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Variability and recent trends in the African carbon balance

P. Ciais[1], **S.-L. Piao**[2], **P. Cadule**[1], **P. Friedlingstein**[1], **and A. Chédin**[3]

[1]LSCE, UMR CEA-CNRS, CE, L'Orme des Merisiers, Gif-sur-Yvette, France
[2]Department of Ecology, College of Urban and Environmental Sciences, Peking University, Beijing, China
[3]Groupe Analyse du Rayonnement Atmospherique, Laboratoire de Meteorologie Dynamique, Institut Pierre Simon Laplace, ARA/LMD/IPSL, Ecole Polytechnique RD 36, Palaiseau, France

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Correspondence to: P. Ciais (philippe.ciais@lsce.ipsl.fr)

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Abstract

We modeled the African carbon balance over the past century using the process based ORCHIDEE model, forced by changing climate and human induced changes in land use. The model includes a simple parameterization of natural fires, but the natural vegetation dynamics was ignored. The period analyzed is 1901–2002. Overall, we found that the African net carbon balance (Net Biome Productivity, NBP) increased from a net carbon source of $-0.14\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1980s to a net carbon sink of $0.15\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1990s. Deforestation is estimated to be a source of $0.13\,\mathrm{Pg\,C\,yr^{-1}}$, implying a compensating effect of climate trends (mainly increasing precipitation) plus CO_2 fertilization, causing a sink of $0.28\,\mathrm{Pg\,C\,yr^{-1}}$. We found that the interannual variability of NBP is mostly driven by photosynthesis changes. Over savannas, photosynthesis changes from one year to the next are strongly correlated with rainfall changes (R^2=0.77 in northern Africa, and R^2=0.42 in southern African savannas). Over forests, such a control by rainfall is not found. The main spatial pattern of interannual variability in NBP and in gross carbon fluxes is related with ENSO, with dryer conditions prevailing over savannas during El Niño and wetter conditions over forests. Climate induced variations in fire emissions respond to this ENSO forcing, but they do not determine strongly the NBP variations. Finally, we model that ecosystem respiration variations (mostly due to autotrophic respiration) are tailing with those of photosynthesis, on interannual as well as on decadal time scales, but this result is uncertain given the potential for acclimation for autotrophic respiration processes.

1 Introduction

Little is known about the carbon balance of the African continent. One particularity of Africa is the extensive presence of savannas, with $15.1\times10^6\,\mathrm{km}^2$, roughly 50% of the continent (Menaut et al., 1985) and 70% of the World's savannas. Savannas is a productive vegetation (Lieth and Wietaker, 1975; Scholes and Hall, 1996) as compared to other biomes, with an average Net Primary Productivity (NPP) of 590±220 g C m^{-2} yr^{-1} (Grace et al., unpublished results). Scaling up this estimate to the entire African savanna biome gives an NPP of 8.9 Pg C yr^{-1}, that is 13.6% of the global NPP. Apart from savanna, forest is also an important biome in Africa. African forests are among the most pristine on Earth and contain large carbon stocks in biomass, up to 400 tC ha^{-1} in Equatorial rainforests (Brown et al., 1996). These forest carbon stocks are vulnerable to human impact and to climate change.

The main reason for better quantifying the carbon balance of Africa and its component fluxes, is that the population is increasing faster than in other regions of the globe (source: http://maps.grida.no/go/graphic/population_and_development_in_africa). Further, more than 40% of the African population lives in arid, semi arid or dry sub-humid areas, increasing the pressure on ecosystem services, in particular for agricultural production (Sultan et al., 2005; Ingram et al., 2002). Currently, the human appropriation of NPP in populated regions of Africa is as high as in Europe (Haberl et al., 2007).

Therefore, it is important to quantify the mean productivity of natural ecosystems, as well as its variability and trends, as the NPP of cultivated ecosystems is most likely lower than natural NPP in this region (Haberl et al., 2007). West Africa, the most densely populated region of the continent, is subject to strong interannual and decadal precipitation changes. There is a drought trend in this region since 1950, followed by a reversal to wetter conditions after 1980 but rainfall has not yet reached back the 1950 levels. The recent drought strucked the region at the end of the 1960s till the beginning of the 1990s. The recent years (1994–2006) are characterized by still dry conditions in the Western Sahel while the Eastern Sahel benefits from wetter conditions (Ali and Lebel, 2008[1]). Further, changes in global and local economic drivers, in population density and wealth are likely to modify regionally the regime of fires, which in turn will change the productivity and the carbon balance of savannas and forests.

A second important motivation for studying the carbon balance of Africa is that defor-

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[1] A. Ali and J. Lebel: The sahelian standardized rainfall index revisited, Int. J. Climatol., submitted, 2008.

estation in Central Africa, has been historically less pronounced than in other tropical continents (Houghton et al., 2003), but is now catching up. Although their exploitation is partly regulated, Central African forests are under the threat of accelerated logging, with 30% of these forests being under logging concessions (Laporte et al., 2007). The wood removal from African forest increased from 500×10^6 m^3 (roughly 0.125 Pg C yr^{-1}) to 660×10^6 m^3 in 2005 (FAO, 2007). The area of forest and other woodlands in Africa decreased between 2000 and 2005 at a high rate of 6×10^6 ha per year, explaining more than half of the global decline in forest area (FAO, 2007). The African forest carbon stocks thus appear to be particularly vulnerable, although they have been spared from massive deforestation so far. In the context of the REDD reduced deforestation mechanism, it is thus important to quantify both the carbon stocks and the carbon fluxes of African forests, since these stocks may be larger and less affected by clearing than in other regions of the Tropics.

Unfortunately, in situ data are scarce and incomplete to characterize the African carbon balance. Apart from forest inventories in few countries (FAO, 2007), some ecosystem scale measurements (e.g. Abadie et al., 2006) or regional campaigns like the SAFARI-2000 programme, the IGBP African transects initiated 10-years ago (Kochs et al., 1995) have not delivered comprehensive information on carbon stocks and fluxes. In that context, remote sensing data and ecosystem models form the base of our knowledge to tackle the problem of quantifying and understanding the African carbon balance and drivers (e.g. Hiernaux et al., 2008[2]).

In this paper, we use the ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms; Krinner et al., 2005) process-based global vegetation model to simulate the carbon balance of the African continent, and its component fluxes of photosynthesis, respiration and fire emissions. The period of study is the past century, allowing to analyze interannual variability, and to gain further insights on decadal vari-

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[2] Hiernaux, P. H. Y., Mougin, E., Diarra, L., Soumaguel, N., Lavenu, F., and Tracol, Y.: Sahelian rangeland response to changes in rainfall over two decades in the Gourma region, Mali, J. Hydrol., submitted, 2008.

ability. After a description of the modeling framework (Sect. 2), we analyze the impacts of climate variability on carbon fluxes (Sect. 3). The associated continental-scale and regional modes of variability are discussed. Since the ORCHIDEE model also participated to the CAMIC (CarboAfrica Model Inter Comparison) experiment, which covers the past 25 years (Weber et al., 2008[3]), we will give more focus here in the discussion of interannual variability during the past century. Then, the effects of long-term climate trends, rising CO_2, and changes in land use are studied (Sect. 4). In that context, the results of ORCHIDEE are evaluated against long-term satellite observation of vegetation greenness and against river runoff observations.

The goal of this preliminary work is not to provide a realistic quantitative assessment of the African carbon balance and its drivers. Neither at this early stage of the CARBOAFRICA project, nor through past projects, we have enough data to falsify or confirm the model predictions. Rather, we seek to gain a deeper understanding of our model's behavior over Africa, attempting wherever this is possible to check and understand the arising model output against global datasets.

2 Methods

2.1 Model structure

The ORCHIDEE model (Krinner et al., 2005) is a dynamic global vegetation model representing key vegetation processes governing terrestrial biogeochemistry and biogeography. The ORCHIDEE model includes three coupled submodels: a surface-vegetation-atmosphere transfer model SECHIBA (Ducoudré et al., 1993), a model dealing with vegetation dynamics processes (i.e., fire, sapling establishment, light

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[3] Weber, U., Jung, M., Reichstein, M., Beer, C., Braakhekke, M., Lehsten, V., Ghent, D., Kaduk, J., Viovy, V., Ciais, P., Gobron, N., and Rödenbeck, C.: The inter-annual variability of Africas ecosystem productivity: a multi- model analysis, Biogeosciences Discuss., accepted, 2008.

competition, and tree mortality), and a biogeochemical process model STOMATE. SECHIBA calculates the transfer of radiation, water and heat in the vegetation-soil-atmosphere system at half hourly time step. ORCHIDEE distinguishes over Africa 11 plant functional types with different photosynthetic, phenological and morphological characteristics. Root water uptake (U) in ORCHIDEE is function of the biome-dependent constant c and of the dry soil depth d, defined as the dry fraction of the first soil moisture layer ($U=e^{-cd}$, where U varies between 0 and 1, $c=0.8$ for forest and $c=4$ for grassland). The STOMATE submodel simulates plant phenology and key processes of ecosystem carbon cycling such as gross primary productivity (GPP), growth and maintenance respiration, NPP allocation, and litter and soil organic matter decomposition. Plant CO_2 assimilation interacts with stomatal conductance and is regulated by environmental factors such as air humidity, temperature, radiation, and atmospheric CO_2 concentration. Photosynthesis in ORCHIDEE is based on the leaf model equations of Farquhar et al. (1980) for C3 plants and of Collatz et al. (1992) for C4 plants (savannas). Maintenance respiration is a function of each living biomass pool and temperature. Growth respiration is computed as a fraction of the difference between assimilation inputs and maintenance respiration outputs to plant biomass. Heterotrophic respiration parameterization is taken from the CENTURY model (Parton et al., 1988). ORCHIDEE has altogether eight litter pools and six soil carbon pools.

In ORCHIDEE, fire is one of the main disturbance affecting the terrestrial vegetation. A simple parameterization following McNaughton et al. (1989) is included in ORCHIDEE. The formulation of fire occurrence follows an intermediate approach between the fire history concept (using statistical relationships between the length of the fire season and the area burnt) and a process-oriented methodology (estimation of fire conditions based on litter quantity and moisture) such as for instance in Thonicke et al. (2001). Land use change is another major disturbance that can greatly modify terrestrial carbon storage and flux. The fractions of each land use type (PFT) are updated annually. After a transition in land use, a fraction of the aboveground heartwood and sapwood carbon pools is transferred to three product pools with different turnover times. The carbon contained in other biomass pools which remain in the ecosystem is added to the litter reservoir, and eventually released to the atmosphere by decomposition. For tropical forest, fractions of 59.7%, 40.3%, and 0% of the harvested heartwood and sapwood aboveground biomass are assigned to product decay pools with 1 yr, 10 yr and 100 yr turnover time (Mc Guire et al., 2001). For temperate forest (only 12% of African forest) these fractions are 59.7%, 29.9%, and 10.4% .

ORCHIDEE was validated against observed seasonal cycles of heat, CO_2 and H_2O exchanges at various Fluxnet sites around the world (Krinner et al., 2005; Ciais et al., 2005; Chevallier et al., 2006) but not specifically at savanna sites. It was evaluated as well as with the satellite derived spatial distribution of vegetation traits and leaf density at global or regional scales (Krinner et al., 2005; Demarty et al., 2007). The interannual variability in leaf area index (LAI), carbon fluxes, and runoff is also consistent with that of historical satellite-observed LAI, seasonal cycle of atmospheric CO_2, and observed runoff, respectively (Piao et al., 2006; Piao et al., 2007; Piao et al., 2008). In the recent Dynamic Global Vegetation Model (DGVM) comparison of Sitch et al. (2008), the ORCHIDEE simulated response of net carbon exchange to future climate and rising CO_2 concentration was found to be intermediate among the five participating DGVM, the other models being S-DGVM, HYBRID, TRIFFID and LPJ.

2.2 Input datasets

2.2.1 Climate data

The meteorological data used to drive ORCHIDEE include air temperature, precipitation, wet day frequency, diurnal temperature range, cloud cover, relative humidity of the air and wind speed. Monthly data sets, with a spatial resolution of $0.5^\circ \times 0.5^\circ$ for 1901–2002, were supplied by the Climatic Research Unit (CRU), School of Environmental Sciences, University of East Anglia, UK (Mitchell and Jones, 2005). Data on annual atmospheric CO_2 concentration were obtained from Rayner et al. (2005). The current soil texture map is based on Zobler (1986).

2.2.2 Land use data

Cropland area is prescribed each year from the dataset of Ramankutty and Foley (1999). We have combined this dataset with that of Goldewijk (2001) to account for the extent of pasture. The distribution of natural vegetation at each grid cell is derived from Loveland et al. (2000). The extent of natural vegetation varies with time as a function of the prescribed extent of cropland and pasture. The evolution of area for each type of African vegetation is shown in Fig. 6c.

2.3 Simulations setup

Using transient climate data during the period 1901–1910 and the 1860 atmospheric CO_2 concentration of 286.05 ppm, we first ran the model at resolution of $2^\circ \times 2^\circ$ until the carbon pools reach equilibrium. From this initial equilibrium state, two simulations from 1860 to 2002 were carried out, in order to separate the relative contribution of atmospheric CO_2, climate change, and of land use change. In simulation S1, atmospheric CO_2 and climate were varied. In simulation S2, atmospheric CO_2 concentration, climate and land use were varied. The individual effects of land use change were estimated by subtracting S1 from S2. Due to lack of climate data before 1901, the average climate data during the period of 1901–1910 was used for the 1860–1900 initialization.

In addition, we performed three shorter simulations over the period 1980–2002, to isolate the effects of temperature and precipitation alone, and the role of CO_2. We checked that our climate forcing dataset during that period is quite similar to the dataset based upon CRU climate combined with NCEP analysis and TRMM satellite rainfall prepared by Weber et al. (this issue) for the CAMIC model intercomparison. In this way, our attribution of flux variations to rising CO_2 vs. climate drivers could be extrapolated to the ORCHIDEE results part of the CAMIC intercomparison. To perform the attribution of fluxes to each driving variable, we carried a simulation S3 in which only CO_2 is varied, a simulation S4 in which precipitation alone is varied, and a simulation S5 in which temperature alone is varied.

3 Interannual variability

In this section, we analyze the results of simulation S1 to investigate the mechanisms of interannual variations in carbon fluxes. Five main results emerge from our analysis. First, the interannual variability in the Net Biome Productivity (NBP) is of smaller magnitude than the variability of each gross flux separates, suggesting a strong coupling causing a positive correlation between Total Ecosystem Respiration (TER) and Gross Primary Productivity (GPP) in the model. This is shown in Fig. 1. This result, valid over the entire African continent, is similar to the one obtained by Ciais et al. (2005) in their analysis of the summer 2003 drought in Europe. Further, our simulations suggest that TER variations are smaller than GPP variations, although in phase with them. In other words, the GPP anomalies are systematically tailed with TER anomalies of the same sign (see Fig. 2). In the model, each strong drought such as 1913, 1984 (the last extreme drought in Western Africa), and 1987 causes a drop in GPP (see Fig. 1) and in the subsequent allocation of assimilates to leaves and roots, which limits the production of litter for respiration. In addition, during these droughts, the decomposition of soil organic matter is further reduced by soil dryness. However, the drought induced GPP reductions are always larger in ORCHIDEE than the coincident TER reductions (Fig. 2). In response to extreme drought years (Fig. 2) defined when continental scale precipitation drops by more than 5% below the 9-year average centered over that year, autotrophic respiration RA ($-16\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) is decreased more than two times heterotrophic respiration RH ($-7\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$). The converse is true for extremely wet years. This shows that, in the ORCHIDEE model, the variations in TER consecutive to those of GPP are two-third explained by changes in the modeled autotrophic respiration and one third explained by heterotrophic respiration processes.

Second, the interannual variability in the Net Biome Productivity (NBP) is driven by the interanuality of GPP rather than by the one of TER. This is shown in Fig. 3. This feature of the ORCHIDEE model is rather widespread and has been diagnosed in global simulations to extend from the southern half of Europe and North America

(Ciais et al., 2006) to tropical regions. The mean coefficient of correlation between NBP and GPP variations over the period 1901–2002 (R^2=0.53; p<0.001) is greater than the one of NBP with TER (R^2=0.28; p<0.001). The biome where NBP and GPP are best correlated is savanna south of the Equator (R^2=0.63). The one where they are the least correlated is croplands in northern Africa (R^2=0.41; see Table 2). For rainforests distributed around the Equator, the correlation between NBP and GPP is lower than for savanna. This suggests a stronger decoupling in forests between TER and GPP, likely due to stem respiration and stem growth processes.

Third, the interannual variability of GPP and hence of the carbon balance, is driven by rainfall fluctuations rather than by temperature at the continental scale. This is illustrated in Fig. 4. The correlation between GPP and rainfall (P) during the interval 1901–2002 is positive and significant over 70% of the grid points. The dominant driving climate variable also varies between each biome (Table 3). The correlation between GPP and P is the highest for savanna. About 77% and 42% of interannual variations of GPP in savanna is explained by precipitation, respectively in southern and northern savanna. In contrast, rainfall only weakly explains the interannual variability of GPP in forest (7% in northern, and 6% in southern forests), slightly less than temperature (9% in northern and 19% in southern forest). Moreover, the slope of the GPP vs. P regression is smaller for forest (0.5–0.6 $\mathrm{g\,C\,m^{-2}\,yr^{-1}\,mm^{-1}}$) than for savanna (0.9–1 $\mathrm{g\,C\,m^{-2}\,yr^{-1}\,mm^{-1}}$). This result may be related to the fact that, in the hydrology module of ORCHIDEE, forests can access deeper water sources than grasses. In addition, the different growth environments may contribute to the different response of GPP to temperature and rainfall. Forests are always located in areas with relatively abundant rainfall, whereas savannas are distributed in more arid environments, where vegetation growth is more frequently limited by soil moisture (Knapp et al., 2001).

Fourth, the dominant spatial pattern of interannual variability in GPP, TER, fire emissions and NBP over Africa is related to the El Niño mode of the global ENSO oscillation, with a negative anomaly in GPP and a coincident net carbon loss by ecosystems during El Niño episodes. This is seen in Fig. 5 where a Principal Component Analysis has been applied to the ORCHIDEE output (ESRI, 1992). In this figure, the first EOF, explaining 52% of the carbon balance variability, is nearly identical to the average NBP anomaly during an El Niño episode. At the continental scale, the impact of an El Niño episode is however not associated with a uniform change in rainfall/temperature patterns, but rather with regionally warmer and dryer conditions over Southern Africa from December to February and wetter conditions in the Great lakes region (see http://iri.columbia.edu/cgitest-bin/enso_map-req1.pl). A La Nina event manifests itself by a symmetrical pattern in anomalous rainfall (see also: http://iri.columbia.edu/climate/ENSO/globalimpact/temp_precip/region_lanina.html). Over West Africa, the rainfall variability in Sudan and Sahel is also highly positively correlated with ENSO, but rainfall variability near the Guinean Coast is better predicted by the more local signal of SST anomalies in the Guinean gulf (Joly et al., 2007). There has been a rather abundant literature on possible carry-over effects of soil moisture on climate in Sahel, without yet a clear evidence for such a mechanism (Douville et al., 2007). Similarly, vegetation feedbacks on climate in the driest part of Sahel have been suggested (Los et al., 2006; Zeng et al., 1999). From the response of NBP to El Niño shown in Fig. 5, we expect forests in the inner-tropical band from the Congo basin to the Great Lakes region to store more carbon during El Niño episodes, while savannas are exposed to dryer conditions and show a reduced photosynthetic activity (see NDVI anomalies in Fig. 5), and thus a reduced GPP and NBP (Fig. 2). The net carbon balance anomalies of savannas are however not only driven by GPP, but also by fire disturbance as well (e.g. Williams et al., 2007), with wet years being committed to larger fire emissions during the next dry season (Barbosa et al., 1999; Balfour and Howison, 2001). In the fire module of ORCHIDEE, however, the role of fire emission (R^2=0.15, P<0.001) in explaining the interannual variability of NBP is much lower than that of GPP (R^2=0.53, P<0.001) or even TER (R^2=0.28, P<0.001) (Fig. 1). For the magnitude in response to El Niño (5 g C m^{-2} yr^{-1}), fire anomaly is much lower than that of GPP (50 g C m^{-2} yr^{-1}) and TER (20 g C m^{-2} yr^{-1}).

A fifth result is that the continental wide fire emissions in ORCHIDEE are only weakly sensitive to ENSO related climate variability, like in satellite-derived emissions. Fire emissions are linked to climate variability both directly via a bigger fire risk during the dry season, and indirectly via the controlling effects of climate on the growth of biomass during the former wet season, as a source of fuel. African fire emission proxy data have been analyzed by Chédin et al. (2008) from the Diurnal Tropospheric Excess (DTE), a variable derived from the TOVS satellite observations over the period 1987–1991 (Chédin et al., 2003, 2005). We also analyzed the GFEDv2 emission dataset estimated from EOS-Terra-MODIS burned area (Giglio et al., 2006) prescribed to the CASA model over the period 1997–2004 (Van der Werf et al., 2006). Both satellite-based fire datasets indicate consistently over their respective period of coverage that the ratio of fire emissions of an El Niño to a La Nina year remains close to unity at the continental scale, indicating no big change in fire emission between these two contrasted patterns of climate. This feature is well captured by ORCHIDEE (Table 4) over the whole period 1901–2002. Considering only the period 1987–2000, the modeled El Niño to a La Nina ratio of emissions varies between 0.82 and 1.07, also in correct agreement with the satellite datasets.

The satellite data further suggest (Chédin et al., 2008) that El Niño to La Niña emission ratio are lower than unity for northern tropical Africa, and higher than unity for southern tropical Africa. This asymmetric response of fire emissions in each hemisphere is shown by the DTE dataset for the ratio of the 1987 El Niño to the 1989 La Nina. It is also shown by the GFEDv2 dataset for the ratio of the 1997/1998 El Niño to the 1999 La Nina (Table 4). For savannas, Van der Werf et al. (2006) further pointed out that the interannual variability in fire emissions is decoupled from the variability in burned area, and thus could be driven instead by the amount of fuel available. To further test the hypothesis that a distinct El Niño to La Nina ratio of fire emissions in each hemisphere is driven by fuel load availability rather than by climate, we calculated in ORCHIDEE the corresponding ratios of NPP, and of standing biomass before the fire season. But no evidence for an asymmetric El Niño response of NPP and biomass in each hemisphere was found in our simulations (Table 4). This could reflect model shortcomings in capturing the interannual dynamics of biomass, more complex processes (lagged effects of fires, nutrients), or regional decoupling between biomass available for fuel and actual fire emissions (human induced landscape fragmentation, nature of combustions).

4 Decadal variability and trends

Overall, we found that the African NBP increased from a net carbon source of $-0.14\,\mathrm{Pg\,yr^{-1}}$ in the 1980s to a net carbon sink of $0.15\,\mathrm{Pg\,yr^{-1}}$ in the 1990s. There are four main results arising from our set of simulations. The first result is that land use change during the last two decades implies a smaller source of CO_2 to the atmosphere than expected from a global bookkeeping model using national land use area statistics (Houghton et al., 2003). The ORCHIDEE modeled carbon balance due to land use change is a net source of $0.08\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1980s and of $0.13\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1990s. This source is close to the estimation of the previous study of Jain et al. (2005) based on the same land use area data but using a simpler carbon cycle model ($0.09\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1980s). Our estimate is only half of the Houghton et al. (2003) bookkeeping model ($0.19\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1980s and $0.24\,\mathrm{Pg\,C\,yr^{-1}}$ in the 1990s). The primary cause at the continental scale for a smaller land use flux to the atmosphere in our simulation than in the bookkeeping model may be the very different rate of change in cropland area (Jain et al., 2005). The Ramankutty et al. (1999) dataset which we used, gives an African cropland area of $1.4\times10^4\,\mathrm{km^2}$ in the 1990s with a strong decreasing trend, compared to an area of $5.2\times10^4\,\mathrm{km^2}$ used by Houghton et al. (2003) with an increasing trend. Jain et al. (2005) found that $0.036\,\mathrm{Pg\,yr^{-1}}$ more carbon is emitted by land use change in the 1980s when applying the cropland area of Houghton et al. (2003) instead of Ramankutty et al. (2000). The relatively small source contributed by land use changes in Africa as compared to other tropical forest regions reflects smaller deforestation rates. In “hot-spot” regions of deforestation like Malaysia, Indonesia or in the Brazilian Amazon, most of forest suppression is driven by large clearings >500 ha (van der Werf, personal communication). Over these clearings are established palm oil plantations in Malaysia, Indonesia, Thailand (ECD, 2000; Stone, 2007), and soybean fields followed by ranching in the Amazon (Morton et al., 2006). In Africa, most of the forests remain state-owned and despite widespread logging in Cameroon, the northern part of the Republic of Congo and in the western part of Gabon (Lepers et al., 2005; Laporte et al., 2007), there is no incentive policy or population pressure in Central Africa which favors large scale deforestation for agriculture or plantation (Lambin et al., 2003), unlike in Asia and South-America.

Second, there is an upward trend of GPP and NBP between 1980 and 2002, which is widespread over the continent except for forested regions in Central Africa and around the Great Lakes. At the continental-scale, the trend of GPP is closely matching the trend in satellite observed NDVI (see Figs. 7 and 8). At the regional scale, our simulated trend in GPP is also consistent with an increased vegetation activity over Sahel reported by Eklunds and Olsson (2003) and Olsson et al. (2005). This upward trend of GPP over savannas is parallel with a rise in precipitation (Trenberth et al., 2008, their Fig. 3.13), itself maybe associated with a polewards expansion of the Tropical belt (Seidel et al., 2008). At the continental-scale, the trend of GPP can be explained using our factorial simulations (Sect. 2) by the CO_2 fertilization effect (70%) ameliorated by the increase in P (44%). Other factors like temperature and solar radiation contributed only marginally to the continental trend of GPP (Fig. 7). In response only to temperature change, the total GPP even shows a statistically significant decreasing trend (R^2=0.25, P<0.05) likely due to an increase in the transpiration to precipitation ratio. Excluding land use change, carbon sink for savanna is 0.05 Pg C yr^{-1} while that of forest is about 0.3 Pg C yr^{-1} in the 1990s. In contrast to the drivers of the GPP trend, the contribution of CO_2 fertilization (25%) to the trend of NBP is much less than that of precipitation (74%). NBP is the difference between gross fluxes, whose driving forces partly compensate each other. The small extra quantity of carbon fixed from the atmosphere by the fertilization effect is systematically returned to the atmosphere by fires and by microbial decomposition, so that the NBP trend is less sensitive to the effect of rising CO_2 than the GPP trend (Fig. 8).

Third, slow decadal-scale variations of GPP are followed by TER variations. This coupling between gross fluxes on decadal time scales (see Botta et al., 2002) also implies that the spatial patterns of GPP trends are parallel with similar patterns of TER trends, as shown by Fig. 8. This coupling of GPP and TER slow variations can also be seen in Fig. 1, superimposed on the interannual variability signal. In ORCHIDEE, the CO_2 fertilization over forests between 10° S and 10° N, and the effect of rising P elsewhere over the savannas, explain the GPP and TER trends during the past 20 years. On the other hand, the NBP trend during that interval (as well as the NBP slow decadal variations during the past century) is driven by more subtle, second-order controlling variables, like the negative effect of regionally declining precipitation in Central Africa and the Great Lakes (Fig. 8).

Fourth, there is a increase in African river runoff since 1980 which is attributed to increasing rainfall, with a small additional contribution of decreasing forest area rather than to increasing CO_2 in our simulations. At the continental scale, the modeled annual runoff due to the combined effects of climate, land use, and atmospheric CO_2 reveals a significant positive trend of 1.24 mm yr^{-2} (R^2=0.19, $P<0.05$) from 1980 to 2002 (Fig. 9). Such a dramatic increase in runoff is mainly due to increasing precipitation (1.39 mm yr^{-2}) and land use change (0.09 mm yr^{-2}). In contrast, rising atmospheric CO_2 and temperature change caused a slight decrease in runoff by −0.04 mm yr^{-2} and 0.06 mm yr^{-2}, respectively. Such a decrease in runoff in response to rising atmospheric CO_2 suggests that transpiration is not suppressed by higher CO_2 levels, because the increased water use efficiency is offset by faster plant growth and more leaf area (Piao et al., 2007).

5 Concluding remarks

In our model simulation, the African net carbon balance increased from a net carbon source of −0.14 Pg C yr^{-1} in the 1980s to a net carbon sink of 0.15 Pg C yr^{-1} in the

1990s. Included in this number is a land use change induced source of 0.13 Pg C yr^{-1}. Our estimate of NBP, however, does not include the impact of logging on the forest carbon balance, which is highly uncertain (FAO, 2007) but is likely to contribute another source. The quantity of harvested wood alone amounts to 0.125 Pg C yr^{-1}. If Africa remains a net sink in our simulation, it is because photosynthesis has increased in excess of respiration and fire emissions during the last decades, increasing carbon sequestration. In savannas, we found that carbon accumulates in the soil (95%). These ecosystems accounts for 13% of the natural sink over the continents, excluding land use changes. Note however that this model result is not confirmed by field observations (E. Mougin, personal communication) over Sahelian savannas, where the observed soil C sink is very low. The Sudan savannas may have a very different carbon balance than the Sahel savannas, though.

In forest, carbon is mainly sequestered into biomass and accounts for another 89% of the natural sink at the continental scale. The forest sink is thus 7 times larger than the savanna sink. Note however that Africa was a carbon source during the 1980s, and that even during the 1990s, NBP is not always a carbon sink each year (Fig. 1). We expect the African forest carbon stocks to remain vulnerable in the coming decades. Africa has currently the smallest deforested area of tropical regions (Achard et al., 2004), but shows higher forest clearing rate than e.g. South America (Achard et al., 2002). This is partly linked to the establishment of plantations (50% of deforested areas being converted to savanna and woodland, not agriculture). Further, there is a trend to intensified logging in Central Africa. The pristine African forests least affected by logging, are located in eastern Central Africa (Laporte et al., 2007), where we found that the recent regional drying trend has decreased GPP. This regional GPP decline is corroborated by satellite observation.

The next logical step will be to evaluate in details the model predictions. This can be done using forthcoming eddy covariance measurements (http://www.fluxnet.ornl.gov/fluxnet/networkname.cfm?networkid=36). Satellite measurements of soil moisture changes (Wagner et al., 2007) could also be used, with the benefits of existing long

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time series. But a better "observation operator" would be needed in ORCHIDEE to match with surface soil moisture observations from space, the current simple 2-buckets model hydrology being rather ill-adapted to arid and semi-arid regions. Productivity and phenology changes can be further evaluated by using remote sensing visible and infrared reflectance indexes (as briefly attempted here), as well as by compiling existing long time in situ series of NPP. The main structural development that is needed in ORCHIDEE is a better description of the savanna biome functioning, in particular a more realistic hydrology, fire module and phenology. One should account in this context for the co-existence and competition between trees and grasses (Botta et al., 2002) in modelling savannas carbon stocks and fluxes. Our simulations show that ecosystem respiration variations are systematically tailing out with those of photosynthesis, and that 2/3 of the respiration anomalies are caused by autotrophic respiration. In that context, the possible acclimation of autotrophic respiration to high-temperature and drought (Maseyk et al., 2008) should be accounted in new model parameterizations.

The main model input dataset that are needed are a more reliable crop present and historical land-cover dataset for Africa, and more generally, information on the human land use pressure, including grazing and logging trends. Regarding climate forcing data, a monthly time step for precipitation as in the CRU dataset (that we further interpolated to hourly data with a weather generator), is clearly a big source of error. In dry regions, herbaceous vegetation is composed of annual plants that can grow immediately after rain. The phenology of this vegetation type will only be captured in models with a more realistic daily rainfall forcing data.

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Table 1. Description of simulations used in this study.

Simulation	Period	Factors
S1	1901–2002	Climate+atmospheric CO_2
S2	1901–2002	Climate+atmospheric CO_2+land use change
S3	1980–2002	atmospheric CO_2
S4	1980–2002	precipitation
S5	1980–2002	temperature

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Table 2. ORCHIDEE model derived square of correlation coeffcient (R^2) between GPP and NBP and TER and NBP for each biome.

		R^2 (GPP–NBP)	R^2 (TER–NBP)
Northern Hemisphere	Forest	0.48	0.33
	Savanna	0.55	0.24
	Croplands	0.41	0.21
Southern Hemisphere	Forest	0.48	0.29
	Savanna	0.63	0.24
	Croplands	0.52	0.22

Table 3. Square of correlation coeffcient (R^2) and slope (gC m^{-2} yr^{-1} mm^{-1} or gC m^{-2} yr^{-1} °C^{-1}) between GPP and precipitation (P), GPP and temperature (T), NBP and precipitation (P), and NBP and temperature (T).

		GPP vs. P		GPP vs. T		NBP vs. P		NBP vs. T	
		R^2	Slope	R^2	Slope	R^2	Slope	R^2	Slope
Northern Hemisphere	Forest	0.07	0.5	0.09	174	0.06	0.1	0.08	−28
	Savannas	0.77	1.0	0.09	−79	0.50	0.3	0.07	−24
	Crop	0.52	0.8	0.04	−56	0.25	0.1	0.004	−13
Southern Hemisphere	Forest	0.06	0.6	0.19	244	0.24	0.3	0.04	−24
	Savannas	0.42	0.9	0.07	−67	0.50	0.4	0.09	−36
	Crop	0.45	0.8	0.01	−30	0.35	0.3	0.04	−19

Table 4. Ratio of fire emissions (mainly in savannas) between El Niño and La Nina climate conditions. Comparison between satellite emission datasets and ORCHIDEE modeled fire emissions, as well as NPP and biomass, the two latter variables being taken as a proxy of the fuel available for burning.

Ratio El Niño to La Nina	87/88	87/89	98/00	98/99
Satellite fire emissions	Chédin et al. (2008)	Chédin et al. (2008)	GFEDv2	GFEDv2
Region				
Total Africa	1.1	1.0	1.0	1.1
NH	0.8	0.7	0.8	0.9
SH	0.94	0.89	0.88	0.99
Modeled fire emissions				
Total Africa	1.04	1.07	0.82	0.84
NH	1.10	1.09	0.76	0.84
SH	0.97	1.05	0.90	0.84
Modeled NPP				
Total Africa	0.89	0.86	0.97	1.01
NH	0.85	0.83	1.07	1.03
SH	0.94	0.89	0.88	0.99
Modeled biomass				
Total Africa	0.89	0.85	0.95	1.09
NH	0.92	0.88	1.00	1.10
SH	0.83	0.82	0.86	1.07

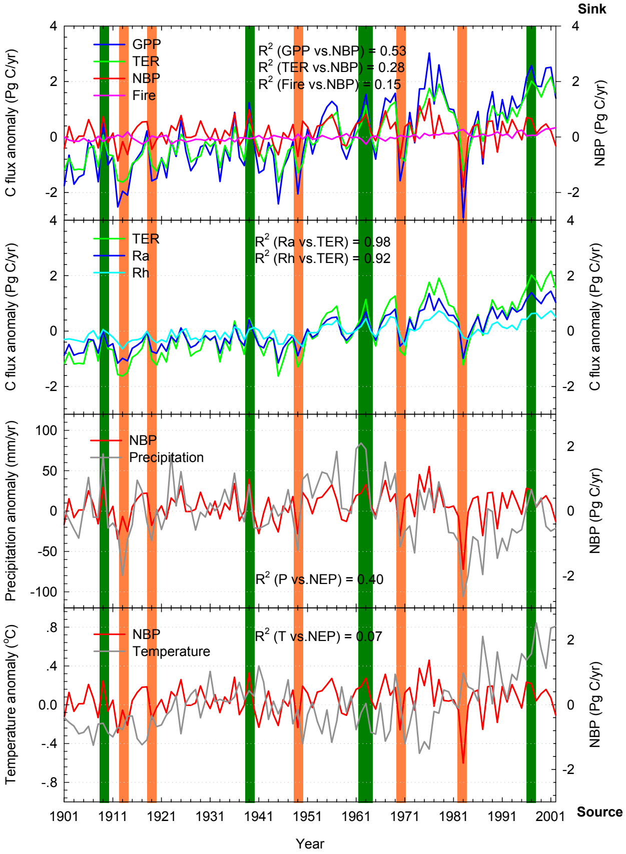

Fig. 1. Interannual changes in anomalies of total GPP, TER, Fire emission, NBP, Ra, Rh, annual precipitation, and annual mean temperature from 1901 to 2002. Positive values of NBP indicate carbon sink and negative values of NBP indicate carbon source. Orange vertical bars indicate the dryest years, and dark green bars the wettest years.

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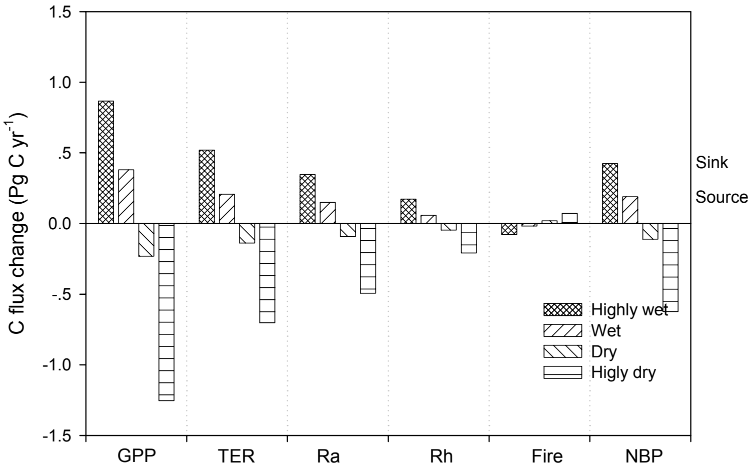

Fig. 2. The average response of GPP, TER, Ra, Rh, carbon emission driven by fire, and NBP in Africa to the change precipitation. Highly wet year is the year when precipitation is higher than 5% of the 9-year means over the period surrounding each event by ±4 years; wet year is the year when precipitation is higher than 0–5% of the 9-year means over the period surrounding each event by ±4 years; dry year is the year when precipitation is les than 0–5% of the 9-year means over the period surrounding each event by ±4 years; and highly dry year is the year when precipitation is less than 5% of the 9-year means over the period surrounding each event by ±4 years.

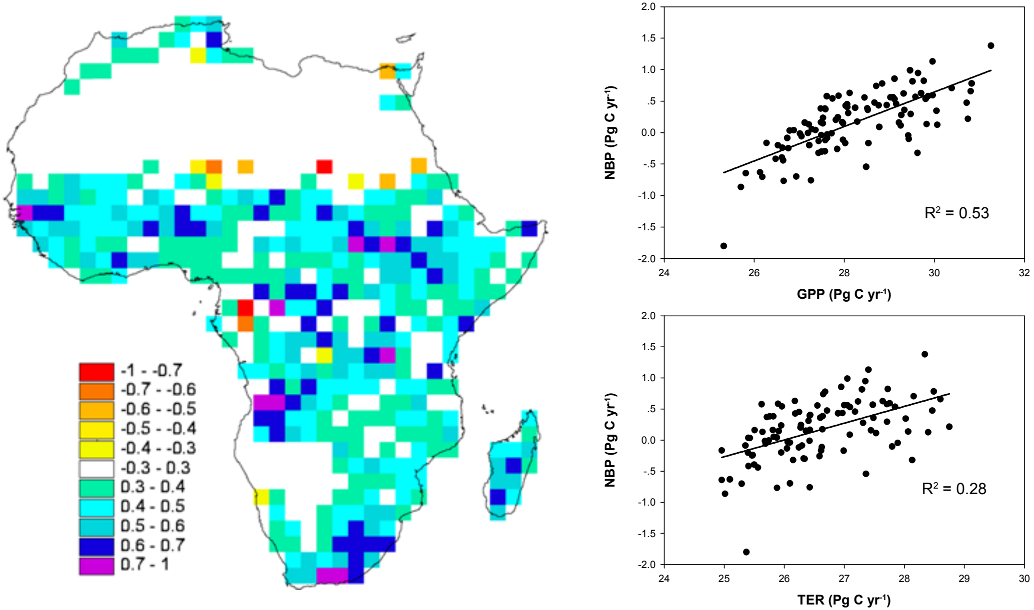

Fig. 3. Spatial distribution of the difference of explained interannual variance (R^2) of GPP and TER on NBP. A blue color indicates that NBP variations are mostly driven by GPP variations. A red color indicates a dominant control of TER variations.

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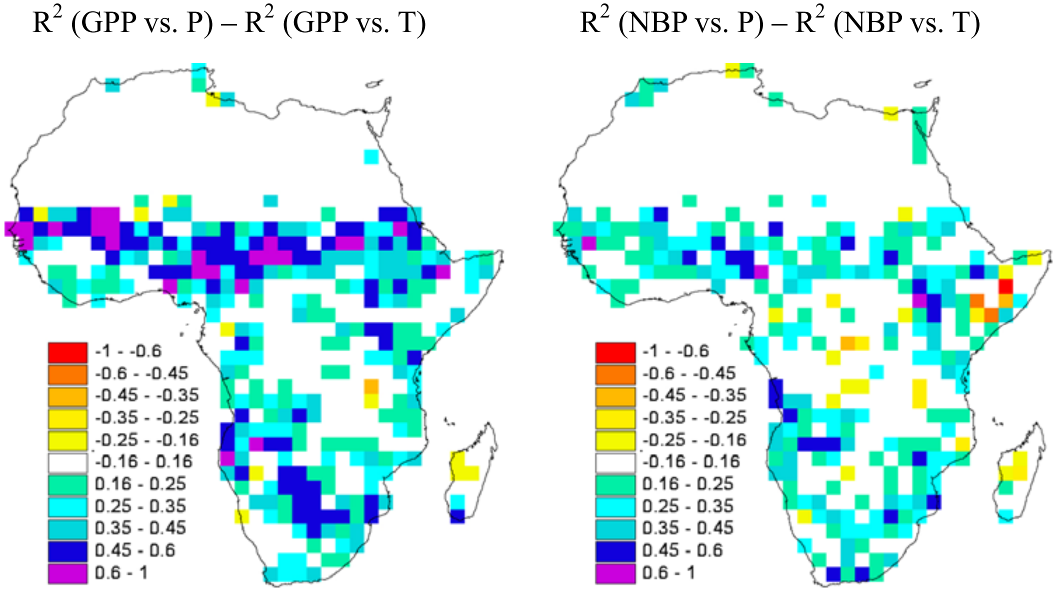

Fig. 4. Spatial distribution of the difference of explained interannual variance (R^2) of precipitation (P) and temperature (T) on the GPP and NBP.

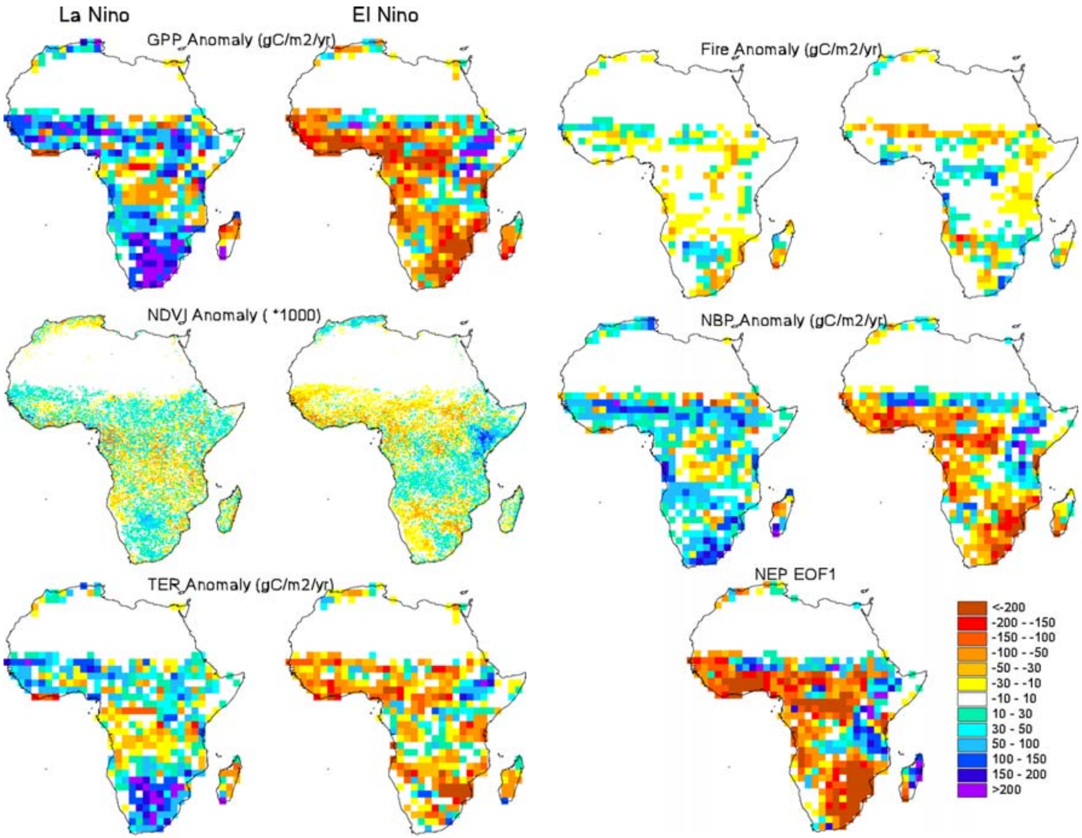

Fig. 5. Anomalies of GPP, NDVI, TER, Fire emission, and NBP in El Niño years (1983 and 1998) and La Niña years (1976 and 1989).

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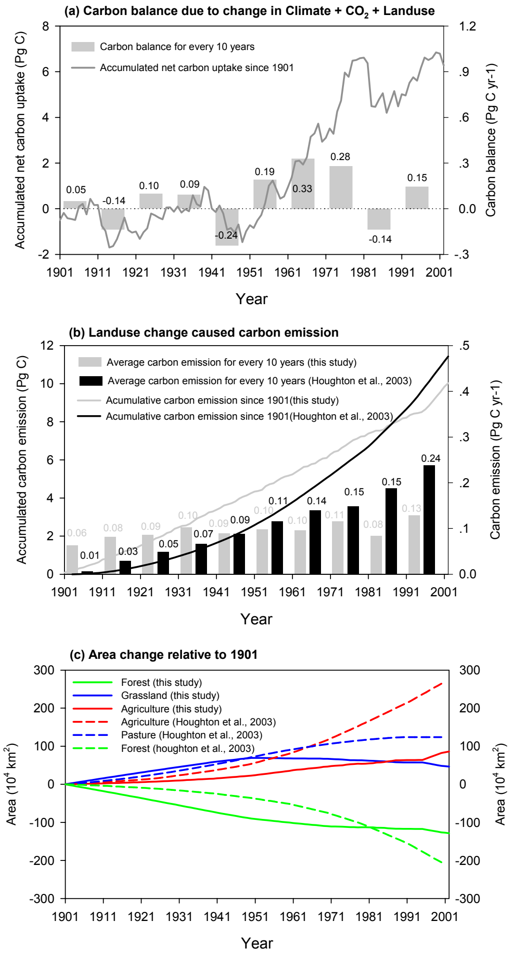

Fig. 6. ORCHIDEE modeled carbon emission due to land use change from 1901–2002.

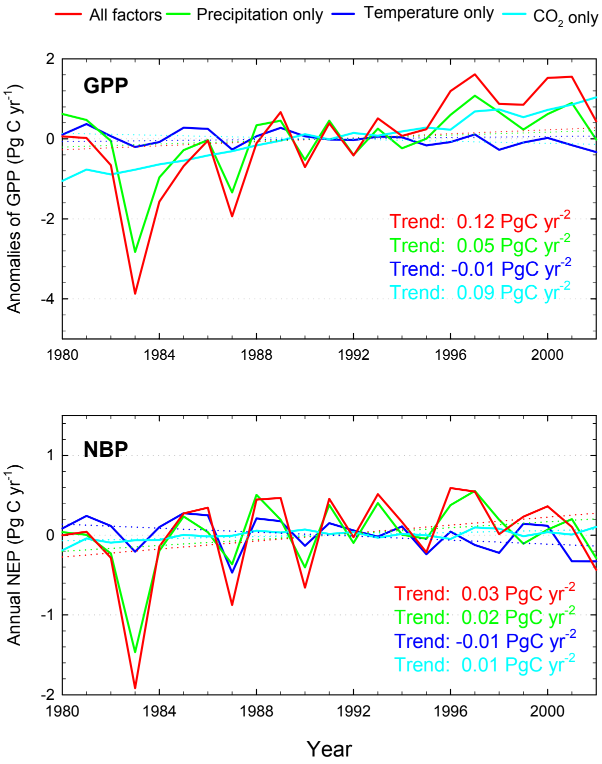

Fig. 7. Interannual changes and trends of GPP and NBP driven by different factors.

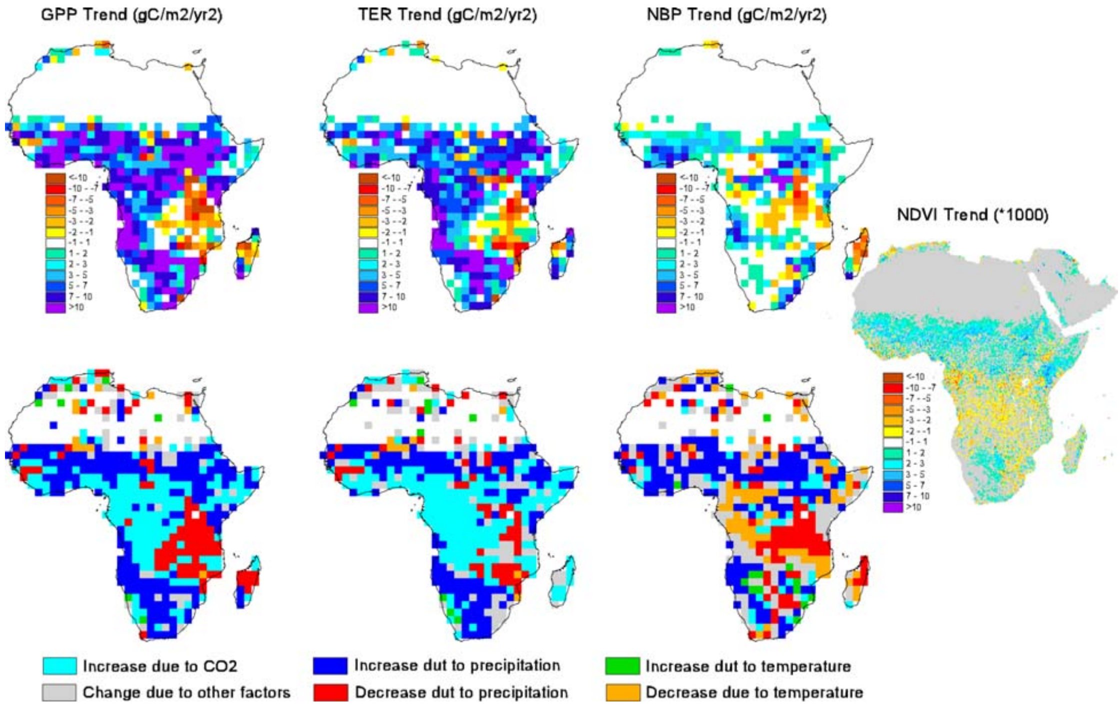

Fig. 8. Spatial distributions of the trends in annual GPP, TER and NBP s from 1980 to 2002 and of their main driving factor. In the bottom panels, the main driving factor among chaning rainfall, CO_2 and temperature for each grid point is calculated as the factor whose trend explains most of the trend in the simulation where all the factors are combined.

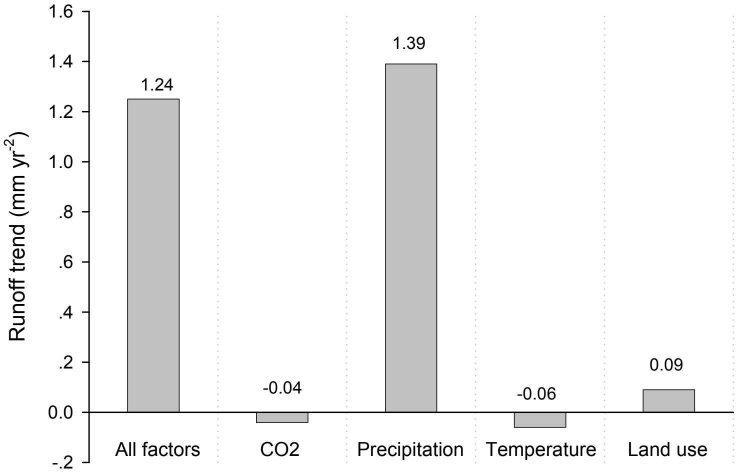

Fig. 9. Trend in African runoff driven by different environmental factors.