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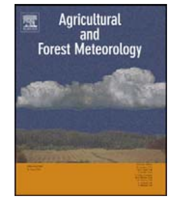

Intercomparison of a 'bottom-up' and 'top-down' modeling paradigm for estimating carbon and energy fluxes over a variety of vegetative regimes across the U.S.

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ABSTRACT

Biophysical models intended for routine applications at a range of scales should attempt to balance the competing demands of generality and simplicity and be capable of realistically simulating the response of CO_2 and energy fluxes to environmental and physiological forcings. At the same time they must remain computationally inexpensive and sufficiently simple to be effectively parameterized at the scale of application. This study investigates the utility of two modeling strategies for quantifying coupled land surface fluxes of carbon and water, which differ distinctly in their description of CO_2 assimilation processes. 'Bottom-up' models of land–atmosphere carbon exchange are based on detailed mechanistic descriptions of leaf-level photosynthetic processes scaled to the canopy whereas 'top-down' scaling approaches neglect the behavior of individual leaves and consider the canopy response to its environment in bulk. Effective intercomparisons of a light-use-efficiency (LUE)-based model of canopy conductance and a mechanistic model of leaf photosynthesis–stomatal response that employs a 'two-leaf' scaling strategy are facilitated by embedding both canopy sub-models in the Atmosphere–Land Exchange (ALEX) surface energy balance model. Water and carbon flux simulations are evaluated across time scales of hours, days, seasons and years for a variety of natural and agricultural ecosystems, using micrometeorological data from several AmeriFlux sites across the U.S. While both modeling paradigms reproduced observed magnitudes and variances of carbon and water vapor exchange on hourly and daily timescales with acceptable accuracy, the simpler LUE-based model often performed better than the more detailed scaled-leaf model, which has many adjustable species-specific model parameters. Actual light-use efficiencies vary significantly in response to changing environmental conditions and the success of LUE-based modeling frameworks rely on their ability to realistically respond to changes in light environment, atmospheric humidity, CO_2 concentration and a desiccating environment.

1. Introduction

An accurate quantification of energy and carbon fluxes is of great importance for a wide range of ecological, agricultural, and meteorological applications. The modeling of atmosphere–land exchange processes at a range of spatial and temporal scales can improve our understanding of ecosystem functioning. These flux evaluations are also important in the context of climate change for the establishment of regional and global carbon budgets. Additionally, reliable regional assessments of land–surface water and energy fluxes have utility in water resource management, yield forecasting, and numerical weather prediction.

Plant physiological research carried out in the 1980s and early 1990s provided new insights into the biochemical mechanisms controlling the CO_2 assimilation of leaves and how stomata respond to environmental and physiological factors (e.g., Farquhar et al., 1980; Ball et al., 1987; Collatz et al., 1991). Stomata simultaneously regulate the conflicting demands of allowing CO_2 assimilation by leaves and minimizing water loss from the leaves to the environment, and this stomatal conductance has been recognized as a key for assessing carbon and latent heat exchange between vegetated surfaces and the atmosphere. The predictive power of biophysical models has been significantly enhanced by coupling fluxes of carbon dioxide and water vapor

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using semi-empirical models of stomatal functioning (e.g., Wang and Leuning, 1998; Anderson et al., 2000; Kellomaki and Wang, 2000; Sellers et al., 1996; Zhan and Kustas, 2001; Baldocchi and Wilson, 2001; Anderson et al., 2008).

Biophysical models intended for routine applications at regional scales should be capable of realistically simulating the response of canopy-scale CO_2 and energy fluxes to environmental and physiological forcings but should also remain computationally inexpensive and be sufficiently simple to be effectively parameterized at the scale of application. Very complex modeling systems may require land–surface parameters that cannot be defined with adequate accuracy over large spatial domains.

Two contrasting modeling strategies are currently used widely to quantify canopy-scale exchange processes of CO_2 and water vapor at local, regional and global scales. 'Bottom-up' models of land–atmosphere CO_2 and energy exchange are based on detailed mechanistic descriptions of leaf-level photosynthetic processes scaled to the canopy, whereas 'top-down' scaling approaches neglect the behavior of individual leaves and consider the canopy response to its environment in bulk. 'Bottom-up' models of coupled CO_2–water vapor exchange rely on the specification of an appropriate leaf-to-canopy scaling framework. Big-leaf models that treat the canopy as a single leaf have been used extensively to parameterize land–surface in climate models (e.g., Sellers et al., 1996; Dickenson et al., 1998) but have been shown to introduce significant errors into calculations of canopy photosynthesis (De Pury and Farquhar, 1997; Spitters, 1986). Multi-layer integration schemes (e.g., Leuning et al., 1995; Baldocchi and Wilson, 2001) consider multiple layers with many different leaf angle classes and numerically integrate fluxes for each leaf class and layer to derive total canopy fluxes. The complexity and high computational demand is an evident drawback of the multi-layer approach. The two-leaf concept represents a simplified canopy integration scheme that largely overcomes the limitations of 'big-leaf' models as it considers the highly non-linear response of leaf photosynthesis to the different light environments of sunlit and shaded leaves (De Pury and Farquhar, 1997; Wang and Leuning, 1998). 'Bottom-up' (scaled-leaf) models generally require the specification of many species-dependent leaf-scale parameters but have proven effective in reproducing observed fluxes at a range of scales (Leuning et al., 1998; Houborg and Soegaard, 2004; Zhan and Kustas, 2001; Dai et al., 2004).

'Top-down' models are generally less complex, as they are constrained by some empirical relationship developed at the stand-level and thus implicitly incorporate scaling effects. The light-use-efficiency (LUE), defined here as the ratio between net CO_2 assimilation rate and absorbed photosynthetically active radiation (APAR), is a fundamental quantity used by a suite of simple biophysical models (e.g., Ruimy et al., 1994; Prince and Goward, 1995; Potter et al., 2003; Running and Hunt, 1993) that assume conservation of LUE for major vegetation types under unstressed conditions. Models constrained by LUE generally require the specification of only few tunable parameters. However due to the embedded empiricism LUE-based models may need modification in order to respond realistically to climate changes such as elevated CO_2 (Harley et al., 1992).

The objective of this study is to compare a simple analytical LUE-based model of canopy resistance with a mechanistic model of leaf-level photosynthesis–stomatal response that employs a 'two-leaf' scaling strategy. The two modeling paradigms differ considerably in their scaling approach and complexity, and a key objective is to test the potential utility of the contrasting modeling paradigms for regional to continental-scale CO_2 and water vapor flux modeling. Effective model evaluations are facilitated by setting up the models using parameterizations for broad categories of vegetation environments as reported in the ecological literature. The study also aims at providing insight into the challenges of model parameterization for the two types of canopy models and may act as a guideline for the degree of model simplicity required for useful flux predictions at larger scales on a routine basis. For the purpose of intercomparisons, both canopy sub-models have been embedded in the Atmosphere–Land Exchange (ALEX) surface energy balance model, which is a simplified version of a detailed soil–plant–atmosphere model Cupid (Norman, 1979; Norman and Campbell, 1983; Norman and Polley, 1989; Norman and Arkebauer, 1991); ALEX was specifically developed for operational applications. The ability of the two canopy sub-models to reproduce observed patterns in energy and carbon fluxes across time scales of hours, days, seasons and years is evaluated for a variety of natural and agricultural ecosystems, using micrometeorological data from several AmeriFlux sites across the U.S.

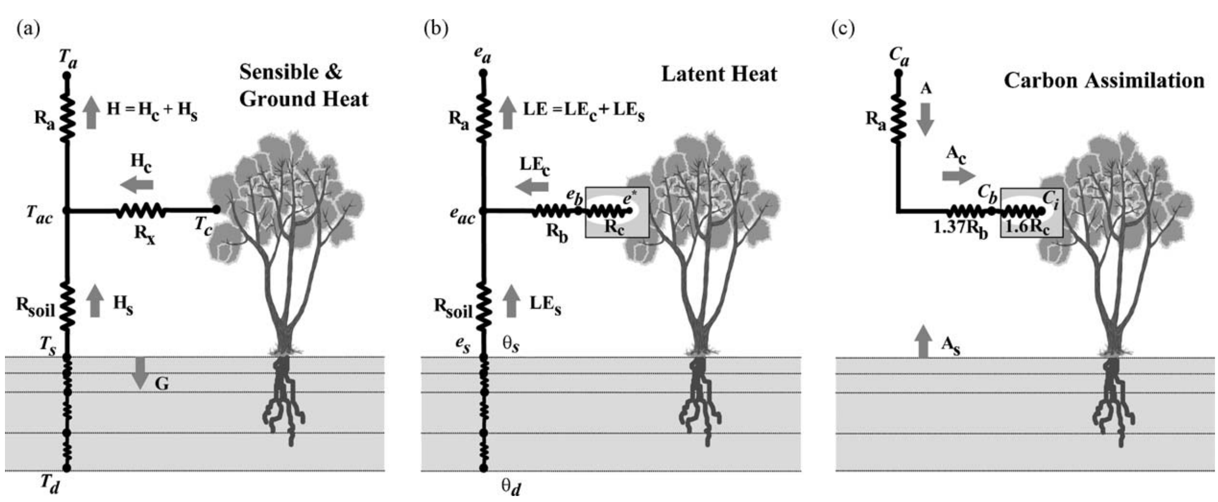

Fig. 1. Transport resistance networks used in the ALEX model to estimate fluxes of (a) sensible (H) and ground heating (G), (b) latent heating from the insides of leaf stomates (LE_c) and the soil surface (LE_s), and (c) net ecosystem CO_2 exchange (A). The subscripts 'a', 'ac', 'b', and 'i' refer, respectively, to conditions above the canopy, within the canopy air space, within the boundary layer at the leaf surface, and inside sub-stomatal cavities. R_a is the aerodynamic resistance to turbulent transport between the canopy air space and measurement reference height, R_b is the resistance of the leaf boundary layer, R_c is the stomatal resistance to water vapor diffusion, and R_{soil} is the aerodynamic resistance of the boundary layer between the soil surface and the canopy air space. The 1.6 and 1.37 resistance multipliers (c) account for the difference in diffusivity between CO_2 and water vapor.