Biogeosciences Discuss., 10, 11857–11897, 2013
www.biogeosciences-discuss.net/10/11857/2013/
doi:10.5194/bgd-10-11857-2013

Biogeosciences
Discussions
Open Access

Evaluating the potential of large scale simulations to predict carbon fluxes of terrestrial ecosystems over a European Eddy Covariance network

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Received: 29 June 2013 – Accepted: 8 July 2013 – Published: 16 July 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Understanding and simulating land biosphere processes happening at the interface between plants and atmosphere are important research activities with operational applications for monitoring and predicting seasonal and inter-annual variability of terrestrial carbon fluxes in connection to a changing climate. This paper reports a comparison between three different Land Surface Models (LSMs), ORCHIDEE, ISBA-A-gs and CTESSEL used in the Copernicus-Land project precursor, forced with the same meteorological data, and compared with the carbon fluxes measured at 32 Eddy Covariance (EC) flux tower sites in Europe. The results show that the three models have the best performance for forest sites and the poorest performance for cropland and grassland sites. In addition, the three models have difficulties capturing the seasonality of Mediterranean and Sub-tropical biomes, characterized by dry summers. This reduced simulation performance is also reflected in deficiencies in diagnosed Light Use Efficiency (LUE) and Vapour Pressure Deficit (VPD) dependencies compared to observations. Shortcomings in the forcing data may also play a role. These results indicate that more research is needed on the LUE and VPD functions for Mediterranean and Sub-tropical biomes. Finally, this study highlights the importance well representing phenology (i.e. Leaf Area evolution) and management (i.e. rotation/irrigation for cropland, and grazing/harvesting for grassland) to simulate the carbon dynamics of European ecosystems and the importance of ecosystem level observation in models development and validation.

1 Introduction

Terrestrial ecosystems currently mitigate climate warming by sequestering in plants and soils a significant portion of anthropogenic carbon dioxide (CO_2) emissions, which are considered to be primarily responsible for the increase in global surface air temperature since the mid 20th century (IPCC, 2007). In particular, European terrestrial ecosystems have been reported to be a significant sink of CO_2 (Luyssaert et al., 2012).

The mechanisms that drive the net carbon uptake in Europe partially depend on the changes in the environmental conditions that occurred during the recent years (Gilmanov et al., 2007; Beer et al., 2010; Jung et al., 2010). In addition, the net carbon uptake is also affected by forest re-growth (Churkina et al., 2007; Vetter et al., 2005; Bellassen et al., 2011), land management practices (Ciais et al., 2010; Kutsch et al., 2010), nitrogen deposition (Magnani et al., 2007; Churkina et al., 2010), and response to extreme climate events (Ciais et al., 2005).

With the aim to improve biophysical fluxes (e.g. latent heat, sensible heat, momentum) and biochemical fluxes (CO_2) in the last 20 yr, Land Surface Models (LSMs) have started to include ecological and hydrological sub-models in their schemes to describe changes in terrestrial biomass and water. Examples are represented by CLM4 (Bonan et al., 2011), CTESSEL (Boussetta et al., 2013); ISBA-A-gs (Calvet et al., 1998), LPJ (Sitch et al., 2003) or ORCHIDEE (Krinner et al., 2005). However, the differences in the model schemes and in their assumptions, have led to considerable discrepancies between the different LSMs in simulating the present situation (Jung et al., 2007; Schwalm et al., 2010; Weber et al., 2009) and in projecting future scenarios of human activities (Friedlingstein et al., 2006). In this context, an extensive comparison between LSM outputs and in-situ flux measurements can help defining processes and parameters that determine differences in dynamic carbon simulations observed between LSMs (Friedlingstein et al., 2006; Gregory et al., 2009).

Thanks to the FLUXNET network of worldwide Eddy Covariance (EC) measurements (Aubinet et al., 2012), continuous multiannual EC data are now available for a wide range of ecosystems. Most LSMs use a classification according to Plant Functional Types (PFTs) to represent the main species. The observational information has a highly relevant role in understanding the land-atmosphere CO_2 processes (Baldocchi, 2008) and in evaluating/validating carbon LSMs (Friend et al., 2007) at regional and global scale. For these reasons, EC data represent an essential resource to describe with greater confidence how ecosystems processes (Net Ecosystem CO_2 Exchange – NEE, Gross Primary Production – GPP and Ecosystem Respiration – Reco) act in response to past and present climate changes in Europe (Gilmanov et al., 2007; Ciais et al., 2010). EC measurements have been extensively used for the development of LSMs. They are typically used for calibration/optimization (Kuppel et al., 2012) and for the evaluation of model performance over one or more flux towers (Morales et al., 2005; Friend et al., 2007; Gibelin et al., 2008; Stöckli et al., 2008; Mercado et al., 2009; Randerson et al., 2009; Williams et al., 2009; Zaehle and Friend, 2010; Bonan et al., 2011; Boussetta et al., 2013), or at global scale using data-oriented models (Jung et al., 2010). In addition, all information collected at EC flux towers, such as biomass and soil carbon content, can be helpful for benchmarking analysis. However, most of these studies focus on the analysis of specific ecological response function over few eddy covariance sites, mainly on the forests, or on the evaluation of a sole model at regional or global scale.

In this work, three generic LSMs namely ORCHIDEE, ISBA-A-gs and C-TESSEL, forced by ERA-Interim surface atmospheric variables, are compared using European EC sites as reference. This experimental setup aims at reproducing a realistic scenario for the operational Copernicus-Land which would will link state-of-the-art Numerical Weather Prediction (NWP) products with state-of-the-art LSMs for the monitoring of terrestrial carbon exchanges at the global scale. The sensitivity of the simulations to errors in the atmospheric forcing may be large (Zhao et al., 2012) and may vary from one LSM to another depending how LAI is described (either prognostic or derived from satellite observations). Our aim is to assess the capability of basic model simulations to describe the carbon dynamics for a variety of ecosystems and to identify potential ways to improve these simulations. More specifically we test: (i) how well the models perform for daily, seasonal and interannual variability of carbon fluxes; (ii) how well the models describe carbon dynamics for different ecosystems (forest, grassland and cropland) and climate; (iii) and how well the models are able to describe main ecological functions controlling carbon exchanges.

2 Models and methods

Carbon fluxes from the three LSMs (ORCHIDEE, ISBA-A-gs and CTESSEL) are compared with the fluxes measured in 32 EC flux tower sites (Table 1), which represent the main European ecosystems.

2.1 Models description

Table 2 reports the main characteristics of the three analyzed LSMs. All models were forced using the same meteorological data set, ECMWF ERA-I (see Sect. 2.2).

2.1.1 The ISBA-A-gs model

The ISBA-A-gs LSM (Calvet et al., 1998, 2004, 2008; Gibelin et al., 2006) is a CO_2-responsive version of the ISBA (Interactions between Soil, Biosphere, and Atmosphere) (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996) model. It is part of SURFEX (SURFace EXternalisée) platform developed by Météo-France to be used in operational numerical weather prediction (NWP) models (Le Moigne et al., 2009). The photosynthesis and carbon release are simulated following the A-gs scheme (Calvet et al., 1998; Calvet, 2000). According to the model classification framework set out in Arora (2002), the photosynthesis model within ISBA-A-gs is based on a soil-vegetation-atmosphere transfer biochemical approach. The representation of photosynthesis is based on the model of Goudriaan et al. (1985) modified by Jacobs (1994) and Jacobs et al. (1996). This parameterization is derived from the set of equations commonly used in other land surface models and it has the same formulation for C4 plants as for C3 plants, differing only by the input parameters. Moreover, the slope of the response curve of the light-saturated net rate of CO_2 assimilation to the internal CO_2 concentration is represented by the mesophyll conductance (g_m). Therefore, the value of the g_m parameter is related to the activity of the Rubisco enzyme (Jacobs et al., 1996), while in the Farquhar model, this quantity is represented by a maximum carboxylation rate parameter ($V_{\mathrm{C,\,max}}$). The model also includes an original representation of the soil moisture stress. Two different types of the plant response to drought are distinguished, for both herbaceous vegetation (Calvet, 2000) and forests (Calvet et al., 2004). In order to obtain the CO_2 balance at the ecosystem scale, the A-gs model is coupled to an ecosystem respiration module with a dependency on soil moisture and surface temperature. The ecosystem respiration is described as a basal rate modulated as a function of soil moisture and temperature (Albergel et al., 2010). In this study, leaf biomass and LAI are calculated interactively by a simple growth model accounting for nitrogen dilution (Calvet et al., 1998; Gibelin et al., 2006). The SURFEX version 6.2 is used with the "NIT" option of ISBA-A-gs, as in Szczypta et al. (2012). The simulations are performed several times per grid cell in order to simulate the various PFTs.

2.1.2 The CTESSEL model

Carbon-TESSEL (CTESSEL) is the latest version of Hydrology-Tiled ECMWF scheme for Surface Exchange over Land model (H-TESSEL) (Boussetta et al., 2012; Balsamo et al., 2009, 2011; van den Hurk et al., 2000; Viterbo and Betts, 1999; Viterbo et al., 1999; Viterbo and Beljaars, 1995). It contains a carbon module that simulates photosynthesis and respiratory processes at the surface (Boussetta et al., 2013). The photosynthesis and canopy conductance dynamics follow the same scheme as ISBA-A-gs (Calvet et al., 1998; Calvet, 2000). Ecosystem respiration is described by empirical functions of vegetation type, soil moisture, soil temperature and snow depth (Boussetta et al., 2013; Normann et al., 1992). This carbon module does not have a prognostic land surface carbon pool as generally included in land ecosystem exchange models (ORCHIDEE, NCAR-DGVM (Bonan et al., 2003), JULES (Clark et al., 2011)). To represent the effects of the soil carbon pool, a dependency on vegetation types and cover is adopted. Two vegetation types are selected per grid box as part of the tiling approach namely one for high vegetation and one for low vegetation. Spatial distribution of vegetation is prescribed by the Global Land Cover Characterization Database (GLCC) and phenology follows MODIS LAI (collection 5) derived climatology (Boussetta et al., 2012) rather than prognostically estimated. As reported by Boussetta et al. (2013), parameters for a particular PFT were optimized by grouping a number of eddy covariance sites with the same PFT for the year 2006. These parameters are the unstressed mesophyll conductance (g_{m}^{*}) and the reference respiration (R_0). Others parameters were taken from the literature (White et al., 2000; Calvet et al., 2000, 2004). The EC sites used in the parameters optimization were not considered in the validation and comparison of CTESSEL with others models.

2.1.3 The ORCHIDEE model

ORCHIDEE is a dynamic global vegetation model which can be run either coupled to global or regional atmospheric circulation models, or forced by meteorological fields. ORCHIDEE consists of three linked sub-modules (Krinner et al., 2005); the “SECHIBA” module (Ducoudré et al., 1993) is a land surface energy and water balance model with a 30 min time step. The phenology (Botta et al., 2000) and carbon fluxes of terrestrial ecosystems are modelled in the “STOMATE” module (Viovy, 1997) that simulates the processes of photosynthesis, carbon allocation, litter decomposition, soil carbon dynamics, maintenance and growth respiration, and phenology on a daily time step, and long-term processes (on yearly time step) of vegetation dynamics including sampling establishment, light competition, and tree mortality are adapted according to LPJ (Sitch et al., 2003). For the current study we did not activate the dynamic part but we used an accurate satellite derived vegetation map (Vérant et al., 2004). The photosynthesis at canopy level, and the instantaneous energy and water balance of vegetated and non-vegetated surfaces are simulated by coupling leaf-level photosynthesis and stomatal conductance processes based on Ball et al. (1987) and Farquhar et al. (1980). Stomatal conductance is reduced by soil water stress (McMurtrie et al., 1990), as a function of soil moisture and root profiles. This reduction is done indirectly by reducing maximum rubisco carboxylation rate ($V_{\mathrm{C,max}}$) which then reduces stomatal conductance (G_{s}). Two soil water reservoirs are considered: a surface reservoir which refills in response to rain events and which is brought to zero during dry periods, and a deeper soil reservoir updated according to evaporation, root uptake, percolation and runoff. ORCHIDEE uses a tiled approach allowing the simulation of different PFTs within a grid cell, and the tiles of a grid cell share the same soil water reservoir. Here, we used the Olson classification to derive spatial distribution of vegetation, distinguishing 13 different PFTs (Vérant et al., 2004). For cropland we considered winter wheat for C3 and maize for C4; irrigation and harvesting were not activated.

2.2 Atmospheric forcing

All the simulations reported in this paper were forced with 3 hourly meteorological data extracted from the ECMWF ERA-Interim (ERA-I) reanalysis (Dee et al., 2011), which covers the period from 1979 to present. The motivation for selecting re-analysis for the forcing rather than observations is twofold: (i) to run the models, the forcing needs to be absolutely uninterrupted which can only be achieved for observations by rigorous gap filling, which has inevitably shortcomings, and (ii) it was the intention to test a system that could run on continental or global scales. For that reason, also the model vegetation type selection for a particular tower location is according to the model climate data set rather than the vegetation type of the tower location. If the tower location is representative for a large area, it is likely to be the same, but this is not always the case. So it is important to realize that the evaluation reported here does not only include model errors, but also errors in the forcing and the potential mismatch between vegetation type in the footprint of the EC tower and the model vegetation type for that location. So it is an evaluation of a system rather than the model only.

The ERA-I data is available on a reduced Gaussian grid (N128) corresponding to a resolution of about 80 km. The ERA-I grid point nearest to the tower location has been selected for the forcing. The temperature, surface pressure, humidity and wind fields are instantaneous values and representative of the lowest level in the atmospheric model corresponding to a height of 10 m above the surface. The incoming surface radiation (in its long and short-wave components), rainfall and snowfall are provided as 3 hourly accumulations. The instantaneous fields are linearly interpolated in time to the model time-step of the land surface model. They are from the 3, 6, 9 and 12 h forecasts starting from the daily analyses at 00:00 and 12:00 UTC. As a compromise between spin-up effects (mainly in radiation) and forecast errors, the fluxes are averages from the forecast intervals 9–12, 12–15, 15–18 and 18–21 h starting from the daily analyses at 00:00 and 12:00 UTC. Fluxes and instantaneous fields are matched by verification time. Precipitation is kept constant over the 3 hourly interval, long-wave downward radiation is linearly interpolated and downward solar radiation is disaggregated in time making use of the solar angle, but conserving the 3 hourly integral. Land surface variables like soil temperature, soil moisture, and snow depth are slow variables and are not taken from ERA-I but are the result of the time integration of the land surface scheme. The potential effect of the initial condition is eliminated by performing long cyclic runs to achieve equilibrium (i.e. to get a proper equilibrium between e.g. soil moisture and the soil characteristics of the particular model).

It is known that carbon models can be sensitive to the forcing data (see e.g. Zhao et al., 2006), but it is difficult to make general statements about the accuracy of the forcing data. For instance, ERA-I precipitation, which is a major component of the forcing, turns out to be very competitive compared to e.g. GPCP products for mid-latitudes with sometimes a small benefit from bias correction (Balsamo et al., 2012; Szczypta et al., 2011). The realism of the forcing can also be seen in the derived products from offline land surface simulations in verification of soil moisture, snow and runoff (Albergel et al., 2012; Balsamo et al., 2012).

2.3 FLUXNET sites description and data elaboration

The eddy covariance technique allows measuring directly CO_2, latent heat (LE) and sensible heat (H) fluxes between the ecosystem and the atmosphere relative to an area (the footprint) of hundreds of meters around the EC tower depending on the tower and vegetation heights. The EC data are collected at high frequency (10 Hz) and converted to fluxes over thirty minutes or one-hour integration periods using standard methodologies (Aubinet et al., 2012). Data gaps due to sensors malfunctioning or less ideal turbulence conditions (Papale et al., 2006) are filled using the MDS method described in Reichstein et al. (2005). The two main components of the net carbon exchange (GPP and Reco) are estimated using the flux-partitioning technique based on the extrapolation of night-time flux observations with temperature dependent relations (Reichstein et al., 2005). The methodology is the one proposed and implemented in the European Fluxes Database (http://www.europe-fluxdata.eu) and used also in the context of the FLUXNET synthesis activities.

The geographical distribution of the EC sites covers the main PFTs as defined by the International Geosphere–Biosphere Programme (IGBP) existing in Europe. The selected sites include 8 croplands (CRO), 4 broadleaf deciduous forests (DBF), 2 evergreen broadleaf forests (EBF), 5 evergreen needleleaf forests (ENF) and 13 semi-natural and managed grassland locations (GRA) (Table 1). Details about the flux EC sites, the years of available data and their characteristics as well corresponding PFT and Köppen–Geiger climate class are provided in the Table 1.

2.4 Performance of the large scale simulations

The analysis is based on 32 sites (Table 1), for a total of 164 site/year data, selected on the basis of the data availability and to cover different PFT and climate. Only the sites containing at least one year of carbon flux data of good quality and only daily data with a percentage of gap-filled half hours less than 15 % were used in this analysis.

The simulation performance in predicting EC fluxes was performed using the following statistical parameters: Correlation Coefficient (CORR), Efficiency (*E*), Root Mean

Square Error (RMSE) and Bias:

$$\mathrm{CORR} = \frac{\sum_{i=1}^{N} (P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N} (P_i - \bar{P})^2 \sum_{i=1}^{N} (O_i - \bar{O})^2}} \quad (1)$$

$$E = \frac{\sum_{i=1}^{N} (O_i - \bar{O})^2 - \sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \quad (2)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2} \quad (3)$$

$$\mathrm{Bias} = \frac{1}{N} \sqrt{P_i - O_i} \quad (4)$$

where O_i is daily averaged measured fluxes and P_i daily simulated fluxes; $\bar{O}$ and $\bar{P}$ denote their means.

CORR explains how much of the variance between the observed and simulated data is described by linear fit. It can vary between −1 to +1 indicating a decreasing linear relationship or a perfect increasing linear relationship, respectively. A CORR of 0 means that there is no linear relationship. The E indicates how much the simulations are accurate. It can range from $-\infty$ to 1 and an E close to 1 indicates a perfect match between simulated and observed data. An E less than zero occurs when the observed mean is a better predictor than the simulation. The RMSE is the residual standard deviation and Bias the residual mean. A value of RMSE close to zero indicates that simulations are close to the measured data. Positive values of Bias indicate average overestimation by the simulation and negative values indicate average underestimation.

To analyze if and how much climate and PFT properties affect the performance of the different simulations, statistical analysis of the simulation output – EC measurements was performed grouping the EC sites by PFTs and Köppen–Geiger climate classes (Peel et al., 2007).

In addition to better evaluate how much simulations are able to reproduce the climate impact on the ecosystems functionalities we analyzed the net carbon flux seasonal variation and inter-annual variability (IAV). IAV analysis has been done for the sites with at least nine years of fluxes data and it is computed according to the equation (Eq. 5):

$$\mathrm{IAV}_{\mathrm{NEE,\,yr}} = \mathrm{NEE}_{\mathrm{yr}} - \mathrm{avg(NEE)} \tag{5}$$

where $\mathrm{IAV}_{\mathrm{NEE,\,yr}}$ is the interannual variability of NEE for the year yr; $\mathrm{NEE}_{\mathrm{yr}}$ is the NEE for year yr; and avg(NEE) is the average of NEE for all available years (i.e. climatological mean). For example a positive value of IAV for the year yr indicates that the $\mathrm{NEE}_{\mathrm{yr}}$ is higher than the average e.g. the carbon uptake is lower for this year following the convention that negative NEE means uptake by the ecosystem.

Moreover we analyzed the simulation capability to perform environmental response curves comparing observed and modeled GPP response to shortwave incoming radiation (Rg-GPP or LUE), GPP response to vapor pressure deficit (VPD-GPP) and the Reco response curve to air temperature (Ta-Reco) for forest sites, excluding any anthropogenic impact on the ecosystems.

3 Results and discussion

3.1 Performance by PFTs

Table 3 reports the mean performance values of the simulated daily carbon fluxes (NEE, GPP and Reco), stratified by PFT, for the three models (ISBA-A-gs, C-TESSEL and ORCHIDEE), while the boxplots reported in Fig. 1 show their distribution.

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Overall, the three models show their best performance in simulating GPP of evergreen needleleaf forests (ENF, Table 3 and Fig. 1d) and deciduous forest (DBF, Table 3 and Fig. 1b). The ORCHIDEE model has a consistent positive GPP bias and a high RMSE. In contrast, ISBA-A-gs and CTESSEL tend to underestimate GPP (negative bias). For NEE, all models performed best on at ENF sites (ENF, Table 3 and Fig. 1d). CTESSEL and ORCHIDEE show good results in simulating Reco at these forest sites. An over- or underestimation of GPP limits the capability of the models to simulate NEE and Reco fluxes. Since Reco depends on biomass and is therefore related to the quality of the GPP estimation, errors in GPP impact the diurnal and seasonal NEE cycles (Schwalm et al., 2010; Richardson at al., 2011; Schaefer et al., 2012).

The high variability of the statistical metrics and the negative values of CORR for DBFs (Fig. 1b) are linked to climatic variability in this PFT class (Table 1). In fact DBFs are located in both Oceanic/European (Cfb) and Sub-tropical (Cfa) climate regions without and with dry summer periods, respectively. The variability in carbon fluxes at tropical and Mediterranean broadleaf forests and deciduous broadleaf forests is not explained by the sole phenology (Migliavacca et al., 2011). However, many environmental factors impact the diurnal and seasonal variability of carbon fluxes in water limited biomes (e.g. soil water moisture, rain pulse).

Table 3 reports the number of sites for which the model efficiency (E) in simulating the fluxes is more than 50 %. In our case, values of $E > 50\,\%$ indicates an acceptable level of performance. It is interesting to note that only CTESSEL presents a site with an E value ($E = 51\,\%$) larger than 50 % in simulating NEE of an evergreen needle forest site (DETha). This site is characterized by a Oceanic-European climate and carbon fluxes can be described by meteorological conditions (Grunwald and Bernhofer, 2007). The difference between CTESSEL and the other model can be related to different model optimization methods. CTESSEL is optimized against EC flux data (Boussetta et al., 2013) but in this study EC sites used in the optimization are not considered in the model evaluation. Considering GPP simulations, ORCHIDEE shows good values of E

for all ENF sites confirming the capacity of this model in predicting GPP of evergreen forest sites.

This study considers only two evergreen broadleaf forests (FR-Pue and PT-Esp; see Table 1), which are located in the Mediterranean area (Csa climate classification). Therefore, we believe that the poor estimations of NEE at these forest sites (Fig. 1c) is related to the summer drought period with reduced soil water content availability, high air temperature and high vapor pressure deficit (VPD) stress, which impact stomatal conductance and photosynthetic activity (Schaefer et al., 2012).

The NEE seasonality of croplands (Fig. 1a) and grasslands (Fig. 1e) depends on management (e.g. irrigation, fertilization, grazing, manure, harvesting) and C3/C4 dynamics. Models used in this study did not consider the anthropogenic impacts in their schemes. Lack of the description of anthropogenic impact and plant dynamics in the models coupled with a limited SWC during the growing period likely cause the negative value of correlation (CORR, Fig. 1a, e). Moreover, Mediterranean grasslands are very sensitive to rain pulse in spring and in autumn, after drought period, (Xu and Baldocchi, 2004). Therefore, an accurate description of ecosystem functionality observed at in-situ level can help to understand carbon fluxes of this biome and to improve model simulations.

Overall, CTESSEL and ORCHIDEE show higher performance values than ISBA-A-gs. The differences in simulating carbon fluxes between ISBA-A-gs and the other two models can be associated with the sensitivity to errors in atmospheric forcing, LAI modelling versus LAI climatology, and the photosynthesis module (Table 2). In ISBA-A-gs a simple growth model is used to compute leaf biomass and LAI, and all the atmospheric variables influence LAI in ISBA-A-gs simulations. Therefore, errors in any of the atmospheric variables can have a marked impact on LAI (Szczypta, 2012). Moreover, in this study, ISBA-A-gs and and ORCHIDEE have a prognostic LAI while CTESSEL assimilates a satellite-derived LAI climatology. Gibelin et al. (2008) have shown that ISBA and ORCHIDEE present similar scores at temperate and high latitudes of the Northern Hemisphere, based on LSM simulations driven by locally observed atmospheric variables.

3.2 Performance by sites

Bar plots in Fig. 2 report the results of statistical parameters for NEE considering separately for each EC flux site grouped by PFT for Cfb (Temperate without dry season and with warm summer; Fig. 2, left panel) and Csa (Temperate with dry and hot summer Fig. 2, right panel) climate classes. This analysis confirms that the performance of the models in predicting NEE is closely related to climate and site characteristics.

On average, ORCHIDEE shows the largest correlation values for all temperate (Cfb) DBFs and ENFs with a reduced variability (Fig. 2b, c; left panel). ORCHIDEE also shows good correlation for croplands (Fig. 2a; left panel), while ISBA-A-gs and CTESSEL for grasslands (Fig. 2d, e; left panel). Across the temperate climate zone, the wide variability of boxplots for grasslands and croplands stems from the specific site management changing year by year (Ceschia et al., 2010): rotation by single (e.g. DK-Ris and IE-Ca1) or more (e.g. BE-Lon, DE-Geb) crops, crop type (C3 or C4), and grazing (FR-Lq1, FR-Lq1) and harvesting (DE-Gri) for grasslands. Therefore, it is interesting to note that all models work well for IE-Ca1 (Fig. 2a; left panel), cropland cultivated with a single crop (spring barley), and for DE-Meh (Fig. 2d; left panel), semi-natural grassland with an extensive management. Poor model performance at grasslands managed by cutting (negligible residual on the field after cutting) and grazing (e.g. De-Gri; Fig. 2d, left panel) is probably due to the high frequency of cutting/harvesting events (3 times per years) and to livestock pressure (e.g. DKLva; Fig. 2d, left panel). This suggests that the models cannot predict carbon fluxes well for a phenology that is different from the natural situation and driven by management. In addition, negative correlation values for cropland sites in the Mediterranean climate area (Csa) (Fig. 2a; right panel) are due to irrigation (Kutsch et al., 2010) that is not accounted for in the models and that affects the seasonality of cropland agro-ecosystems with a dry season. All models show the same behavior in simulating NEE of EBFs (Fig. 2b; right panel) and GRAs (Fig. 2e; right panel) in areas with a dry season (Migliavacca et al., 2011).

3.3 Seasonal variation of forest carbon fluxes

Figure 3 reports the mean seasonal variation of carbon fluxes simulated by ISBA-A-gs (in blue), CTESSEL (in green) and ORCHIDEE (in red) and measured by EC flux towers (in black with the gray area for the standard variation of fluxes over the a PFT classe). This analysis has been conducted considering only the forest sites, that in this study represent natural ecosystems without any notable anthropogenic impact, grouped according to the Koppen's climate classes. Moreover, modeled and measured flux data have been monthly averaged across the sites. It is worth noting that the differences between simulated and measured fluxes are directly linked to the climate condition and plant type. All models capture NEE seasonal variability of ENFs located in Oceanic-continental areas (Cfb/ENF, Fig. 3b) but CTESSEL seams to underestimate GPP and Reco and ORCHIDEE overestimates Reco. However, the NEE seasonal variation for ENFs located in Humid continental areas (Dfb/ENF, Fig. 3a) is not well captured by the models except CTESSEL. It could be linked to an incorrect phenological and LAI description. In addition, large discrepancies between ISBA-A-gs and ORCHIDEE models and EC data are showed for Reco. The three models present some limitations in capturing the seasonality of DBFs (Richardson et al., 2012) located in Oceanic continental area (Cfb/DBF, Fig. 3c) and EBFs located in the Mediterranean area (Csa/DBF, Fig. 3e). This limitation in predicting carbon fluxes of forest sites located in Csa climate zone can be related to the impact of dry conditions and hot summers that control ecosystem GPP and Reco (Migliavacca et al., 2011).

Figure 4 shows the IAV (Eq. 5) of NEE simulated by ISBA-A-gs (in blue), CTESSEL (in green) and ORCHIDEE (in red) and measured by EC flux towers (in black) for four EC sites: DETha (Fig. 4a), DKSor (Fig. 4b), FRPue (Fig. 4c) and ITRen (Fig. 4d). All models present some limitations in simulating NEE interannual variability for IT-Ren forest site. NEE annual mean value measured by EC in 1998 at DKSor deciduous broadleaf forest (NEE_{1998} = 103.95 g C m^{-2} yr^{-1}) (Fig. 4b) shows an intense source activity with a lower carbon uptake respect to the mean period 1998–2008 (−104.71 g C m^{-2} yr^{-1}). ORCHIDEE (NEE_{1998} = 53.96 g C m^{-2} yr^{-1}) seems to simulate better the annual NEE for DKSor in 1998 than other models (ISBA-A-gs NEE_{1998} = −165.19 g C m^{-2} yr^{-1}; and CTESSEL NEE_{1998} = −451.16 g C m^{-2} yr^{-1}). Regarding the FRPue evergreen broadleaf forest located in a Mediterranean area, ISBA-A-gs and ORCHIDEE show a similar IAV pattern in agreement with EC data, while CTESSEL shows higher positive IAV value in 2007 and lower negative values in 2008 indicating a lower and higher NEE value, respectively. Moreover, CTESSEL presents lower and higher values of IAV in 2002 and 2003 for DETha evergreen needleleaf forest indicating a lower and higher carbon uptake respect measured data.

3.4 Environmental controls of fluxes

During summer drought periods, GPP can be limited by a combination of reduced soil water content availability and vapor pressure deficit (VPD) stress, which impacts stomatal conductance, photosynthetic activity and ecosystem respiration, and high air temperature affects on ecosystem respiration. Figure 5 shows the seasonal GPP trend (Fig. 5a), the seasonal SWC trend (Fig. 5b), GPP response to vapor pressure deficit (VPD-GPP; Fig. 5c) and to shortwave incoming radiation (Rg-GPP or LUE; Fig. 5d) and Reco response to air temperature (Ta-Reco; Fig. 5e) for five forest sites. GPP and Reco curves were calculated over July at the maximum uptake period. All models are able to describe ecological functions controlling GPP for site DETha2006 (Fig. 5).

ORCHIDEE and ISBA-A-gs capture Reco-Ta slope derived from EC data while CTESSEL present a slightly lower slope. ORCHIDEE and CTESSEL follow EC data in describing the ecological function of ITRen2006 but CTESSEL is also able to describe Reco-Ta response. However, ORCHIDEE describes better the ecological functions for site DKSor2006 and FRFon2006 (Fig. 5), showing LUE, VPD and GPP-Ta slopes close to those derived from EC data. On the other hand, ORCHIDEE tends to overestimate all the ecological parameters (LUE, VPD slopes) for FRPue2006 EBF Mediterranean sites (Fig. 5) where CTESSEL and ISBA-A-gs show better results. All models present limitations in describing Reco response to the temperature of this biomes (Fig. 5e) showing higher Reco values and lower values of temperature for this period.

4 Conclusions and issues for model improvement

Our study aimed at evaluating the accuracy of three different LSMs (C-TESSEL, ISBA-A-gs and ORCHIDEE) in simulating carbon fluxes of terrestrial European ecosystems over a wide range of climatic conditions and anthropogenic impacts (grazing, rotation, irrigation). To perform a more comprehensive validation we proposed a multiple approach where different tests are applied to the comparison between model results and observations, including analysis of seasonal and interannual trends and ecological relationships. The results show a heterogeneous picture, with differences between models (Table 2), plant functional types (Fig. 1), climate and sites (Figs. 2 and 3).

Our data show that the best performance is obtained for ENF sites in continental and humid climate areas without a dry season. All models show some limitations in capturing the NEE seasonality for Mediterranean and Sub-tropical ecosystems characterized by a dry summer season. This could be due to several environmental factors that control GPP during summer dry conditions with low water availability (Keenan et al., 2009). These results are in agreement with previous studies on the ORCHIDEE (Krinner et al., 2005), ISBA-A-gs (Gibelin et al., 2008), and CTESSEL (Boussetta et al., 2013) models.

The improvement of phenology, of management and of the relationships between LAI, photosynthesis and environmental drivers, should be considered in future development of these models.

4.1 LAI and phenology

The improvements of LAI and phenology are believed to be a high priority in agreement with previous study by Richardson et al. (2012). For monitoring applications, the model vegetation seasonality could be imposed by Near Real Time (NRT) remote sensing products as it would force deciduous forest, grassland and cropland phenology and would help capturing parts of the land management practices (mainly grazing and harvesting). For wider applications, advance in understanding which factors (photoperiod, cold temperatures, and warm temperatures) regulate spring budburst is needed and is a prerequisite to better simulate the vegetation responses to climate change (Richardson et al., 2012).

4.2 Cropland and grassland management

All models show negative correlation values for cropland sites located in the Mediterranean climate area (Csa, Fig. 2 right panel). As reported by Kutsch et al. (2010) these sites are irrigated and their phenology is driven by the presence of water in the soil and not by meteorological condition. Irrigation is not accounted for in the models. Moreover, cropland sites are mainly managed by rotation changing yearly the crops types. Current models assume a single crop type and management. However, grassland in Europe is mainly managed by grazing and cutting which affect their sink/source activity (Soussana et al., 2007; Wohlfahrt et al., 2008).

Cropland covers nearly 25 % of all EU-23 land and grassland covers about 20 % (EUROSTAT, 2005; LUCAS, 2009). Both play a relevant role in the greenhouse balance of agricultural lands in Europe (Jansen et al., 2003; Soussana et al., 2007; Ciais et al., 2010). The grassland and cropland management is crucial in the definition of the entity of carbon sink/source activity for these agro-ecosystems. In addition, cultivated land occupies about 50 % of Earth's surface, and nearly 18 % of the cultivated land now receives supplementary water trough irrigation (IPCC, 2007). Therefore, future efforts should focus on implementing into LSMs new schemes to simulate the greenhouse balance of all agricultural lands, both cropland and grassland. A possible approach is to couple LSMs with existing or new models focused on cropland and grassland management. Alternatively, model development could be consolidated by the introduction of new modules, e.g. land management such as rotation, irrigation, grazing and harvesting, which would help to simulate the carbon uptake of cultivated areas in Europe. For instance, work is already underway to integrate ORCHIDEE with the PASIM model (Vuichard et al., 2007; Ciais et al., 2010), which takes pasture management into account as well as STICS modules (Gervois et al., 2008), related to crops phenology.

4.3 Ecological parameter estimation during drought

The poor model performance during drought periods should be linked to an inadequate representation of observed LUE. Simulated LUE is controlled by the leaf-to-canopy scaling strategy and a small set of model parameters that defines the maximum potential GPP, such as $\epsilon_{\max}$ (light use efficiency), $V_{\mathrm{c,max}}$ (unstressed Rubisco catalytic capacity) or $J_{\max}$ (the maximum electron transport rate). The temperature, humidity, and drought scaling factors determine temporal variability in simulated GPP, but the LUE parameters determine the magnitude of simulated GPP. To improve simulated GPP, model developers should focus first on improving the leaf-to-canopy scaling and the values of those model parameters that control the LUE. Moreover, understanding the functional relationship between soil/root characteristics and vegetation water uptake remain challenging, particularly to describe globally over broad time and space scales the short-term effects on GPP and TER due to dry conditions (Migliavacca et al., 2011). Therefore, further efforts should be focused on the understanding of the most appropriate ecological function able to describe the complexity of the plant eco-physiological responses (e.g. adaptation, mortality, defoliation) in dry conditions (van der Molen et al., 2011).

5 Summary

Our data show that the best performance is obtained for ENF sites in continental and humid climate areas without a dry season. All models showed some limitations in capturing the NEE seasonality for Mediterranean ecosystems characterized by a dry summer season. This could be due to several environmental factors that control GPP during summer dry conditions with low water availability (Keenan et al., 2009). The model stress functions in Fig. 5 show large errors for the drought-affected sites, which suggests that these stress function can be improved. Furthermore, all models show large errors in the description of grassland and cropland phenology. This study suggests that priority areas for research are: (i) modeling and data assimilation of the seasonal evolution of LAI, (ii) modeling of the effects of crop and grassland management including irrigation, and (iii) model parameter estimation in drought conditions. Further efforts should also be directed at identifying new approaches that allow LSMs to simulate the anthropogenic impact on the carbon cycle. Finally, this analysis confirmed the importance of the ecosystem scale observations in model validation and development, suggesting also an integrated set of tests to compare simulations and measurements. With the establishment of long term monitoring networks such ICOS (www.icos-infrastructure.eu) and NEON (www.neoninc.org) the use of direct measurements, also in Near Real Time, will provide an unique framework for these type of activities.

Acknowledgements. This study was supported by the Geoland2 Project (grant agreement No. 218795). We would like to thank all participants to Land Carbon Service of Geoland2. We would like to also acknowledge the PIs of the eddy covariance sites and all technicians, students, PhDs and Post-Docs for providing their data and support to the European Fluxes Database. MB thanks also the GeoCarbon project for the support.

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Table 1. List of sites and years used for the models evaluation and characteristics.

Site ID	Country	Lat [deg]	Lon [deg]	Elevation [m]	Climate koppen[a]	Start Year	Stop Year	Number of Years	Reference
ENF – Evergreen Needleaf Forest									
CZ-BK1	Czech Republic	49.5	18.5	908	Dfb	2002	2008	7	Reichstein et al. (2005)
DE-Bay	Germany	50.1	11.9	775	Cfb	1997	1999	3	Staudt and Foken (2007)
DE-Tha	Germany	51.0	13.6	380	Cfb	1997	2008	12	Grunwald and Bernhofer (2007)
DE-Wet	Germany	50.5	11.5	785	Cfb	2002	2008	7	Rebmann et al. (2010)
IT-Ren	Italy	46.6	11.4	1730	Dfb	1999	2008	9 (no 2000)	Montagnani et al. (2009)
DBF – Decidous Broadleaf Forest									
DK-Sor	Denmark	55.5	11.7	40	Cfb	1998	2008	11	Pilegaard et al. (2003)
FR-Fon	France	48.5	2.8	90	Cfb	2005	2008	4	
IT-Col	Italy	41.9	13.6	1550	Cfa	2001	2008	5 (no 2002–2003)	Valentini et al. (1996)
IT-LMa	Italy	45.6	7.2	350	Cfb	2004	2007	4	
EBF – Evergreen Broadleaf Forest									
FR-Pue	France	43.7	3.6	270	Csa	2001	2008	8	
PT-Esp	Portugal	38.6	−8.6	95	Csa	2002	2006	5 (no 2003)	
GRA – Grassland									
CZ-BK2	Czech Republic	49.5	18.5	855	Dfb	2007	2008	2	
DE-Gri	Germany	51.0	13.5	385	Cfb	2004	2008	5	Prescher, et al. (2010)
DE-Meh	Germany	51.3	10.7	286	Cfb	2003	2006	4	Don et al. (2009)
DK-Lva	Denmark	55.7	12.1	15	Cfb	2004	2008	5	Gilmanov et al. (2007)
ES-VDA	Spain	42.2	1.5	1770	Cfb	2004	2008	5	Gilmanov et al. (2007)
FR-Lq1	France	45.6	2.7	1040	Cfb	2004	2008	5	Gilmanov et al. (2007)
FR-Lq2	France	45.6	2.7	1040	Cfb	2004	2008	5	Gilmanov et al. (2007)
HU-Bug	Hungary	46.7	19.6	140	Cfb	2004	2008	5	Nagy et al. (2007)
HU-Mat	Hungary	47.9	19.7	350	Cfb	2004	2008	5	Pintér et al. (2008)
IE-Dri	Ireland	52.0	−8.8	187	Cfb	2003	2006	4	Byrne et al. (2007)
IT-Mal	Italy	46.1	11.7	1730	Cfb	2003	2004	2	Gilmanov et al. (2007)
NL-Ca1	Netherlands	52.0	4.9	0.7	Cfb	2004	2006	3	Jacobs et al. (2007)
PT-Mi2	Portugal	38.5	−8.0	190	Csa	2005	2008	3 (no 2007)	Gilmanov et al. (2007)
CRO – Cropland									
BE-Lon	Belgium	50.6	4.7	167	Cfb	2004	2008	5	Moureaux et al. (2006)
CH-Oe2	Switzerland	47.3	7.7	452	Cfb	2004	2008	5	Ammann et al. (2007)
DE-Geb	Germany	51.1	10.9	161.5	Cfb	2003	2008	6	Kutsch et al. (2010)
DE-Kli	Germany	50.9	13.5	480	Cfb	2004	2008	5	Prescher et al. (2010)
DK-Ris	Denmark	55.5	12.1	10	Cfb	2004	2008	5	Gilmanov et al. (2007)
ES-ES2	Spain	39.3	−0.3	10	Csa	2004	2008	5	
IE-Ca1	Ireland	52.9	−6.9	50	Cfb	2004	2007	4	Gilmanov et al. (2007)
IT-BCi	Italy	40.5	15.0	20	Csa	2004	2006	3	Kutsch et al. (2010)

[a] Dfb: Humid continental; Cfb: Oceanic/European; Csa: Mediterranean; and Cfa: Sub-tropical.

Table 2. List of models and characteristics and references.

Model	Soil Layers	Vegetation Types/Map	LAI	C3, C4 parameters	Nitrogen Cycle	Canopy Conductance scheme	Respiration parameterization	Calibration with EC data	Reference
C-TESSEL	4	GLCC	Derived from MODIS	No	No	Jacobs (1994); Calvet et al. (1998)	Norman et al. (1992); modified	Yes	Boussetta et al. (2013)
ISBA-A-gs	3	ECOCLIMAP-II	Prognostic	Yes C4: maize	No	Jacobs (1994); Calvet et al. (1998)	Norman et al. (1992); modified in Abergel et al. (2010)	No	Calvet et al. (1998)
ORCHIDEE	2	Olson classification (Vérant et al., 2004)	Prognostic	Yes C4: maize	No	Ball et al. (1987); Farquhar et al. (1980)	Parton et al. (1987) for soil respiration); Autotrophic respiration (Ruimy et al. 1996)	No	Krinner et al. (2005)

Table 3. Performance of the models (ISBA-A-gs, ORCHIDEE, CTESSEL) in simulating daily carbon fluxes for all PFTs: ENF – Evergreen Needleleaf Forest; EBF – Evergreen Broadleaf Forest; DBF – Deciduous Broadleaf Forest; GRA – Grassland; and CRO – Cropland. N.Site – Number of available sites for each PFT; N.Data – Number of available days; CORR – Correlation Coefficient; RMSE – Root Mean Square Error; Bias; N. Sites $E > 50\,\%$ – Number of sites with model Efficiency (E) higher than 50 %.

PFT	Model	N.	N.	NEE				GPP				Reco			
		Site	Data	CORR (–)	RMSE (g C $\mathrm{m^{-2}\,d^{-1}}$)	Bias (g C $\mathrm{m^{-2}\,d^{-1}}$)	N. Sites $E > 50\,\%$ (–)	CORR (–)	RMSE (g C $\mathrm{m^{-2}\,d^{-1}}$)	Bias (g C $\mathrm{m^{-2}\,d^{-1}}$)	N. Sites $E > 50\,\%$ (–)	CORR (–)	RMSE (g C $\mathrm{m^{-2}\,d^{-1}}$)	Bias (g C $\mathrm{m^{-2}\,d^{-1}}$)	N. Sites $E > 50\,\%$ (–)
ENF	ISBA-A-gs	5	15 294	0.60	2.44	0.70	0	0.71	3.21	0.08	3	0.46	2.42	0.78	3
	CTESSEL	5	15 294	0.65	1.87	−0.08	1	0.82	2.91	−1.79	2	0.78	2.61	−1.87	0
	ORCHIDEE	5	15 294	0.65	2.29	1.28	0	0.86	2.00	0.64	5	0.75	2.51	1.92	2
EBF	ISBA-A-gs	2	4199	0.37	2.86	0.56	0	0.43	3.23	−0.91	0	0.36	1.69	−0.35	0
	CTESSEL	2	4199	0.50	2.09	0.99	0	0.65	1.87	−0.87	0	0.43	1.73	0.12	0
	ORCHIDEE	2	4199	0.39	2.16	1.03	0	0.55	2.86	1.57	0	0.59	2.98	2.60	0
DBF	ISBA-A-gs	4	7191	0.39	3.23	0.70	0	0.67	4.07	−1.79	1	0.67	2.45	−1.08	0
	CTESSEL	4	7191	0.49	2.65	0.05	0	0.78	4.41	−2.37	0	0.56	3.42	−2.32	0
	ORCHIDEE	4	7191	0.74	2.67	0.85	0	0.87	3.67	1.60	1	0.67	3.44	2.43	1
GRA	ISBA-A-gs	13	16 311	0.40	1.97	0.30	0	0.61	3.57	−2.28	1	0.53	2.87	−1.98	1
	CTESSEL	13	16 311	0.48	2.12	−1.0	0	0.75	2.45	−0.82	5	0.55	2.72	−1.82	0
	ORCHIDEE	13	16 311	0.41	2.55	0.36	0	0.69	3.00	0.21	2	0.72	1.76	0.57	6
CRO	ISBA-A-gs	8	12 218	0.09	4.57	0.57	0	0.26	5.53	−1.19	0	0.59	1.93	−0.62	0
	CTESSEL	8	12 218	0.25	3.55	−0.52	0	0.51	4.45	−1.05	0	0.71	2.41	−1.56	0
	ORCHIDEE	8	12 218	0.28	5.48	1.05	0	0.41	6.86	0.05	0	0.60	2.56	1.11	0

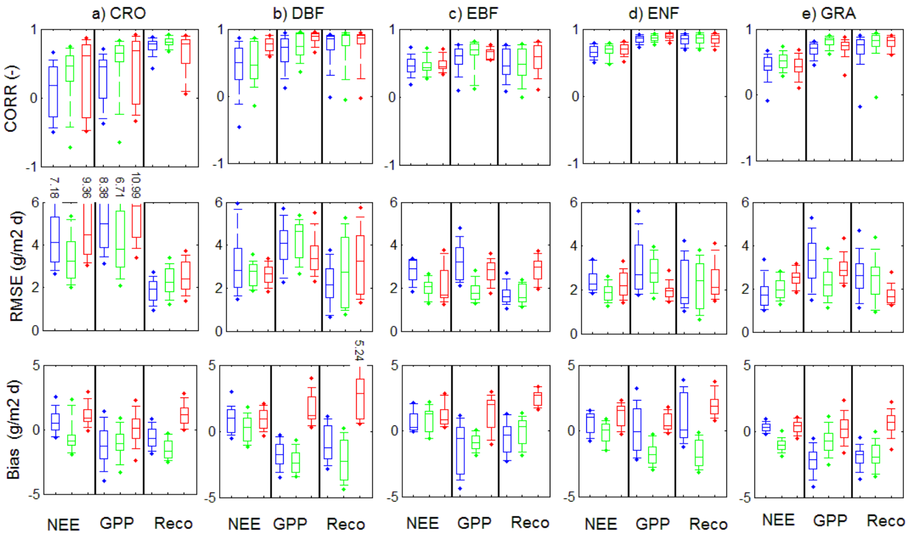

Fig. 1. Performance of the models (ISBA-A-gs in blue, CTESSEL in green and ORCHIDEE in red) in predicting daily carbon fluxes across PFTs and sites. CORR – Correlation coefficient; RMSE – Root Mean Square Error; Bias. The tops and bottoms of each "box" are the 25th and 75th percentiles of the samples, respectively, and the distances between the tops and bottoms are the interquartile ranges. The line in the middle of each box represents the median. The whiskers are drawn from the ends of the interquartile ranges to the furthest observations within the whisker length. Observations beyond the whisker length are marked as outliers and displayed with a black + sign.

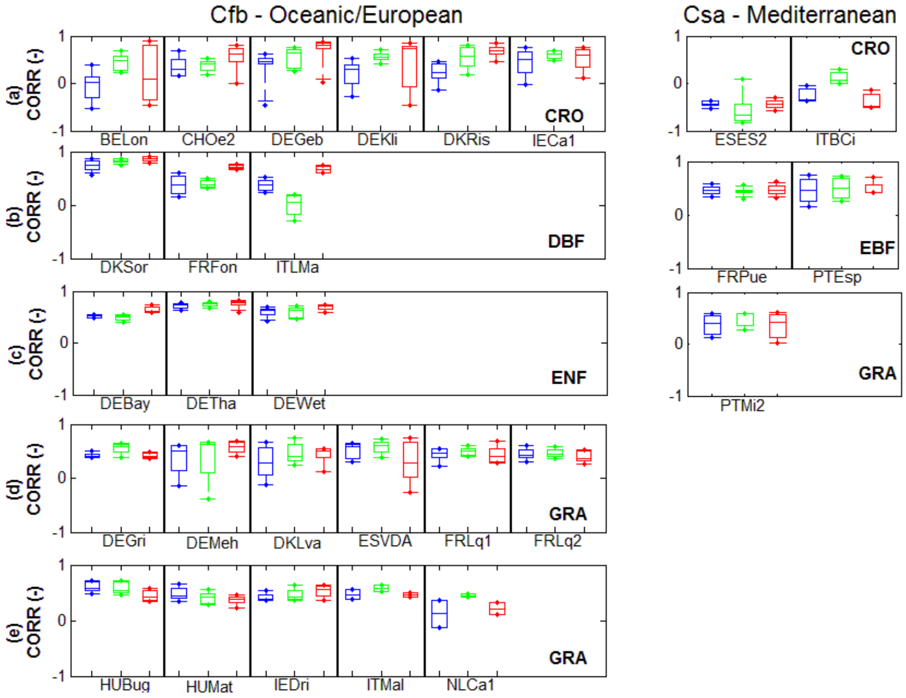

Fig. 2. As Fig. 1 but CORR – Correlation coefficient for each model (ISBA-A-gs in blue, CTESSEL in green and ORCHIDEE in red) in predicting NEE across the EC sites and PFTs for the Koppen's classes: Cfb – temperate without dry season, with warm summer (left panel); Csa – temperate with dry summer; hot summer (right panel).

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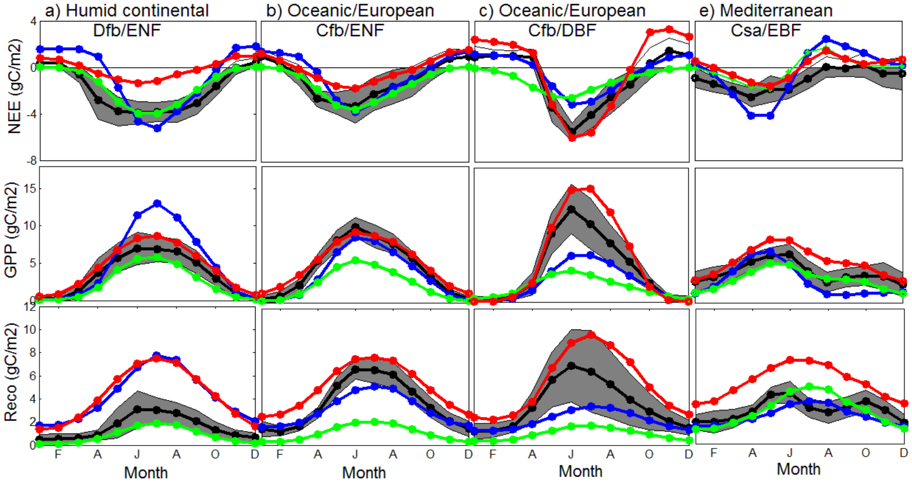

Fig. 3. Seasonal variation of carbon (NEE, GPP, Reco) fluxes for overall sites separated in Koppen's climate classes (Dfb – humid continental; Cfb – Oceanic/European; Csa – Mediterranean) for evergreen nedleleaf forest (ENF), deciduous broadleaf forest (DBF) and evergreen broadleaf forest (EBF) for the models: ISBA-A-gs in blue; CTESSEL in green; ORCHIDEE in red; while in-situ eddy covariance measurements are in black and gray area represents standard variation.

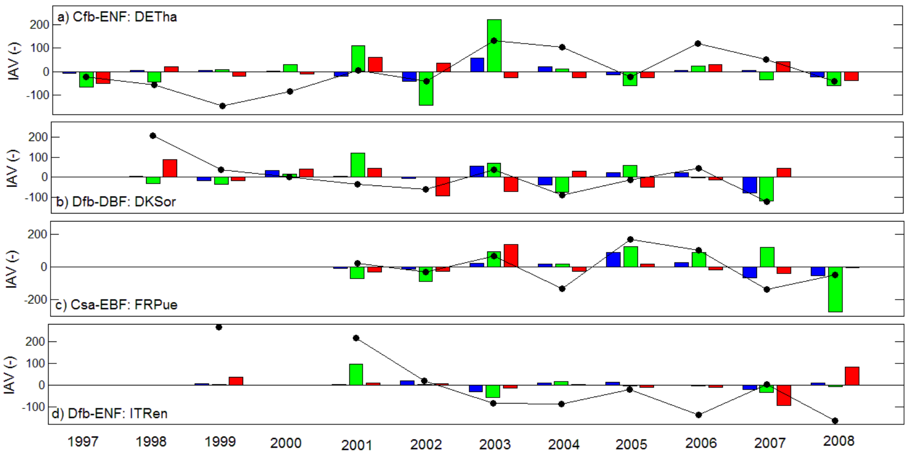

Fig. 4. Interannual variability (IAV) of NEE for some forest sites: **(a)** DETha; **(b)** DKSor; **(c)** FRPue and **(d)** ITRen. ISBA-A-gs model simulation is in blue bar, CTESSEL in green and ORCHIDEE in red, while black dots represent EC measured data.

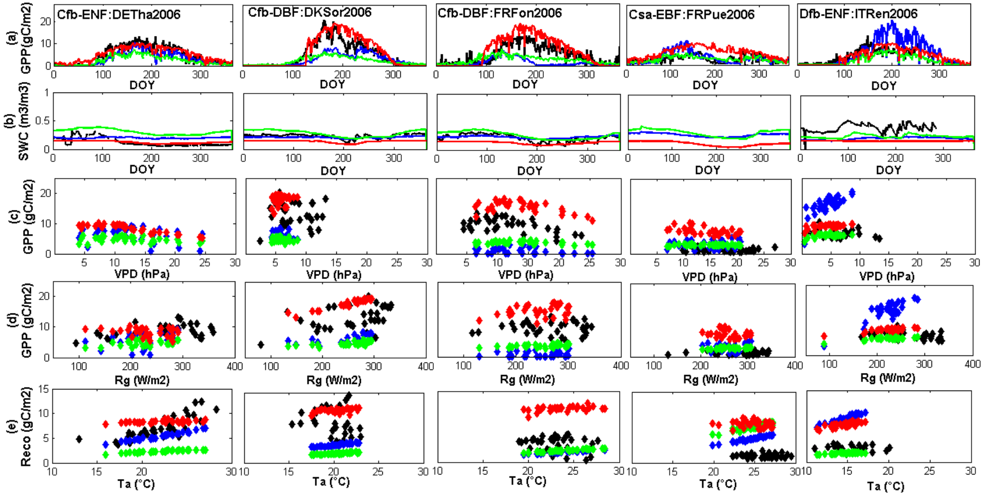

Fig. 5. (a) daily GPP trend; **(b)** daily SWC trend and GPP response curves to **(c)** vapor pressure deficit (VPD), to **(d)** shortwave incoming radiation (Rg-GPP or LUE) and **(e)** Reco response to air temperature (Ta) for five forest sites. GPP and Reco curves were calculated over a summer period considering only daily data from July. ISBA-A-gs model simulation is in blue, CTESSEL in green and ORCHIDEE in red, while black line represents EC measured data.