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From site-level to global simulation: Reconciling carbon, water and energy fluxes over different spatial scales using a process-based ecophysiological land-surface model

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ABSTRACT

Site carbon, water and energy fluxes, such as those measured by eddy covariance, only provide point source information about the earth's surface. A major challenge is scaling these fluxes to regional and global level to forge a unified understanding of both ecophysiology and flux exchange across all spatial scales. Furthermore, the ability of site fluxes to represent global vegetation and climate remains unquantified. The present study examines these questions using a process-based Land-Surface Model (LSM) containing state-of-the-art formulations of biophysical processes such as canopy light interception. The LSM is calibrated, forced and validated using a large and diverse range of established (e.g. FLUXNET) and novel (e.g. soil respiration, global river discharge and Moderate Resolution Imaging Spectroradiometer (MODIS) leaf area index and reflectance) observational datasets spanning different spatial scales. Multiple calibration datasets are expected to provide tighter model constraints, better global coverage and reduced observational bias. Uncertainties, estimated using a Monte-Carlo analysis, are quite large in the global simulation. Nevertheless, the present study reveals an inconsistency in measured carbon and water fluxes at site level compared to regional/global level. The model, once tuned at site-level, predicts a carbon sink of $20 \pm 14\,\mathrm{Gt\,yr^{-1}}$ for the tropics which is inconsistent with atmospheric CO_2 inversion and carbon inventory. Furthermore, evapotranspiration recorded at FLUXNET sites would have to be reduced by 30% to agree with measured global river discharge. Future modelling would benefit from complementary flux measurements in currently underrepresented global vegetation classes (tropical broadleaf forest and C4 grassland) and climate zones (tundra).

1. Introduction

Reconciling flux measurements at site level with global cycles of carbon, water and energy is critical in providing a unified understanding of ecophysiological processes across all spatial scales and is a prerequisite to simulating the correct response of the global land-surface to future climate change. It has long been recognised that computer Land-Surface Models are an invaluable tool in achieving this objective (e.g. Running et al., 1999). To be useful, such models need to be calibrated and validated, preferably on different spatial scales (Falge et al., 2002) but such endeavours are quite rare (Xiao et al., 2012). Peylin et al. (2005) compared regional output from two land-surface models with atmospheric inversion of measured CO_2 concentration but the authors eschew a site calibration of either model owing (at that time) to "the scarcity of long time series of carbon flux measurements over land". Zaehle et al. (2005) simulated global carbon fluxes using the LPJ land-surface model. No calibration as such was conducted since key parameters are allowed to vary within their observed limits using a Monte-Carlo approach. However, the model was validated against site observations of Net Ecosystem Exchange (NEE) and Net Primary Productivity (NPP) and against regional measurements of atmospheric CO_2. (Acronyms and algebraic quantities used frequently in the text are listed in Tables 1 and 3, respectively). More recently, Fisher et al. (2008) calibrated an extended Priestley–Taylor model with latent heat flux recorded at 16 FLUXNET sites in order to estimate global evapotranspiration. Yuan et al. (2010) used both carbon and water fluxes from 54 eddy covariance sites to calibrate and validate a light-use efficiency model which was then run globally and compared with output from previous models. Hickler et al. (2006) carried out a similar exercise to Fisher et al. (2008) but for an enhanced dynamic vegetation model. In this case, zonal output was validated against observed continental river discharge. In addition to these site-to-global scaling studies, there have been several attempts to scale flux measurements from multiple FLUXNET sites to regional level (e.g. Ciais et al., 2005; Chen et al., 2007).

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Table 1
An alphabetical list of acronyms and abbreviations used frequently in the current study.

	Definition
EMDI	Ecosystem Model-Data Intercomparison
GPP	Gross Primary Productivity
JULES-SF	Joint UK land environmental simulator
LAI	leaf area index
LSM	land surface model
MAT	mean annual temperature
MAP	mean annual precipitation
MODIS	Moderate Resolution Imaging Spectroradiometer
NEE	Net Ecosystem Exchange
NPP	Net Primary Productivity
PFT	Plant Functional Type
RMS	Root Mean Square

In spite of the aforementioned studies, efforts to unify over different spatial scales are frustrated by the absence of: (i) geographically extensive databases sampling fluxes and states for all vegetation types and climate regimes; and (ii) comprehensive and reliable datasets at global level of, for example, NEE and runoff (Friend et al., 2007). Furthermore, the hitherto focus has often been on either carbon or water or energy, although all three fluxes are tightly linked and provide simultaneous constraints in modelling experiments. A strong (and unavoidable) reliance on eddy covariance data has led to calibration bias owing to incomplete sampling both geographically (Xiao et al., 2012) and in terms of disturbance/management history (Law et al., 2002; Saleska et al., 2003). Fortunately, the situation is changing. FLUXNET is expanding and complementary datasets (e.g. Ecosystem Model-Data Intercomparison (EMDI) database for NPP; Olson et al., 2008) are slowly being assimilated into models. Moreover, several observational datasets have just recently emerged, for example a global compilation of site soil respiration by Chen et al. (2010). Collective use of a diversity of datasets holds great potential in terms of multiple modelling constraints, better sampling and reduced observational bias (Richardson et al., 2010).

The current study draws on the recent release of datasets for: (i) the driving (MODIS Collection 5 Leaf Area Index (LAI), Princeton reconstructed climatology); (ii) the calibration (FLUXNET, EMDI, MODIS, global soil respiration); and (iii) the validation (e.g. continental discharge and plant trait database) of a process-based LSM containing state-of-the-art formulations of biophysical processes especially canopy light interception. Many of the better calibrated LSMs are statistical machine-learning techniques (Jung et al., 2011) or based on light-use efficiency (e.g. Yuan et al., 2010; Xiao et al., 2010). Such approaches, especially the latter, have the advantage over process-based LSMs in being able to use near real-time satellite data (e.g. MODIS) and often possess a reduced computation time. However, they provide limited understanding of the underlying ecophysiology, especially in the lower canopy and the sub-surface layers (which remain difficult or impossible to detect by satellite) and, therefore, may be of limited use in simulations of future climate change. The current study offers a further novel element in examining all fluxes (carbon, water and energy) together.

The current focus is, firstly, the consistency across different spatial scales of model output against observations and, secondly, the extent to which site calibration datasets sample global vegetation types and climate zones. The importance of temporal variation (seasonal and interannual) is treated elsewhere (e.g. Stoy et al., 2009).

Specific objectives are:

1. to assess the credibility of a state-of-the-art process-based LSM after optimisation against the latest site calibration datasets, including a comparison of retrieved values for key biophysical parameters against compilations of plant traits;
2. to interpret systematic differences in carbon, water and energy at site level according to vegetation class and calibration dataset. (An LSM is essential in this process since different quantities (e.g. NPP, NEE) are measured within each site calibration dataset.);
3. to quantify the ability of current site calibration datasets to represent global vegetation and climate;
4. to determine the accuracy of a site-calibrated LSM by running a global simulation and comparing the model output with the latest observations of regional and global carbon, water and energy balance.

2. Material and methods

The methodology consists of two parts: (1) site simulations permitting model calibration, the retrieval of key biophysical parameters and the comparison of model fluxes between calibration datasets; and (2) a global simulation, validated against regional and global datasets, to evaluate the scaling of carbon, water and energy fluxes from site to global level, and the ability of site calibration datasets to represent global vegetation and climate. First the LSM is introduced. Then the datasets are described which serve either as model input (parameterisation and forcing) or for the purposes of calibration and validation.

2.1. LSM

The current study uses the Joint UK Land Environmental Simulator (JULES-SF) which is an enhanced version of the UK Met.Office Surface Exchange Scheme (Cox et al., 1999). Key equations for JULES-SF are given in the Appendix of Alton and Bodin (2010) but a summary is provided here along with information for two subsequent modifications (plant maintenance respiration and tap roots).

JULES-SF takes account of diffuse and direct sunlight at multiple heights within the canopy and is one of most elaborate land-surface models which operates globally in terms of light interception (Alton et al., 2007). The energy calculation central to JULES-SF is the standard Penman–Monteith approach (Monteith, 1965), ensuring the balance of ingoing and outgoing energy fluxes at the land-surface. Photosynthesis is calculated separately within each of 5 leaf layers according to a biochemical co-limitation model (Collatz et al., 1991), before summing to produce a canopy total. Leaf photosynthesis is linked to transpiration through a Ball-Berry stomatal model (Ball et al., 1987). Plant respiration depends on maintenance and growth terms (Ryan, 1991). The former includes separate, additive terms for leaf and root respiration according to Q_{10} relationships based on canopy and soil temperature (Law et al., 1999). Surface albedo is estimated according to the two-stream approximation of Sellers et al. (1996). Plant water extraction depends on an exponential fine root distribution (Jackson et al., 1996) and a tap root within the lowest soil layer (depth 2–3 m). There are few direct measurements of the partitioning of fine and tap-root biomass but, within the seasonal tropics, 30–40% of roots lie deeper than 1 m (Nepstad et al., 1994; see also Canadell et al., 1996). It is assumed, therefore, that one third of the total root biomass is contained within the tap root.

In this study, JULES-SF uses 10 Plant Function Types (PFTs) to represent vegetation: tropical broadleaf forest, non-tropical broadleaf forest, Mediterranean needleleaf forest, non-Mediterranean needleleaf forest, C3 grassland, C4 grassland, C3 crops, C4 crops, tundra shrubland and non-tundra shrubland. In the global simulation, the fraction of each PFT within each 3° landpoint is taken from the International Geosphere-Biosphere Project classification (Hansen and Reed, 2000) and the agricultural cover of Goldewijk (2001). For the site simulations, PFT is assigned according to site description. For one of the calibration datasets