Final Report

Scaling up of Carbon Exchange Dynamics from AmeriFlux Sites to a Super-Region in the Eastern United States

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Project Summary:

The primary objective of this project was to evaluate carbon exchange dynamics across a region of North America between the Great Plains and the East Coast. This region contains about 40 active carbon cycle research (AmeriFlux) sites in a variety of climatic and landuse settings, from upland forest to urban development. The core research involved a scaling strategy that uses measured fluxes of CO_2, energy, water, and other biophysical and biometric parameters to train and calibrate surface-vegetation-atmosphere models, in conjunction with satellite (MODIS) derived drivers. To achieve matching of measured and modeled fluxes, the ecosystem parameters of the models will be adjusted to the dynamically variable flux-tower footprints following Schmid (1997). High-resolution vegetation index variations around the flux sites have been derived from Landsat data for this purpose. The calibrated models are being used in conjunction with MODIS data, atmospheric re-analysis data, and digital land-cover databases to derive ecosystem exchange fluxes over the study domain.

SECTION I: Technical Plan

1 Objectives

1. Our primary objective is *to estimate the magnitude and dynamics of biotic carbon exchange at hourly to interannual resolution over a super-region*. The term super-region is used to indicate a large area that spans significant gradients of climatic, ecosystem and landscape diversity. Originally, the proposed study area extended over the part of the United States east of an axis approximately aligned with the lower Mississippi River. *In this renewal, it is expanded to include the planned tall tower and Ameriflux tower sites for the Mid Continental Intensive (MCI)*. The focus will be on determining the net ecosystem exchange (NEE) components of the carbon balance over this region at fine spatial and temporal resolution. This objective closely matches the first goal of the U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999), the North America Carbon Program (Wofsy and Harris, 2002), and the MCI Science Plan.

2. *Regional aggregation while maintaining high resolution*. We will aggregate carbon exchange dynamics over the super-region for a year or longer, while explicitly resolving variability due to diel cycles of biophysical forcings, and due to local scale variability in land cover and topography. Tracking the local evolution of diel variability and seasonal changes over a large region in a comprehensive and unified framework is new and has not been achieved for carbon exchange before. While the range of spatial and temporal variability remains daunting for ecosystem carbon cycle models, the approaches here have a proven record in meteorology (e.g., weather forecasting and re-analysis). Thus, the basic tools for data assimilation and numerical modeling are well known, as are their strengths and weaknesses, and can be adapted to questions of carbon exchange. However, the carbon exchange measurement infrastructure that forms the observational backbone of such an approach has only recently become available, with the development of the FLUXNET/AmeriFlux network (Baldocchi et al., 2001).

3. *Methodology development of a bottom-up scaling strategy, and cross-validation of carbon exchange estimates*. To achieve our primary objective we will develop a new strategy that combines several independent approaches for estimating terrestrial carbon exchange: *in-situ* micrometeorological observations, atmospheric boundary layer and ecophysiology models, ecological biomass inventory estimates, satellite observations, and ecosystem models. We will match these independent approaches across several orders of spatial and temporal scales, and will cross-validate them at scales of overlap. This comprehensive cross-validation will be of great value to the carbon cycle science community.

   Our results will allow direct comparison with other carbon balance estimates based on a remote sensing/ecosystem modeling approach (e.g., on-going activities using data from the MODIS instrument, with an eight-day time-step), and with results from inverse modeling approaches at much coarser spatial and temporal resolutions. They also will enable us to examine the adequacy of the flux tower network within the super-region in terms of site density, location, and range of land cover types, and propose improvements to the observation program. *We will also provide eddy-covariance (EC) tower flux up-scaled estimates to be compared with the planned top-down and bottom scaling inter-comparisons planned for the MCI*. Hence, the MCI campaign will allow us to rigorously test the proposed scaling framework.

2 Rationale: Broad Outline of Activities

Our primary activity will be to develop and apply a new strategy for estimating large-scale terrestrial biotic carbon dynamics based on a bottom-up approach that integrates eddy-covariance flux measurements, ecosystem-scale modeling, and a mesoscale meteorological model. Robustness in our scaling and aggregation strategy is achieved by cross-links to independent observations and model products at various scales and sites. These links offer opportunities for direct comparisons to alternative approaches and impose constraints on aggregation errors.

The proposed bottom-up carbon exchange scaling strategy

We propose a new strategy to scale up carbon exchange from observations at specific sites to a large region by combining four general classes of information (Figure 1):

1. *Flux observations*. We will integrate eddy-flux observations of CO_2 exchange from over 40 active AmeriFlux sites into our scaling strategy by applying flux footprint-based selection criteria.
2. *Numerical models*. We will use several different numerical models to provide both the functional link between flux observations and their biophysical drivers, and the spatial link between the observational nodes of the AmeriFlux network.
3. *Meteorological Re-analysis Data*. To provide spatial coverage of meteorological drivers for the ecosystem exchange models, reanalysis data will be used.
4. *Satellite data products and surface databases at nested resolutions and coverage domains*. Surface databases and satellite derived ecosystem indices form the spatial context in which our numerical models will operate.

These sources of information are linked in a scaling strategy involving five principal stages (Figure 1). The steps leading from one stage to the next are governed by the following overarching considerations:

A. *In-situ flux observations are in general spatially and/or temporally limited.* Therefore, to achieve valid regional exchange rates, models must be used to interpolate and extrapolate the temporal and spatial domain covered by these observations.

B. *Observations and model results can only be linked if they represent the same ecosystem type and time period.* Because all ecosystems are spatially heterogeneous at some range of scales, this requirement may be a problem, but can be satisfied by selecting observations that are representative of the type of ecosystem identified in the model (Schmid, 1997). The spatial representativeness of flux observations in inhomogeneous ecosystems can be tested using a flux footprint methodology, which is the time-varying “field-of-view” of an eddy-flux sensor.

C. *Comparisons of observations and independent models at various scales can form plausibility constraints on modeling results and aggregation errors.* Such comparisons also serve to test and develop our understanding of the mechanistic functioning of ecosystem exchange and its biophysical drivers. Spatial data (such as satellite derived variables, topography, inventories, or soil information) are needed as boundary conditions for numerical models. They are essential in linking observations and models at small scales to models of ecosystem exchange at large scales.

Table 1: The active AmeriFlux sites in the study region

Site	Veg.	Lat. (N)	Lon. (W)	Site	Veg.	Lat. (N)	Lon. (W)
Kennedy SFC-1, FL	1	28.60858	80.67153	Goodwin Creek, MS	6	34.25000	89.97000
Kennedy SFC-2, FL	2	28.45831	80.67090	Duke-pine, NC	2	35.97817	79.09419
Gainsville-1, FL	5	29.77043	82.20810	Duke-hardwood, NC	1	35.97358	79.10043
Gainsville-2, FL	2	29.80282	82.20315	Duke-fallow, NC	6	35.97120	79.09338
Gainsville-3, FL	2	29.76480	82.24482	Walker Branch, TN	1	35.95877	84.28743
Gainsville-4, FL	2	29.73807	82.21877	Lost Creek, WI	5	46.08268	89.97919
Gainsville-5, FL	2	29.75477	82.16328	Park Falls/ WLEF, WI	4	45.94588	90.27231
MMSF~flux, IN	1	39.32312	86.41314	Willow Creek, WI	4	45.80593	90.07986
Harvard-hemlock, MA	2	42.53933	72.17794	Canaan Valley, WV	6	39.06333	79.42083
Harvard-main, MA	1	42.53776	72.17147	Camp Borden, ONT	1	44.31666	79.93333
Howland main, ME	4	45.20410	68.74020	Mer Bleue, ONT	5	45.40940	75.52000
Howland west, ME	4	45.20910	68.74700	Groundhog River, ONT	4	48.21670	82.15560
Howland harvest, ME	4	45.20720	68.72648	Boreal Cutover, QUE	2	49.26712	74.03650
UMBS~flux, MI	1	45.55984	84.71382	Turkey Pt-mature, QUE	2	42.71222	80.35722
Great Mountain, CT	3	41.96666	73.23333	Turkey Pt-mid age, QUE	2	42.70944	80.34861
Cub Hill, MD	8	39.41251	76.52080	Turkey Pt-seedl., QUE	2	42.66361	80.56000
Sylvania, MI	1	46.24202	89.34765	Turkey Pt-young, QUE	2	42.77569	80.45900
Bondville, IL	7	40.00610	88.29187				

Vegetation: 1: broadleaf forest 2: coniferous forest 3: mixed forest 4: boreal transitional forest 5: wetland, bog, fen 6: pasture, open field 7: cropland 8: suburban

Our scaling-up methodology begins with tower based eddy-covariance (EC) flux measurements from all flux tower sites within the study area (Table 1; flag 1, Figure 1). The EC integrated footprint constitutes our 'finest-scale' in the scaling-up. At each site, a flux footprint model will be used in conjunction with a high-resolution ecosystem index data-base (Section 3.2) to examine how well the footprint area represents the dominant ecosystem type, following Schmid and Lloyd (1999). Only spatially representative ecosystem flux observations will be linked to modeled values (flag 2, Figure 1). At a number of sites, NEE is estimated from carbon stock inventories, in conjunction with enclosure fluxes and process level mechanistic models on seasonal to annual time scales (e.g., Ehman *et al.*, 2002; Curtis *et al.*, 2002). These findings will be used as independent constraints on eddy-covariance based estimates of annual NEE and its components. Spatially representative carbon exchange at the varying scales also will be modeled by mechanistic ecosystem models of varying complexity (Section 3.3). The performance of these models is being examined by driving the models with biophysics measured at the flux sites and comparing results with representative ecosystem fluxes measured by eddy-covariance (flag 3, Figure 1).

Deliverables

Our main product will be an analysis of ecosystem-atmosphere exchange of carbon over the super-region, at a spatial resolution of ~1-10 km and at hourly time steps for a year or longer. Our focus will be on net primary production (NPP), as well as net ecosystem exchange (NEE). Both NPP and NEE estimates will be used in cross validation exercises with MODIS derived estimates, such as those that are currently being conducted by the AmeriFlux model validation study (http://public.ornl.gov/ameriflux/Analysis/Model_Evaluation).

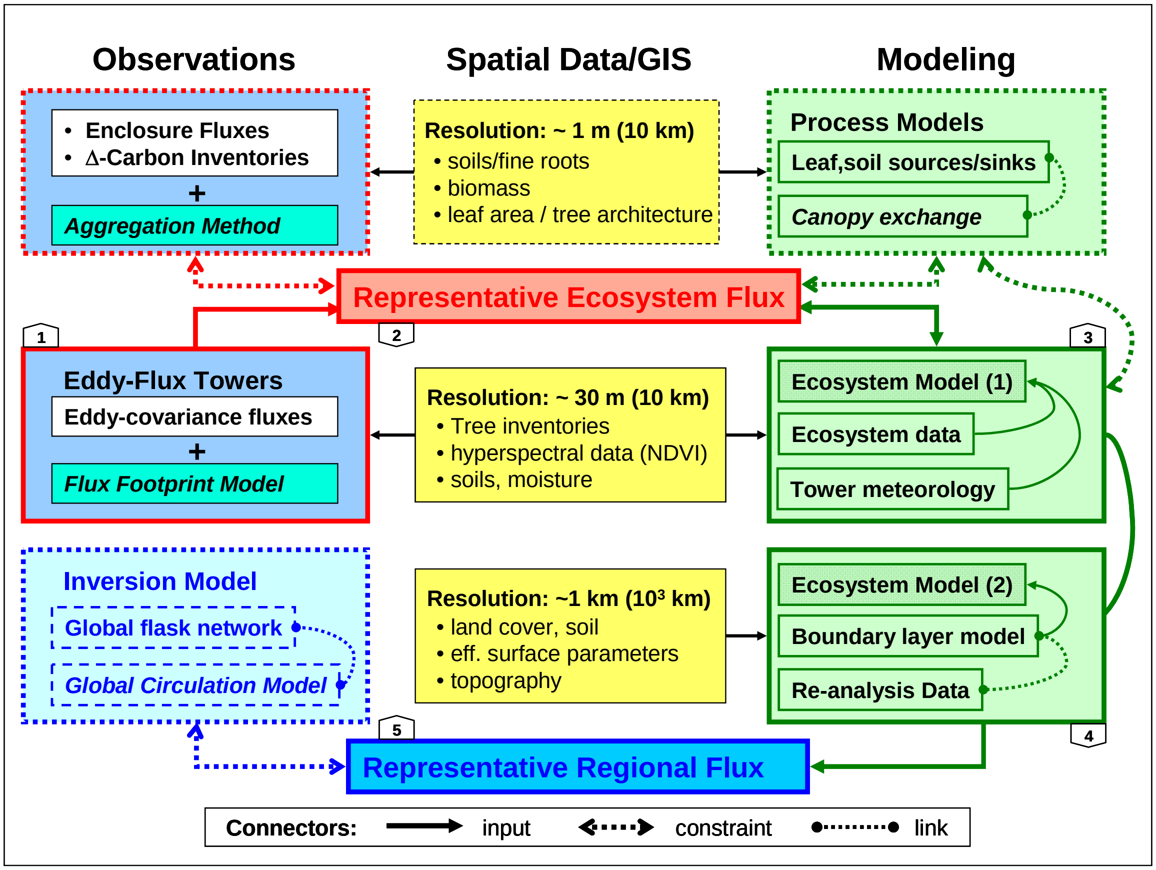


Figure 1: A strategy to scale-up carbon fluxes from local observation footprints to a large region. The five stages of this bottom-up scaling strategy are indicated by the numbered flags on the boxes. Dashed boxes and arrows indicate links to observations or models that are external to the scaling/aggregation process, but can be used as plausibility checks and constraints. In particular, the link of the regional flux to an inversion model offers the potential for a constraint on the aggregation error, and can enhance our interpretation of both bottom-up and top-down approaches.

General advantages of our bottom-up strategy

- The integration of *in-situ* observations with several mechanistic models of varying complexity allows examination and testing of current hypotheses of processes governing biosphere-atmosphere carbon exchange.
- Multi-year coverage of measured and modeled NPP and NEE at hourly resolution, with spatial resolution of ~10^2 m to 10^4 m, and coverage over a large region makes the product of our study amenable to analysis of complexity in spatial and temporal dimensions.
- Our proposed strategy gains robustness because it uses direct observations of biosphere-atmosphere exchange to constrain the model results at the individual site scale. It will also be tested against other bottom-up and top-down scaling strategies for the MCI region. For example, aircraft derived fluxes provide reasonable spatially ‘aggregated’ constraints on short time scales.

3 Methods

In this section, the observational and modeling components of our scaling strategy described above are presented separately in more detail.

3.1 Spatial Representativeness of Tower Fluxes

All natural ecosystems exhibit spatial variability of vegetation density or composition at some range of scales. Trace gas material released from sources within such vegetated surfaces have variable probability to be carried past a tower-mounted flux sensor, depending on their location relative to the sensor and the flow and turbulence field that provides the transport. Most sources that have a non-negligible probability to contribute to the measured flux lie in an upstream source area with approximately elliptical dimensions (Schmid and Oke, 1990). The probability distribution of all such potential sources is commonly termed the flux source weight function or the flux footprint (Schuepp et al. 1990). The footprint of a flux measurement is analogous to the field of view of the sensor. It is formally defined as the transfer function that relates a distribution of surface sources or sinks to the turbulent flux measured at height (for a review, see Schmid, 2002). Measured fluxes of biosphere-atmosphere exchange are thus expected to be representative of a given ecosystem only to the extent that the vegetation characteristics in the flux footprint reflect average ecosystem conditions. Schmid (1997), Schmid and Lloyd (1999) and Schmid et al. (2002) present a practical method to assess the spatial representativeness of a turbulent flux measurement quantitatively, using the flux footprint approach. Taking leaf area index (LAI) as the most important ecosystem driver for gross primary production (GPP), Schmid et al. (2003) compared the LAI distribution contained in the flux footprints to the MODIS-derived LAI for the tower location. Figure 2a shows a map of five classes of LAI (derived from IKONOS satellite data at a spatial resolution of 4 m) around the MMSF tower, and the grid outlines of a subset of 7×7 MODIS pixels (transformed to the UTM coordinate system). The tower is seen to be located at the edge of pixels 32 and 33. The LAI map is overlaid by a rectangular mask showing the footprint field-of-view for neutral stability and a wind direction of 240°. The transparency of the footprint mask is proportional to the potential of the surface beneath it to contribute to the tower flux. Here, the simple analytical footprint model of Schmid (1997) was used. For the proposed work, however, a more general footprint model suitable for forest canopies will be used (e.g., Rannik et al. 2000; Kljun et al. 2002, 2004; Villani et al., 2003). The pilot study of Schmid et al. (2003) showed that a resolution of 30 m, achieved by Landsat images, is sufficient to capture the essential scales of variability. Thus, in the proposed work we intend to use Landsat imagery for this purpose.

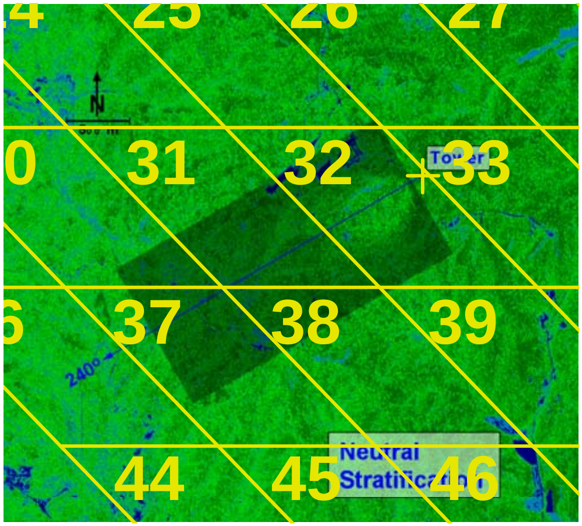


Figure 2a: Distribution of LAI and a footprint mask over the Indiana site, aligned with wind direction 240°. Greens = high LAI, blue tones = low LAI. The numbered grid marks the location of a subset of MODIS pixels.

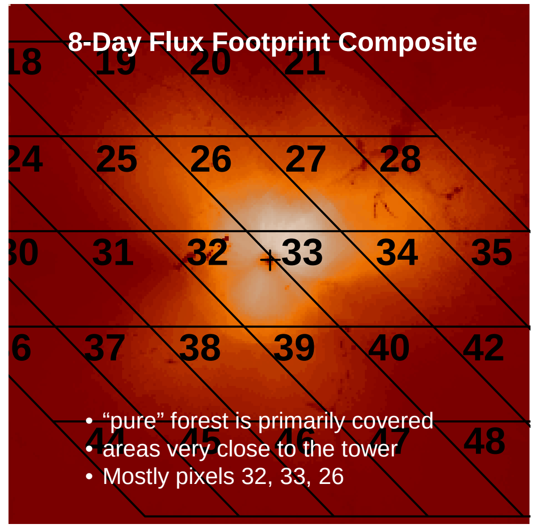


Figure 2b: Composite of hourly flux footprints from Aug. 5-13, 2001, overlaid over Landsat derived LAI, and the grid of a subset of MODIS pixels. The footprint composit represents areas mainly in pixels 32, 33, and 26.

In the present example (Figure 2a), the footprint is almost entirely contained within pixel 32, but with a wind direction shift to easterly, the footprint would swing around and come to lie primarily over pixel 33. Thus, the measured flux is not always representative of the same MODIS pixel area. The resulting failure to co-reference the tower flux and the MODIS product introduces a location bias in addition to measurement and modeling uncertainties. In areas with significant heterogeneity at the scale of the footprint or the MODIS pixel, this additional bias can be important, and would introduce bias in any tower-based upscaling. Application of the footprint overlay method allows quantification of this location bias (Schmid and Lloyd, 1999) and the formulation of an objective representativeness criterion: if the average vegetation index covered by the flux footprint matches the vegetation index used in the model (i.e., the value LAI of the MODIS pixel in the present example) to within a given tolerance, the measured flux may be used to evaluate or calibrate the model product. In effect, this method is equivalent to matching the scales of the observations to that of the model.

The standard MODIS GPP product is available as an average over an 8-day period. To compare the MODIS LAI to a footprint representative LAI, the composite of all hourly footprints over the 8-day period was constructed (Figure 2b). The example in Figure 2b shows that the relatively small footprints from unstable mid-day conditions dominate the composite, so that the 8-day composite eddy-flux is seen to over-sample the relatively homogeneous high-LAI forest area in the immediate vicinity of the tower (within 1 km).

The analysis of the footprint averaged LAI values over the growing season of 2001 confirms that the footprint LAI is higher than the value averaged over the entire MODIS pixel-32 (Figure 2c). The flux-weighted LAI takes into account that a mismatch is more important in periods when the flux is high, but is rather irrelevant when fluxes are small. It is computed by weighting every hourly footprint averaged LAI with the measured flux. Overall, the mismatch amounts to 9.8% (0.54 LAI units), but in mid-summer, when fluxes are strongest, it can go up to almost 20% for a given 8-day period at this site.

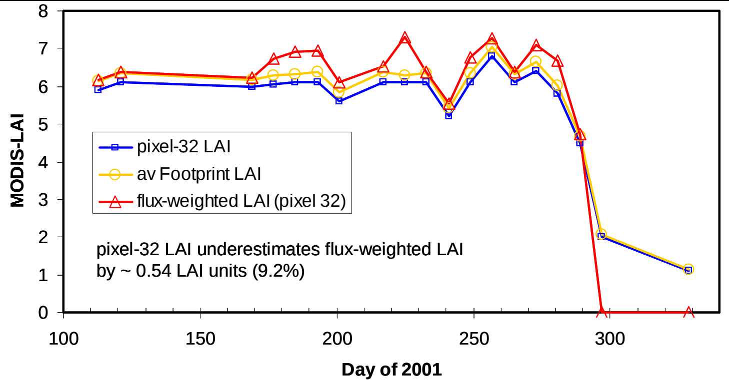


Figure 2c: Comparison of MODIS pixel-32 LAI to 8-day averaged footprint LAI, and flux-weighted footprint LAI. The mismatch caused by non-congruence between the composite footprint and pixel-32 amounts to just under 10% in the average over the growing season.

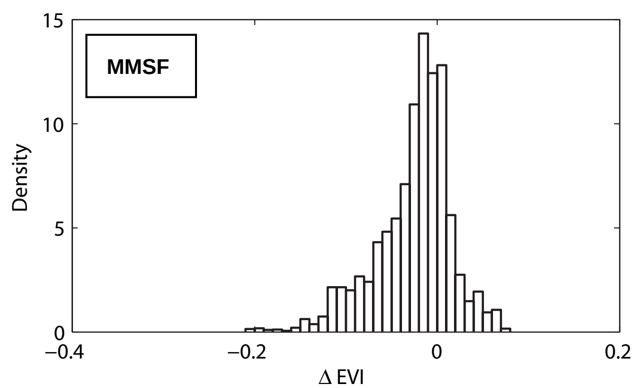
It should be noted that the MMSF site represents one expected end-member – a very homogeneous site at the relevant scales, and therefore the mismatch due to a location bias is not expected to be significant here. Thus, we anticipate that tower fluxes and model results should generally agree well at MMSF, if both the observations and the model results are independently valid. However, this is not likely the case for many AmeriFlux sites in the study area that are located in smaller ecosystems, close to an edge, or are confronted with severe landscape fragmentation.

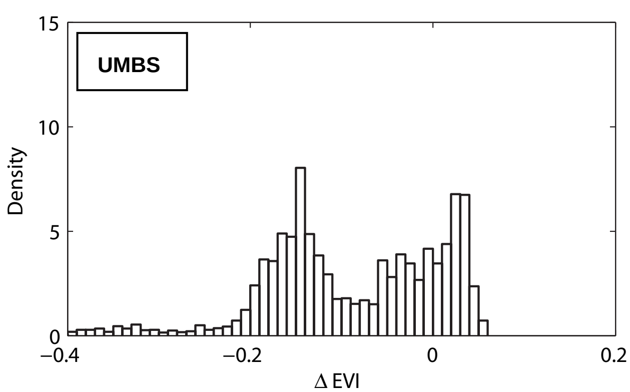
3.1.1 Results: Spatial representativeness of sites

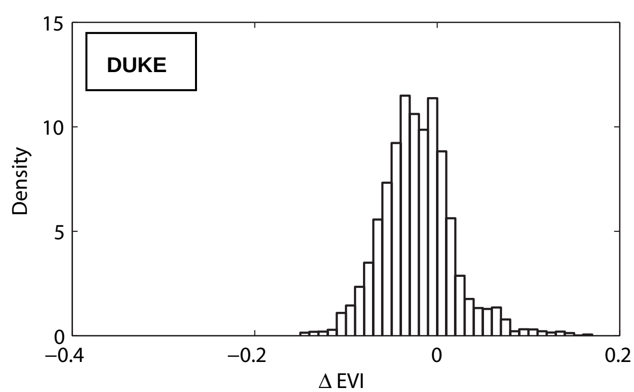
As further illustration of this point, Figure 3 shows three sites in the proposed study area and the distributions in the difference between the hourly flux footprint enhanced vegetation index (EVI – used as it does not saturate at higher LAI values in satellite imagery) and the EVI for a 1km^2 area around the tower (to simulate a MODIS pixel) during the daytime, growing-season carbon fluxes.

As can be seen, the ΔEVI distribution for a very homogenous site like MMSF is relatively narrow and peaked. For a site like the Duke Hardwood tower that lies in a vegetated, but very diverse, landscape with the tower footprint encompassing not only temperate forest but also coniferous

Figure 3: Distributions of ΔEVI for homogenous (MMSF – *right*), mixed, but vegetated (Duke – *bottom right*) and vegetated:non-vegetated (UMBS – *bottom left*) landscapes. The distribution for MMSF is narrow, though slightly skewed, indicating that the hourly fluxes are generally representative. In a more heterogeneous landscape like the Duke tower site, the distribution is much wider indicating that all hourly NEE measures may not necessarily represent the targeted ecosystem (hardwood forest). The UMBS figure clearly shows the impact of the lake near the tower producing a bi-modal distribution.



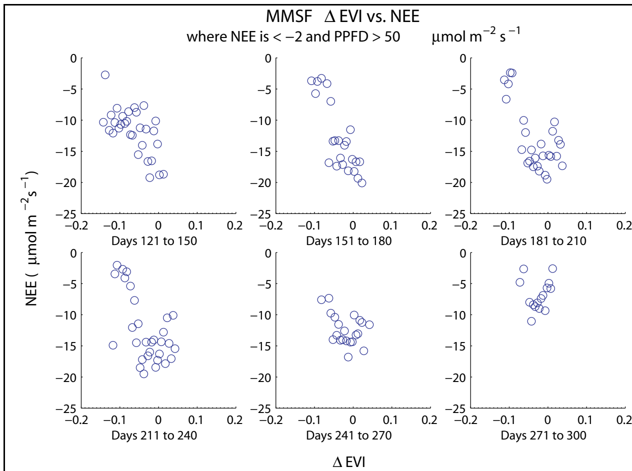


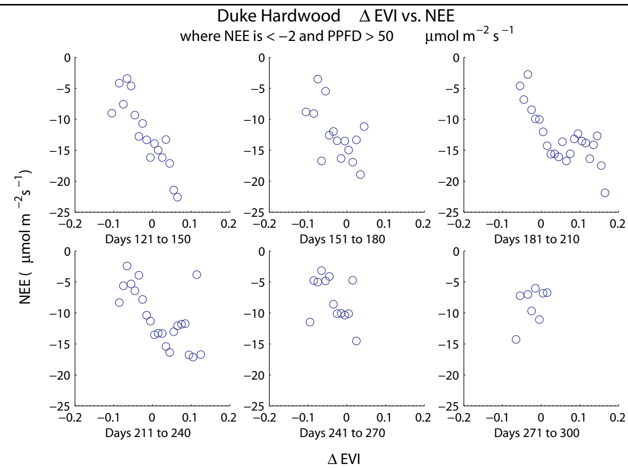


forest and a reforesting abandoned agricultural field the distribution is noticably wider. At the UMBS tower site the distribution is very bi-model due to the large lake near the tower that is, at times, influencing the foot EVI depending on wind direction. Clearly, carefully choosing reference fluxes is very important for any modeling effort. Small deviations in ΔEVI are linked to shifts in hourly NEE as shown in Figure 4. Negative ΔEVI values represent areas where there is less leaf area than seen in the general area, associated with this should be lower carbon uptake during the growing season and vice versa. In heterogeneous areas, like the Duke site, the trend is clear during the growing season even at the seasonal margins. For MMSF, the pattern exists but is less clear due to the narrower distribution. Also, in the seasonal margins, the pattern is less coherent indicating that NEE is being influenced by other local scale factors other than leaf area. At UMBS the pattern is not clear during the growing season or seasonal margins showing the effect if the bi-modal nature of the landscape.

In these cases the methodology outlined above will effectively identify conditions when the flux data is representative of the ecosystem type used by a model. In contrast, data that fail the representativeness criterion will not be used in the model evaluation and calibration that lies at the heart of the proposed upscaling strategy.

This footprint based analysis of spatial representativeness will be performed primarily at Indiana University for all the sites in Table 1, in collaboration with Prof. Rahman (including the MCI sites that will become available). The large amount of image data and their convolutions with computed footprint distributions will be handled by Indiana University's massive data storage





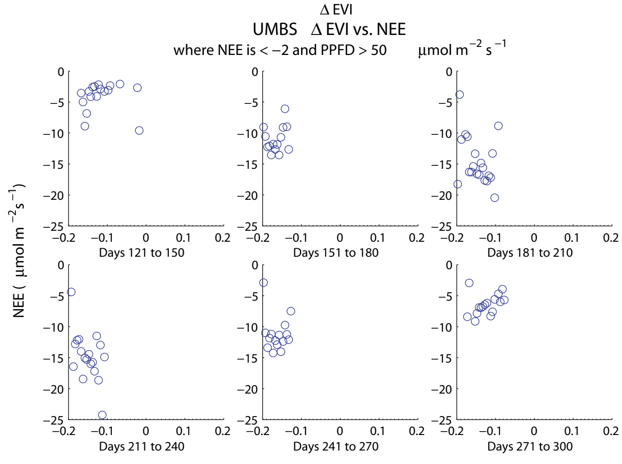


Figure 4: Comparison of ΔEVI values with respect to hourly NEE in 30-day binned blocks encompassing the growing season and seasonal margins for three proposed sites. Negative ΔEVI values represent lower than average leaf areas and vice versa and NEE should vary inversely to this. At the Duke site, this trend is clear during the growing even at the seasonal margins. For MMSF, the pattern exists but is less clear due to the narrower distribution. At the seasonal margins, the pattern is less clear indicating that NEE being influenced by other local scale factors. At UMBS the pattern is not clear during the growing season or seasonal margins showing the effect if the bi-modal nature of the landscape.

system (MDSS) and by the Research SP high performance computing cluster. We will make the methodology and numerical routines emerging from this work available on a dedicated project website in Matlab and Fortran along with documentation and examples.

Surface information with spatial coverage of several km^2 around each flux tower site (i.e., the expected footprint range) will be derived from high resolution remote sensing data, based on Landsat multispectral scenes, with resolution of 30 m. Land cover information and vegetation indices derived from these satellite data will be used for the footprint modeling based assessment of spatial representativeness at each site (Section 3.2). Because *in-situ* data of soil parameters and carbon stocks outside of the flux tower sites are relatively sparse (e.g. FIA plots, maintained by the USDA-Forest Service), we will rely primarily on satellite remote sensing products and on digital maps for coverage of surface information over the entire study region. Our objective is to match or exceed the resolution of the meteorological re-analysis data. Soil information can be obtained from the Soil Survey Geographic Data Base (SSURGO, USDA, 2002a) or STATSGO, for counties where the soil survey has not been completed and digitized, available through the USDA Natural Resources Conservation Service (USDA, 2002b). Davidson and Lefebvre (1993) stress the importance of high-resolution soil data. They find that aggregation errors of estimating soil carbon stocks based on coarse resolution maps can be significant in areas of large spatial variability. Topographic data will be obtained from digital elevation models at various resolutions (e.g., at 1 km resolution from the National Geophysical Data Center, NOAA, 2002). Also, in situ soil parameters are needed to estimate the drainage flux in the hydrologic model. Satellite-derived land surface products, such as LAI or FPAR from the MODIS instrument, will be obtained with the assistance of CDIAC (see Supplementary Documentation). Cihlar (2000) argues that satellite-based land cover classification mapping has made significant progress over the last 5-10 years and is now available in routinely updated datasets at high resolution. As an example, Hansen et al. (2000) presented a global land cover classification data set at 1 km resolution that is available through the University of Maryland. In addition, we will use the Spring Indices phenology model of the University of Wisconsin-Milwaukee (Schwartz and Reiter, 2000; Schwartz and Reed, 1999), to determine the onset of the vegetative season across our study domain.

3.2 Ecosystem Modeling

In coupling the canopy morphology to the spatially representative tower-based EC fluxes above the canopy for the sites in Table 1, we will explore three approaches of varying hierarchical complexity:

1) Semi empirical light-and-temperature response curves relating day- and- nighttime NEE to photosynthetically active radiation (PAR) and temperature (often used in gap-filling).
2) Revise the first methodology by estimating photosynthesis from a bulk canopy conductance (G_c) formulation derived from water vapor fluxes as a function of PAR, vapor pressure deficit (VPD), and soil moisture (θ) using a Jarvis-type formulation. This formulation will then be combined with an effective intercellular to ambient CO_2 concentration C_i/C_a estimates obtained by optimizing C_i/C_a to match, in a least-squares sense, photosynthesis derived from the eddy-covariance data. We note that the temporal variability in C_i/C_a is relatively small when compared to that of G_c; hence, in a first order analysis, it can be replaced by an effective long-term value (Katul et al., 2000). The advantage of the second methodology over the first is in its use of another scalar, water vapor to constrain canopy photosynthesis. Also, the

optimized C_i/C_a can be independently compared with porometry and stable isotope measurements where available. This approach is the basis for the 4C-A model described in Schäfer et al. (2003).

3) Revise the second formulation to estimate photosynthesis using a multilayer canopy model in which the vertical variability in leaf area density and all the radiative, physiological, and turbulent transport processes are explicitly resolved. In terms of “input parameter” space, this approach is “high-dimensional” and the model complexity is substantially increased.

3.2.1 Results: Simplified Models for Up-scaling Measured Fluxes:

In any EC flux up-scaling exercise, ecosystem models must be implemented. All ecosystem process-based models for NEE and ET, regardless of their complexity, require species and/or site-specific parameterization. A key challenge with the scaling-up approach is the *a priori* specification of these parameters when only a limited number of non site-specific ecosystem attributes are available at course scales (i.e. 1 km). Using in-situ eddy-covariance observations of carbon and water fluxes from the long-term Ameriflux sites in the super region, we explored inter-specific functional convergences between key physiological parameters and readily obtainable climatic, edaphic, and land cover data. Specifically, flux-measurement records from roughly half of the Ameriflux sites, combined with a synthesis of previously reported parameter values from the literature, were used to examine relationships between: 1) evaporation to precipitation data and physical soil properties, 2) canopy transpiration rates to canopy architecture, and 3) ecosystem assimilation and respiration parameters to climatic and hydraulic (e.g. plant height and leaf area) features. *Measurement records from the remaining sites and data to be gathered as part of the MCI region will be used in the analysis to test the utility of these relationships.*

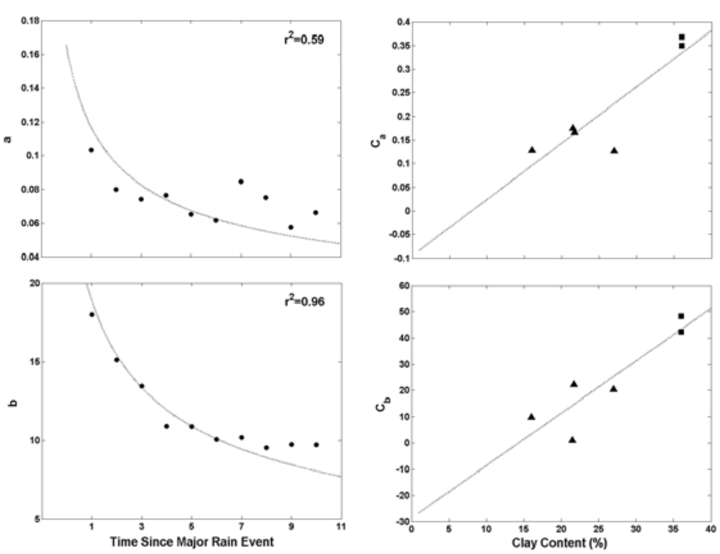
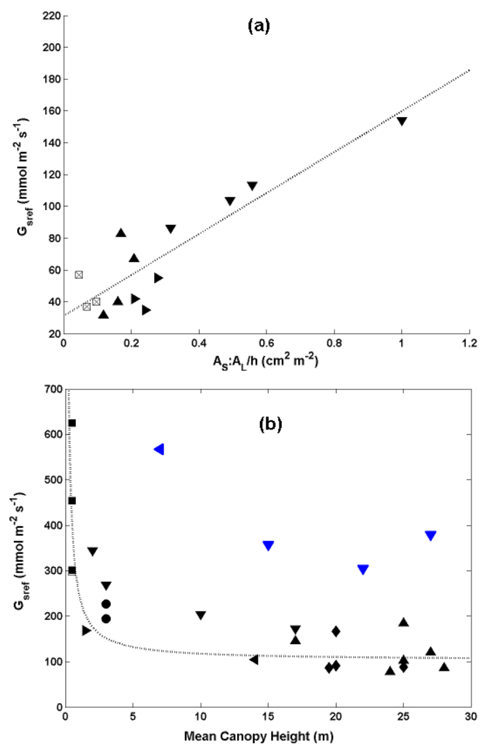


Figure 5: The slope (a) and intercept (b) of the linear relationship between evaporation and net radiation decline with time since a measurable rain event, as shown here for the Duke Hardwood site. This decay can be well represented by an equation of one parameter (C_a and C_b, respectively), which itself is correlated with the clay content of the soil (r^2=0.79 for C_a and 0.81 for C_b).

The principle components of ET -- evaporation and transpiration -- are controlled by different physical and biological drivers and process-based models for both fluxes are necessary to: 1) partition eddy-covariance derived ET fluxes for use in model parameterization exercises, and 2) implement the flux-weighted up-scaling scheme across a diverse landscape with spatially variable ratios of evaporative and transpiration fluxes. To develop a generic model for ecosystem evaporation, we applied a simple linear relationship between evaporation and incident net radiation ($E = a \cdot R_n + b$) to measured

ET fluxes during periods when LAI is close to zero and snow cover is negligible. This condition, which implies that measured ET is dominated by evaporation, was met for at least one month each year for six sites used for ‘model training’ in the super region. We found that both the slope and intercept of this simple relationship decayed with the square root of time (in days) since a measurable rain event (t_p). This decay can be approximated by the functions $a = C_a / \sqrt{t_p}$, $b = C_b / \sqrt{t_p}$ (Figure 5a,b), and furthermore, the constants in these decay functions are well correlated with the fractional clay content of the soil, which is a proxy for soil field capacity, as determined by STATSGO (Figure 5c,d). While a number of soil data records are available, The STATSGO database covers the entire super-region and is adopted here. Evaporative fluxes calculated with this simple model agreed well will the measured fluxes across the six ‘training’ sites (r^2=0.86). This model was used to estimate evaporation, and hence transpiration, from measured ET can be determined across all sites by attenuating incident radiation after Beer’s Law (after Stoy et. al. 2006). This is a preliminary generic approach that can be extended to estimate evaporation across the study domain. The choice of $t_p^{-1/2}$ here is not arbitrary or statistical, but follows from standard porous media theory for soil-regulated evaporative losses (Jury et al., 1991; Parlange et al., 1992). The response of transpiration to environmental variables is often described with a Jarvis-type multiplicative function (Jarvis 1976) that relates mean canopy stomatal conductance per unit leaf area to a reference rate (G_{sref}) that is adjusted at a high temporal resolution to reflect variable light, humidity, soil water, and leaf area conditions. Given the recent focus on hydraulic limitations to canopy conductance (Ryan et al. 2006, Hickler et al. 2006), and recent developments in the remote sensing of canopy architecture (Lefsky et al. 2005), we focused on incorporating features of canopy architecture into a generic model for G_{sref} . In particular, canopy height is becoming an available product at coarse scales from Shuttle Radar Topography mission (SRTM) elevation data (Kellndorfer et. al. 2004).

Figure 6: (a) Reference conductance is related to the product of the ratio of sapwood to leaf area and the inverse of canopy height, and (b) canopy height. Blue symbols represent open canopy forests.



Using a synthesis of previously published data, we found a strong relationship between G_{sref} and the ratio of sapwood to leaf area (A_s:A_L, Figure 6A) for closed canopy ecosystems. Further, using the eddy-covariance derived estimates of transpiration, we found a significant relationship between G_{sref} and canopy height across closed canopy ecosystems (Figure 6B), suggesting that canopy height alone may significantly improve estimates of canopy conductance, and hence transpiration, across many of the temperate ecosystems that comprise our study domain.

Additionally, we found a strong correlation between the ratio of intercellular-to-ambient carbon dioxide concentration (c_i/c_a) and the mean annual vapor pressure deficit across the Ameriflux sites used in this training exercise (Figure 7). This ratio, often assumed constant in simplified models (Katul et al. 2000), can now be combined with modeled conductance to generate assimilation fluxes. We are also exploring theoretical arguments based on ecosystem water use efficiency optimization theories as to why the data set in Figure 7 collapses to a singular relationship despite the large differences in vegetation type and climatic conditions. Such a strong relationship can constrain long-term estimates of photosynthesis if canopy conductance is well modeled from light, vapor pressure deficit, surrogates for soil water stress, and plant hydraulics.

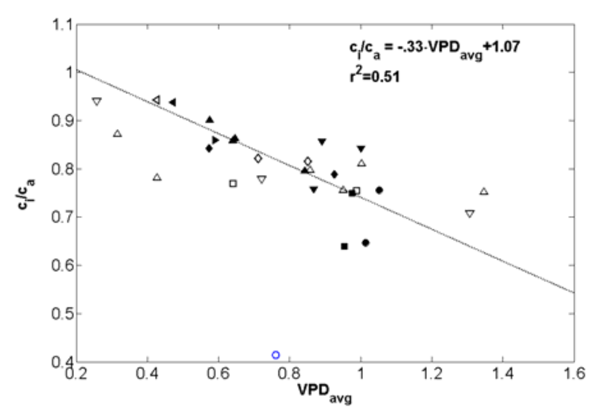


Figure 7: Canopy c_i/c_a is related to the long term average VPD. The blue data point represents a maize crop site that would be expected to have a low c_i/c_a.

3.2.2 Preliminary Results: Complex Models Guiding the Development of Simplified Models

Quantifying the exchange rate of CO2, H2O, and air temperature between leaves and their local environment (hereafter referred to as microenvironment) is frustrated by a 2-way interaction in which the microenvironment exerts controls over scalar exchange at the leaf surface, and leaves have some capacity to regulate their own microenvironment through stomatal opening and closure. This 2-way interaction is further complicated by the vertical distribution of foliage within the canopy leading to significant vertical gradients in the radiation environment and airflow regimes. The intrinsic non-linearity in leaf physiological responses (e.g. leaf-level photosynthesis and transpiration) to radiation further exasperates this problem. **To date, most eco-physiological approaches to up-scaling carbon and water fluxes focused on radiative transfer and the non-linearity in the physiological response to incident radiation at the leaf surface** (Aber et al., 1996; De Pury and Farquhar, 1997; Kirschbaum et al., 1998; Leuning et al., 1995; Luo et al., 2001; Naumburg et al., 2001; Wang and Leuning, 1998; Williams et al., 1998; Williams et al., 1996). These models assume that within the canopy volume, scalar concentration (primarily CO2, H2O, and temperature) is constant and identical to its state above the canopy (hereafter, referred to as the well-mixed assumption, WMA). This is not surprising because at annual or inter-annual time scales, any attempt to resolve such 2-way interaction adds significant computational burden and model complexity with perhaps 'modest gains' in predictive skills, though the degree of improvement remains largely unexplored. Furthermore, uncertainties in describing the non-stationarity and vertical inhomogeneity in physiological parameters (e.g., in photosynthesis calculations) may overshadow any improvements gained by resolving this 2-way interaction. While the well-mixed assumption may be defensible for some canopy types, it is too simplistic for forested ecosystems, where experimental evidence suggest that vertical variations in excess of 50 ppm for CO2 concentration and 3 degrees or more for air temperature occur inside the canopy volume during day time conditions (Lai et al., 2002a; Siqueira and Katul, 2002). Because the vertical variations in mean scalar concentration profiles are not random within the canopy, the well-mixed assumption may inject systematic biases in modeling scalar sources, sinks, and fluxes. Hence, the developments in simple ecosystem carbon-water source-sink models will benefit from answering two inter-related questions: 1) *If the well-mixed assumption is to be 'relaxed', then how detailed must the turbulent transport model be to resolve this 2-way interaction*? 2) *Is the predictive skill gained by resolving this 2-way interaction much smaller than biases incurred by not correcting for non-stationarity in physiological parameters such as the ones most pertinent to leaf photosynthesis*? Several multi-layer one-dimensional models have been developed to resolve the two-way interaction between leaf and microclimate using turbulent transport theories in conjunction with detailed physiological and radiative transfer principles (Baldocchi, 1992; Baldocchi et al., 1997; Baldocchi and Meyers, 1998; Leuning et al., 1995; Meyers and Paw U, 1987; Raupach and Finnigan, 1988; Raupach, 1989; Simon et al., 2005a; Simon et al., 2005b). The term 'CANVEG' (for 'canopy vegetation') was coined for such multi-layer models (Baldocchi, 1992; Baldocchi et al., 1997; Baldocchi and Meyers, 1998). As part of this project, we developed a multilayer biosphere-atmosphere model that retains the detailed eco-physiological parameterization and radiative transfer principles in CANVEG, but the complexity in the turbulent transport scheme needed to capture this two-way interaction between the canopy and its microclimate is varied in a hierarchical manner. Different closure approximations ranging from first- to third-order schemes are employed to parameterize higher order turbulent moments in the governing conservation equations for both momentum and scalar transfer. As a reference, we contrast these model calculations with scalar sources and flux calculations made by assuming a well-mixed state for the mean scalar fields (Figure 8). Using the record from the Duke Forest Ameriflux pine site, we found that (Figures 8 and 9): (a) sensible heat flux predictions were most biased with respect to eddy-covariance measurements when using the WMA, (b) first-order closure schemes are sufficient for reproducing the seasonal to inter-annual variations in scalar fluxes provided the canonical length scale of turbulence is properly specified, (c) second-order closure models best agree with measured mean scalar concentration (and temperature) profiles inside the canopy as well as scalar fluxes above the canopy, (d) there were no clear gains in predictive skills for all scalar quantities when using third-order closure schemes over their second-order closure counterpart, and (e) at inter-annual time scales, we showed that biases in modeled scalar fluxes incurred by using the WMA exceed those incurred when correcting for the seasonal amplitude in the maximum carboxylation capacity provided its mean value is properly specified. Using this modified CANVEG approach, we are currently exploring adjustments to the simplified models presented earlier. These adjustments are derived using the vertical distribution of leaf area as well as LAI.

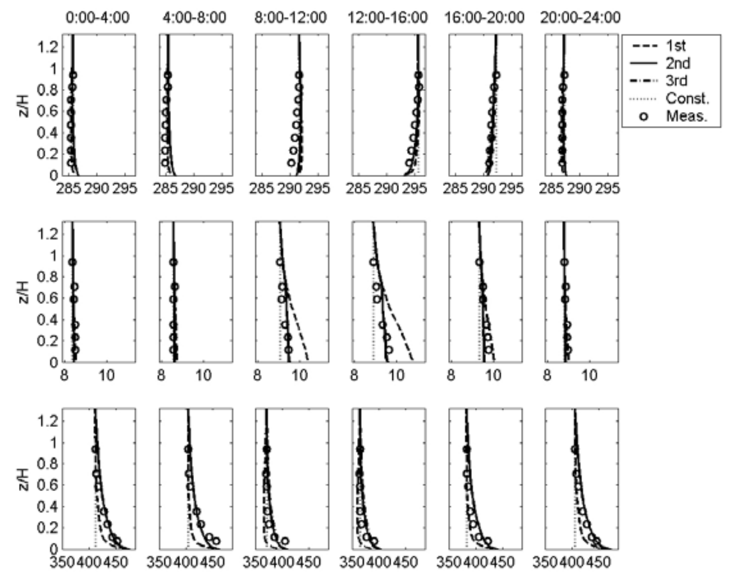


Figure 8: Ensemble-averaged profiles of mean air temperature (K, upper panel), mean water vapor concentration (g kg^{-1}, middle panel), and mean CO_2 concentration (ppm, lower panel) for different closure approximations over different times of day in 2005. All model results were derived using atmospheric stability corrections. Note that the model results for the second- and third-order closure are almost indistinguishable. Well-mixed conditions are shown as vertical dotted lines for reference.

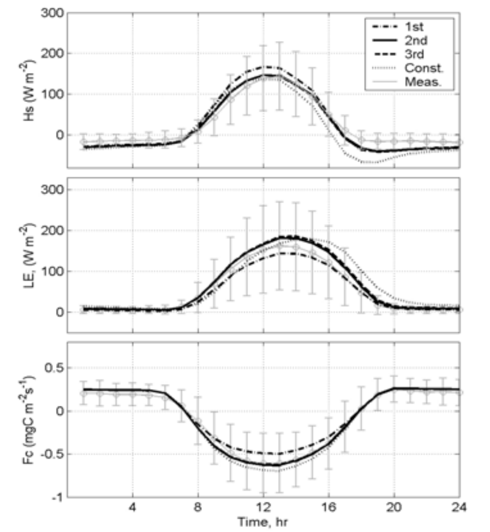


Figure 9: Comparisons between hourly ensemble-averaged measured (open circles) and modeled (lines) sensible heat flux (H_S), latent heat flux (LE) and carbon dioxide flux (F_C) at the top of the canopy in 2005. The model results were derived using different closure approximations (first-order to third-order) as well as the well-mixed assumption for scalars. Ensemble averaging was conduced across each hour of day in 2005. Vertical bars represent one standard deviation around the ensemble-averaged EC measurements.

3.3 Boundary Layer and Hydrologic Modeling

To link the large-scale meteorological fields from NCEP (32 km horizontal resolution – see below) to ecophysiological models within a MODIS pixel, we will use a simplified mixed-layer slab (MLS) model for the atmospheric boundary layer (ABL) depth. Our aim here is not to reproduce the precise evolution of ABL height dynamics, potential temperature, water vapor or CO_2 concentrations; rather, we seek a methodology that takes large-scale air temperature and water vapor concentration from NCEP data (described later) and "spatially downscales" them to an EOS-MODIS pixel in a manner consistent with the ecophysiology model and surface attributes. That is, within a heterogeneous landscape mosaic composed of several MODIS pixels, we do not expect the vapor pressure deficit (VPD) just above a bare soil MODIS pixel to be identical to a neighboring pixel primarily populated by a transpiring forest even though the NCEP analysis provides one VPD and one air temperature for these two MODIS pixels. Hence, linking the MLS model to any of the ecophysiological models (described earlier) permits us to iteratively solve for VPD, latent and sensible heat fluxes, and NEE from the re-analysis data in a manner consistent with the predominant land cover within each MODIS pixel.

The MLS model developed in our current project (a) ignores heat source/sink terms within the atmospheric boundary layer (ABL) except at the surface and at the top of the ABL, and (b) adopts a standard encroachment assumption at the top of the ABL. The MLS is based on an integrated one-dimensional continuity equation for heat used to predict the growth of the convective ABL if sensible heat flux is known (as will be accomplished by the simplified models). A major limitation to this approach is the lack of available data on ABL height to independently test these MLS model calculations. The simplified MLS model developed here predicts both (i) the growth of the ABL during daytime conditions, and (ii) the lifting condensation level (LCL). We showed that one indirect method to assess the predictive skills of ABL height dynamics from surface sensible heat flux is to estimate the timing at which the modeled LCL intersects the modeled ABL (Figure 10). This timing can be interpreted as the trigger of convective rainfall. If conditions are favorable to rainfall formation, and rainfall was locally recorded (say by a tipping bucket gage), one can explore whether this timing of recorded rainfall is consistent with the modeled timing when the convective rainfall was triggered. We tested this scheme using the 3 towers at the Duke Forest Ameriflux sites (representing the land cover of 10 km x 10 km area) with good agreement between predictions and timing measurements (Figure 11).

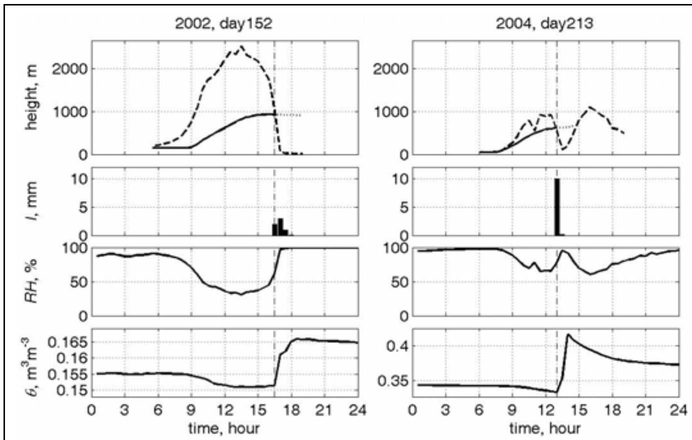


Figure 10: The modeled ABL height (z_i) (solid line) and LCL (dashed line), and the corresponding *measured* rainfall, relative humidity RH and soil moisture (θ) on day 152 of 2002 (left) and on day 231 of 2000 (right) at the Duke forest Ameriflux region (10 km x 10 km).

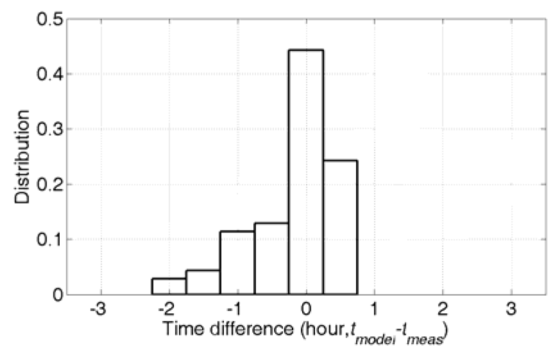


Figure 11: The probability density function of the onset time difference between modeled ($z_i = H_{LCL}$) and measured convective precipitation when precipitation is actually recorded by the tipping bucket gage (30 minute intervals).

To generate soil moisture content at the MODIS scale, which is needed for canopy conductance and respiration calculations, we use the hydrologic model of Rodriguez-Iturbe et al. (1999) and Porporato et al. (2002) on a daily time step. The model formulation can be shown to reduce to a non-linear ordinary differential equation whose state is stored water in the root zone, the non-homogeneous term is precipitation reduced by interception losses (that vary with LAI), drainage losses that vary as a power-law with stored water and soil texture, and transpiration losses also affected by stored water through the bulk canopy conductance. This model, described in Kumagai et al. (2004) has been tested for the 8-year soil moisture record at the Duke Forest Ameriflux site on ½ hourly time scale (see Figure 12). Gabriel Katul, Hans Peter Schmid, Ram Oren, and a post-doctoral fellow at Duke University will conduct this work.

We emphasize that all three model components (boundary layer, hydrological, and ecophysiological) can reproduce the variability in the three land-surface fluxes at “sub-seasonal” time scales. Much of the anticipated variability in these land surface fluxes is likely to occur at seasonal and longer time scales.

Large-Scale Meteorological Re-analysis Fields

We will use the North American Regional Reanalysis (NARR) data archive (last updated February, 2004), which is a reprocessing of the historical meteorological observations using NCEP's regional forecast model (ETA) and associated data assimilation system (EDAS). The products of NARR are new sets of meteorological analyses covering the North American domain with a 32 km horizontal resolution, 3 hour temporal resolution, and 50 hPa vertical resolution for October 1978 and onwards. We will use the NARR precipitation, incident shortwave radiation, surface wind speed, mean air temperature, and mean relative humidity, along with estimates of tropospheric CO_2 derived over the upper Midwest and Northeastern United States for 2000-2003. This period includes a severe drought, several ice storms, and a "normal precipitation" year. The 19 Ameriflux tower sites listed in Table 1 reasonably sample (>60%) this period. The assembly of the NAAR record for the spatial region of interest will be carried out by Gabriel Katul, Hans Peter Schmid, a post-doctoral fellow at Duke University, in collaboration with Tom Boden at CDIAC.

3.4 Satellite Data and Surface/Land Cover Data Base

The basis for spatial aggregation and scaling-up of biosphere-atmosphere exchange to the super-region is a comprehensive surface and land-cover database. This database will supply topographic, surface cover, vegetation, and soil parameters needed to run our ecosystem, flux footprint, and boundary layer models, and to assimilate the meteorological re-analysis fields. Due to the nested approach of our scaling strategy, the spatial resolution and temporal reference of various segments of the surface database also will have a nested structure. The highest spatial resolution is required around each site, within the range of the expected flux footprint. It is standard practice at all AmeriFlux sites to measure soil properties, above-ground biomass, leaf nitrogen, LAI, and other stand level parameters at periodic intervals in the vicinity of the flux towers. These data will be the most important surface drivers to run the models off-line (i.e., in stand-alone mode) for each site (see Figure 1).

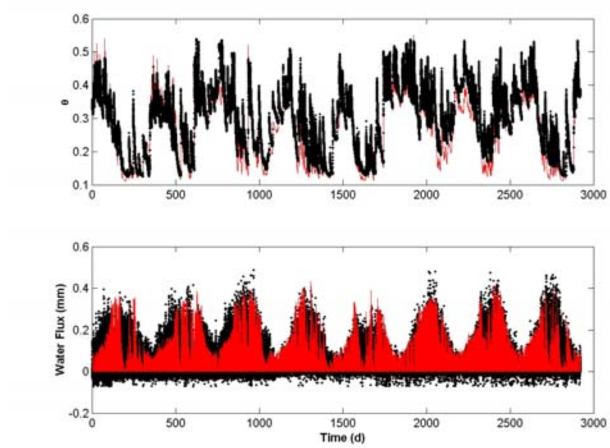


Figure 12: Comparison between measured (black) and modeled (red) soil moisture (top). The modeled transpiraration (T) and EC based measured ET is also shown (bottom).

4 Broader Impacts

Relevance to government and private sector concerns. The need for verifiable estimates of carbon storage across major land surfaces will increase as national and international efforts to reduce greenhouse gas accumulation gain momentum. Indeed, a centerpiece of the climate change mitigation strategy developed by the Intergovernmental Panel on Climate Change is the Clean Development Mechanism (CDM), which provides an avenue for meeting emissions reductions targets through enhanced carbon storage by terrestrial ecosystems (IPCC 2001). The CDM has received broad support from industry and the emerging carbon credits market could result in an entirely new area of commodities trading. Our research will establish a new framework for quantifying carbon sequestration at local, regional, and super-regional scales. Ours is not the only way to achieve this end, but it is of great importance that multiple, independent approaches be pursued for the requisite confidence to be developed in the policy and investment communities for the CDM to succeed. The temporal and spatial resolution of our results match the needs of both public and private sectors very well, and we expect that they will prove very useful to all parties involved in climate change mitigation efforts.

Education and scientific outreach. The interdisciplinary science of biosphere-atmosphere interactions has arisen within the last decade, fueled by the scale and complexity of the scientific problems at hand, and the emergence of a suite of new technologies that have allowed linkages among previously separate disciplines. Our research will have direct impact on training the next generation of scientists to work at the interface of the biological and atmospheric sciences. This will come about primarily through direct training of graduate, undergraduate, and postdoctoral students at our home institutions. A primary expense of this grant is the cost of supporting students and other trainees. We will provide a total of 81 person-months of training for students in biosphere-atmosphere interactions. Finally, for reaching out to the broader scientific community, we will make available all the routines and functions used in this scaling exercise (in Fortran and Matlab) on a dedicated website at Indiana University, which will include the source code, documentation, and examples from this project.

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