The Effects of Remotely Sensed Data on Modeled Land-Surface-Atmosphere Interactions: Consequences for Global Carbon Balance Research

L. Prihodko

INTRODUCTION

Anthropogenic emissions of CO_2 into the atmosphere are a primary concern in global change research. Current studies suggest that increasing levels of CO_2 in the atmosphere will lead to a warming of the atmosphere in the next century. Even a slight increase in global temperature could have a significant effect on Earth systems (IPCC, 1990). However, there is a disparity between current estimates of anthropogenic emissions and measurements of accumulated CO_2 in the atmosphere, indicating a terrestrial and/or oceanic sink (IPCC, 1990; Schimel, 1995). An understanding of this discrepancy is critical to our ability to monitor and manage CO_2 concentrations in the future. Improving our understanding of the feedbacks between land surface CO_2 exchange with the atmosphere through the coupling of land surface and atmospheric models will help us to understand the significance of land surface-atmosphere interactions in both regional and global carbon balance. If we can clarify the processes by which CO_2 is being sequestered in terrestrial ecosystems today we will be better able to predict how such sinks might operate in the future.

Most modeling efforts of land-atmosphere interactions at regional and global scales rely to some extent on remotely sensed inputs, either to represent surface processes or to provide state variables. This is especially true of SiB2 (see Sellers, et al., 1996a,b). The advantage of using remote sensing in environmental modeling is its ability to provide parameter fields not easily measured, either temporally or spatially, at the ground surface. However, as spatial scales increase from local to regional to global, the modeled interactions between the land surface and the atmosphere may vary because of changing landscape heterogeneity and contrasting surface properties. It is therefore important to understand more fully the contribution of remotely sensed data to modeled results if we are to have confidence in them and use them appropriately. Currently, the relationships between ground measurements and remotely sensed data, and the sensitivity of land surface and atmospheric models to remotely sensed inputs, are not well resolved. The work in this proposal addresses these issues.

BACKGROUND

Given that a significant portion of the earth's surface, roughly one quarter (~1.3 x 10^{14} m^2), is vegetated (Harte 1988), interactions between vegetation and the atmosphere, such as energy and moisture exchange, are likely to have a notable effect on climate and weather patterns. This has been recognized and studied for some time now (since at least (Charney 1975)) with respect to global climate and weather patterns, but vegetation-atmosphere interactions at regional to local scales have, until recently, been less well understood (Pielke et al., 1998; Pitman et al., 1999). The land surface and the atmosphere interact primarily through exchanges of heat, moisture and momentum. Characteristics of the land surface that affect these exchanges include topography, fractional vegetation cover, albedo, land cover heterogeneity, surface roughness and water status, among others. The partitioning of incoming energy and it's spatial variability have important implications for the interaction between the land surface and the atmosphere, for example how much moisture is available for precipitation, how much energy is available for boundary layer growth and how atmospheric circulations will develop.

The role of vegetation is in this process is complex. The fractional vegetation cover of the surface affects the surface energy budget through changes in albedo, surface roughness, surface temperature and the partitioning of energy between the soil and the vegetation. As vegetation cover and leaf area increase, there is more surface area for evapotranspiration as well as a decrease in albedo. Lower surface albedos lead to more absorption of radiation, higher surface temperatures and increased latent heat flux (Stohlgren et al. 1998). The phenology of vegetation is also important, when leaves are not present, the surface roughness is altered and there is more sensible heat flux, which can lead to a deeper boundary layer (Cotton and Pielke Sr. 1995; Pielke, et al. 1998).

The exchange of moisture between vegetation and the atmosphere is driven by two processes, direct evaporation from soil and wet surfaces and transpiration. Transpiration is the evaporation of water into the atmosphere that has flowed through the plant. In moist conditions, more available energy is partitioned into latent heat flux. When water is limited, however, stomata shut down to reduce water loss from the plant and more energy is partitioned into sensible heat. Evapotranspiration from the land surface accounts for approximately 14% of the atmospheric water content and is significant because it can account for up to 75% of the precipitation that falls over the land surface (Gash and Shuttleworth 1991; Hayden 1998; Bunyard 1999). The amount of water vapor in the air near the land surface is also important as a modifier of minimum and maximum surface temperatures (Hayden 1998).

The spatial composition of the landscape also affects vegetation-atmosphere interactions at the regional scale. Gradients in temperature and pressure between adjacent patches of the land surface have been shown to initiate mesoscale circulations in regional atmospheric models (Mahfouf, et al. 1987; Segal, Avissar et al. 1988; Avissar and Pielke 1989; Hong, et al. 1995). Significant variability in surface albedo (Pielke, et al. 1993), conductance of the vegetation (Avissar and Pielke, 1991), soil moisture (Segal et al., 1980) and land use (Chase et al., 1999; Pielke et al., 1999) are all conditions that can initiate local and mesoscale flow.

The interactions between vegetation and the atmosphere are important to studies of regional and global carbon balance because they regulate the conditions for photosynthesis, respiration and transport. To adequately quantify fluxes of CO_2 on regional to global scales, spatially explicit coupled land surface-atmosphere models are used. SiB2 (Sellers, et al., 1996a,b) is an example of a land-surface model that was developed with the objective of coupling it to general circulation models (Randall et al., 1996). SiB2 is a single canopy-layer scheme that incorporates leaf-level physiology controlling photosynthesis (Farquhar et al., 1980; Collatz et al., 1991; Collatz et al., 1992) and the Ball-Berry (Ball et al., 1987) description of stomatal behavior and carbon assimilation. SiB2 exploits the near linear relationship between fapar and the simple ratio to scale leaf level processes to the canopy.

Land surface-atmosphere models for regional to global applications, such as SiB2, often rely on remotely sensed data to represent surface processes and/or to provide state variables. The advantage of using remote sensing in such modeling efforts is its ability to provide parameter fields not easily measured, either temporally or spatially, at the ground surface. This advantage, however, can also be seen as a disadvantage in that the spatial and temporal resolutions of the data are fixed (30m, 250m, 1Km, every 2 days, every 10 days, etc…) and may or may not be appropriate to represent the processes of interest accurately.

How models are formulated is important in determining whether the scale of representation is appropriate and what the effects of subgrid scale heterogeneity will be (Avissar, 1995; Wood, 1995; Friedl, 1996; Hu and Islam, 1997; Moran et al., 1997; Kustas and Jackson, 1999 – among others). Lumped models use grid level parameters as input and produce grid level results and rely as much as possible on scale-invariant relationships. To represent more heterogeneity, smaller grid scales must be used. Distributed models account for subgrid scale variability, usually through statistics or areal weighting. Since the effects of scale and subgrid scale heterogeneity are likely to be most important where small changes in parameterization lead to large changes in predictions, it is critical to understand where models are most sensitive. In highly parameterized models this can be difficult. Recent work has suggested that when large numbers of parameters are required in models such as SiB2, there may be compensation between parameters which results in physically reasonable simulations across a wide range of parameter values (equifinality) (Franks et al., 1997; Franks, 1998).

How the parameters are determined is also critical. When a landscape is relatively homogeneous, the subgrid scale effects appear to be fairly minor and whether you aggregate radiances, vegetation indices or parameters calculated from vegetation indices does not introduce too much error (Kustas and Jackson, 1999). When a landscape is heterogeneous, however, more error is introduced and how and when you aggregate becomes important. For instance, the normalized difference vegetation index is near linear with fpar, however it is not scale invariant with respect to radiance (Hall et al., 1992), so whether you choose to aggregate individual radiances, NDVI or fpar will affect the results. The aggregation method, whether it is averaging across space, choosing the most dominant value, weighting by areal coverage or statistically representing variability will also affect results (Wood and Lakshmi, 1993; Moran et al., 1997; Kustas and Jackson, 1999; Milne et al. 1999).

Representing the land surface and its processes appropriately also depends on how well conditions such as patchy rainfall, variable radiation, stable versus unstable atmospheric conditions and variable turbulent fluxes are incorporated (Avissar, 1995; Moran et al., 1997). The magnitude and spatial variability of surface fluxes varies directly with these conditions, even within a homogeneous vegetation cover.

Most research on scaling and aggregation has so far been concerned with how well surface fluxes of sensible and latent heat are modeled. Taking the next step and understanding how these interactions and competing effects influence regional and global carbon balance estimates will help to clarify sources of uncertainties in our predictions for the future.

PROBLEM STATEMENT

Research using the CSU-GCM suggests that a strong correlation exists between CO_2 flux from the terrestrial land surface and fluctuations in the depth of the planetary boundary layer (PBL) which results in higher annual mean concentrations of CO_2 in areas where the vegetation is strongly seasonal (Denning et al. 1995; Denning et al., 1996a,b). It has also been suggested that increasing levels of CO_2 in the atmosphere may affect the photosynthetic regime of vegetation (Bazzaz, 1990; Körner, 1993). As CO_2 increases, stomata of many plant species tend to close (Jones, 1992). This may lead to decreases in latent heat flux and therefore increasing water use efficiency. As latent heat flux decreases, sensible heat flux will increase to compensate. Thus the energy balance of the surface may change with increasing levels of CO_2 (Friend and Cox, 1995, Sellers et al. 1996) and these changes may produce a positive feedback to the PBL because of the dependence of PBL height on sensible heat flux. As spatial scales of inquiry change from local to regional to global, interactions between land surface CO_2 exchange and the PBL may vary because of changes in landscape heterogeneity, vegetation type and other surface properties (roughness, topography, etc.).

The proposed research examines the effects of remotely sensed data on the modeled results of land surface and atmospheric models. This will be done in two ways. First, the sensitivity of modeling results to parameterizations of input fields will be evaluated. Second, the sensitivity of modeling results to land surface heterogeneity and the ability of models to capture system dynamics at the reduced spatial and temporal resolutions of the remotely sensed inputs will be assessed. By choosing to address a particular aspect of land surface-atmosphere interaction, the exchange of CO_2 between the land surface and the PBL at different temporal and spatial scales, a focused effort can be made to understand the function of remotely sensed data in global carbon balance research.

METHODS

Site Description

Micrometeorological, eddy covariance and CO_2 concentration measurements have been made since 1995 on a tall tower (a 500 m TV relay tower) located in the Chequamegon National Forest, near Park Falls, Wisconsin (Figure 1). Fluxes of CO_2, water vapor and heat, and standard meteorological variables are measured at three levels (30, 122, 396 meters). CO_2 concentration is measured at six levels (11, 30, 76, 122, 244 and 396 meters). Studies are being undertaken at the tall tower and in the surrounding region to assess the exchange of CO_2 and energy between the forest and atmosphere and the processes contributing to these fluxes. Additional studies address questions of scale, measurement of regional surface processes by remote sensing and the role of atmospheric boundary layer dynamics in regulating the carbon dioxide concentration near the ground. Collectively, these studies form the Chequamegon Ecosystem/Atmosphere Study (CHEAS) (for details see http://www.cheas.umn.edu/).

The Chequamegon National Forest covers an area of approximately 325,000 ha in northern Wisconsin. The vegetation of the region is composed of mixed northern hardwoods, upland Jack and Red pine, lowland conifers, aspen and wetlands (Figure 2). Much of the area was logged from 1860-1920 and has since regrown. Human population density in the area is sparse; approximately 5 people per square kilometer. The climate is cool continental, mean annual temperature is 4.1 C (-11.17 in January, 16.6 in July), and average precipitation is 800 mm. The mean elevation of the area is approximately 342 meters (minimum of 183, maximum of 670).

Figure 1. View of one of the sonic anemometers from the tower

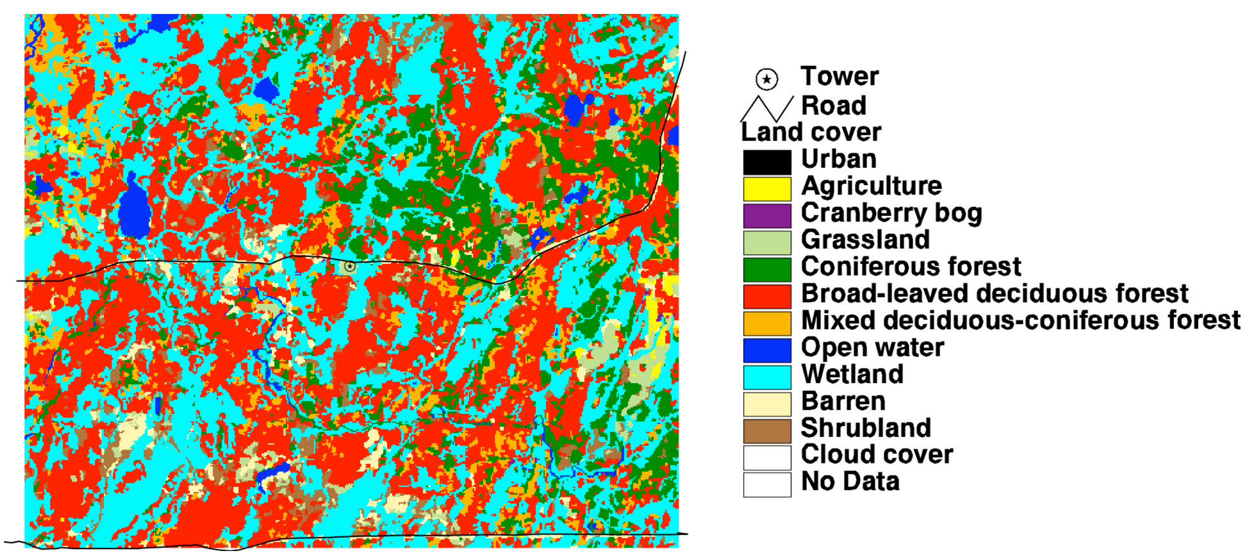

Figure 2. Land cover classification of the area surrounding the WLEF tower in Park Falls, Wisconsin

Model Description

A land surface model which deals explicitly with carbon exchange at the land surface and which incorporates remotely sensed information, (SiB2) (Sellers, et al., 1996a,b), has been parameterized for the WLEF TV tower site near Park Falls, Wisconsin (see description above). The SiB2 model developed by Sellers and collaborators (Randall et al., 1996; Sellers et al., 1996a,b) is a single canopy-layer scheme describing the transfers of heat, water and carbon in the soil-vegetation-atmosphere continuum. SiB2 is formulated to be driven by remotely sensed estimates of vegetation properties and incorporates leaf-level physiology controlling photosynthesis (Farquhar et al., 1980; Collatz et al., 1991; Collatz et al., 1992) and the Ball-Berry (Ball et al., 1987) description of stomatal behavior and carbon assimilation. In SiB2, primary parameters affecting land surface-atmosphere exchanges include canopy and soil structural and optical properties and physiological parameters controlling photosynthesis and respiration. SiB2 has been parameterized for the WLEF site using a global parameter set (Sellers, et al., 1996b). The un-tuned model simulates measured CO_2 fluxes well, although some systematic overestimation of heat fluxes is apparent in the middle of the day (Figure 3). This version of SiB2 has recently been coupled to a mesoscale atmospheric model, the Regional Atmospheric Modeling System (RAMS, Pielke et al., 1992). RAMS is a non-hydrostatic model with bulk microphysics. RAMS utilizes a nested grid structure and can be run at resolutions from hemispheres to 100's of meters or less.

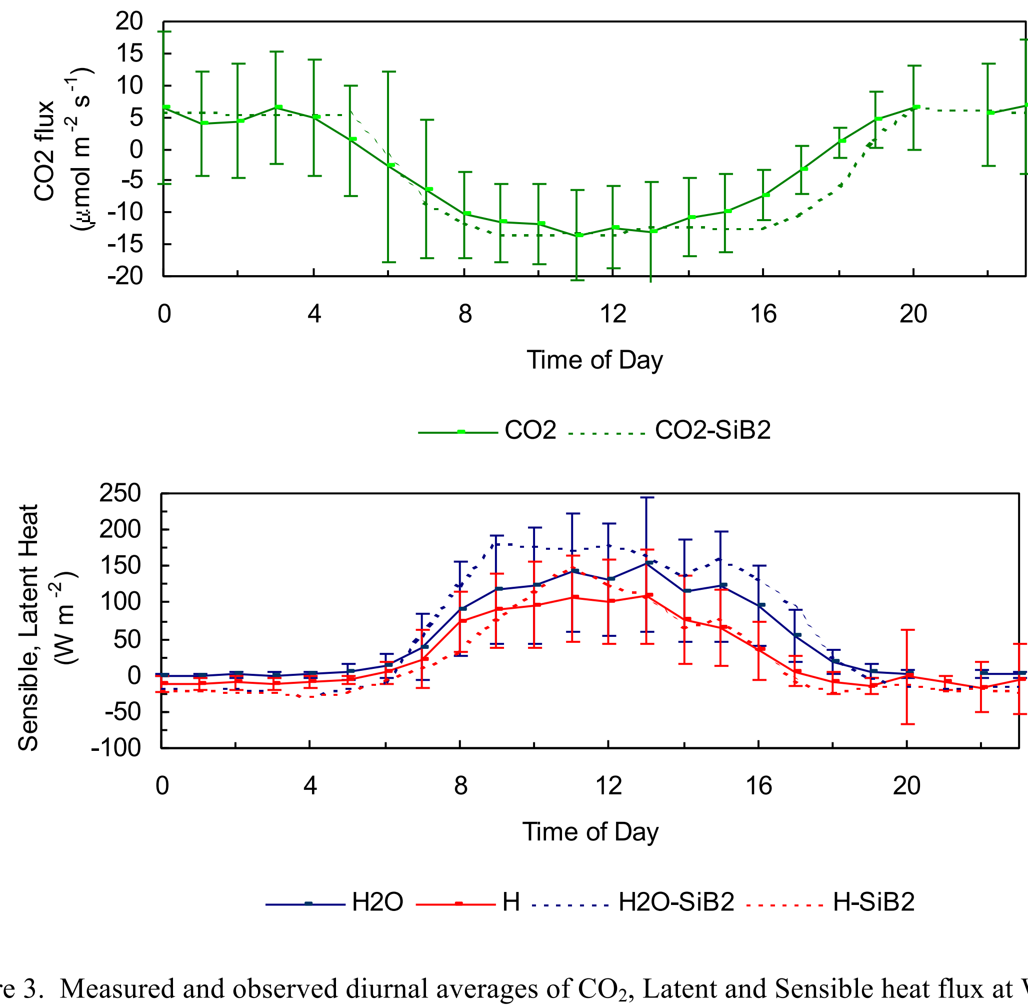

Figure 3. Measured and observed diurnal averages of CO_2, Latent and Sensible heat flux at WLEF.

Model Experiments

Sensitivity of SiB2 to its parameterization

The sensitivity of fluxes of CO_2, latent and sensible heat simulated by SiB2 to the parameterization and formulation of SiB2 will be tested using the General Likelihood Uncertainty Estimation (GLUE) methodology (Beven and Binley, 1992; Freer et al., 1996). GLUE utilizes a Monte Carlo methodology whereby all input parameters are simultaneously randomized within physically feasible ranges and the model is run many thousands of times. An error calculation is made between simulated results and observations. The runs are then divided into performance classes based on the error ranking for each variable of interest and cumulative frequency diagrams are produced which show model sensitivity to parameterization.

An initial test of the procedure has been completed. 37 SiB2 parameters were randomized within physically feasible ranges (see Table 1) and 10,000 simulations run for the period June-July of 1997. Root mean square error (RMSE) was calculated between simulations and observations of CO_2, latent and sensible heat flux for each parameter set. Most parameters showed a degree of equifinality across the parameter range. Cumulative frequency plots were created for each parameter for each variable and model sensitivity was assessed (Prihodko et al., 1998).

Parameter Name	Units	Range	Parameter Description
Z2	Meters	15-30	Canopy-top height
Z1	Meters	0.2Z2-0.8Z2	Canopy-base height
VCOVER		0.7-1.0	Vegetation cover
CHIL		-0.5-0.5	Leaf angle distribution factor
SODEP	Meters	0.5-4.0	Soil depth
ROOTD	Meters	0.2SODEP-0.9SODEP	Rooting depth
PH	Meters	-450 - -50	½ critical leaf water potential
TRAN11		0.0-0.1	Green-leaf transmittance (PAR)
TRAN21		0.05-0.3	Green-leaf transmittance (NIR)
TRAN12		0.0-0.1	Brown-leaf transmittance (PAR)
TRAN21		0.0-0.1	Brown-leaf transmittance (NIR)
REF11		0.02-0.2	Green-leaf reflectance (PAR)
REF21		0.2-0.5	Green-leaf reflectance (NIR)
REF12		0.05-0.25	Brown-leaf reflectance (PAR)
REF22		0.2-0.5	Brown-leaf reflectance (NIR)
VMAX	$\mu mol\ m^{-2}\ s^{-1}$	25-150	Rubisco velocity of sun-leaf
EFFCON	$mol\ mol^{-1}$	0.03-0.13	Quantum efficiency
GRADM		3-18	Conductance-Photosynthesis slope param
BINTER	$mol\ m^{-2}\ s^{-1}$	0.0-0.2	Minimum stomatal conductance
ATHETA		0.5-1.0	Light & Rubisco coupling parameter
BTHETA		0.5-1.0	Light, Rubisco and CHO sink parameter
TRDA	K^{-1}	0.1-1.5	Respiration temperature response
TRDM	K	1.04TROP-1.1TROP	Respiration inhibition ½-point temp.
TROP	K	283-308	Respiration optimum temperature

RESPCP		0.01-0.1	Leaf respiration fraction of Vmax
SLTI	K^{-1}	0.1-1.5	Photosynthesis low temp. response
SHTI	K^{-1}	0.1-1.5	Photosynthesis high temp. response
HLTI	K	270-290	P/S low temp inhibition ½-point temp.
HHTI	K	1.04HLTI-1.1HLTI	P/S high temp inhibition ½-point temp.
SOREF1		0.01-0.4	Soil reflectance (PAR)
SOREF2		1.1SOREF1-1.5SOREF1	Soil reflectance (NIR)
BEE		4.0-8.5	Soil wetness exponent
PHSAT	Meters	-0.05—0.35	Soil water potential at saturation
SATCO		2.5E-6-100E-6	Saturated hydraulic conductivity
POROS		0.4-0.5	Soil porosity
SLOPE		0.1-0.25	Cosine of mean terrain slope
FPAR		0.7-1.0	Fractional PAR interception
ZLT	$m^2 m^{-2}$	Dep. on Fpar	Leaf area index
GREEN		N/C	Canopy greeness fraction
GMUDMU		N/C	Mean leaf projection
Z0	Meters	0.13Z1	Canopy roughness coefficient
D	Meters	0.66Z1	Zero plane displacement
RBC	$m^{-1/2} s^{1/2}$	N/C	Bulk boundary layer resistance coefficient
RDC		N/C	Ground to canopy air-space coefficient

Table 1. Parameter ranges used to generate random parameter sets in GLUE simulations

When all parameters were simultaneously varied, we found that FPAR influenced latent heat flux but not CO_2 flux, that soil depth influenced CO_2 flux but not latent heat flux and that the minimum stomatal conductance was influential over all three fluxes. Other influential parameters included root depth, Vmax, the respiration and photosynthesis temperature response parameters and canopy height.

This initial analysis was conducted during the peak growing season for a period of only two months. To better elucidate the sensitivities of SiB2 the analysis will be extended for the period of one year to include both seasonal and soil effects not captured in the initial run. We also neglected to correctly vary the resistance coefficients RBC and RDC. To correct for this we are planning to calculate all of the aerodynamic parameters (Z0, D, RBC, RDC) for each of the parameter sets using the randomized parameters and software developed by P. Sellers (sibx) for SiB2. Further, in the initial analysis we varied fpar between 0.7 and 1.0. Leaf area index (ZLT) was dependant on fpar but fractional vegetation cover was not (it varied independently between 0.7 and 1.0) and greenness was neglected. In the new analysis we will be altering instead the translation parameters of NDVI to fpar and then recalculating the parameters dependent on fpar (ZLT, FVF, greenness) for each of the randomized parameters sets. Translation parameters include the minimum and maximum simple ratio value, the actual simple ratio value (which is dependent on measured NDVI) and the limits to fpar (the minimum and maximum allowable). We will also look at fixing all parameters while allowing one to vary to identify model sensitivities not discernible using the GLUE methodology. For instance, in our initial simulations it appeared that CO_2 flux was insensitive to fpar while latent heat flux was. However, it is possible that this is due to the simultaneous varying of parameters such as VMAX, which have a stronger effect on rates of CO_2 flux than on latent heat flux.

The information gained from this experiment will be used to focus subsequent work and to help quantify errors related to model and parameter sensitivities.

The effects of surface heterogeneity on CO_2, latent and sensible fluxes estimated using SiB2

Higher resolution satellite data is expected to give a better representation of the heterogeneous land surface. Therefore, progressively diminishing the spatial resolution of the satellite data should have a smoothing effect on the heterogeneity of the land surface as represented by the satellite. This should, in turn, affect parameters generated from the remotely sensed data. This experiment is designed to test the effects that coarsening the resolution of data has on the estimation of fpar and the subsequent impact on fluxes of CO_2, latent and sensible heat.

Image maps of near infrared and red reflectance will be created at one-meter resolution. The idea is to represent the heterogeneity and clumpiness of the landscape at high resolution including the vegetation type (deciduous, coniferous, grass, etc…) and gaps in between trees. Ideally we would use a stem map generated for the WLEF area to develop as accurate a representation of the distribution of cover types and crown densities as possible. If a stem map is unavailable, we will base our one-meter map on field data as much as possible. Plot level measurements of basal area by species and leaf area index exist for multiple plots in the greater WLEF area. We will base our reflectance in the red and near infrared on measured canopy reflectance values either from the field or from the literature. Fpar will be calculated from the red and near infrared reflectances using the methodology of Sellers et al., (1996b).

To progressively diminish the resolution of the image map, reflectances will be averaged across grid increments. For example, to decrease the resolution of the generated image to five meters, reflectances in a five by five meter block will be averaged and fpar calculated. This will be done to decrease the resolution of the image map. We will progressively decrease the resolution to approximately 1Km. We will calculate scene average differences in predicted fpar at each new resolution. Utilizing the information from the first experiment on the sensitivity of predicted fluxes to parameterization we will try to predict the flux error due to changing surface resolution.

Sensitivity studies on the use of satellite data in 3-dimensional land surface-atmosphere models of carbon dioxide exchange

In the first two modeling experiments, the sensitivity of the predictions of a land surface model to its parameterization and to surface heterogeneity were examined. The atmosphere was not considered in either case. In the final modeling experiment, we will consider whether the atmosphere moderates or intensifies these effects and how modeled interactions between the land surface and the atmosphere are affected by the level of heterogeneity resolved by the land surface model.

For this study, the coupled SiB2/RAMS model will used. The coupled model has been parameterized using AVHRR data for a domain in the upper Midwest United States and Canada. The domain covers an area of 1200 x 1200 Kilometers, the center of which is the WLEF tall tower site. One year of monthly NDVI maximum value composites (Eidenshink and Faundeen), a 1Km land cover type map (Hansen et al., 2000) and the STATSGO soils database were used as inputs into the Mapper software (Sellers et al, 1996b). Figure 4 shows an example parameter map of Leaf Area Index for the domain. Preliminary simulations using the coupled model show the land surface and atmosphere interacting and variations in CO_2 concentration driven by these interactions.

We will run the coupled model in three configurations. First, the coupled model will be run with a grid increment of 16Km across the domain (approximately 75x75 grid cells). Then the coupled model will be run with an outer grid of 16Km grid increments and an inner nest of 4 Km increments. Finally the coupled model will be run with an outer grid of 16Km grid increments, a nest of 4Km increments and a final inner nest of 1Km grid increments. We will look at changes in the local variation of fluxes of CO_2, latent and sensible heat between the three simulations and compare the results to field observations of CO_2 flux and latent and sensible heat flux as well as of CO_2 concentration profiles and depth of the PBL. We will also try to quantify errors in flux predictions due to coarse versus fine resolution land surface representation.

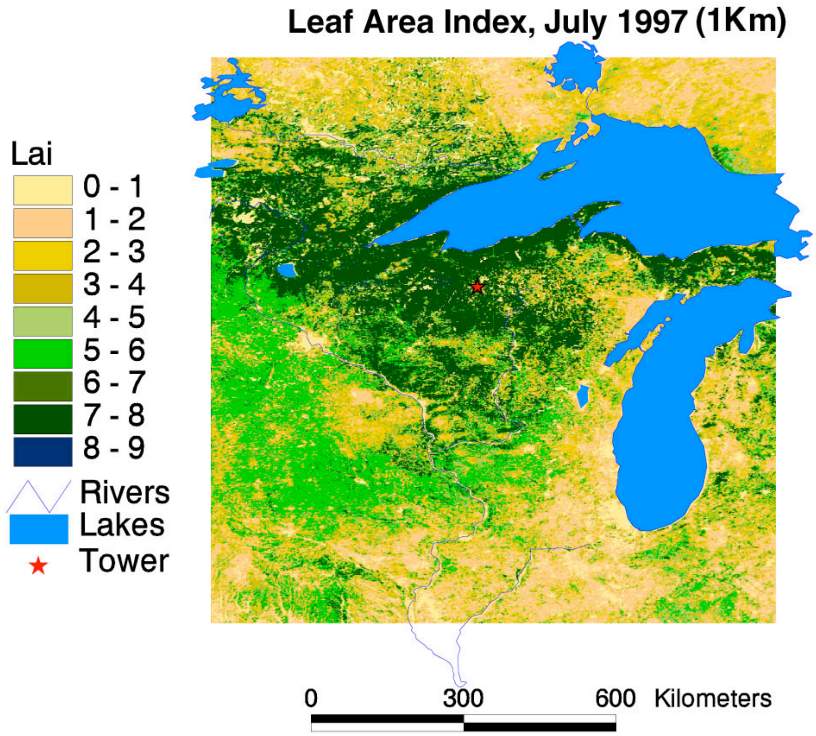

Figure 4. Leaf Area Index for the mesoscale domain

EXPECTED RESULTS AND BENEFITS

The potential significance of the exchange of CO_2 between the land surface and the PBL to measurements of global carbon balance was identified through modeling the PBL and annual carbon balance at the global scale (Denning et al. 1995; Denning et al., 1996a,b). The research objectives in this proposal are designed to help interpret these observations and understand the physical and physiological linkages between CO_2 exchange at the land surface and interactions with the PBL using measurements and models at the local and regional scale. By utilizing remotely sensed data, questions regarding the sensitivity of the modeled interaction to scale and accuracy of satellite input parameters, to heterogeneity of the landscape and to temporal dynamics in the landscape can be answered. This is essential because remote sensing is the critical link we use in process modeling to go from local to regional to global scales. It is expected that the research outlined in this proposal will lead to a better understanding of the processes which contribute to global carbon dynamics.

REFERENCES

Avissar, R. and R. A. Pielke (1989), A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology, *Monthly Weather Review,* 117: 2113-2136.

Avissar, R. and R.A. Pielke (1991), Impact of stomatal control on mesoscale atmospheric circulations, *Agricultural and Forest Meteorology*, 54:353-372.

Avissar, R. (1995) Scaling land-atmosphere interactions: an atmospheric modeling perspective, *Hydrological Processes*, 9:679-695.

Ball, J. T., I. E. Woodrow, et al., (1987), A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. Progress in Photosynthesis Research. J. Biggens, Dordrecht, Martinus Nijhoff, IV:221-224.

Beven, K. and A. Binley (1992), The future of distributed models: model calibration and uncertainty prediction, *Hydrological Processes,* 6: 279-298.

Bazzaz, F.A. (1990), The response of natural ecosystems to the rising global CO_2 levels, *Annual Review of Ecological Systems*, 21:167-196.

Bunyard, P. (1999) Eradicating amazon rainforests will wreak havoc on climate, *The Ecologist* 29(2): 81-84.

Charney, J.G. (1975) Dynamics of deserts and drought in the Sahel, *Quarterly Journal of the Royal Meteorological Society*, 101:193-202.

Chase, T. N., et al. (1999), Potential impacts on Colorado Rocky Mountain weather due to land use changes on the adjacent great plains, *Journal of Geophysical Research* 104(D14): 16673-16690.

Collatz, G. J., J. T. Ball, et al., 1991, Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer, *Agricultural and Forest Meteorology,* 54: 107-136.

Collatz, G. J., M. Ribas- Carbo, et al., 1992, Coupled photosynthesis-stomatal conductance model for leaves of C_4 plants, *Australian Journal of Plant Physiology,* 19:519-538.

Cotton, W. R. and R. A. Pielke Sr. (1995),. Human Impacts on Weather and Climate, Cambridge, Cambridge University Press.

Denning, A.S., Fung, I.Y., Randall, D. (1995), Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota, *Nature*, 376:240-243.

Denning, A.S., Collatz, G.J., Zhang, C., Randall, D.A., Berry, J.A., Sellers, P.J., Colello, G.D., Dazlich, D.A. (1996a), Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part I: Surface carbon fluxes, *Tellus*, 48B:521-542.

Denning, A.S., Randall. D.A., Collatz, G.J., Sellers, P.J. (1996b), Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part II: Simulated CO_2 concentrations, *Tellus*, 48B:543-567.

Eidenshink, J.C. and J.L. Faundeen, The 1-Km ABHRR Global Land Data Set: First Stages in Implementation, http://edcwww.cr.usgs.gov/landdaac/1km/paper.html

Farquhar, G. D., S. von Caemmerer, et al., (1980) A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species, *Planta*, 149: 78-90.

Franks, S. W., K. J. Beven, et al., (1997) On the sensitivity of soil-vegetation-atmosphere transfer (SVAT) schemes: equifinality and the problem of robust calibration, *Agricultural and Forest Meteorology,* 83:63-75.

Franks, S. W., 1998. An evaluation of single and multiple objective SVAT model conditioning schemes: parametric, predictive and extrapolative uncertainty. Callaghan, University of Newcastle: 34.

Freer, J., K. Beven, et al., (1996) Bayesian estimation of uncertainty in runoff prediction and the value of data: An application of the GLUE approach, *Water Resources,* 32(7):2161-2173.

Friedl, M.A. (1996), Relationships among remotely sensed data, surface energy balance, and area-averaged fluxes over partially vegetated land surfaces, *Journal of Applied Meteorology*, 35:2091-2103.

Friend, A.D., Cox, P.M. (1995), Modelling the effects of atmospheric CO_2 on vegetation-atmosphere interactions, *Agricultural and Forest Meteorology*, 73:285-295.

Gash, J. C. and W. J. Shuttleworth (1991), Tropical deforestation, albedo and the surface energy balance, *Climatic Change,* 19(1-2): 123-133.

Hall, F.G., Huemmrich, K.F., Goetz, S.J., Sellers, P.J. and Nickeson, J.E. (1992) Satellite remote sensing of surface energy balance: Successes, failures and unresolved issues in FIFE, *Journal of Geophysical Research*, 97:19061-19089.

Hansen, M.C., DeFries, R.S., Townshend, J.R.G., and Sohlberg, R., Global land cover classification at 1km spatial resolution using a classification tree approach, *International Journal of Remote Sensing*, 21(6):1331-1364.

Harte, J. (1988). *Consider a Spherical Cow: A Course in Environmental Problem Solving*. Sausalito, University Science Books.

Hayden, B. (1998), Ecosystem feedbacks on climate at the landscape scale, *Philosophical Transactions of the Royal Society,* (353): 5-18.

Haughton, J.T., Jenkins, G.J. and Ephraums, J.J. (Eds.) (1990), *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Cambridge.

Hong, X., et al. (1995), Role of vegetation in generation of mesoscale circulation, *Atmospheric Environment,* 29(16): 2163-2176.

Hu, Z. and Islam, S. (1997), Effects of spatial variability on the scaling of land surface parameterizations, *Boundary Layer Meteorology*, 83(3):441-461.

Jones, H.G. (1992) *Plants and Microclimate*, Cambridge University Press, Cambridge.

Korner, C. (1993) CO_2 Fertilization: The great uncertainty in future vegetation development, in *Vegetation Dynamics and Global Change*, A.M. Solomon and H.H. Shugart (Eds.), pp. 53-70, Chapman and Hall, New York.

Kustas, W.P. and Jackson, T.J. (1999) The impact on area-averaged heat fluxes from using remotely sensed data at different resolutions: a case study with Washita '92 data, *Water Resources Research*, 35(5):1539-1550.

Mahfouf, J.-F., et al. (1987), The influence of soil and vegetation on the development of mesoscale circulations, *Journal of Climate and Applied Meteorology*, 26: 1483-1495.

Milne, B.T. and Cohen, W.B. (1999) Multiscale assessment of binary and continuous landcover variables for MODIS validation, mapping, and modeling applications, *Remote Sensing of Environment*, 70:82-98.

Moran, M.S., Humes, K.S. and Pinter, P.J. (1997) The scaling characteristics of remotely-sensed variables for sparsely vegetated heterogeneous landscapes, *Journal of Hydrology*, 190:337-362.

Pielke, R.A., Cotton, W.R., Walko, R.L., Tremback, C.J., Lyons, W.A., Grasso, L.D., Nicholls, M.D., Moran, M.D., Wesley, D.A., Copeland, J.H. (1992), A comprehensive meteorological modeling system - RAMS, *Meteorological and Atmospheric Physics*, 49:69-91.

Pielke, R. A., et al. (1993), Influence of albedo variability in complex terrain on mesoscale systems, *Journal of Climate,* 6(9): 1798-1806.

Pielke, R. A., et al. (1993), Atmosphere-terrestrial ecosystem interactions: implications for coupled modeling, *Ecological Modeling*, 67: 5-18.

Pielke, R. A., et al. (1998), Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate, *Global Change Biology,* 4(5): 461-475.

Pielke, R. A., et al. (1999), The influence of anthropogenic landscape changes on weather in southern Florida, *Monthly Weather Review,* 127: 1663-1673.

Pitman, A., et al. (1999). The role of the land surface in weather and climate: does the land surface matter? Global Change Newsletter**:** 4-11.

Prihodko, L., Denning, A.S., Hanan, N.P., Collatz, J.G., Bakwin, P. and Davis, K., Simulation and sensitivity analysis of carbon fluxes in the boundary layer at the WLEF-TV tower site, Wisconsin, American Geophysical Union Annual Fall Meeting, San Francisco, December 1998.

Randall, D.A., Dazlich, D.A., Zhang, C., Denning, A.S., Sellers, P.J., Tucker, C.J., Bounoua, L., Berry, J.A., Collatz, G.J., Field, C.B., Los, S.O., Justice, C.O., Fung, I.Y. (1996), A revised land surface parameterization (SiB2) for Atmospheric GCMs. Part III: The greening of the Colorado State University general circulation model, *Journal of Climate*, 9(4):738-763.

Schimel, D. (1995), Terrestrial ecosystems and the carbon cycle, *Global Change Biology*, 1:77-91.

Segal, M., et al. (1988) Evaluation of vegetation effects on the generation and modification of mesoscale circulations, *Journal of the Atmospheric Sciences,* 45(16): 2268-2292.

Segal, M., et al. (1989) The impact of crop areas in northeast Colorado on midsummer mesoscale thermal circulations, *Monthly Weather Review,* 117: 809-825.

Sellers, P.J., Bounoua, L., Collatz, G.J., Randall, D.A., Dazlich, D.A., Los, S.O., Berry, J.A., Fung, I.Y., Tucker, C.J., Field, C.B., Jensen, T.G. (1996), Comparison of radiative and physiological effects of doubled atmospheric CO_2 on climate, *Science*, 271:1402-1406.

Sellers, P.J., Randall, D.A., Collatz, G.J., Berry, J.A., Field, C.B., Dazlich, D.A., Zhang, C., Collelo, G.D., Bounoua, L. (1996a), A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation, *Journal of Climate*, 9(4):676-705.

Sellers, P.J., Los, S.O., Tucker, C.J., Justice, C.O., Dazlich, D.A., Collatz, G.J., Randall, D.A., (1996b), A revised land surface parameterization (SiB2) for Atmospheric GCMs. Part II: The generation of global fields of terrestrial biophysical parameters from satellite data, *Journal of Climate*, 9(4): 706-737.

Stohlgren, T. J., et al. (1998), Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas, *Global Change Biology,* 5(4): 495-504.

United States Department of Agriculture, Natural Resources Conservation Service, 1994 State Soil Geographic Data Base (STATSGO).

Wood, E.F. and Lakshmi, V. (1993), Scaling water and energy fluxes in climate systems: three land-atmospheric modeling experiments, *Journal of Climate*, 6:839-857.

Wood, E.F., (1995), Scaling behavior of hydrological fluxes and variables: empirical studies using a hydrological model and remote sensing data, *Hydrological Processes*, 9:331-346.