Preface to special section on New Approaches to Quantifying Exchanges of Carbon and Energy Across a Range of Scales

Henry W. Loescher[1] and J. William Munger[2]

Received 29 January 2006; accepted 5 May 2006; published 26 July 2006.

Citation: Loescher, H. W., and J. W. Munger (2006), Preface to special section on New Approaches to Quantifying Exchanges of Carbon and Energy Across a Range of Scales, *J. Geophys. Res.*, *111*, D14S91, doi:10.1029/2006JD007135.

[1] Estimating carbon and energy exchanges in the soil-plant-atmosphere continuum across spatial and temporal scales is a primary focus of coordinated interagency collaborations (i.e., U.S. Global Change Research Program, Climate Change Science Program, and the Carbon Cycle InterAgency Working Group) that are outlined in North American Carbon Plan [*Wofsy and Harriss*, 2002], Carbon Cycle Science Plan [*Sarmiento and Wofsy*, 1999], Intergovernmental Panel on Global Climate Change [*Intergovernmental Panel on Global Climate Change*, 1995] and other position papers. Eddy covariance (EC) has served well to define these exchanges over scales of 10–100 ha in relatively simple terrain under well-mixed conditions. These data have contributed to significant advances in our understanding of important ecosystem processes and quantifying the key biotic and abiotic processes that control these rates [*Loescher et al.*, 2003, 2005; *Law et al.*, 2002, 2003; *Anthoni et al.*, 1999, 2002; *Bowling et al.*, 2001; *Clark et al.*, 1999; *Goulden et al.*, 1996], and useful in developing regional approaches to constraining the global CO_2 budget [*Townsend et al.*, 2002; *Battle et al.*, 2000]. However, extension to complex terrain and measurement under non-ideal meteorological conditions requires new approaches. New approaches are also needed to increase our ability to scale these exchanges. The focus of this thematic issue is to quantify uncertainty in energy and carbon fluxes, and introduce new approaches for extending the measurements to larger scales.

[2] This thematic issue presents a suite papers covering a wide range of topics including estimation of uncertainties in flux measurements, examination of problems associated with nighttime fluxes, extraction of physiological parameters from flux measurements, methodological issues with measurements, use of isotopic measurements, and regionalization. The section begins with *Loescher et al.* [2006] outlining the uncertainties associated with EC measurements (e.g., random and systematic errors, gap filling, and flows not accounted for), how these errors scale with time and space, and how these errors compare to the errors associated with traditional estimates of ecosystem respiration and net primary productivity.

[3] Estimating the uncertainty in EC data can be challenging because the variability in 30-min EC estimates increase with the magnitude of the estimate, i.e., heteroscedastic quantities. Moreover, it is now a criterion to provide an estimate of uncertainty in EC estimates when reporting data from any (and all) AmeriFlux site. *Hagen et al.* [2006] provide a robust methodology to accomplish these goals. By using bootstrapping and an artificial neural network, these authors found by that the uncertainty in EC was ~100% for 30-min estimates, but was reduced with longer temporal scales (annual estimates) to ~10%. Their research site was micrometeorologically ideal (average and uniform surface roughness, flat topography), so other unaccounted flows did not likely contribute to this study.

[4] The combination of thermally stratified, decoupled nocturnal boundary layers and structurally complex forest structures make nighttime EC estimates difficult to estimate and create the conditions when drainage of CO_2 below the height of the measured turbulent flux can occur. *Goulden et al.* [2006] used remotely sensed data to examine potential nighttime CO_2 drainage patterns in an Amazon forest and surrounding landscape, and identify when drainage flows develop and become significant. *Juang et al.* [2006] provide a promising inverse approach (Eulerian rather than Langrangian) using below-canopy air temperature to model ecosystem respiration. *Lai et al.* [2006] use stable carbon and oxygen isotopes of respired CO_2 to partition the abiotic controls on ecosystem-level uptake and respiration from a C_3/C_4 grassland.

[5] Using eddy covariance data to estimate annual integrals is hampered by incomplete data sets due to enviable data gaps due to calibrations, instrument failure, precipitation, and power problems. Gap filling strategies have included look-up tables, interpolations or estimates of uptake and respiration (e.g., those based on Ball-Berry and Q_{10} equations). *Gove and Hollinger* [2006] present an innovative methodology to gap fill data that relies on the heteroscedastic nature of EC-derived 30-min, and optimizes parameters used in uptake and respiration equations.

[6] *Wolf et al.* [2006] invert a model and constrain the governing equations by measured EC data to estimate key ecosystem parameters from uncertainties associated with light use efficiency models that primarily stem from the

[1]Department of Forest Science, College of Forestry, Oregon State University, Corvallis, Oregon, USA.

[2]Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, USA.

0148-0227/06/2006JD007135

saturation and the nonlinear behavior of absorbed incident light.

[7] Two papers address methodological uncertainties. Our dependence on accurate and precise in situ CO_2 estimates relies on the World Meteorological Organization–Climate Monitoring and Diagnostic Lab CO_2 traceable primary standards (http://www.cmdl.noaa.gov/ccgg/refgases/index.html) to calibrate infrared analyzers use in eddy covariance, stable isotopic and atmospheric transport studies. *Zhao and Tans* [2006] provide precision and accuracy estimates of these standards and discuss their use in CO_2 studies.

[8] There are often significant differences between scaled chamber measurements and EC-derived estimates of ecosystem respiration, calling into question the representativeness of both types of measurement [e.g., *Davidson et al.*, 2005; *Bolstad et al.*, 2004; *Law et al.*, 1999]. *Xu et al.* [2006] have found a significant source of error in soil chamber estimates due to pressure inequilibrium between the internal chamber and ambient environments, and provide a new approach to account for this bias.

[9] Ultimately our goal is to quantify carbon budgets at scales larger than a single tower. (1) *Gitelson et al.* [2006] have constrained a remote-sensed light use efficiency model to scale agronomic crops to larger areas with changes in measured chlorophyll, and (2) *Binford et al.* [2006] use Landsat imagery and look-up tables to estimate long-term carbon dynamics (1972–2001) from a North Florida region. *Gitelson et al.* [2006] test these approaches over structurally simple ecosystems, whereas the *Binford et al.* [2006] study applies their scaling effort over a diverse land uses and forested and urban environments alike.

References

Anthoni, P. M., B. E. Law, and M. H. Unsworth (1999), Carbon and water vapor exchange of an open-canopied ponderosa pine ecosystem, *Agric. For. Meteorol.*, *95*, 151–168.

Anthoni, P. M., M. H. Unsworth, B. E. Law, J. Irvine, D. D. Baldocchi, S. Van Tuyl, and D. Moore (2002), Seasonal differences in carbon and water vapor exchange in young and old-growth ponderosa pine ecosystems, *Agric. For. Meteorol.*, *111*, 203–222.

Battle, M., M. L. Bender, P. P. Tans, J. W. C. White, J. T. Ellis, T. Conway, and R. J. Francey (2000), Global carbon sinks and their variability inferred from atmospheric O_2 and $\delta^{13}C$, *Science*, *287*, 2467–2470.

Binford, M., H. L. Gholz, G. Starr, and T. A. Martin (2006), Regional carbon dynamics in the southeastern coastal plain: Balancing land-cover type, timber harvesting, environmental variation, and fire, *J. Geophys. Res.*, doi:10.1029/2005JD006820, in press.

Bolstad, P. V., K. J. Davis, J. Martin, B. D. Cook, and W. Wang (2004), Component and whole-system respiration fluxes in northern deciduous forests, *Tree Physiol.*, *24*, 493–504.

Bowling, D. R., P. P. Tans, and R. K. Monson (2001), Partitioning net ecosystem carbon exchange with isotopic fluxes of CO_2, *Global Change Biol.*, *7*, 127–145.

Clark, K. L., H. L. Gholz, J. B. Moncrieff, F. Cropley, and H. W. Loescher (1999), Environmental controls over net exchanges of carbon dioxide from contrasting Florida ecosystems, *Ecol. Appl.*, *9*, 936–948.

Davidson, E. A., A. D. Richardson, K. E. Savage, and D. Y. Hollinger (2005), A distinct seasonal pattern of the ratio of soil respiration to total ecosystem respiration in a spruce-dominated forest, *Global Change Biol.*, *11*, 1–10.

Gitelson, A. A., A. Viña, S. B. Verma, D. C. Rundquist, T. J. Arkebauer, G. Keydan, B. Leavitt, V. Ciganda, G. G. Burba, and A. E. Suyker (2006), Relationship between gross primary production and chlorophyll content in crops: Implications for the synoptic monitoring of vegetation productivity, *J. Geophys. Res.*, *111*, D08S11, doi:10.1029/2005JD006017.

Goulden, M. L., J. W. Munger, S.-M. Fan, B. C. Daube, and S. C. Wofsy (1996), Effects of interannual climate variability on the carbon dioxide exchange of a temperate deciduous forest, *Science*, *271*, 1576–1578.

Goulden, M. L., S. D. Miller, and H. R. da Rocha (2006), Nocturnal cold air drainage and pooling in a tropical forest, *J. Geophys. Res.*, *111*, D08S04, doi:10.1029/2005JD006037.

Gove, J. H., and D. Y. Hollinger (2006), Application of a dual unscented Kalman filter for simultaneous state and parameter estimation in problems of surface-atmosphere exchange, *J. Geophys. Res.*, *111*, D08S07, doi:10.1029/2005JD006021.

Hagen, S. C., B. H. Braswell, E. Linder, S. Frolking, A. D. Richardson, and D. Y. Hollinger (2006), Statistical uncertainty of eddy flux–based estimates of gross ecosystem carbon exchange at Howland Forest, Maine, *J. Geophys. Res.*, *111*, D08S03, doi:10.1029/2005JD006154.

Intergovernmental Panel on Climate Change (1995), *Second Assessment Report: Climate Change*, Geneva, Switzerland.

Juang, J., G. G. Katul, M. B. S. Siqueira, P. C. Stoy, S. Palmroth, H. R. McCarthy, H. Kim, and R. Oren (2006), Modeling nighttime ecosystem respiration from measured CO_2 concentration and air temperature profiles using inverse methods, *J. Geophys. Res.*, *111*, D08S05, doi:10.1029/2005JD005976.

Lai, C., W. Riley, C. Owensby, J. Ham, A. Schauer, and J. R. Ehleringer (2006), Seasonal and interannual variations of carbon and oxygen isotopes of respired CO_2 in a tallgrass prairie: Measurements and modeling results from 3 years with contrasting water availability, *J. Geophys. Res.*, *111*, D08S06, doi:10.1029/2005JD006436.

Law, B. E., M. G. Ryan, and P. M. Anthoni (1999), Seasonal and annual respiration of a ponderosa pine ecosystem, *Global Change Biol.*, *5*, 169–182.

Law, B. E., et al. (2002), Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, *Agric. For. Meteorol.*, *113*, 97–120.

Law, B. E., O. Sun, J. L. Campbell, S. Van Tuyl, and P. Thornton (2003), Changes in carbon storage and fluxes in a chronosequence of ponderosa pine, *Global Change Biol.*, *9*, 510–524.

Loescher, H. W., S. F. Oberbauer, H. L. Gholz, and D. B. Clark (2003), Environmental controls on net ecosystem-level carbon exchange and productivity in a Central American tropical wet forest, *Global Change Biol.*, *9*, 396–412.

Loescher, H. W., H. L. Gholz, J. M. Jacobs, and S. F. Oberbauer (2005), Energy dynamics and modeled evapotranspiration from a wet tropical forest in Costa Rica, *J. Hydrol.*, *315*, 274–294.

Loescher, H., B. E. Law, L. Mahrt, D. Hollinger, J. L. Campbell, and S. C. Wofsy (2006), Uncertainties in and interpretation of carbon flux estimates using the eddy covariance technique, *J. Geophys. Res.*, doi:10.1029/2005JD006932, in press.

Sarmiento, J. L., and S. C. Wofsy (1999), A US carbon cycle science plan, report of the Committee of the US Interagency Carbon Cycle Science Program, U.S. Global Change Res. Program, Washington, D. C.

Townsend, A. R., G. P. Asner, J. W. C. White, and P. P. Tans (2002), Land use effects on atmospheric ^{13}C imply a sizable terrestrial CO_2 sink in tropical latitudes, *Geophys. Res. Lett.*, *29*(10), 1426, doi:10.1029/2001GL013454.

Wofsy, S. C., and R. C. Harriss (2002), The North American Carbon Program, report of the NACP Committee of the US Interagency Carbon Cycle Science Program, U.S. Global Change Res. Program, Washington, D. C.

Wolf, A., K. Akshalov, N. Saliendra, D. A. Johnson, and E. A. Laca (2006), Inverse estimation of Vc_{max}, leaf area index, and the Ball-Berry parameter from carbon and energy fluxes, *J. Geophys. Res.*, *111*, D08S08, doi:10.1029/2005JD005927.

Xu, L., M. D. Furtaw, R. A. Madsen, R. L. Garcia, D. J. Anderson, and D. K. McDermitt (2006), On maintaining pressure equilibrium between a soil CO_2 flux chamber and the ambient air, *J. Geophys. Res.*, *111*, D08S10, doi:10.1029/2005JD006435.

Zhao, C. L., and P. P. Tans (2006), Estimating uncertainty of the WMO mole fraction scale for carbon dioxide in air, *J. Geophys. Res.*, *111*, D08S09, doi:10.1029/2005JD006003.

H. W. Loescher, Department of Forest Science, College of Forestry, Oregon State University, Corvallis, OR 97331, USA. (hank.loescher@oregonstate.edu)

J. W. Munger, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA.