean annual NEP in the 1980s but had higher NEP than the Americas in the 1990s. The increases in the global NEP were mainly caused by increases in precipitation and atmospheric CO_2. The strong warming in the period had a negative effect on NEP by reducing NPP in tropical latitudes and enhancing soil respiration globally. The increases in NEP can explain almost all of the increases in the terrestrial carbon sink in these periods. The ENSO cycle in these periods caused an interannual variation in NEP up to 1.4 Pg C, with clear decreases in El Niño and increases in La Niña in South America and Africa and a mixed response in North America and Eurasia.

The mechanisms of the terrestrial carbon sink can be classified into natural mechanisms (including CO_2 fertilization, climatic variation and nutrient deposition) and land use mechanisms (including agricultural abandonment, forest regrowth and afforestation). The relative contribution of the natural mechanisms has been estimated in some studies (Friedlingstein et al., 1995; Thompson et al., 1996; Houghton et al., 1999) to be 60–70%, but in other studies as less than 20% (Caspersen et al., 2000; Schimel et al., 2000). Caspersen et al. (2000) indicated that land use changes have caused most of the current terrestrial carbon sink in the United States with only a minor contribution from natural mechanisms. In the present study, the NEP that was induced by CO_2 fertilization and climatic variation accounted for 30% of the total terrestrial carbon sink implied by the atmospheric carbon budget (Schimel et al., 2001), and the fraction changed from 13% in the 1980s to 49% in the 1990s. According to the regional partitioning of the carbon sink in Schimel et al. (2001), the contribution of NEP varied from 18% in the northern latitudes to 31% in the tropical latitudes and from 16% in Eurasia to 28% in North America in the early 1990s. The lower relative contribution of the climate-induced NEP to the carbon sink in Europe and North America may be related to their land use history of agricultural abandonment and afforestation, which caused substantial terrestrial carbon uptake (Caspersen et al., 2000; Janssens et al., 2003).

The higher NEP in the tropics than in the north emphasizes the importance of tropical ecosystems in the terrestrial carbon sink, a conclusion that is supported by recent regional atmospheric carbon budgets and some site measurements (Malhi and Grace, 2000). However, the carbon budget for tropical terrestrial ecosystems is highly uncertain (DeFries et al., 2002; Houghton, 2003). The tropical net land carbon flux inferred from atmospheric inverse modelling is controversial because of sparse atmospheric sampling in those regions (Schimel et al., 2001; Gurney et al., 2002). A recent study based on remote sensing data (DeFries et al., 2002) indicated that land use-induced carbon release from the tropics might be just half of that value widely used in global and tropical carbon budgets (Schimel et al., 2001; Houghton, 2003) and increased from the 1980s to the 1990s. Unlike in the north, few systematic, networked carbon flux measurements and ecosystem carbon inventories are conducted in tropical regions, so direct observational data are lacking to evaluate atmosphere- and satellite-based estimates. To reduce the uncertainties in the tropical carbon budget requires networks of multiscale, integrated observations from space (e.g. using approaches of remote sensing and atmospheric measurements) and on land (e.g. ecosystem inventories and eddy flux measurements) and data–model fusion based on multiscale observations as have been planned and implemented in North America (Wofsy and Harriss, 2002) and Europe (Sezzi and Valentini, 2003).

The estimated increases in NEP accounted for almost all of the increase in the global terrestrial carbon sink (Schimel et al., 2001; Gurney et al., 2002), implying that changes in climate and atmospheric CO_2 drove the increase in the carbon sink from the 1980s to the 1990s. Houghton (2003) estimated that the terrestrial carbon sink increased by much less; if this is so the result of the present study suggests that other factors might cause substantial increases in carbon release to offset a part of the increase in NEP. Our estimated increase in NEP was the result of long-term changes in climate and atmospheric CO_2 as well as short-term climate fluctuation; the increase in the terrestrial carbon sink from the 1980s to the 1990s therefore was a continuation of the trend since the middle of the twentieth century, rather than merely a consequence of short-term climate variability (Schimel et al., 2001). This study focused on the effect of climate variation and atmospheric CO_2 increases, but land use changes are also important for terrestrial carbon uptake so we are using high-resolution remote sensing data (e.g. from the Moderate Resolution Imaging Spectroradiometer, MODIS, aboard the Earth Observation System satellites) to investigate the combined effects of changes in climate and land use on the carbon cycle of the terrestrial ecosystem. In the present study, the estimated response of carbon fluxes in the ecosystem to climate change using the climate data set with a spatial resolution of 0.5° (the best available) may not capture the spatial variability caused by some climatic phenomena at smaller scales. Therefore, higher-resolution data for climate and other factors are needed to obtain more a accurate estimate of changes in the terrestrial carbon sink.

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