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How was the carbon balance of Europe affected by the summer 2003 heat wave?

A study based on the use of a Dynamic Global Vegetation Model; LPJ-GUESS

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Master degree thesis in Physical Geography and Ecosystem Analysis

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Abstract

Extreme events are believed to become frequent, intense and long lasting with climate change. An example of such extreme event is the record breaking summer 2003 heat wave. The 2003 heat wave, accompanied by drought conditions, had severe impacts on the European terrestrial ecosystems. In this study we have used an ecosystem model LPJ-GUESS to investigate how the carbon balance of Europe was affected by the European summer 2003 heat wave. The model was first tested on a smaller scale and later on run for all of Europe in the domain bounded by 23.5^o W - 35^o E and 36^o N – 70.5^o N. To be able to regionally examine the changes in climate and terrestrial ecosystem carbon fluxes, Europe is further divided into three regions: Northern, Western and Eastern Europe. In this study, we addressed the following secondary questions: (1) How large were the 2003 European terrestrial ecosystem carbon flux anomaly relative to the reference period 1998-2002, (2) were there regional differences in climate and carbon flux anomalies during the growing season 2003, (3) how unusual was the 2003 European terrestrial ecosystem carbon balance in the context of last century, (4) which component(s) of climate (i.e. temperature or drought) played the greatest role in the 2003 terrestrial carbon flux anomalies, and (5) which ecosystem process (photosynthesis (GPP) or respiration (TER)) controlled the carbon balance anomaly of 2003 relative to the reference period (1998-2002).

The results show that, at the regionally scale, Northern and Eastern European terrestrial ecosystems acted as a sink of carbon (0.01GtC and 0.01GtC respectively) while Western European terrestrial ecosystems acted as a source of carbon (0.04 GtC) to the atmosphere over the growing season of 2003 relative to the reference period. Our results also suggest that, the growing season gross primary production and terrestrial ecosystem respiration reduction in Western Europe can be explained by the extreme summer heat and drought condition while that of Eastern Europe can be explained by the drought condition. At the continental scale, LPJ-GUESS predicts a 2003 growing season carbon source anomaly of about 0.03GtC to the atmosphere in response to heat wave and drought in 2003 relative to the reference period 1998-2002. Our growing season estimates fall within the range of other previous studies. This 2003 negative carbon balance anomaly is controlled by the ecosystems experiencing reductions in both photosynthesis and terrestrial ecosystem respiration. Over the last decades (1980-2006), LPJ-GUESS predicts a net carbon uptake of about 170Tg C/yr which is equivalent to about 11% of the annual-average European (EU-27) greenhouse gas emissions between 1980 –2005.

Keywords: Heat waves, LPJ-GUESS, Europe, carbon balance, climate change, drought, terrestrial ecosystems.

Dedication

I dedicate this project work to God Almighty, for the gift of life, guidance, love, strength, protection and wisdom and also to my beloved parents; Mr Njumbe Samuel Ebang and Mrs Tchemeli Magerate for their endless devotion (morally and materially) in helping me to become wise.

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1. Introduction.

Ever since the twentieth century, there has been an increasing evidence of global warming, with an increase in the mean surface air temperature of between 0.6 and 0.7°C (WMO, 2004; IPCC, 2007). As the Earth's climate changes, extreme events (e.g. heat waves) are believed to become more frequent, intense and long lasting (Beniston, 2004; Yang *et al*., 2010; Schär *et al*., 2004). Changes in the frequency and intensity of heat waves have already been observed in many places (IPCC, 2007). An example of such an extreme event is the record-breaking European summer heat wave of 2003 that affected large parts of the European continent extending from June to mid-August (Schär *et al*., 2004; Ciais *et al*., 2005; Fink *et al*., 2004) with repeated maximum daily temperatures of 35 to 40°C (Beniston and Diaz, 2004). Contrary to Northern Europe whose summer temperature in 2003 was considered warm and beautiful, most parts of Central and Southern Europe experienced severe persistent heat (Schär and Jendritzky, 2004). The mean temperature of June, July and August in 2003, exceeded the mean of the climate standard period (1961-1990) by about 3°C over large areas and by approximately 5°C regionally (Schär *et al*., 2004). The occurrence and persistent of the summer 2003 heat wave is said to be influenced by a number of factors; such as the prolonged high sea surface temperatures in the northern North Atlantic and Mediterranean and even the intense negative soil moisture anomaly in central Europe with its resulting feedback mechanism etc (Garcia-Herrera *et al*., 2010). However, these causative factors are not relevant in this research.

Readers should bear in mind that, the 2003 heat wave was also accompanied by drought. The severe 2003 drought lasted for more than six months in some areas like Germany and France and was considered the strongest drought for the last 50 years (Granier *et al*., 2007). The 2003 extreme summer weather had enormous severe adverse socio-economic and environmental consequences across Western and Central Europe such as the death of thousands of vulnerable people, crop failure, the destruction of large forest areas by fire, effects on water ecosystem and even glaciers (UNEP, 2004; Schär and Jendritzky, 2004; COPA COGECA, 2003; Ciais *et al*., 2005).

This summer event provides a good opportunity to examine the response of terrestrial ecosystems to extreme climatic conditions, thus providing an insight into how the future extreme climatic events might affect ecosystems (Schär *et al*., 2004). This heat and drought is said to have contributed to an estimated 30% reduction in terrestrial gross primary production which led to a net carbon release of about 0.5Gt of carbon to the atmosphere relative to the reference period (1998-2002) (Ciais *et al*., 2005). Another previous study estimated a net carbon release of about 0.02-0.27Gt of carbon over the growing season (July-September) in 2003 relative to the baseline period 1998-2002 (Vetter *et al*., 2008). The 2003 reduction in terrestrial ecosystem productivity can be explained by the rainfall deficit and the extreme summer heat in Eastern and Western Europe respectively (Ciais *et al*., 2005).

A number of previous studies suggest a substantial net carbon uptake by the European terrestrial ecosystems over the last decades.

Table 1. The mean carbon balance of Europe from model simulations and land –based data compilations

References	Carbon sink TgC yr^{-1}	Uncertainties TgC yr^{-1}	Area 10^6 Km^2	Time period
Schulze *et al.*, 2009	235	± 50	9.29	2000-2005
Janssens *et al.*, 2003	111	± 280	10.4	Unspecified
Vetter *et al.*, 2007	157	70 - 230 (intermodel range	9.32	1980-2005
Zaehle *et al.*, 2007	30	– 45-106 (interannual variability range)	3.7	1990-1999
Churkina *et al.*, 2010	100	±45(intermodel difference), ±85 (Interannual variability range)	9.32	1980-2007

Table 1 above shows the mean carbon balance of Europe. Schulze *et al.* (2009) reviewed recent estimates of European carbon dioxide, methane and nitrous oxide fluxes between 2000 and 2005 using two methods; top-down estimates based on atmospheric observations and bottom-up estimates derived from ground–based measurements. Both methods yielded similar results suggesting European net carbon uptake of 235 ± 50 TgC yr^{-1}. Similarly, Janssens *et al.*, 2003, used both land based and atmosphere based approaches and estimated a European net terrestrial ecosystem carbon sink of 111± 280 TgC yr^{-1}. Furthermore, Churkina *et al.*, 2010, used four process-based terrestrial ecosystem models: BIOME-BGC, JULES, ORCHIDEE and O-CN to simulate carbon fluxes of Europe for the period 1980-2007 .All four models suggested European terrestrial ecosystems as a sink of carbon at a rate of 100TgC yr^{-1}. In addition to this, Vetter *et al.*, 2008, used seven vegetation models to analyze the causes and spatial pattern of the European 2003 carbon flux anomaly. The results indicated a terrestrial ecosystem carbon up take of 157 Tg/yr for the period 1980-2005. Zaehle *et al.*, 2007, used the Lund-Potsdam-Jena dynamic global vegetation model (LPJ-DGVM) to assess the effect of land use and land cover change on European terrestrial carbon balance and estimated a net carbon uptake of 30 TgC/year between 1990-1999 with a large inter-annual variability of between -106 TgC/year indicating a net uptake and +45TgC/year indicating a net loss.

This study aims at investigating how the carbon balance of Europe was affected by the European summer 2003 heat wave. The dynamic ecosystem model LPJ-GUESS was being used to assess the changes in terrestrial ecosystem carbon fluxes in Europe during 2003 and their impacts on the net carbon balance. Carbon balance can be defined as the difference between the carbon assimilated by plants by means of photosynthesis and carbon emitted through autotrophic and heterotrophic respiration (Churkina *et al.*, 2010). According to Reichstein *et al.*, 2007, the response of the carbon balance to climate is based on the responses of gross primary production and terrestrial ecosystem respiration to climate. Thus an increase in photosynthesis can cause the ecosystem to act as a sink of carbon while an increase in respiration and decomposition of soil carbon can lead to carbon release to the atmosphere.

The results from this study would add to the existing knowledge on the continental scale changes in net carbon balance in Europe during the 2003 heat wave. In addition to this, our understanding of the ecosystems response to heat wave and drought is very important given that such events are projected to occur more frequently in future (IPCC 2007, Schär *et al.*, 2004 ; Meehl and Tebaldi 2004; Luterbacher *et al.*, 2004).

In this study we will also address the following secondary questions: (1) how large was the 2003 European terrestrial ecosystem carbon flux anomaly relative to the reference period 1998-2002, (2) were there regional differences in climate and carbon flux anomalies during the growing season of 2003, (3) how unusual is the 2003 European terrestrial ecosystem carbon balance in the context of last century, (4) which component(s) of climate (i.e. temperature or drought) played the greatest role in the 2003 terrestrial carbon flux anomalies, and (5) which ecosystem processes controlled the carbon balance anomaly of 2003 relative to the reference period (1998-2002)?

2. Background

2.1. Definition of heat wave

Several approaches have been used in the literature to define heat waves taking into consideration a number of indices like; heat wave duration, heat wave intensity, heat wave number and heat wave frequency (Beniston *et al.*, 2007; Yang *et al.*, 2010; Fischer and Schär, 2010).

Beniston *et al.*, 2007 presents the following definitions of these indices; heat wave number is the number of heat wave events in a given time interval (e.g. per decade), heat wave frequency is the over-all duration (in days) of all the heat wave events in a given time interval, heat wave duration is the longest period of a heat wave measured in days of all the heat waves, lastly heat wave intensity is the highest exceedance of a given threshold of temperature expressed in degree-days, for all the heat wave events in a given time interval.
The following are some examples of the definition of heat wave in the literature.

Kysely, 2002, used two threshold values to define heat wave i.e. T1=30^{o}C, T2=25.0^{o}C. As such, heat wave was defined as a continuous period during which
1. The daily maximum temperature of the entire period is greater than 30^{o}C for at least three days.
2. The average daily maximum temperature for the entire period is greater than 30^{o}C.
3. The daily maximum temperature is greater than 25^{o}C for every day within the entire period.
In the study by Alexander *et al.*, 2006, heat wave is defined as a period of at least six consecutive days with daily maximum temperature higher than the 90th percentile. This is also in line with the definition by Fisher and Schär, 2010.

Similarly, in the study of western European heat waves since 1880 by Della-Marta *et al.*, 2007, a heat wave is defined as the number of consecutive three day periods in summer that exceed the long term 80th percentile of daily maximum temperature.
Furthermore, Khaliq *et al.*, 2005, defined heat wave as a run of consecutive days (say from 1 to 10 days) for which the observed average daily maximum temperature is the highest of the year.

In a study by Meehl and Tebaldi, 2004, a heat wave is defined as the longest period of consecutive days satisfying the following conditions;
1. The daily maximum temperature must be greater than the 97.5th percentile for at least three days
2. The average daily maximum temperature must be greater than 97.5th percentile for the whole year
3. The daily maximum temperature must be greater than 81st percentile for every day of the whole period.

2.2. The European heat and drought of 2003

In 2003, a series of strong persistent heat waves occurred and affected large parts of the Europe, extending from June to mid-August (Schär *et al.*, 2004; Fink *et al.*, 2004) with repeated daily maximum temperatures of 35 ^{o}C to 40^{o}C (Beniston and Diaz, 2004). Peak temperatures rose above 40^{o}C for several days during August in many locations (WMO, 2004; Granier *et al.*, 2007; Beniston and Diaz, 2004). In the northern parts of the continent, the European summer of 2003 was seen as beautiful and warm while in most parts of central and southern Europe, the heat was so severe and persistent (Schär and Jendritzky, 2004) with temperatures rising by about 3 to 5^{o}C than normal (Schär *et al.*,2004; IPCC,2007).

Extreme weather events like the 2003 heat wave is said to have two properties: intensity and the duration of the period that a threshold is exceeded (Kürbis *et al.*, 2009). This heat wave was associated with at least three distinct heat waves namely; in June, July and August but the most severe positive anomalies in monthly mean temperatures during this event were recorded in two periods; the first in June and the second during the first half of August (Schär and Jendritzky, 2004; Fink *et al.*, 2004; Schär *et al.*, 2004; Levison and Waple, 2004). The first episode of the heat wave began in June and lasted throughout the whole month with increases in monthly mean temperatures of approximately 6 to 7^{o}C (Fink *et al.*,2004), this was followed by a second but modest period of July that was just slightly warmer than average by about 1-3^{o}C (Fink *et al.*,2004). Above all, the strongest and most persistent episode of the temperature anomaly was observed between the 1st and 13th of August (+7^{o}C) (Fink *et al.*, 2004; Beniston and Diaz, 2004). The heat wave in August was so severe because it coincided with the normal summer temperature peak and was also accompanied by an almost complete absence of rainfall (Levison and Waple, 2004). During this month, the average daily maximum temperatures exceeded 40^{o}C across most of the interior of Spain, 36^{o}C-38^{o}C across southern and central France and 32^{o}C- 36^{o}C across northern France (Levison and Waple, 2004).

The summer 2003 mean temperature is said to have exceeded the mean of the climate standard period (1961-1990) by about 3^{o}C over large areas and by approximately 5^{o}C regionally (Schär *et al.*, 2004). In June, July and August, most of Europe from southern Spain to Central France experienced daily maximum temperature of above 34^{o}C on 30-50 days, which was 20 days more than average (Levison and Waple, 2004). Studies have shown that France, Germany, Switzerland, Portugal, Spain and the UK are some of the countries that experienced record-breaking maximum temperatures in summer 2003 (Schär *et al.*, 2004; WMO, 2004; Beniston, 2004; Levinson and Waple, 2004; Fink *et al.*, 2004). In Germany, summer 2003 was the hottest since 1901 with an average temperature of 19.6^{o}C, 3.4^{o}C above the 1961-90 base periods (Levison and Waple, 2004). In Switzerland several stations recorded temperatures greater than 7^{o}C above the 1961-90 average in June making it an extraordinary event in the historical record (Levinson and Waple, 2004). In August 2003, the United Kingdom recorded its highest ever daily maximum temperature of about 38.5^{o}C (Levinson and Waple, 2004).

The European heat wave of 2003 was also accompanied by an annual precipitation deficit of up to 300mm yr^{-1}, up to 50% below the average (IPCC 2007; Ciais *et al*., 2005). The 2003 drought was exceptionally severe both in duration and intensity in many regions of Europe (Granier *et al*., 2007). Regional findings have indicated that, at the start of year 2003, soil moisture storage was relatively high due to the summer and autumn 2002 high precipitation anomaly over Central and Eastern Europe (Fisher *et al.*, 2007; Garcia-Herrera *et al*., 2010) but decreased rapidly from February-August, leading to very dry conditions throughout the entire 2003 summer (Fink *et al*., 2004; Fischer *et al*., 2007; Garcia-Herrera *et al*., 2010). A reduction in average precipitation by more than 50% occurred over large parts of Central Europe in just four months; February to May (Fischer *et al*., 2007). Throughout April-August 2003, a precipitation deficit of about 75-100mm was observed throughout Central Europe (Levison and Waple, 2004). In contrast to the summer 2002 devastating flooding across Central Europe, in July 2003 most of the rivers e.g. Danube and Elbe were at their lowest levels for several decades, while Hungary experienced its worst drought since 1950 (Levison and Waple, 2004). The 2003 drought that lasted for more than six months in areas like Germany and France is said to be the strongest drought for the last 50 years (Granier *et al*., 2007) .With the exception of the Rhine catchment where the soil drying estimates for summer 2003 are comparable with the dry summer of 2001, the 2003 soil drying is said to have exceeded the long term average by far (Garcia-Herrera *et al*., 2010).

2.3. 2003 European summer in the context of the last centuries and the future

2.3.1. Last centuries

Many attempts have been made to measure and understand past and present trends of extreme weather events and to project them in future (WMO, 2004). Lately, a growing number of studies have taken a close examination of the European summer heat wave of 2003 in the context of past centuries and have even made projections about the future (e.g. Luterbacher *et al*., 2004; Chuine *et al* .,2004 ; Meehl and Tebaldi,2004; Fink *et al.*, 2004 ;Meier *et al*.,2007; Menzel ,2005; Schär *et al*., 2004)

Luterbacher *et al*., 2004, made use of monthly and seasonal surface temperatures as far back as 1500 in Europe based on a combination of quality checked long instrumental data series and multi-proxy combinations (e.g. Greenland ice core, tree rings from Scandinavia etc) to discuss the evolution of temperature variability, trends and extremes in Europe since 1500. Taking into consideration the uncertainties in the reconstruction, the European summer temperature mean series from 1500 -2003 indicated that the warmest decade was 1994-2003 ($\Delta T_{\sim}$ +1.2°C), the warmest summer was that of 2003 and the coolest was in 1902. The European summer of 2003 exceeded the European summer temperature of 1901 -1995 by

Similarly, Chuine *et al*., 2004 used French records of grape harvest date series from Burgundy (in Eastern France) for the period 1370-2003 to reconstruct spring –summer temperature anomalies that had occurred in the area and found that although there had been other warm periods in the past like that of the 1380s, 1420s, 1520s and between the 1630s and the 1680s, the anomaly of summer 2003 was an exceptional event since 1370.

Meier *et al.* 2007, made use of documentary records of grape harvest dates data from Switzerland as a proxy to reconstruct April to August temperature anomalies for the 1480-2006 period and found that the earliest harvest was in 2003 (due to the warmer conditions) and the latest in 1916 (cooler conditions) indicating that the summer of 2003 represents an exceptional event in the context of the past centuries.

More so, Menzel 2005 used historical grape harvest dates in Western Europe, starting from 1984 to reconstruct and assess the growing season temperatures and found the 2003 heat wave as an extreme event both for the instrumental period and the preceding 500 years.
Despite the fact that the above studies were based on different areas and time period, the general conclusion is that the summer of 2003 was very exceptional.

2.3. 2. Future Projections

The extreme event of 2003 alongside the current trend in summer temperatures have provoked a number of model studies and projections about the future trends in summer heat waves (Fink *et al*., 2004) .Many studies have projected a high risk of extreme summer heat waves in Europe similar to that of 2003 (Schär *et al*., 2004; Beniston, 2004; Luterbacher *et al*., 2004; Meehl and Tebaldi, 2004; IPCC, 2007). According to Schär *et al*., 2004, the future European summer climate would experience a severe increase in the year-to-year variability which would lead to a higher incidence of heat waves and drought.

HIRHAM4 regional climate model simulations by Beniston *et al*., 2007, projects an increase in heat wave duration, intensity, number and the frequency of heat wave days over a large part of Europe by 2071-2100. In addition to this, it’s projected that Mediterranean droughts would commence earlier in the year and last longer in Europe (Beniston *et al*., 2007).

It is also projected that, by the end of the 21st century, the most affected areas of 2003 summer heat wave will experience an increase in the number of summer days by about 35-48 days, with maximum temperature above 30°C (Fink *et al*., 2004). Simulation results also shows that, by the end of this century, many parts of Europe like France and Hungary may experience many days/years, with temperatures above 30°C (Beniston *et al*., 2007).

2.4 The effects of moisture and temperature on photosynthesis and respiration

Since photosynthesis and respiration respond differently to the environment, a change in climate may alter the balance between them thus affecting the ecosystem carbon accumulation and the net carbon flux (Ryan, 1991).

2.4.1 Photosynthesis

Temperature has an impact on photosynthesis. At low temperature, plant photosynthesis is limited directly by temperature, at high temperatures; photosynthesis also declines due to increased photorespiration (the production of CO_2 as a result of the oxygenation reaction catalyzed by Rubisco) while under extreme conditions, it declines due to enzyme inactivation and destruction of photosynthetic pigments (Stuart *et al*., 2002). Photosynthesis often increases up to a certain optimal temperature after which it starts to decrease for example the optimal temperature range for most C3 plants to photosynthesis is $15^{o}C$ to $30^{o}C$ (Bonan, 2002). Desert plants generally have higher temperature optima than arctic or alpine plants (Bonan, 2002).

Water is also very essential for photosynthesis. With sufficient water supply, leaves open their stomata in response to high light but as leaf water stress occurs, stomatal conductance declines to reduce water loss which in turn reduces photosynthetic rates (Stuart *et al*., 2002). The water potential of plant leaves decreases when transpiration is more than root uptake and when this happens, the plants becomes dehydrated, leaves dry up and become floppy and the absorption of soil nutrients and translocation of photosynthetic carbon products within the plant are inhibited (Bonan, 2002).

2.4.2. Ecosystem respiration

Ecosystem respiration is the combined respiration of plants, animals and microbes (Stuart *et al*., 2002). It is divided into plant respiration (autotrophic respiration) and heterotrophic respiration**.** Heterotrophic respiration is the respiration by organisms (microbes and animals) that gain their carbon by consuming organic matter rather than producing it themselves (Stuart *et al*., 2002). It is said plant respire about 50% of available carbon from photosynthesis while the remainder is used for growth, propagation, nitrogen acquisition and litter production (Ryan 1991).

Rising temperature leads to an exponential increase in microbial respiration over a wide range of temperature (Stuart *et al*., 2002). Temperature affects decomposition directly by promoting microbial activity and indirectly by changing soil moisture and the quantity and quality of organic matter inputs to the soil (Stuart *et al*., 2002). This impact of high temperature on decomposition explains the small litter pool in the tropical forest despite their high productivity (Stuart *et al*., 2002). Temperature also affects decomposition indirectly by reducing soil moisture and by increasing evaporation and transpiration (Stuart *et al*., 2002). Respiration increases with soil moisture (Foley *et al*., 1996). However, high soil moisture restricts decomposition leading to high carbon accumulation (Stuart *et al*., 2002).

2.5. Impacts of European heat wave and drought of 2003

The European summer 2003 heat wave and drought had enormous environmental and socio-economic adverse effects like the death of thousands of vulnerable people, reduction in agricultural production, and even the destruction of large areas of forest by fire.

This 2003 extreme event is seen as one of the ten deadliest natural disasters in Europe for the last 100 years and the worst in the last 50 years (UNEP,2004).The event led to approximately 22000 - 35000 heat-related deaths across Europe (Schär and Jendritzky, 2004,). The World Health Organization 2003 estimated more than 15000 excess heat related deaths in France, Portugal and Italy respectively (WHO, 2003). Generally, the elderly people were among the most affected during this period (WHO, 2003). One contributing factor to the excess mortality connected to the heat wave was the fact that temperatures at night did not cool off that much, at the time when daily temperatures were extreme (Beniston and Diaz, 2004)

The extreme 2003 event also had a negative impact on the vegetation, for example an annual precipitation deficit of up to 300mm is said to have contributed to an estimated 30% reduction in gross primary productivity over Europe (Ciais *et al*., 2005). The negative impact on agricultural sector, was prominent in Central and Southern Europe (UNEP, 2004) and this was noticed mostly in green fodder supply, livestock and the arable sectors (COPA COGECA, 2003).The effect of this event on the agricultural sector led to a financial loss of several hundred million Euros in Germany, the United Kingdom and Italy, and in the range of billion-Euro in France (Beniston and Diaz, 2004).

Furthermore, the 2003 extreme temperature and drought aggravated forest fires in many parts of Europe (WMO, 2004). More than 25,327 forest fires were recorded in Portugal, France, Spain, Italy, Austria, Finland, Denmark and Ireland (COPA COGECA, 2003).
More so, this persistent high temperatures caused the European Alps to loss about 5-10% of their total mass of ice cover (Fink *et al*., 2004; Beniston and Diaz, 2004; UNEP, 2004) which led to a series of severe rock falls in the mountain faces (Schär and Jendritzky, 2004; Fink *et al*., 2004; Beniston and Diaz, 2004).
In addition to this, the extreme event also affected many of the major rivers like Rhine, Loire and Danube (Beniston and Diaz, 2004) thus affecting inland navigation, irrigation and even power-plant cooling (Beniston and Diaz, 2004).

2.6. Model description

In this study, the dynamic ecosystem model LPJ-GUESS (Smith *et al*., 2001; Sitch *et al*., 2003) is used to investigate how the 2003 heat wave affected the carbon balance of Europe. A general description of the model is given below. See Smith *et al*., 2001 and Sitch *et al*., 2003, for additional details like the key process equations. LPJ-GUESS is a model of the dynamics of ecosystem structure and functioning at the landscape, regional and global scale (Smith *et al*., 2001). The version of the model used in this study contains most of the code updates included in the recent LPJ-GUESS version 2.1 release (Paul Miller, personal communication). Vegetation in LPJ-GUESS is represented as a mixture of plant functional types (PFTs), characterized by different structural, physiological, phenological and life history characteristics (Morales *et al*., 2007) see Table 2.

Table 2. PFTs implemented in LPJ-GUESS individual mode and their characteristics as used in this study

Plant functional Types (PFT)	Min.coldest month Temperature for survival (^oC)	Leaf Phenology	Min.growing season temperature sum to enable establishment (^oC day)	Shade tolerance	Fire tolerance
BNE (boreal needle evergreen tree)	– 31	Evergreen	500	High	Medium
BINE (boreal needle evergreen tree)	– 31	Evergreen	500	Low	Medium
BNS (boreal needle Leaved summer green tree	No limit	Summer green	500	Low	Medium
TeBS (Shade-tolerant temperate broadleaved summer green tree	– 14	Summer green	1100	High	Low
IBS (Shade intolerant broad leave Summer green tree	– 30	Summer green	350	Low	Low
TeBE (temperate broad leaved evergreen tree	– 1	evergreen	2000	High	Medium
C3G (Cool(C3)grass	No limit	Summer green	No limit	Low	high

The model also takes into consideration the dynamic changes in individual size and form, competition between PFTs and soil biogeochemistry (Sitch *et al*., 2003). Physiological ("fast") processes simulated on a daily or monthly time step include: photosynthesis, stomata regulation, respiration and associated fluxes of carbon and water between soil layers, vegetation and the atmosphere (Hickler *et al*., 2004) while “Slow” processes simulated on an annual time step include: individual allocation and growth, leaf, root and sapwood turnover, population dynamics (including tree establishment and mortality), and disturbance (Smith *et al*., 2001).

The environmental input data into the model include precipitation, temperature, cloudiness or incoming shortwave radiation, atmospheric CO_2 concentration and soil physical properties (Morales, 2007). On the other hand the output data from the model include current values of state variables as well as biogeochemical fluxes of CO_2 and H_2O from ecosystems to the atmosphere or hydrosphere. The yearly amount of carbon taken up by individual PFTs (i.e. NPP) is influenced by factors such as temperature, atmospheric CO_2 concentration, absorbed photo- synthetically active radiation (PAR) and even stomata conductance (Morales *et al.*, 2007). Carbon uptake by photosynthesis and water losses via transpiration is coupled through stomata conductance (Haxeltine and Prentice, 1996). In the model, three decomposable carbon pools with different rates of decomposition are distinguished, namely the litter pool, the intermediate pool and the slow soil organic matter pool (Sitch *et al.*, 2003). The rate of respiration is influenced by soil temperature (Lloyd and Taylor, 1994) and increases with soil moisture (Foley *et al.*, 1996).

LPJ-GUESS implements two different ecosystem models as alternative vegetation modes. Population mode is a version of the dynamic global vegetation model LPJ-DGVM (Sitch *et al.*, 2003); while cohort and individual mode corresponds to the General Ecosystem Simulator, GUESS (Smith *et al.*, 2001). In this study, we made use of the cohort (age class) mode because its vegetation dynamic processes are simulated in a more detailed and realistic manner since it is able to distinguish age classes and patches.

LPJ-GUESS has been tested in a number of studies against observed water fluxes, terrestrial carbon, and even vegetation patterns (e.g. .Smith *et al.*,2001; Hickler *et al.*, 2004; Morales *et al.*, 2007), but not on the effect of heat wave (e.g. 2003 heat wave in Europe) on the carbon balance of Europe. The model calculates net primary production (NPP), gross primary production (GPP); net ecosystem exchange (NEE), soil water content, carbon pools and even terrestrial ecosystem respiration (TER), all vital for this present study.

3. Methodology

3.1. Flux Sites

Before running the LPJ-GUESS model for the whole of Europe (continental scale), we first tested the model´s ability to produce the observed 2002 and 2003 changes in ecosystem carbon fluxes on a smaller scale at 14 eddy covariance sites. The choice of these sites is based on our desire to compare results with those of previous studies like Ciais *et al*., 2005.

Table 3: Test sites description derived from the CarboEurope IP, Ecosystem component database

Site names	**country**	**Latitude**	**Longitude**	**Climate**	**Ecosystem**	**Ecosystem description**	**Dominant Species**
El Saler	Spain	39.20 N	00.19 W	Mediterranean/ sub arid	ENF	Evergreen needle Leaf forest	High maquia +pine
Castelporziano	Italy	41.42 N	12.22 E	Mediterranean/ Montane	EBF	Evergreen broad Leaf forest	Oak
Roccarespampani	Italy	42.24 N	11.55 E	Mediterranean	DBF	Deciduous broad Leaf forest	Oak
San Rossore	Italy	43.43 N	10.17 E	Mediterranean	ENF	Evergreen needle Leaf forest	Pine
Le Bray	France	44.43 N	00.46 W	Mediterranean/ Montane	ENF	Evergreen needle Leaf forest	Pine
Laqueuille	France	45.38 N	02.44 E	Mediterranean	G	Grassland	grass
Pianosa	Italy	42.35 N	10.04 E	Mediterranean	M	Abandoned pasture And Cultivated fields, Mediterranean Macchia	Shrub/crop
Puechabon	France	43.44 N	03.35 E	Mediterranean	EBF	Evergreen broad-Leaf forest	Oak
Hesse	France	48.40 N	07.03 E	Mediterranean/ Montane	DBF	Deciduous Broad leaf	beech
Vielsalm	Belgium	50.18 N	06.00 E	Temperate/ continental	MF	Mixed forest	Fagussylvatica ,Pseu-dot-suamenziensii
Tharandt	Germany	50.57 N	13.34 E	Temperate/ continental	ENF	Coniferous Evergreen	Spruce
Hainich	Germany	51.04 N	10.27 E	Mediterranean/ montane	DBF	Mixed broad leave Deciduous forest	beech
Soroe	Denmark	55.29 N	11.38 E	Temperate/ Oceanic	ENF	Mixed	beech
Hyytiälä	Finland	61.50 N	24.17 E	Temperate/ continental	ENF	Evergreen needle Leaf forest	Scots pine

Table 3 shows the test sites used in this study. These sites are; El Saler, Castelporziano, Roccarespampani, San Rossore, Le Bray, Laqueuille, Pianosa, Puechabon, Hesse, Vielsalm, Tharandt, Hainich, Soroe, and Hyytiälä .These eddy covariance sites are located in different parts of Europe mainly; Spain, Italy, France, Belgium, Germany, Denmark and Finland. The eddy covariance sites have either Temperate or Mediterranean type of climate with ecosystems ranging from forest to cropland. The most common dominant species in these ecosystems are; oak, pine, grass, beech, spruce, and shrub/crop.

From these eddy covariance test sites, the 2003 climate and ecosystem carbon flux anomalies of two sites; San Rossore and Hesse were further examined and the results plotted below (Figs.3& 4).

3.1.1. San Rossore

San Rossore is a site located in Italy in the region of Toscana, around latitude 43.43 N and longitude 10.17 E. This site experiences a Mediterranean climate with a mean annual temperature of about 14.2°C and an annual precipitation of about 920mm.It also has a flat topography. The ecosystem type is an evergreen needle leaf forest with Pine being the dominant plant species in the ecosystem. Flux measurement at the site started in 1998 (CarboEurope IP).

3.1.2. Hesse

Hesse is another test site used in this study. It's located in France in the region of Lorraine latitude 48.40 N and longitude 07.03 E. It has an elevation of about 300m and experiences a Mediterranean/montane climate with an annual mean air temperature of about 9.9°C and an annual precipitation of about 975mm.The land cover is made up of deciduous broadleaf forest with beech as the dominant species. Flux measurement at the site started since 1996 (CarboEurope IP).

3.2. Modeling Protocol

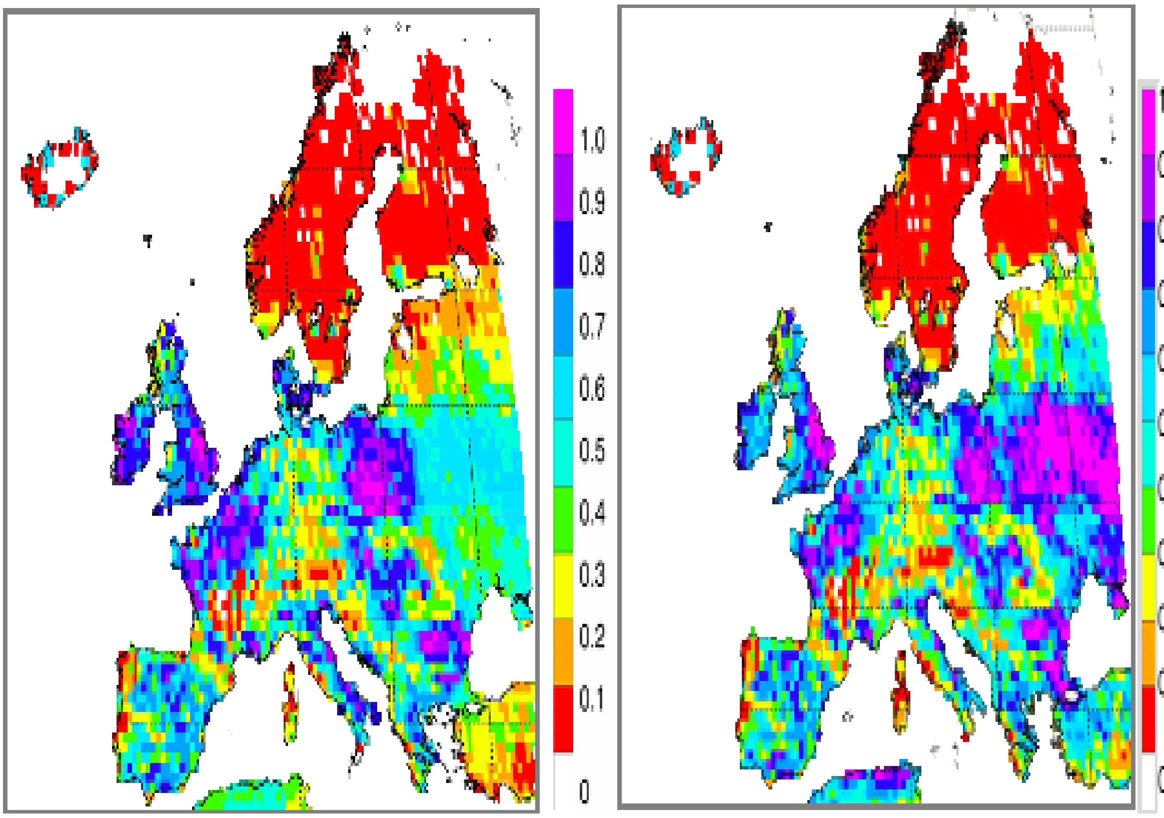
3.2.1. Forcing data

This study made use of the monthly temperature, precipitation and cloudiness climate data obtained from the Climate Research Unit (www.Cru.uea.ac.uk) on a 0.5°x 0.5° grid for the periods 1901 to 2006. Our choice for this climate data is due to its high quality and the fact that it's often used in climate research. The historical CO_2 concentrations from 1901-2006 taken from the ENSEMBLES project, supported by the European commission's 6th framework programme was also used in this study (http://www.ensembles-eu.org/) The Soil texture data are used as in Sitch *et al*., 2003.

3.2.2 .Land use data

To have a more realistic picture of the European land use in 2003, the widely used historical cropland data set spanning the years 1700-1992 from Ramankutty and Foley 1999, was used and the 1992 values retained and used to represent the situation of 2003 with the assumption that the land use has not changed that much ever since 1992.

The land use data is divided into two main groups; cropland and the natural vegetation. From this dataset, the following land use maps of Europe were generated (Fig.1).



a) **b)**

Fig.1. European land use map for 1901**(a)** and 2003 **(b),** indicating cropland fraction (%) in each grid cell.

In this study, we made use of only the 2003 land use data for further calculations because we noticed that, the land use of 1901 is very much similar to that of 2003 (Figs .1a and 1b). The land use map shows the fraction of cropland for each grid cell in Europe. The areas in red indicate a very small fraction of cropland especially in the northern part of Europe while those in pink indicates a larger fraction of cropland.

3.2.3. Model set-up and simulations

Generally, the LPJ-GUESS model is linked to four main files; the forcing data which includes the CO_2 file and the CRU data file , a grid list file containing a list of 0.5 x 0.5 degree grid cells to simulate, output files and an instruction file .The instruction file tells the model;
-Where to find the latitudinal -longitude grid list of the sites
-where to obtain the input data (forcing data)
-The parameters to run and the options e.g. whether to calculate soil respiration daily or not, the duration to spin up the simulation, whether to rain on wet days only or to rain a bit every day etc.
-where to put the simulated output data (yearly and monthly output)
-The plant functional types to simulate

-The general and the specific parameters for every plant functional type e.g. parameters common to all the grasses, etc.

The grid list for the test sites is created based on the CRU points that contain the flux tower. In the event that a flux tower lies outside an available CRU grid point, the nearest point is chosen. The continental grid list contains 3833 cells and covers an area of 7.12 million km^2. The model uses the forcing data to perform simulations first over the test sites and secondly over Europe in the domain bounded by 23.5^o W- 35^o E and 36^o N – 70.5^o N.

All simulations of the ecosystem structure starts from a bare ground that is, with no vegetation present and then spins up for 500 years until when the vegetation, soil and litter carbon pools have accumulated and are in equilibrium with the climate. The spin up time is followed by the vegetation growth using observed climate forcing from 1901 up to 2006.

From the model simulations, the following outputs are obtained; monthly Gross primary production (GPP), Net primary production (NPP), and leaf area index (LAI), carbon pools, monthly net ecosystem exchange (NEE), monthly heterotrophic and autotrophic respiration and monthly soil water content.

GPP is the sum of the photosynthesis by all leaves measured at the ecosystem scale (Stuart *et al*., 2002).This flux of carbon into the ecosystem via photosynthetic assimilation is a very important flux that drives the carbon budget of the ecosystem (Jung *et al*., 2008). NPP is the net carbon gain by vegetation calculated thus NPP= GPP - R_{plant} (Stuart *et al*., 2002), where R_{plant} is the autotrophic respiration. TER is the combined respiration of plants (autotrophic respiration) and heterotrophic respiration carried out by organisms (e.g. animals and microbes) that gain their carbon and energy by consuming organic matter rather than producing it themselves (Stuart *et al*., 2002). This combined release of CO_2 from the ecosystems to the atmosphere is also a vital flux in the carbon cycle compensating the CO_2 uptake by plants through photosynthesis (Mahecha *et al*., 2010). NEE, is the difference between the gross primary production and the terrestrial ecosystem respiration (Churkina *et al*., 2010).The NEE provides a direct measure of the net CO_2 exchange between ecosystems and the atmosphere (Stuart *et al*., 2002.)

Table 4. PFTs implemented in LPJ-GUESS individual mode and their characteristics as used in this study.

Plant functional Types (PFT)	Min.coldest month Temperature for survival (^oC)	Leaf Phenology	Min. growing season temperature sum to enable establishment (^oC Day)	Shade tolerance	Fire tolerance
BNE (boreal needle evergreen tree)	– 31	Evergreen	500	high	Medium
BINE (boreal needle evergreen tree)	– 31	evergreen	500	low	Medium
BNS (boreal needle Leaved summer green tree	No limit	Summer green	500	low	Medium
TeBS (Shade-tolerant temperate broadleaved summer green tree	– 14	Summer green	1100	high	Low
IBS (Shade intolerant broad leave Summer green tree	– 30	Summer green	350	low	Low
TeBE (temperate broad leaved evergreen tree	– 1	evergreen	2000	high	Medium
C3G (Cool(C3)Grass	No limit	Summer green	No limit	low	high

Table 4 shows the main plant functional types (PFTs) in the model ; BNE (Boreal needle leaved evergreen tree), BINE (Boreal needle leaved evergreen tree), BNS (Boreal needle leaved summer green tree), TeBS (Shade-tolerant temperate broad leaved summer green tree), IBS (Shade-intolerant broadleaved summer green tree), TeBE (temperate broad leaved evergreen tree), C3G (Cool (C3) grass) .These PFTs have different minimum coldest month temperature requirement for survival e.g. -31^{o}C for BNE and BINE, -30^{o}C for IBS, -14^{o}C for TeBS, -1^{o}C for TeBE and no limit for C3 grass and BNS. The leaf phenology of the plant functional types ranges from evergreen to summer green. As regards shade tolerance characteristics, some have high shade tolerance e.g. the temperate broad leaved evergreen tree while others have low shade tolerance like the C3 grass. These PFTs also differ in their fire tolerance capacity; while some have high fire tolerance such as C3 grass, others medium e.g. boreal needle leaved summer green tree, and some have low fire tolerance such as shade tolerant temperate broadleaved summer green tree. Lastly the PFTs differ in their minimum growing season temperature sum to enable establishment. While some have no limit like the C3 grass, others like the temperate broad leaved evergreen tree requires up to 2000 growing season ^{o}C day to be able to establish.

3.2.4. Analysis of climate and ecosystem carbon flux anomalies in 2003.

In order to estimate changes in carbon fluxes in 2003 for a better comparison with results from previous similar studies (e.g. Ciais *et al.*, 2005), an analysis based on the ecosystem carbon fluxes simulated for both the test sites over 2002 and 2003 and for the whole of Europe for the period 1998-2002 and 2003 is carried out. We defined the summer (growing season) as from the beginning of July to the end of September (NB, this is just part of the growing season).

3.2.4. a. Site tests

The ecosystem carbon flux anomalies in 2003 for each grid cell are analyzed by comparing the averages for the period of July to September for 2002 and 2003 and then the mean for the entire year 2002 and 2003 respectively.

1. Summer ecosystem carbon flux anomaly in 2003 $= Sf2003_{ab} - Sf2002_{ab}$

2. Annual ecosystem carbon flux anomaly in 2003 $= Af2003_{ab} - Af2002_{ab}$

-Where Sf2003, and Sf2002 denotes the average carbon fluxes over summer (JAS) in 2003 and 2002 respectively.

-Af2003 and Af2002 denote the total annual carbon fluxes in 2003 and 2002 respectively.

- a and b are the longitude and latitude respectively.

3.2.4. b. European domain

For the European test, the model is run twice; once for potential natural vegetation (PNV) and once for grass, which we take as a proxy for cropland in the absence of a process-based crop growth model. Assuming that the land area of Europe is made up of mainly potential natural vegetation and cropland, we then went further to combine the observed land use data with the data results of the two model runs making use of the simple equations below.

1. Ecosystem carbon fluxes in 1998-2002$= Ov_{2003} \times Sv_{1998\text{-}2002} + Oc_{2003} \times Sg_{1998\text{-}2002}$

2. Ecosystem carbon fluxes in 2003$= Ov_{2003} \times Sv_{2003} + Oc_{2003} \times Sg_{2003}$

Where

- Ov_{2003} denotes the observed fraction of 2003 natural vegetation
- $Sv_{1998\text{-}2002}$ denotes the simulated potential natural vegetation averaged over the period 1998-2002
- Oc_{2003} denotes the observed fraction of 2003 cropland
- $Sg_{1998\text{-}2002}$ denotes the simulated grass averaged over the period 1998-2002
- Sv_{2003} denotes the simulated potential natural vegetation in 2003
- Sg_{2003} denotes the simulated grass in 2003

The changes in annual and the growing season ecosystem carbon fluxes in 2003 are obtained by comparing the data for 2003 and the average of 1998-2002.

1. Summer ecosystem carbon flux anomaly in 2003 $= Sf2003_{ab} - Sf\,1998\text{-}2002_{ab}$

2. Annual ecosystem carbon flux anomaly in 2003 $= Af2003_{ab} - Af1998\text{-}2002_{ab}$

-Where Sf2003 denotes the average carbon fluxes over summer (JAS) 2003 and Sf1998-2002 denotes the averaged carbon fluxes over five summers (1998-2002)
- Af2003 denotes the total annual carbon flux over 2003 and Af1998-2002 denotes the total annual carbon flux over the period 1998-2002.
-a and b are the longitude and latitude respectively.

The climate anomalies were derived in a similar way like the ecosystem carbon flux anomalies described in the Site tests and the whole of Europe. The climate anomalies include; the summer season (July, August and September) averages for temperature, and the monthly precipitation. The data obtained from all the above analysis are used in creating graphs and maps showing the anomalies in climate, soil water content and ecosystem carbon fluxes in 2003 (see fig. 5 & 6 below).

In order to determine the entire European delta NPP, NEE, GPP and TER (i.e. 2003-(1998 – 2002 average)), a grid list of areas (in m^2) is used in calculating changes in the annual and summer fluxes by multiplying the flux data for each grid by that grid area to get fluxes in grams of carbon, and then converting the entire sum to Gigatonnes of carbon.

In addition to this, to regionally examine the changes in terrestrial carbon fluxes, Europe is further divided into three regions based on the temperature map in figure 5a (below) and the latitude and longitude of Europe. These regions are: Northern, Western and Eastern Europe. Areas with latitudes greater than 55^o are classified as region 1 (northern Europe), areas with latitudes below 55^o and longitude below 20^o are classified region 2 (Western Europe) and lastly, areas with latitude below 55^o and longitude above 20^o are classified as region 3 (Eastern Europe).

3.2.5. Attribution test

To determine which component(s) of climate (i.e. temperature or drought) played the greatest role in the terrestrial carbon flux anomalies in 2003, two sites are chosen based on the “hot spots" of this extreme climatic event :Hesse site (48.5^{o}N, 7W) is chosen as one of the sites that falls in the area with extremely high temperature and drought (this site represents the western region) while the Ukraine site (45^{o}N,33.5E) is chosen because it falls in the region which experienced very low temperature in the summer of 2003 (see fig.5a) (this site represents the Eastern region).Therefore these are located within two extreme regions one with low temperature and another with high temperature. Secondly these sites differ in their vegetation types as shown in the land use map of 2003 (Fig.1b). Hesse is a forested site while Ukraine is mostly dominated by cropland.
The model was run four times for each site (with 2003 climate, 2003 temperatures replaced by 2002 temperatures, 2003 precipitation replaced by 2002 precipitation, and lastly with 2002 climate replacing 2003 climate) and the GPP and TER data were then plotted on graphs (see Fig.9).

4. Results

4.1. European carbon balance – Site tests

An analysis of the simulated changes in carbon fluxes and stocks was done and results presented for the 14 eddy covariance sites for the period 2002-2003 (table 2), and for Europe as a whole, as the difference between 2003 and the average of 1998-2002 (Table 6). Units for the July to September period are in gC m^{-2} month^{-1} while that of the yearly period are in gC m^{-2} year $^{-1}$.

Table 5: changes in climate and ecosystem CO_2 fluxes between 2002 and 2003 at 14 eddy covariance sites in Europe based on LPJ-GUESS.

					July-September					Annual		
Site names	**Simulated Vegetation**	**Country**	**LON**	**LAT**	**ΔTemp**	**ΔPrecip**	**Δ GPP**	**ΔTER**	**Δ NEE**	**ΔGPP**	**ΔTER**	**ΔNEE**
El saler	C3G,TeBE	SP	-0,5	39	2	-10	-58	-11	-47	-246	-33	-215
Castelporziano	TeBE,C3G	IT	12	41,5	2,8	-39	-52	10	-62	-162	14	-173
Roccarespampani	TeBE,C3G	IT	11,5	42	3	-42	-81	2	-83	-279	-35	-243
san rossore	BNE,IBS,BINE,C3G	IT	17	43,5	1,9	-105	-38	-21	-16	-293	-218	-73
Bray	TeBE,IBS,BeBs,C3G	FR	-1	44,5	2,8	-33	-79	-3	-75	-331	-107	-220
Laqueuille	IBS,BeBs,BNE,BINE	FR	2,5	45,5	3,3	-38	-15	8	-23	58	-4	-52
Pianosa	TeBE,BeBs,IBS,C3G	IT	9	42	3,3	-38	-192	-45	-146	-702	-285	-416
Puechabon	TeBE,BeBs,IBS,C3G	FR	3,5	43,5	3	-21	-88	11	-99	-436	-74	-360
Hesse	TeBs,IBS,C3G,TeBE	FR	7	48,5	2,5	-37	-31	-23	-8	-135	-119	-12
Vielsalm	TeBs,IBS,C3G,TeBE	BE	6	50	2	-44	3	-12	14	33	-92	125
Tharandt	BNE,Ibs,BeBs,BINE,C3G	GE	13,5	50,5	1,1	-52	-33	-61	28	-150	-340	189
Hainich	TeBS,IBS,BNE,C3G,BINE	GE	10,5	51	1,3	-38	-14	-32	17	-51	-164	110
Soroe	TeBs,Ibs,C3G	DK	11,5	55	-0,6	-9	-31	-20	-10	-128	-90	-41
Hyytiälä	BIN,BINE,Ibs,TeBs,C3G	FL	24	61,5	0	5	-1	0	-1	-31	-11	-21

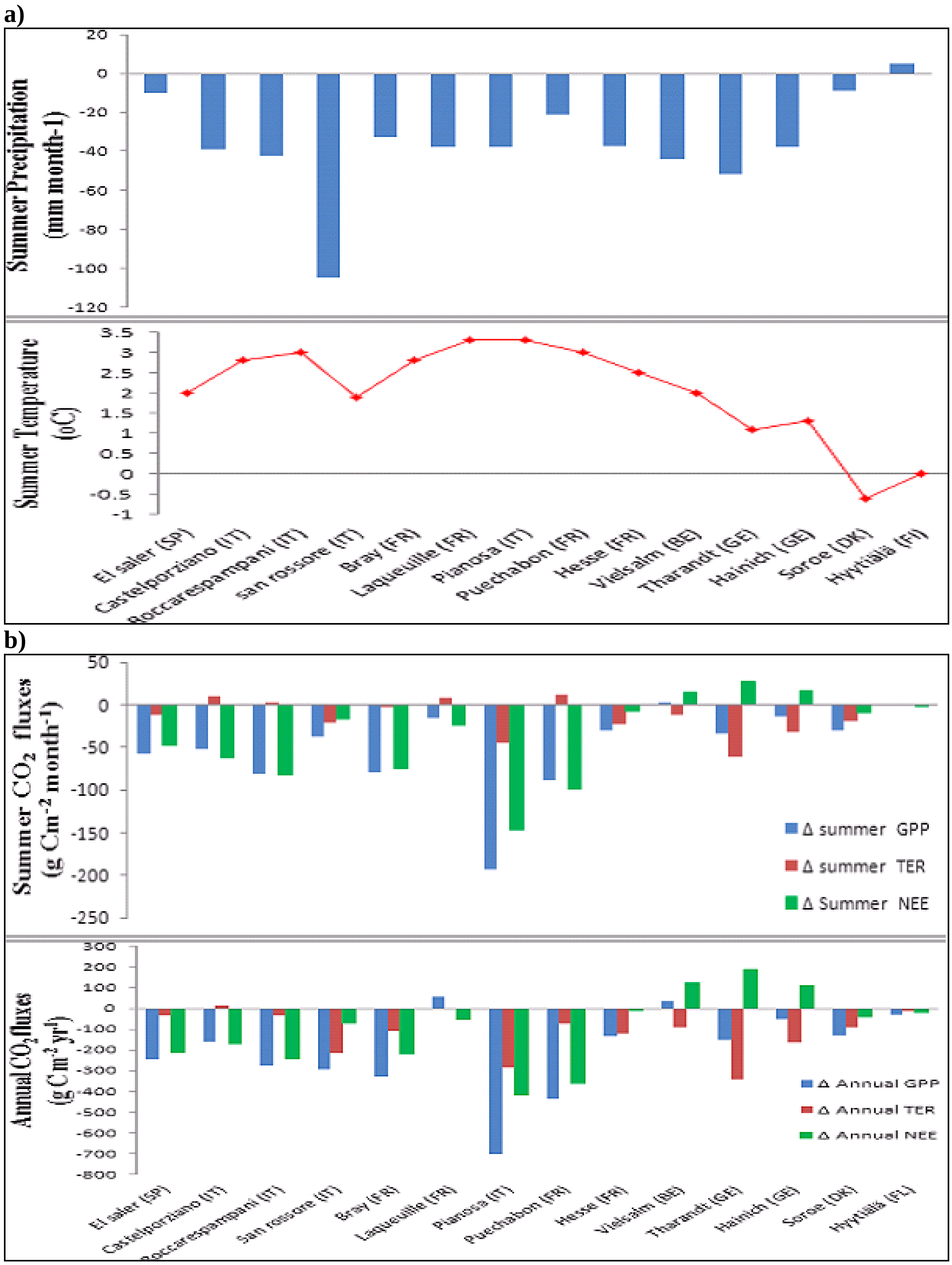


Fig.2. Changes in climate and ecosystem carbon fluxes between 2002 and 2003 at 14 eddy covariance sites in Europe based on LPJ-GUESS.

The climate data shows that with the exception of Soroe and Hyytiälä, all the sites experienced a positive growing season air temperature anomaly in 2003 relative to 2002 (Table 5, Fig 2a). The highest positive temperature anomaly of 3°C and above occurred mostly in the Mediterranean sites namely; Laqueuille (France), Pianosa (Italy), Roccarespampani (Italy) and Puechabon (France) (Table 5, Fig.2a). Soroe in Denmark was the only site that experienced a slight drop in its temperature (0.6°C) relative to that of 2002 while Hyytiälä`s experienced no change in temperature. Similarly, the growing season precipitation dropped in all sites except in Hyytiälä in Finland which experienced a small precipitation increase of about 5mm relative to 2002 (Table 5, Fig 2a) in this site, the year 2002 was also relatively dry and even drier than 2003 (Granier *et al.*,2007). The largest negative precipitation anomaly occurred in San Rossore (Italy) i.e. a drop of about 105mm relative to that of 2002 as shown in Fig.2a. Other sites with large negative precipitation anomalies include; Tharandt, Hainich,Vielsalm, Pianosa, Largueuill and Roccarespampani (Table 5, Fig2a).

These climate anomalies in 2003 had impacts on the ecosystem carbon fluxes at various sites. The model indicated a reduction in GPP in almost all sites especially over the growing season (Fig2b). The Mediterranean sites were the most affected sites in terms of GPP reduction with the largest negative GPP anomaly occurring in Pianosa (Italy) (Fig.2b). The reduction in summer GPP also coincides with the drop in precipitation and an increase in temperature during the same period.

Despite the increase in temperature which everything being equal, was supposed to increase TER (Ciais *et al.*, 2005), instead terrestrial ecosystem respiration dropped in most of the sites in 2003, though to a lesser extent than GPP (Fig.2b). This reduction in TER is as a result of the drought that affects microbial soil respiration, and the decrease in plant substrate which affects plant respiration (Ciais *et al.*, 2005). The only sites with a small positive TER anomaly include Castelporziano/ Roccarespampani in Italy and, Laqueuille/ Puechabon in France (Fig 2b, Table 5). These sites may already have been dry, so they could not get much drier. Hence the soil respiration would not have been reduced so much.

Furthermore, those sites that experienced a severe reduction in gross primary production also experienced a reduction in their net carbon uptake (NEE) (Table 5, Fig2b) .Generally, the highest reduction in CO_2 uptake from the atmosphere in 2003 occurred in the Mediterranean sites especially at Castelporziano (62 gC m^{-2} $month^{-1}$, 173 gCm^{-2} yr^{-1}), Roccarespampani (82 gC m^{-2} $month^{-1}$, 243 gC m^{-2} yr^{-1}), Pianosa (146 gC m^{-2} $month^{-1}$, 416gC m^{-2} yr^{-1}) all in Italy, Bray (75 gC m^{-2} $month^{-1}$, 220 gC m^{-2} yr^{-1}) /Puechabon (99 gC m^{-2} $month^{-1}$, 360 gC m^{-2} yr^{-1}) in France, and El saler (47 gC m^{-2} $month^{-1}$, 215 gC m^{-2} yr^{-1}) in Spain (Table 5, Fig 2b). On the other hand, some Temperate sites which acted as a greater sink of carbon in 2003 include; Vielsalm in Belgium (14 gC m^{-2} $month^{-1}$, 125 gC m^{-2} yr^{-1}), Tharand (28 gC m^{-2} $month^{-1}$, 189 gC m^{-2} yr^{-1}) and Hainich (17 gC m^{-2} $month^{-1}$, 110 gC m^{-2} yr^{-1}), both in Germany (Table 5, Fig 2b).

From the 14 eddy covariance test sites, two sites Hesse and San Rossore were further examined (Figs.3&4).

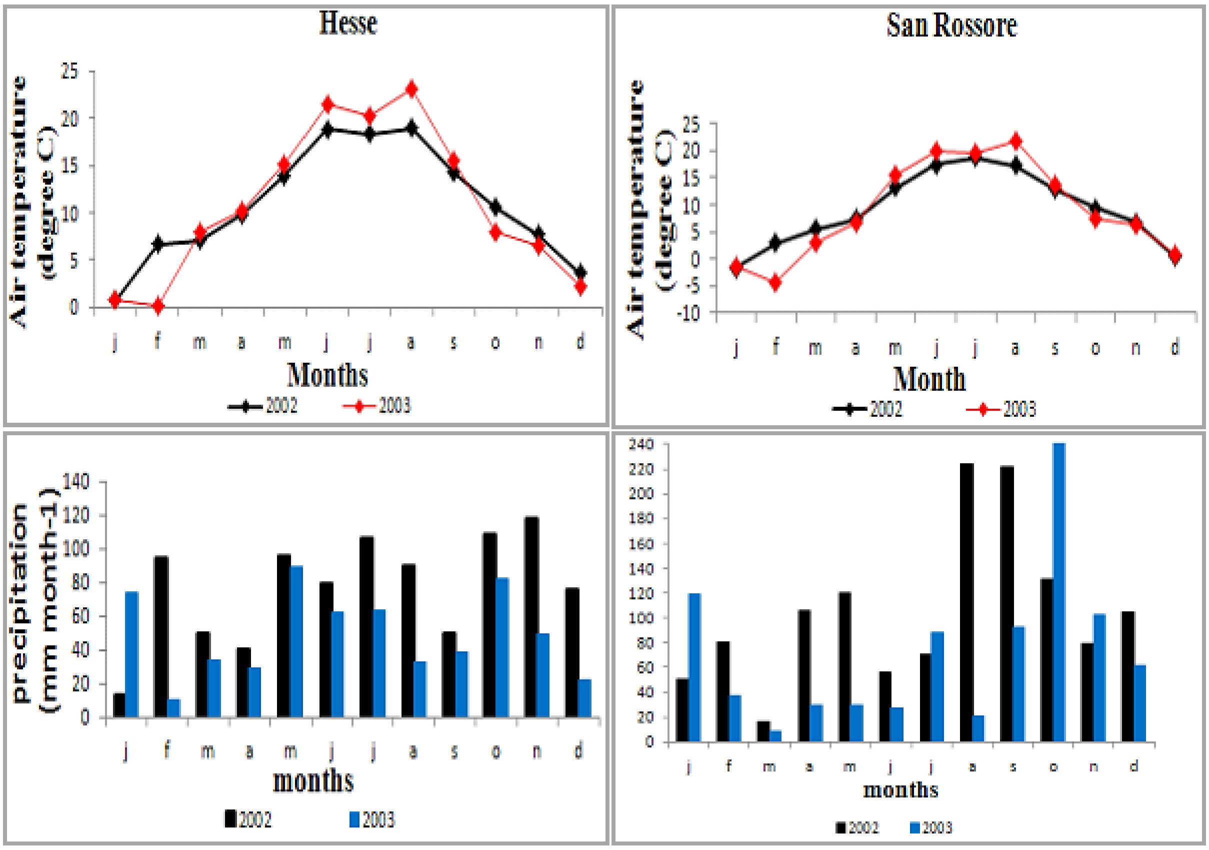


Fig.3. Climate anomaly over the 2003 summer at two forest sites (Hesse in France and San Rossore in northern Italy).

Fig.3 shows the climate anomaly over the 2003 summer at two forest sites i.e. Hesse in France and San Rossore in Italy. The data for 2002 are in black while that of 2003 are in color. The temperature graphs indicate a higher temperature over the growing season of 2003 than that of 2002 in both sites. More so, the highest temperature occurred in the month of August. This is not a surprise because other previous studies have also pointed to that fact that, the month of August experienced the strongest and most persistent episode of temperature anomalies during the 2003 summer extreme event (Fink *et al.*, 2004; Beniston and Diaz, 2004). In Hesse, temperature in August was about 23.2^{o}C while that of San Rossore was about 21.6^{o}C. The model also shows a reduction in the growing season precipitation especially in August of 2003 relative to that of 2002 .In August, the precipitation in Hesse was 31.9mm while in San Rossore ,it was about 20.9mm. Generally, the heat wave in August 2003 was so severe because it coincided with the normal summer temperature peak and was also accompanied by an almost complete absence of rainfall (Levison and Waple, 2004).

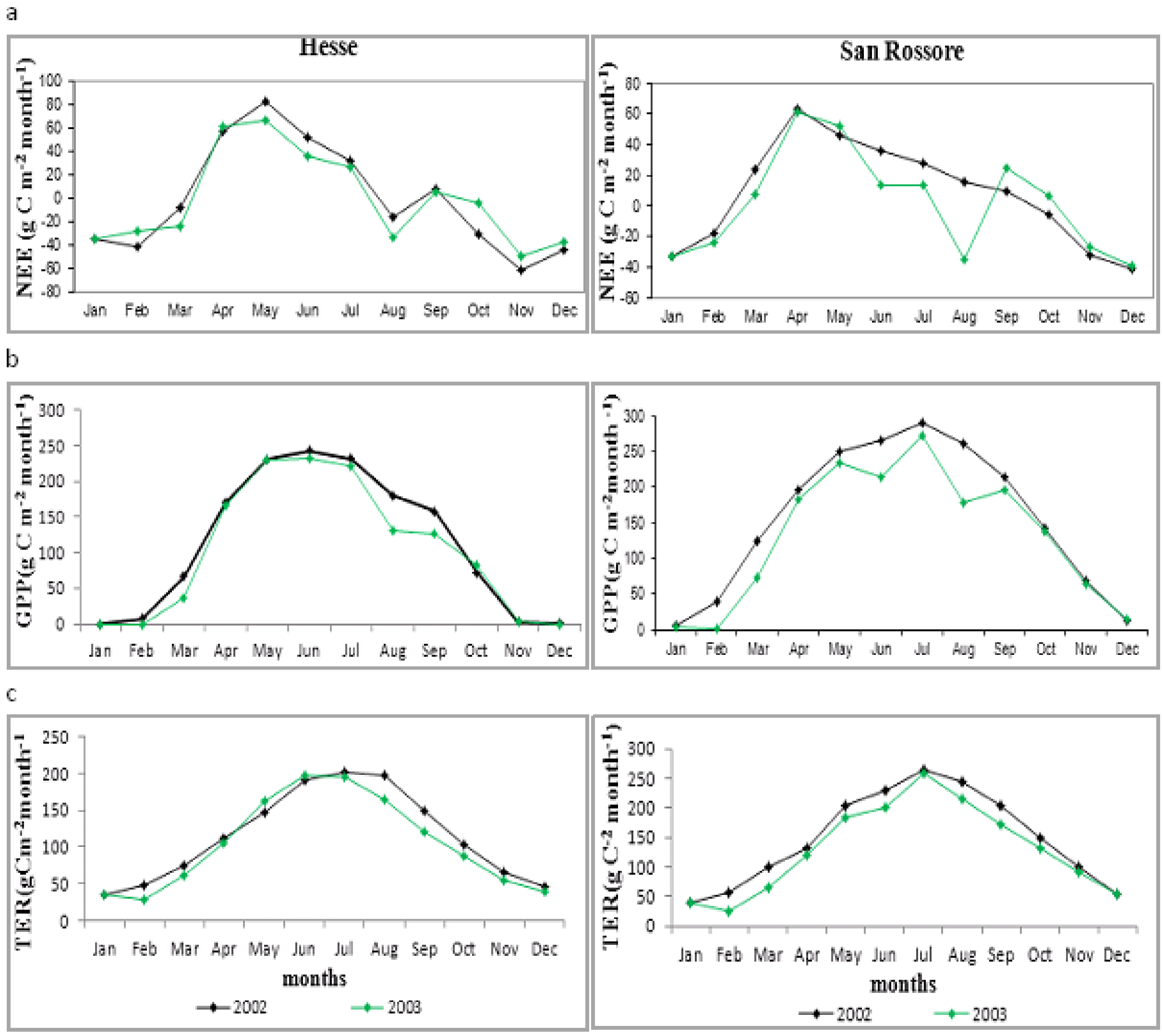


Fig .4.The modeled ecosystem carbon fluxes during 2002 and 2003 at two forest sites (Hesse and San Rossore)

Regarding the ecosystem carbon fluxes, fig. 4 shows that these forests were greatly affected by the extreme climatic event in 2003 compared to the case 2002. Both sites experienced a growing season GPP reduction in 2003 compared to that of 2002 especially in August and September. The highest GPP occurred in July especially in San Rossore (272 gC m^{-2}) compared to Hesse (221 gC m^{-2}) (Fig.4b). TER also shows a reduction in 2003 compared to the case of 2002 especially in September; San Rossore (173 gC m^{-2}) and Hesse (121 gC m^{-2}) (Fig.4c). The growing season NEE shows that, both sites; Hesse and San Rossore were releasing carbon to the atmosphere in the month of August (35 gC m^{-2}) (Fig.4a). The 2003 NEE pattern for July, August and September for Hesse is similar to that of 2002 (because reductions in GPP are largely cancelled out by TER reductions). But for San Rossore, the ecosystems took up more carbon in July, August and September of 2002 (Fig.4a)

4.2. European carbon balance

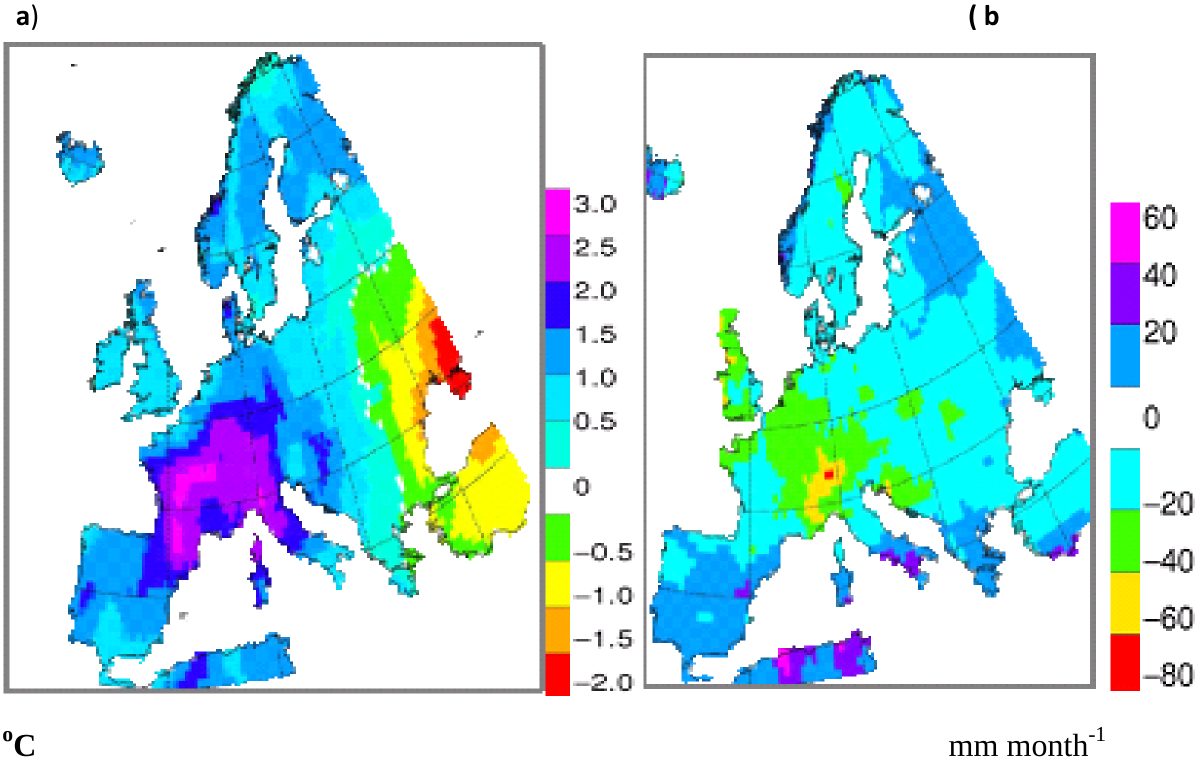
4.2.1. Regional carbon flux anomalies of 2003

Table 6. Regional estimates of annual carbon flux anomalies and their corresponding growing season (July-September) anomalies in brackets. All data compare 2003 with the average of 1998-2002.

Ecosystem C fluxes in (GtC)	Region 1 (Northern Europe)	Region 2 (Western Europe)	Region 3 (Eastern Europe)	Total
GPP	0.11 (0.02)	– 0.31(-0.06)	– 0.24 (-0.004)	– 0.43 (-0.04)
NPP	0.07 (-0.29)	– 0.29 (-0.37)	– 0.12 (-0.19)	– 0.33 (-0.85)
TER	0.01 (0.01)	– 0.16 (-0.02)	– 0.21(-0.02)	– 0.36(-0.03)
NEE	0.11 (0.01)	– 0.15 (-0.04)	– 0.03 (0.01)	– 0.07(-0.01)

Table 6 shows the regional estimates of carbon flux anomalies in 2003 relative to the reference period 1998-2002 average. Negative anomalies indicate that the ecosystems took up less carbon in 2003 relative to that of the reference period 1998-2002.

Figs. 5 & 6 show the European wide anomalies of climate and terrestrial ecosystem carbon fluxes during 2003. All the data compares the result of 2003 and those of the reference period (1998-2002)



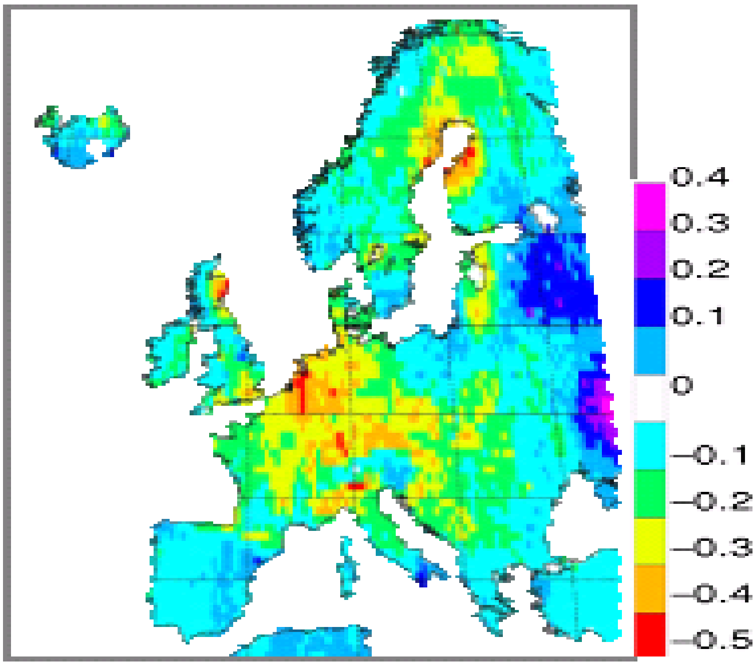
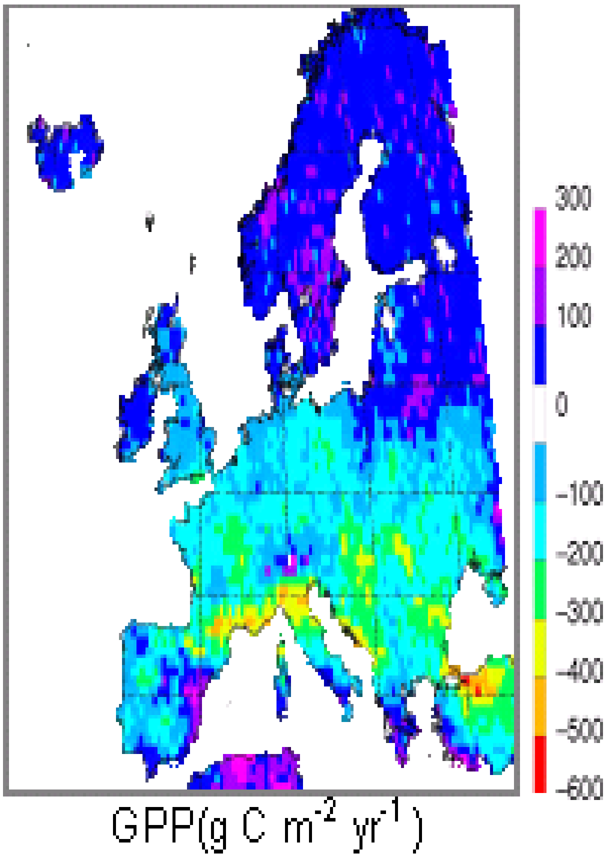


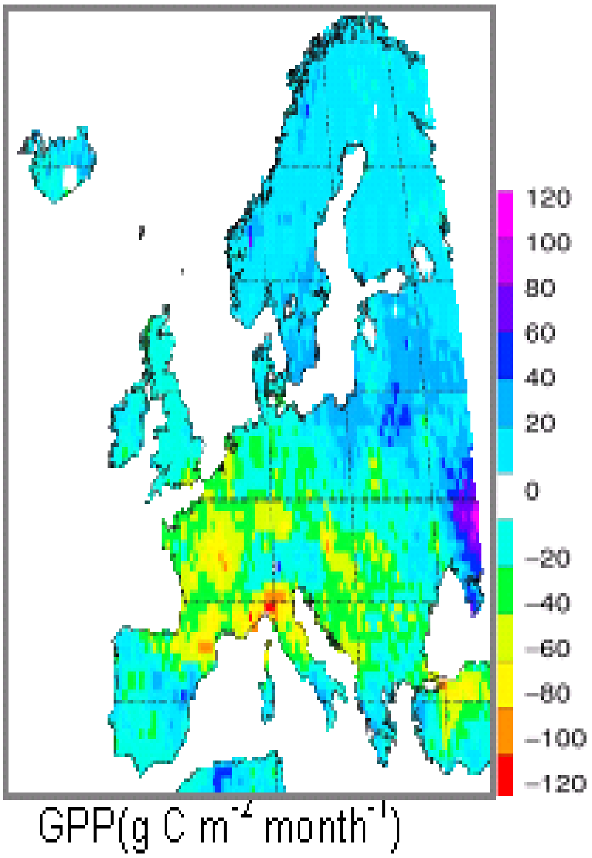
Fig.5. European–wide anomalies in climate and soil water content (i.e. fraction change in available water holding capacity in the top 0.5 m of soil) in 2003 relative to the reference period (1998-2002).

(a) Growing season (July-September) temperature anomaly 2003: turquoise - Pink areas indicate temperature increase relative to reference period, green - red areas indicate a decrease in temperature. **(b)** Precipitation anomaly 2003: blue – pink areas: increase in annual precipitation relative to reference period, turquoise - red areas indicates a decrease. **(c)** The fraction change (0 to 1) of the available water holding capacity in the top 0.5m of soil: blue – pink areas indicates an increase in soil water content relative to reference period, while turquoise – red areas indicates a decrease.

a)


300
200
100
0
-100
-200
-300
-400
-500
-600
GPP(g C m-2 yr-1)

(b


120
100
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20
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-60
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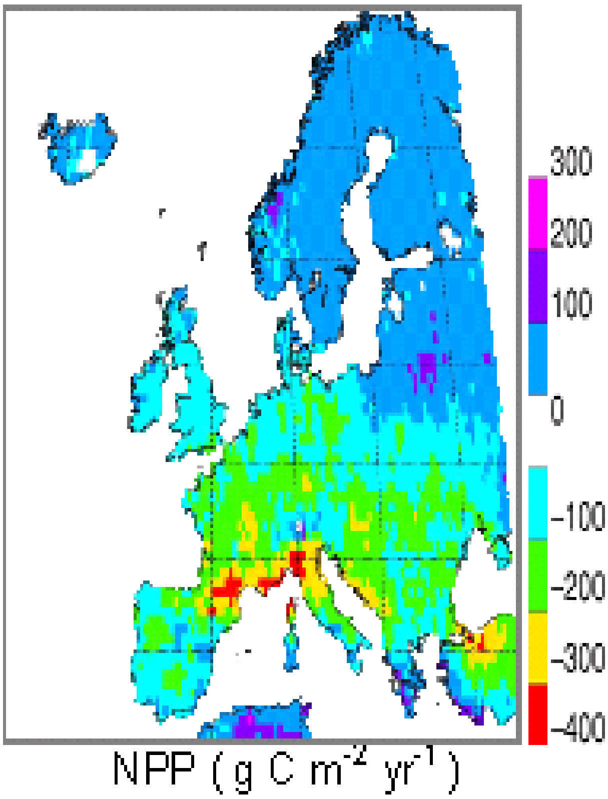
-100
-120
GPP(g C m-2 month-1)

c)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200
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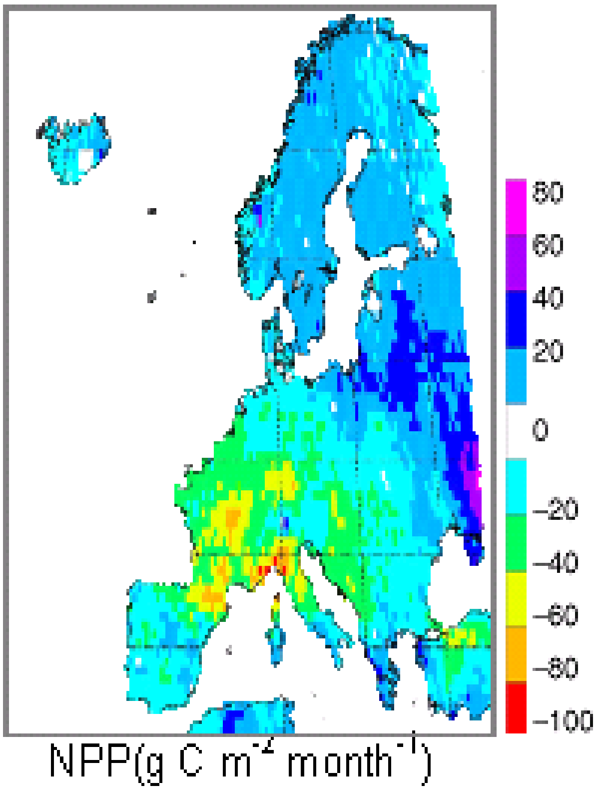
0
-100
-200
-300
-400
NPP (g C m-2 yr-1)

(d


80
60
40
20
0
-20
-40
-60
-80
-100
NPP(g C m-2 month-1)

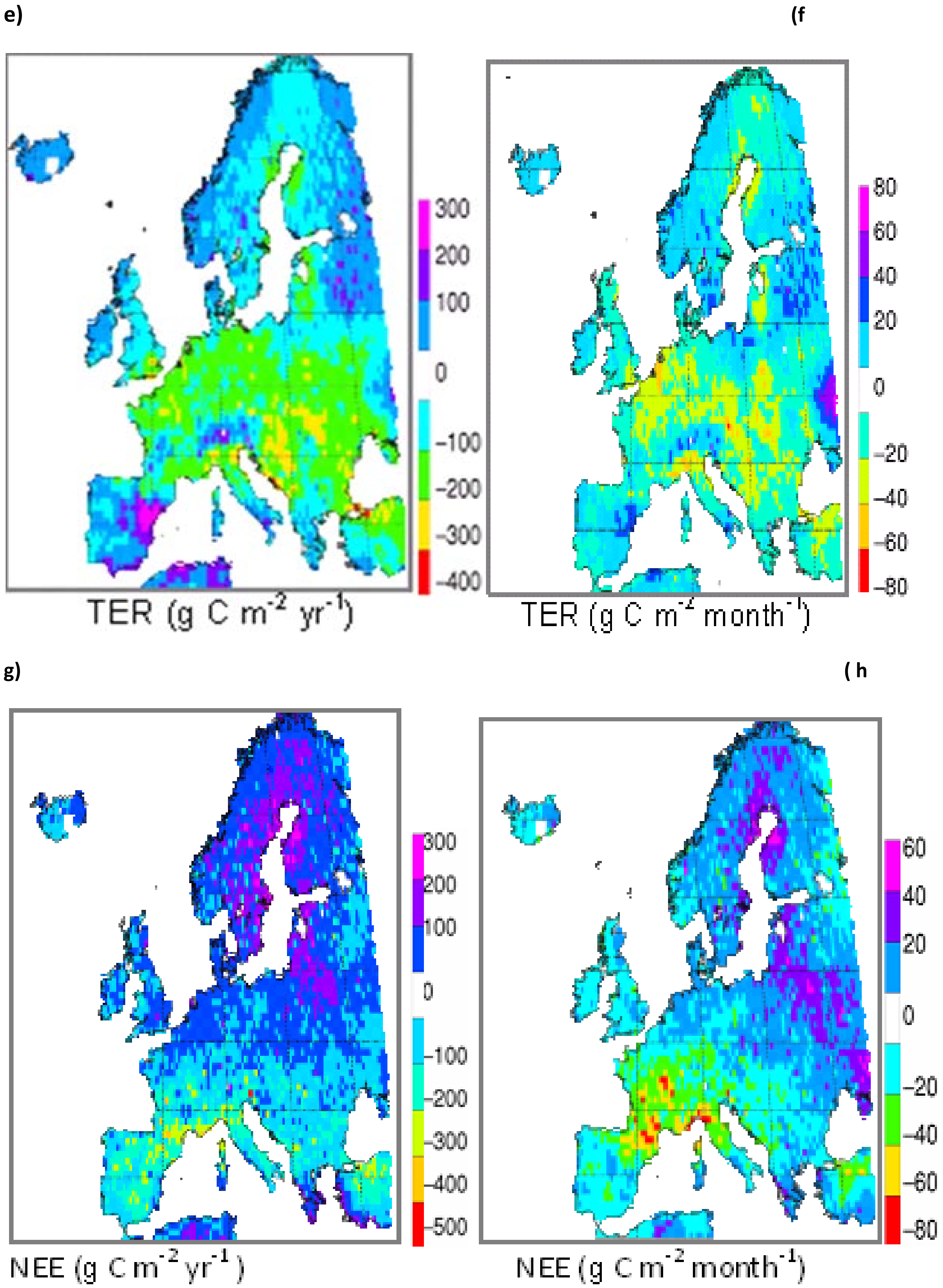


Fig.6. European –wide anomalies in terrestrial ecosystem carbon fluxes during 2003 relative to the reference period (1998-2002).

(a) Represents the simulated changes in annual GPP. (**b)** Simulated changes in growing season (July-September) GPP. **(c)** Simulated changes in annual NPP. **(d)** Simulated changes in the growing season NPP. **(e)** Simulated changes in annual TER. (**f**) Simulated changes in growing season TER. (**g)** Simulated changes in Annual NEE. (**h**) Simulated changes in the growing season NEE.

4.2.1a. Northern Europe

In 2003, the northern region of Europe experienced a moderate warming relative to 1998-2002 average. The growing season temperature rose above the 1998-2002 average by about 1.0-1.5^{o}C (Fig.5a). The region experienced moderate changes in annual precipitation. For example precipitation reductions of about 20mm month^{-1} in Sweden, Denmark and the northern part of Finland (Fig.5b). In addition to this, most parts of the region experienced a reduction in soil water content in summer. The model indicated an increase in the annual and growing season GPP in this region in 2003 relative to the reference period (Table 6) especially in the southern part of Sweden and Norway (Figs.6a & 6b). This increase in GPP could be as a result of the rise in temperature in the region (about 1.0-1.5^{o}C) relative to the reference period and the less severe precipitation deficit. This region also experienced an increase in annual NPP though it reduced over the growing season (Table 6) especially in parts of Norway and Finland (Fig.6d). The TER anomaly in 2003 indicates a small increase in respiration in 2003 relative to the 1998-2002 average (Table 6) which could be explained by the rise in temperature in 2003. The resulting NEE anomaly 2003 in the northern region indicates an increased land carbon uptake relative to the reference period (Table 6, Fig.6g & 6h).

4.2.1b. Western Europe

In 2003, this region experienced the strongest heat anomaly over Europe as shown in Fig.5a. The growing season's temperature anomaly ranged between 0.5-3.0^{o}C (Fig. 5a). The highest anomaly occurred around France, 3.0^{o}C, followed by Switzerland, Germany and Northern Italy with about 2.3^{o} C relative to the reference period (Fig. 5a). The temperature anomaly was also accompanied by a decrease in precipitation (Fig. 5b).The severe negative precipitation anomaly was also pronounced in France, Switzerland, Germany and the UK. The model indicates that Switzerland was the core of the precipitation anomaly -60 to -80mm month^{-1}. Similarly, this region experienced the strongest soil water deficit especially around France, Belgium, Netherlands, Germany, and Switzerland ranging from -0.3 to -0.5 (Fig.5c).

In addition to this, the model showed a severe reduction in GPP especially over the growing season of 2003 relative to the reference period (Table 6, Figs. 6a & 6b). This reduction in 2003 GPP is in agreement with the findings of other previous studies (Ciais *et al*., 2005; Reichstein *et al*., 2006; Vetter *et al*., 2008). The region also experienced a reduction in NPP in 2003 relative to the reference period (Table 6, Figs. 6c & 6d) .Generally, we find the largest GPP and NPP reduction around France, Germany, Switzerland, Belgium, Austria and

Northern Italy (Figs.6a, b, c, d). This severe reduction in GPP and NPP is in line with the extreme heat and drought which this region experienced in 2003 (Figs.5a & 5b). With the exception of some areas in Spain and Portugal where TER increased in 2003 (Fig.6e), LPJ-GUESS estimated a negative TER anomaly in this region in 2003 relative to the reference period (Table 6, Fig 6e & 6f). This reduction in TER could be explained by the reduction in plant respiration (caused by the reduction in plant substrates) and/or heterotrophic respiration due to the 2003 drought condition (Ciais *et al.*, 2005) which affected the soil moisture negatively (Fig. 5c). All these resulted into a negative NEE anomaly which is much more pronounced over the growing season especially in France, Italy and Switzerland (Table 6 and Figs.6g & 6h).

4.2.1c. Eastern Europe

Unlike the other regions, this region was colder in 2003 relative to the reference period (Fig.5a). The growing season's temperature anomaly ranged from -0.5 to -2.0^{o}C. The lowest temperature anomaly (-2^{o}C) occurred around Ukraine (Fig. 5a).With the exception of areas like Greece, Albania, Macedonia, Ukraine and some parts of Asia which experienced an increase in precipitation relative to the reference period, the other areas experienced a negative precipitation anomaly of about 20mm/month relative to the reference period (Fig.5b) Furthermore, with the exception of areas like Ukraine, with an increase in soil moisture content, the rest of the region experienced a soil water deficit relative to the reference period (Fig.5c).

In 2003, this region also experienced a negative GPP and NPP anomaly relative to the reference period (Table 6) though with the exception of places like Ukraine where GPP and NPP instead increased especially in summer (Figs. 6a, b, c, & d). In addition to this, the model also estimated a reduction in TER in 2003 in the region (Table 6, Figs.6e & 6f). However, areas like Ukraine experienced positive anomaly in 2003 especially over the growing season as shown in Fig.6f. All these resulted into a negative annual NEE anomaly and a positive growing season NEE anomaly in 2003 relative to the 1998-2002 average (Table 6)

4.2.2. The 2003 European terrestrial ecosystem carbon fluxes in the context of last century.

In order to be able to place the 2003 anomalies in terrestrial ecosystem carbon fluxes in the context of last century and be able to compare results with other previous studies, we went further to analyze LPJ-GUESS simulated data for the periods 1901-2006, 1961-1990, 1980-2006, and 1998-2002.

Fig.7 below shows the pattern of the European terrestrial ecosystem carbon fluxes estimated by LPJ-GUESS over the period 1901-2006. The red line shows the situation in 2003. A negative NEE indicates a release of carbon into the atmosphere while a positive NEE indicates an uptake of carbon by the ecosystem.

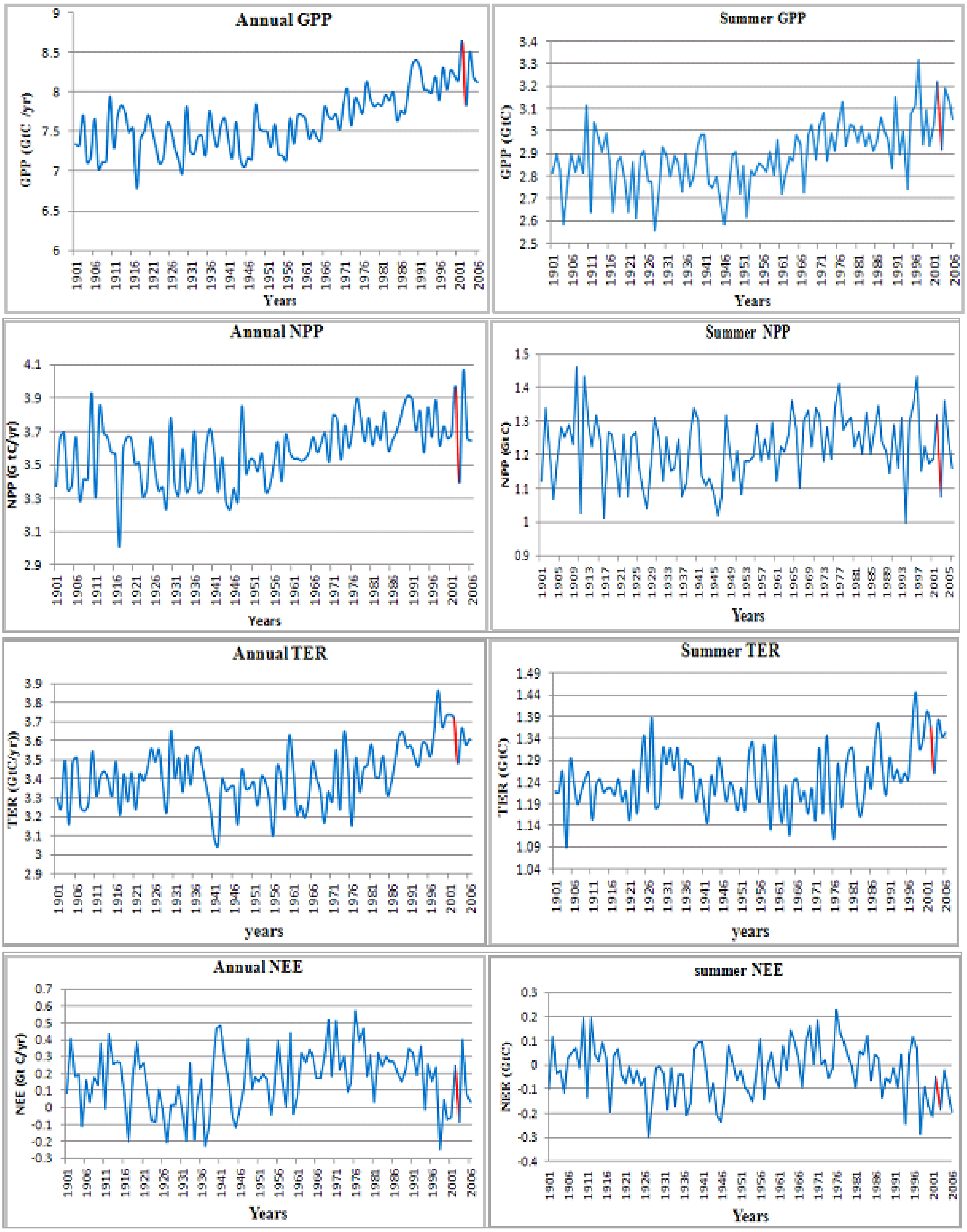


Fig.7. European carbon fluxes in the 20th and part of the 21st century estimated with LPJ-GUESS

Figure 7 shows the European terrestrial carbon fluxes in the 20th and part of the 21st century. The model shows an increasing trend of annual GPP from around 1966 to 2006. The highest annual GPP for the period 1901-2006 is seen in 2002 (8.6GtC) while the smallest GPP is seen in 1917 (6.8GtC), 1929 (6.9GtC), 1907 (7.0GtC). Between 1988 and 2006, 2003 is shown to have the smallest annual GPP (7.6GtC) followed by that of 1996 (7.9GtC). The growing season GPP for the period 1901-2006 fluctuates between approximately 2.5 -3.3GtC. The highest GPP in summer is seen in 1997 (3.3GtC) followed by that of 2002 (3.2GtC) while the lowest is seen in 1928 (2.55GtC) followed by that of 1904 and 1946 (2.6GtC/year).Between the period 1995-2006, 2003 appears to be the year with the lowest growing season GPP (2.9GtC).

The annual NPP for the period 1901-2006 fluctuates between 3 to 4.1GtC yr^{-1}. Throughout this period, the highest NPP is seen in 2004 (4.1GtC), followed by that of 2002 (4GtC), 1910 and 1990 (3.9GtC).The smallest NPP is seen in 1917 (3GtC) followed by that of 1929 (3.2GtC), and 1947 (3.3GtC). For the period 1959-2006, 2003 shows the smallest NPP (3.4GtC). The summer NPP fluctuates between 1 to 1.5GtC/year. The highest growing season NPP is seen in 1910 (1.46GtC). High NPP is also seen 1910, 1912, 1977, and 1997 (approximately 1.4GtC/year). The lowest growing season NPP is seen in 1994 (0.99GtC) followed by that of 1917 (1.01GtC), 1946 (1.01GtC), and 1911 (1.02GtC). For the period 1995-2006, 2003 is seen to have the lowest growing season NPP (1.07GtC).

The annual TER for the period 1901-2006 fluctuates between approximately 3-3.9GtC/year. The highest annual TER is seen in year 1998 (3.9GtC) followed by that of 2000, 2001 and 2002 (3.7GtC/year). The lowest TER is seen in 1942 (3.05GtC) and even 1956 (3.10GtC). The 2003 TER of about 3.5GtC appears to be the lowest for the period 1994-2006. The lowest growing season TER for the period 1901-2006 is seen in 1904 (1.08GtC), 1976 (1.11GtC), 1964 (1.12GtC) and even 1959 (1.13GtC) while the highest TER is seen in 1998 (1.44GtC) followed by that of 2001 (1.40GtC) and 1927 (1.38GtC). The 2003 growing season TER (1.26GtC) is the lowest for the period 1997-2006.

Lastly, we have the annual NEE that fluctuates between -0.25 to 0.57GtC/year for the period 1901-2006. The highest terrestrial ecosystem carbon uptake is seen in 1976 (0.57GtC), 1969 (0.52GtC) and even 1971 (0.51GtC) while highest ecosystem carbon release to the atmosphere is seen in 1998 (-0.25GtC), and even in the following years; 1937, 1917, 1927, 1932, and 1934 (approximately -0.2GtC/yr^{-1}). 2003 (-0.09GtC) appears to be the second year (the first being 1998 (-0.25GtC)) with the largest terrestrial ecosystem carbon release to the atmosphere for the period 1946-2006. As for the growing season NEE, the highest terrestrial ecosystem carbon uptake is seen in 1976 (0.23GtC), 1912 and 1910 (approximately 0.2GtC/year) while the highest carbon release to the atmosphere is seen in 1927 (-0.29GtC), 1998 (-0.28GtC) and even in 1994 (-0.24GtC). The NEE graph shows a continuous terrestrial ecosystem carbon release to the atmosphere over the growing season from about 1998 to 2006. Between 1947 and 2006, 2003 occupies the fifth position in terms of the highest terrestrial ecosystem carbon release to the atmosphere in summer i.e. 1998 (-0.28), 1994 (-0.24GtC), 2001 (-0.21GtC), 2006 (-0.19GtC) and lastly 2003 (-0.18GtC).

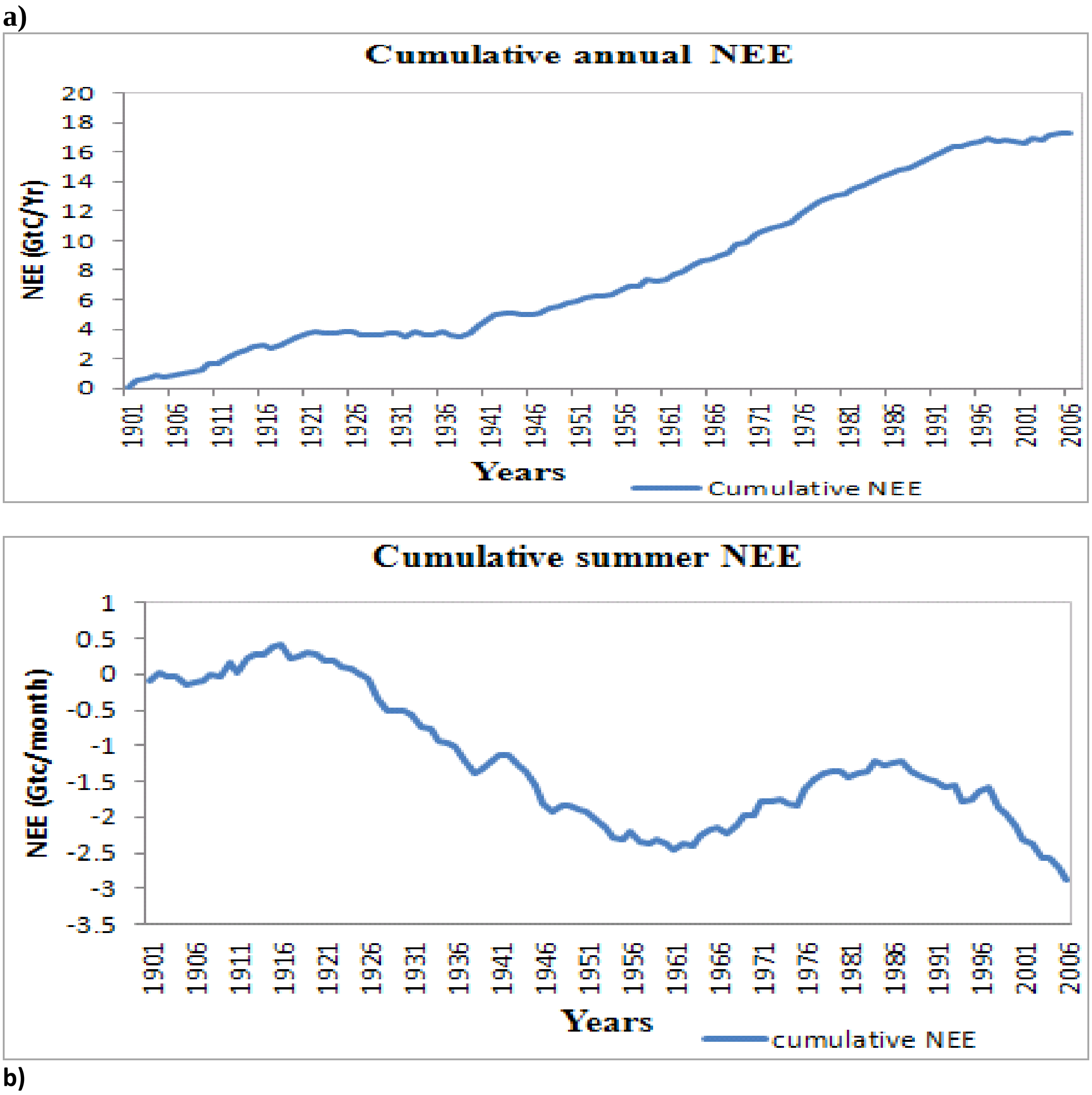


Fig.8. European cumulative NEE (1901-2006). Units: GtC

The Cumulative annual NEE (Fig.8a) shows a positive increasing trend which indicates that European terrestrial ecosystems have mostly been taking up carbon from the atmosphere ever since the last century. The cumulative NEE over the growing season (Fig.8b) shows four patterns. Between 1901 to about 1916, the ecosystems were taking up carbon from the atmosphere in summer, between 1917 to about 1961, the ecosystems were mostly releasing carbon to the atmosphere in summer, between 1962 to about 1986, the ecosystems were mostly taking up carbon from the atmosphere in summer and lastly between the years 1987 to 2006, the ecosystems were mostly releasing carbon to the atmosphere in summer.

Table7. The European carbon fluxes and anomalies (GtC/year) and the corresponding average growing season (July-September) fluxes and anomalies (final column) (GtC/month, in brackets) for the periods 1961-1990, 1980-2006, 1998-2002 and 2003.

Ecosystem C Fluxes	1961-1990 GtC/year (GtC/month)	1980-2006 GtC/year (GtC/month)	1998-2002 GtC/year (GtC/month)	2003 GtC/year (GtC/month)	2003-1998-2002 GtC/year (GtC/month)
GPP	_	_	8.26 (1.01)	7.83 (0.97)	-0.43(-0.04)
NPP	_	_	3.73 (1.21)	3.39 (0.36)	-0.33 (-0.85)
TER	_	_	8.28 (1.07)	7.91 (1.04)	-0.36 (-0.03)
NEE	0.27 (0.01)	0.17 (-0.02)	– 0.02 (-0.05)	– 0.09 (-0.06)	– 0.07(-0.01)

Table7 shows that over the period 1961-1990, the European terrestrial ecosystems were taking up atmospheric carbon at an average level of 0.27GtC yr^{-1} and 0.01GtC over the growing season. For the period 1980-2006 model result shows that, the ecosystems were taking up carbon at a reduced average level of about 0.17GtC yr^{-1} while over the growing season, the ecosystems were releasing carbon to the atmosphere at an average level of about 0.02GtC/month. Between 1998- 2002, the ecosystems experienced a small increase in terrestrial ecosystem respiration over gross primary production which led to a small net carbon release of about 0.02 GtC yr^{-1} and 0.05 GtC/month over the growing season.

In 2003, the terrestrial ecosystem carbon release through TER exceeded the carbon uptake as GPP leading to an annual net carbon release of 0.09 GtC and a growing season carbon release of 0.06GtC/month. A comparison of the carbon fluxes in 2003 with averages of 1998-2002 shows that, the 2003 GPP, TER and NPP was smaller than those of 1998-2002 averages. The resulting annual (-0.07GtC) and summer NEE (-0.01GtC/month) anomalies show that the ecosystems released more carbon to the atmosphere in 2003 relative to the reference period (1998-2002). Overall, the model indicates a trend towards a reduction in the European terrestrial carbon uptake; both annually and over the growing season (see also Figure 7).

4.3. Attribution results

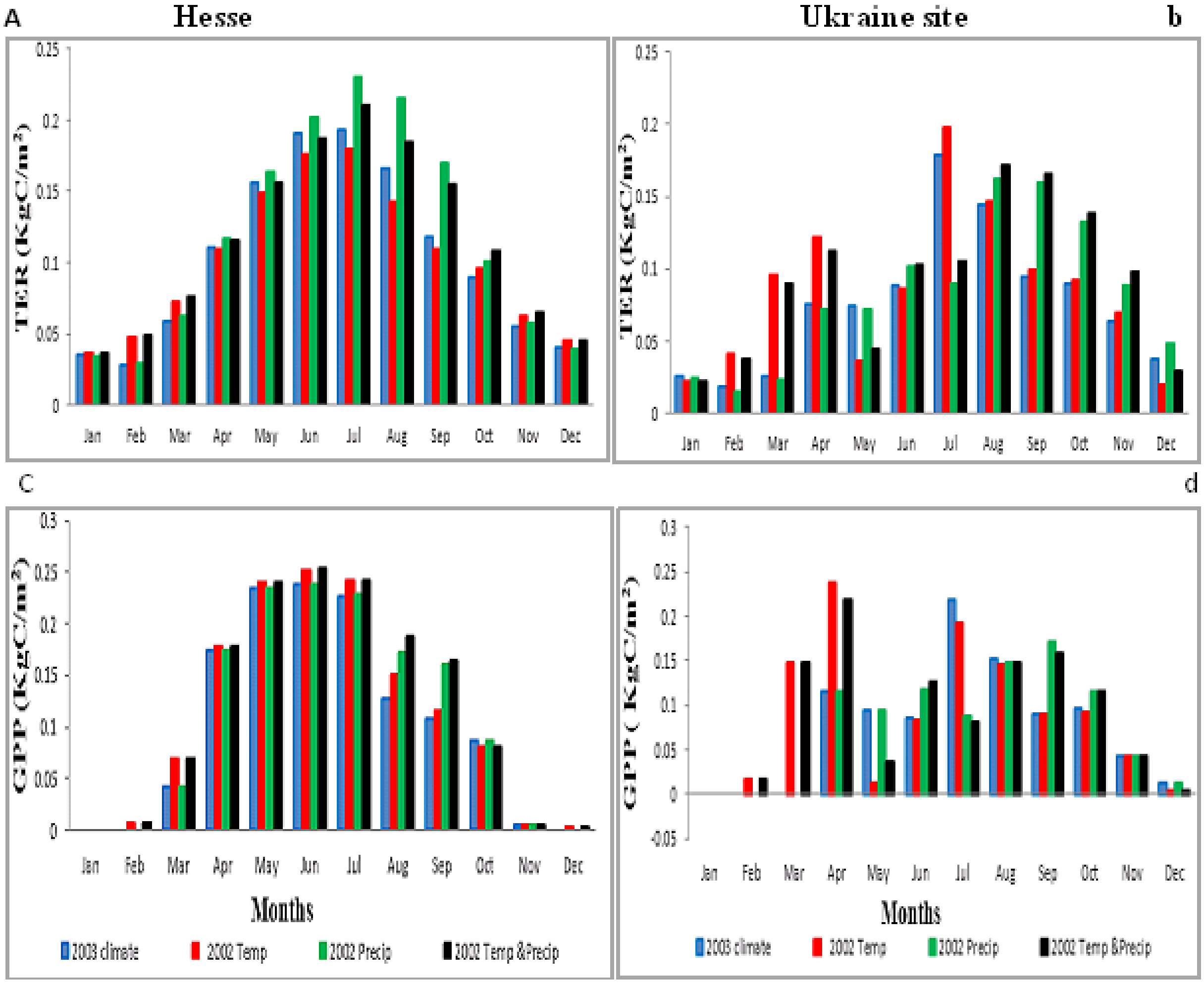


Fig. 9.Attribution of 2003 terrestrial ecosystem carbon flux anomalies at two sites (Hesse and Ukraine site).

Fig.9 shows the attribution results of the 2003 terrestrial ecosystem carbon flux anomalies at two sites; a forest site in France known as Hesse and a grassland (crops) site in Ukraine. **a)**,terrestrial ecosystem respiration for Hesse. **b)**, terrestrial ecosystem respiration for Ukraine site. **c),**gross primary production for Hesse. **d)** gross primary production for Ukraine site.The blue columns represent carbon fluxes based on 2003 climate, red columns represent fluxes based on runs with 2003 temperature replaced by 2002 temperature, green columns represent fluxes based on runs with 2003 precipitation replaced by 2002 precipitation and lastly black columns represents carbon fluxes based on runs with both 2003 temperature and precipitation replaced by their 2002 values.

These two sites experienced contrasting climatic conditions in 2003 which inturn affected their carbon fluxes differently.in 2003, based on Fig.5, France was hot and dry while Ukraine was cold and wet.

4.3.1.Hesse site

The 2003 growing season GPP for Hesse shows a decreasing trend from July to September (Fig.9c). The GPP of July is somehow similar to that of 2002 climate but increases more with 2002 temperature. The smallest GPP is seen in the months of August and September. In the month of August, GPP is 0.13 kgC/m^2 with 2003 climate but with the 2002 climate data, especially precipitation data, it increases to 0.17 kgCm^{-2}. In September, GPP in 2003 is about 0.11 kgC/m^2, but with 2002 climate data especially precipitation alone, it increases to 0.16kgC/m^{-2}. The increase in GPP with the use of 2002 precipitation data in 2003 situation is an indication that the reduction in 2003 growing season GPP was more as a result of the drought condition.

Fig.9a represents the situation of TER. The TER shows a decreasing trend from July to September based on the 2003 climate. But with the 2002 climate data and most especially the precipitation data, TER increases. This result also implies that the 2003 growing season decreasing trend in TER is more as a result of the drought condition in the area.

4.3.2. Ukraine site

The GPP of Ukraine site (Fig.9b) also shows a decreasing trend from July to September thought the GPP of 2003 is greater than that driven by 2002 climate in July and August. The Ukraine site differs from Hesse in terms of GPP in that, in the month of July, the GPP in 2003 climate is relatively very high (0.18 kgC m^{-2}) compared to that of 2002 climate data. The GPP however drops in August and September. Although the GPP drops in August, it is still very similar to that of 2002 climate data. The smallest GPP is seen in September but increases with 2002 climate data especially the precipitation data (0.17 gC m^{-2}) indicating that the 2003 reduction in GPP was as a result of the drought conditions.

Just like in the situation in Hesse, the TER for the Ukraine site in 2003 (Fig.9d) is smaller than that of 2002 climate data and it also shows a decreasing trend from July to September. The highest TER is seen in July but declines in August and most especially in September (0.09kgCm^{-2}). In the month of July, TER increases with 2002 temperature while in August and September, it increases with 2002 climate data most especially the precipitation.This is an indication that the reduction in TER in August and September of 2003 was as a result of the drought condition.

5 Discussions

5.1 The European terrestrial ecosystem carbon balance

In 2003, a majority of the test sites experienced an increase in the growing season temperature relative to that of 2002. The highest temperature anomaly reached 3°C in Laqueuille, Puechabon (France), Pianosa and Roccarespampani both in Italy. Similarly, a majority of the sites experienced a reduction in the growing season precipitation in 2003. These climatic anomalies had impacts on the ecosystem carbon fluxes. The model indicated a reduction in the growing season 2003 GPP relative to the reference period 2002 especially in the Mediterranean sites. This finding is similar to that of previous studies like Ciais *et al.*, 2005. In the Mediterranean climates, the low precipitation and high atmospheric evaporation in summer reduce moisture availability to plants and dry season productivity (Pereira *et al.*, 2007). From the two case study sites; Hesse and San Rossore, it is clearly seen that even after the summer stress of July-September, the GPP could not still recover entirely during the rest of the growing season. In addition to this, most sites experienced a reduction in TER in 2003 relative to that of 2002. According to Ciais *et al.*, 2005, this parallel TER and GPP responses could be explained by two factors; first the reduction in plant respiration caused by the diminished substrate and secondly the reduction in microbial soil respiration caused by the 2003 drought. In addition to this, those sites that experienced a severe reduction in gross primary production also experienced a reduction in their net carbon uptake (NEE). The greatest carbon release to the atmosphere in 2003 occurred in the Mediterranean sites while some Temperate sites like Vielsalm in Belgium, Tharand and Hainich in Germany were instead, taking up carbon.

At the European regional scale, three patterns of the 2003 climate anomaly can be distinguished. Western Europe exhibited a severe heat and drought condition, Eastern Europe a cold and wet condition in some areas and a cold and dry condition in others while Northern Europe exhibited moderate conditions**.** These climatic anomalies had impacts on the terrestrial carbon fluxes of these regions. Our study shows that the growing season temperature over the Western region increased by more than 1.5 degree Celsius in 2003 relative to the reference period. The highest anomaly in temperature is seen around France, 3.0°C, followed by Switzerland, Germany and Northern Italy, 2.3°C relative to the reference period. Previous studies have also shown that, France, Germany, and Switzerland were among the countries which experienced record-breaking maximum temperature in summer 2003 (Schär *et al.*, 2004; WMO, 2004; Beniston 2004; Levison and Waple 2004). According to Fink *et al.*, 2004, during the heat waves in Western Europe, temperature anomalies went up as high as 10°C during a week. The extreme heat and drought conditions in Western Europe led to a severe reduction in GPP, NPP and TER. All these resulted into a negative net ecosystem exchange (NEE) anomaly in 2003 relative to the reference period implying that the terrestrial ecosystem in this region, acted as a net source of carbon to the atmosphere in 2003. This result is in agreement with those of previous studies, (Ciais *et al.*, 2005; Vetter *et al.*, 2008; Reichstein *et al.*, 2006). This 2003 annual and growing season net release of carbon to the atmosphere relative to the reference period was more as a result of the reduction in ecosystem gross primary production and not due to an increase in TER because our results indicate a decrease in terrestrial ecosystem respiration in 2003 relative to the reference period (see Table 6). This finding is also similar that of previous findings (Ciais *et al*., 2005).

Contrary to the situation in the Western region, the moderate climatic conditions in Northern Europe favored an increase in GPP, NPP and TER. The increase in GPP over TER caused the ecosystem to act as a greater sink of carbon in 2003 relative to the 1998-2002 average. According to Churkina and Running (1998), the increase in NEE in the northern region is as a result of the enhanced photosynthesis caused by the increase in temperature and radiation. The Eastern region exhibited the lowest temperature anomaly in 2003. Some areas exhibited dry conditions while others exhibited wet conditions. These climatic conditions led to a reduction in the region's GPP, NPP and TER in 2003 relative to the reference period. Generally the NEE anomalies show that this region took up less carbon throughout the year but took up more carbon over the growing season of 2003. Ukraine exhibited the lowest temperature anomaly (-2^{o}C) in the Eastern region. This area also experienced an increase in precipitation and soil moisture in 2003. These climatic conditions led to an increase in ecosystem productivity and a positive NEE anomaly implying the ecosystems in the area were taking up carbon from the atmosphere.

In both the Western and Eastern region, we find that terrestrial ecosystem respiration decreases alongside gross primary productivity, instead of it increasing with the rise in temperature. The attribution results suggest that the 2003 reduction in GPP and TER over Western Europe (as represented by the Hesse) can be explained by the extreme summer heat and drought conditions while that of Eastern Europe (as represented by the Ukraine site) can be explained by the drought condition. This is in line with previous studies like that of Ciais *et al*., 2005 which suggest that, the reduction in productivity in Eastern Europe can be explained by the rainfall deficit while that of Western Europe can be explained by the extreme summer heat. In summer, drought causes stomata closure and leaf senescence which leads to a general reduction in GPP (Pereira *et al*., 2007).

Despite all these regional variations in climate and carbon fluxes, at the continental scale, LPJ-GUESS estimated negative anomalies for GPP, NPP, TER and NEE over Europe in 2003 relative to the 1998-2002 average (Table 6). Our model study estimates an increase in the overall net carbon release in 2003 of about 0.07GtC and an increase in the associated growing season (July-September) release of about 0.03GtC in response to the 2003 heat and drought. Other previous studies have also suggested that the European terrestrial ecosystems acted as a net source of carbon to the atmosphere over the 2003 growing season.

Table 8. The European growing season carbon balance from different model simulations

References	**Carbon Source**	**Period**
This study,(LPJ-GUESS)	0.03GtC	2003-(1998-2002)
Ciais *et a*l.,2005	0.5GtC	2003-(1998-2002)
Vetter *et al*.,2008	0.02-0.27GtC	2003-(1998-2002)

A multi-model comparison study by Vetter *et al*., 2008 estimated that the European terrestrial ecosystem emitted between 0.02 - 0.27 GtC to the atmosphere over the growing season 2003 relative to the baseline carbon release (1998-2002). Another previous study by Ciais *et al*., 2005, yielded a much stronger estimate of anomalous net source of carbon from the European terrestrial ecosystem of about 0.5GtC to the atmosphere in 2003 using the ORCHIDEE ecosystem model. Our value falls within the range of these previous studies. Just like the study by Ciais *et al*., 2005, our result also shows that the 2003 negative carbon balance anomaly was controlled by the ecosystem experiencing a reduction in photosynthesis and not as a result of any increase in ecosystem respiration (see Table 6). Vetter *et al*., 2008, suggested that the net carbon release over the growing season of 2003 is dominated by the ecosystems experiencing extreme drought. Similarly, Ciais *et al*., 2005 attributed the 2003 European carbon flux anomaly to the drought than the heat wave in 2003

These differences in result value might be as a result of the differences in the forcing data, the definition of the models' European domain, the method/model types used and even the definition of the growing season for example Vetter *et al*., 2008 defined it as the period from May to September while in our study and in Ciais *et al*., 2005, it is from July to September. Vetter *et al*., 2008 considered these differences in the definition of the growing season to justify why the study by Ciais *et al*., 2005, yielded a much stronger anomaly.

5.2 European terrestrial ecosystems carbon fluxes in the context of last century

Putting the 2003 carbon fluxes in the context of last century and part of present i.e. 1901-2006, it is clearly seen that in terms of annual GPP, 2003 (7.6GtC) occupies the first position only for the period 1988-2006. Other past years with lower annual GPP include 1917 (6.8GtC), 1929 (6.9GtC), and even 1907 (7.0GtC). Similarly 2003 growing season GPP (2.9GtC) appears to be the lowest only for the period 1995-2006. Other years with much lower growing season GPP values include; 1928 (2.55GtC) and even 1904 (2.6GtC). As concerns the NPP, the 2003 annual NPP value (3.4GtC) appears to be the lowest only for the period 1959-2006 while that of the growing season (i.e. 1.07GtC) occupies the first position only for the period 1995-2006. Other previous years with much smaller annual NPP include; 1917 (3GtC), 1929 (3.2GtC) and 1947 (3.3GtC). Over the growing season we have; 1994 (0.99GtC), 1917 (1.01GtC), 1946 (1.01GtC) and even 1911(1.02GtC).

Furthermore, the annual TER for 2003 (3.5GtC) is the lowest only for the period 1994-2006 and not for the entire model run period (1901-2006). Other previous years with a much smaller TER values include; 1942 (3.05GtC) and 1956 (3.10GtC). Similarly, the 2003 growing season TER value of 1.26GtC appears to be the lowest just for the period 1997-2006. Much lower TER values are seen in 1904 (1.08GtC), 1976 (1.11GtC), 1964 (1.12GtC) and even 1959 (1.13GtC). Finally, the 2003 annual value of net carbon release (-0.09GtC) shows that, 2003 is the second year with the largest carbon release only for the period 1946-2006.Other past years with much higher carbon release values include; 1998 (-0.25GtC), 1937, 1917, 1927, and 1934 with approximately -0.2GtC/year. Regarding the growing season NEE, 2003 occupies the fifth position for the period 1947-2006, in terms of the highest carbon release value 1998 (-0.28GtC), 1994 (-0.24GtC), 2001 (-0.21GtC), 2006 (-0.19GtC) and lastly 2003 (-0.18GtC).

However, the cumulative annual NEE shows that, the European terrestrial ecosystems have been taking up carbon from the atmosphere ever since the last century while that of the growing season shows four patterns. Between 1901 to about 1916, the ecosystems were taking up carbon from the atmosphere, between 1917 to about 1961, the ecosystems were mostly releasing carbon to the atmosphere, between 1962 to about 1986, the ecosystems were again mostly taking up carbon from the atmosphere and lastly between the years 1987 to 2006, the ecosystems were mostly releasing carbon to the atmosphere.

In a study by Churkina *et al*., 2010, from 1900 to approximately 1960, the average carbon balance of European terrestrial ecosystems estimated by all models was close to zero but from 1960-70s onwards; the ecosystems were dominantly sequestering atmospheric carbon (See Fig.2 in their study). Our study shows a continuous yearly sequestration of carbon by the terrestrial ecosystems only for the period 1961-1993 (see Fig.7, annual NEE). This differences result from the fact that, the study by Churkina *et al*., 2010 took into consideration land cover changes, and nitrogen deposition which our model did not take into consideration and which also has an impact on terrestrial carbon stock.

A number of studies so far suggest a substantial net carbon uptake in European terrestrial ecosystems over the last decades, Table 9.

Table 9.Net carbon uptake in European terrestrial ecosystems over the last decades

References	Carbon Sink TgC yr^{-1}	Area 10^6 km^2	Time Period
This study (LPJ-GUESS Model)	170	7.12	1980-2006
Schulze *et al.,* 2009	235	9.29	2000-2005
Janssens *et a*l.,2003	111	10.4	unspecified
Vetter *et al*.,2008 (modeled)	157	9.32	1980-2005
Zaehle *et al*.,2007 (modeled)	30	9.32	1980-2007
Churkina *et al*.,2010 (modeled)	100	9.32	1980-2007

The average estimate of terrestrial ecosystem net carbon uptake from this study is about 170 TgC yr^{-1} for the period 1980-2006. This simulated carbon sequestration is equivalent to about 11% of the annual-averaged European (EU-27) greenhouse gas emissions between 1980 and 2005 (expressed in CO_2 equivalents) (European Environment Agency). Our carbon sink value falls within the range of the other previous studies. The differences in the values (Table 9) can be explained by the differences in the methods and assumptions used, vegetation types included, forcing data and even the time period. The increasing trend in the European terrestrial ecosystem carbon uptake can be explained by a combination of factors; changes in past land-use and land management practices such as the increase in forest area, increase in productivity through fertilization, and a reduction in the fraction of the forest that is harvested for wood production (Nabuurs *et al*., 2003).

Furthermore, the impacts of nitrogen deposition, CO_2 fertilization and climate change are also believed to be contributing to this increasing terrestrial carbon uptake (Nabuurs *et al*., 2003). However, the extent to which this uptake can continue in the future is still unclear (Nabuurs *et al*., 2003). A study by Zaehle *et al*.,2007, based on 4 illustrative IPCC-SRES storylines (AIFI,A2,B1,B2) shows that, the decrease in agricultural areas and the subsequent increase in forest leads to a simulated net carbon uptake in the European terrestrial ecosystems between 1990-2100. In addition to this, climate and atmospheric CO_2 change will help to enhance the terrestrial ecosystems carbon uptake before 2040, after which they turn into a carbon source in all scenarios due to soil carbon losses resulting from climate warming (Zaehle *et al*., 2007). According to Fang *et al*., 2005, climate change due to fossil fuel emission might greatly alter the terrestrial ecosystems (especially the soil) capacity to take up carbon

5.3 Future projection

A number of studies have projected a likely increase in future extreme summer heat waves in Europe like that of 2003 (Schär *et al*.,2004; IPCC 2007; Meehl and Tebaldi 2004; Luterbacher *et al*.,2004). According to the IPCC 2007, the joined effects of warmer temperature and reduced mean summer precipitation would increase the occurrence of heat waves and drought in the future. Beniston 2004 projected a future increase in the frequency of the physical processes that characterized the 2003 heat wave in Europe; soil moisture depletion, positive feedback on summer temperature, the lack of convective rainfall in many parts of the continent from June to September.

This projected increase in the occurrence of heat waves would probably have some consequences on the future carbon balance of Europe. With the exception of high elevations, it is believed that more frequent heat and drought events may offset the anticipated smooth trends of the warmer temperatures and longer growing seasons, implying a long-term decrease in the productivity of ecosystems, reversing sinks to sources, and contributing to positive carbon-climate feedbacks (Granier *et al*.,2007; Ciais *et al.*,2005). According to Vetter *et al*., 2008, due to the fact that terrestrial ecosystems carbon fluxes to the atmosphere increases with drought, frequent drought may cause a faster increase in atmospheric CO_2 concentration and accelerate global warming. Similarly, Granier *et al*., 2007, pointed to the fact that, if summer droughts become more frequent in the future, the terrestrial ecosystem would probably decrease its carbon uptake and some ecosystem sites might even switch from a sink to a source of carbon. Our result also shows a trend towards a more and more reduction in the European terrestrial ecosystem carbon uptake over the growing season (see also Figure 7) which we believe might continue into the future.

5.4. Strengths and limitations of this study

- The model was successful in predicting the observed response of European terrestrial ecosystem to the 2003 extreme climatic events (heat wave and drought), producing results which are similar to those of previous studies.
- The CRU data considers whole grid cells while a study like Ciais *et al*., 2005 considers data at particular sites which is more realistic. This can also help to explain the differences in the results of the two studies especially the test sites.
- The simulated vegetation types differ from the observed vegetation types as seen in the test sites e.g Laqueille (FR) is a grassland, (but model simulation predicts that its dominated by shade tolerant broad leaved summer green tree). El saler (SP) evergreen needle leaf forest, (model simulations predicts that it is dominated by C3G)

- Since the model is not able to represent crops, we had to assume the simulated grass to be crops.

- The model also simulates plant functional types (PFTs) and not plant species. Plant species give a more realistic picture of the ecosystems, a more diverse forest, more realistic carbon fluxes and pools.

- We were not able to simulate a complete attribution of the European carbon balance. For example the influence of nitrogen deposition and even land use management are not included in this study but are also very important in the understanding of the continental scale carbon cycling.

6 Conclusions

In this study, we pointed out the following facts
Extreme events like that of the 2003 European heat wave and drought are capable of altering the continental scale carbon balances. In 2003 Northern Europe experienced moderate temperature and precipitation condition, Western Europe experienced the strongest heat and drought anomaly while the Eastern region instead experienced a low temperature with some areas experiencing positive precipitation and others negative precipitation anomaly.

Northern European terrestrial ecosystems took up more carbon in 2003 relative to the reference period (0.11GtC), summer (0.01GtC),while Western Europe took up less carbon in 2003 relative to the reference period (-0.15GtC), summer(-0.04GtC), lastly Eastern European terrestrial ecosystems took up less carbon in 2003 relative to the reference period (-0.03GtC) but more over the summer (0.01GtC).

The reduction in GPP and TER over Western Europe in 2003 (as represented by Hesse) can be attributed to the extreme summer heat and drought condition while that of Eastern Europe (as represented by the Ukraine site) can be attributed to the drought condition.

At the continental scale, LPJ-GUESS predicts a 2003 growing season carbon source anomaly of about 0.03GtC to the atmosphere in response to heat wave and drought of 2003 relative to the reference period (1998-2002 average). This estimated value falls within the range of previously reported values such as the 0.5GtC in a study by Ciais *et al*., 2005 calculated with the ORCHIDEE ecosystem model and that of Vetter *et al*., 2008 (0.02-0.27Gt C) based on a multi-model comparison study.

2003 negative carbon balance anomaly is controlled by the ecosystems experiencing reductions in both photosynthesis and terrestrial ecosystem analysis.

In the context of last century and part of present years (1901-2006), 2003 annual NEE (-0.09GtC) appears to be the second year with the largest terrestrial ecosystem carbon release to the atmosphere for the period 1946-2006 only. Other years with more exceptional carbon release include; 1998 (-0.25GtC), 1937, 1917, 1927, 1932, and 1934 (approximately -0.2GtC/yr^{-1}). For the growing season, 2003 occupies the fifth position for the period 1947-2006 i.e. 1998 (-0.28GtC), 1994 (-0.24GtC), 2001 (-0.21GtC), 2006 (-0.19GtC) and lastly 2003 (-0.18GtC).

Over the last decades (1980-2006), LPJ-GUESS predicts a net carbon uptake of about 170Tg C/yr which is equivalent to about 11% of the annual-average European (EU-27) greenhouse gas emissions between 1980 - 2005

Due to the fact that extreme events like the European heat wave and drought of 2003 have been shown to have severe impacts on the functioning of the terrestrial ecosystems, the projected future increase in extreme summer heat waves and drought (Schär *et al.*,2004, IPCC 2007, Beniston 2004), will cause the European terrestrial ecosystems to experience a reduction in their productivity thus a decrease in their carbon uptake with some sites even switching from a sink to a source of carbon to the atmosphere (Granier *et al.*,2007)

Since this study could only focus on the short-term consequences of extreme climatic conditions on European terrestrial ecosystem carbon balance, future research could focus on the long term consequences of such extreme events. In addition to this, other future research could focus only on a particular country in Europe like France or on other continents e.g. Africa.

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