NASA Research Announcement 01-OES-06

Proposal No. _____________________ (Leave Blank for NASA Use)

Title: ________**Spatial Integration of Regional Carbon Balance in Amazônia**_______

Principal Investigator: ______________**Scott Denning**____________________________

Department: ___________________**Atmospheric Science**_________________________

Institution: __________________**Colorado State University**_______________________

Street/PO Box: _________________**4100 W. Laporte Ave** ________________________

City: ____Fort Collins______ State: ______CO_______ Zip: _80521-1371_________

Country: _USA_____________ Congressional District: __Colorado 4th District________
(used for database sorting purposes only)

E-mail: ____denning@atmos.colostate.edu_____________________________________

Telephone: ______970-491-6936_______ Fax: ___________970-491-8449___________

Co-Investigators:

Name	Institution & E-mail Address	Address & Telephone
Prof. Pedro L. Silva Dias	_USP _pldsdias@model.iag.usp.br	São Paulo_ +55 (11) 818-4075
Prof. Maria A. Silva Dias	_USP _pldsdias@model.iag.usp.br	+55 (11) 818-4075
Dr. Saulo Freitas	_USP _pldsdias@model.iag.usp.br	São Paulo_ +55 (11) 818-4075
__________________	_____________________________	_________________________
__________________	_____________________________	_________________________
__________________	_____________________________	_________________________

Budget Request (total, summing all institutions's requirements of NASA):

1st Year: _________ 2nd Year: __________ 3rd Year: _________ Total: ____________

Table of Contents

Abstract

We propose a 3-year continuation of our investigation of processes that control land-atmosphere CO_2 exchange in Amazônia, using a suite of numerical models to extrapolate local results to regional and Basin scale. We emphasize three key areas of research: (1) evaluation of our models across a range of spatial and temporal scales, from local fluxes and isotope ratios to field campaigns in the area of the Flona Tapajos, to large regions sampled by airborne experiments; (2) a collaborative investigation of the effects of surface water and seasonally inundated land on exchanges of energy, water, and CO_2; and (3) estimation of regional and Basin-scale carbon balance on seasonal, annual, and interannual time scales by inversion of atmospheric data using tracer transport modeling.

Evaluation of a new version of the ecophysiology model SiB will be by direct comparison to measured fluxes of heat, water, and carbon; canopy profiles of CO_2; and the stable isotope ratios of fluxes and stored carbon. The model has been coupled to a mesoscale atmospheric model (RAMS), and will also be evaluated by comparison to observed weather and to concentrations and $\delta^{13}C$ of CO_2 in the regional atmosphere, as measured by other teams from towers and airborne platforms. The evasion of CO_2 from the Tapajos River will be investigated in a set of collaborative field campaigns in which other teams will document local fluxes and isotope ratios of CO_2 from the River and from soils and vegetation in different ecosystems. We will then use the coupled SiB2-RAMS model to propagate these fluxes through the regional atmosphere and predict variations in concentrations in space and time and compare to measurements made by other teams from boats and aircraft. At the larger regional and Basin scales, the influence of surface water and inundated land will be investigated by prescribing the areal extent of these surfaces in RAMS from products developed by other teams using radar and microwave imagery. Energy, water, and CO_2 fields simulated using these fields will be compared to those simulated in a control experiment using classifications based on AVHRR imagery, and to observed meteorology and trace gas concentration measured during the COBRA-BRAZIL campaigns. We have developed a synthesis inversion method for estimation of area-averaged surface fluxes from measured CO_2 at regional scales by including lateral inflow fluxes and initial conditions in the calculation. We will extend these methods to use multiple tracers (CO, $\delta^{13}C$) and apply them in the Tapajos intensives, over large regions for COBRA-BRAZIL, and to the entire Basin using a suite of global transport models. These methods yield quantitative estimates of both the area-averaged flxu and the uncertainty in these fluxes.

This investigation directly addresses LBA-E questions CD-Q1 (“What is the (climatically driven) seasonal and interannual variability of the carbon dioxide flux between the atmosphere and different land cover/use types?”); CD-Q3 (“What are the relative contributions of fluxes from natural and disturbed ecosystems to the net Amazônia-wide flux?”); and ND-Q5 (“What is the importance of periodically "wet" environments for the land and atmospheric balances of nutrients, carbon dioxide, trace gases, and water and energy on multiple scales?”). The proposed research addresses NASA Earth Science Enterprise questions of variability in the carbon fluxes across Amazônia in space and time; forcing of these variations by climate and land use, the response of terrestrial ecosystems and the atmosphere to this forcing, and prediction of the consequences for CO_2 concentrations and stale isotope ratios.

Summary of Past Accomplishments

We have completed a three-year study of ecosystem carbon fluxes across Amazônia using the Simple Biosphere model (SiB2) at several spatial and temporal scales, and are currently working on a 6-month extension. We have developed understanding and confidence in the model simulations at local scales by direct evaluation against data collected in the field, and extrapolated to regional, Basin, and even global scales by coupling our local ecophysiological model to a range of atmospheric models. We have improved the model and developed input data from remotely sensed imagery at several scales. We have learned that water stress plays a less significant role in variations of ecosystem carbon flux than previously thought, and that interannual variations in the balance of C_3 and C_4 photosynthesis in the region contribute to substantial variability in the stable isotope ratio of terrestrial CO_2 flux at the global scale. We have demonstrated that a handful of regular measurements of CO_2 in the atmosphere above the region would dramatically improve the confidence of regional carbon budget estimates from global inversions. Finally, we have investigated the role of surface water and seasonally inundated land surfaces in the energy and carbon budgets of the region: preliminary evidence suggests that they play an important and previously neglected part in the Basin-scale carbon balance.

Local-Scale Model Evaluation Studies

We have performed multiyear simulations of ecosystem fluxes of heat, water, and CO_2 at forest and pasture sites, and evaluated the performance of SiB2 by comparison to a range of observations. We tested the model primarily against data from ABRACOS sites because LBA-Ecology flux data have only recently become available. These experiments motivated substantial improvements in the model and its representation of important processes for this region. Soil hydraulic properties were modified, and we now use smaller matric potentials in many areas reflecting the coarse granular nature of many soils in the region despite their clay mineralogy. Soil water holding capacity and rooting depth was increased to allow ecosystems to store sufficient water during the rainy season to continue active transpiration and photosynthesis through protracted dry seasons. The modified model reproduces diurnal and seasonal cycles of ecosystem fluxes quite well at both forest and pasture sites (Inazawa et al, 2000, 2001).

We coupled the improved version of SiB2 to the CSU Regional Atmospheric Modeling System (RAMS), and used the coupled model to investigate the dynamics of ecosystem-atmosphere interactions at several spatial scales. This work also required the development of surface and vegetation parameter sets for SiB2 on a 1-km grid over a mesoscale domain, from vegetation classifications and AVHRR imagery. The coupled SiB2-RAMS model was used to investigate diurnal variability of CO_2 and the interactions between surface energy budgets and PBL development over forest and pasture sites in Rôndonia. Results of these simulations indicated unrealistic behavior of the model during the morning transition from stable conditions with net respiration and very high CO_2 concentrations to turbulent conditions with net assimilation and lower CO_2, especially at the forest site (Rebio Jaru). Simulations of these transitions in the forest with the original coupled model included dramatic drawdown of low-level CO_2 by photosynthesis while the air was still stably stratified. This phenomena arose because, as is the case with most land-surface parameterizations in atmospheric models, SiB2 treated the temperature, moisture, and CO_2 concentration of the canopy air space as a diagnostic quantity without mass or heat capacity. We have introduced a new parameterization with prognostic calculation of canopy air space temperature, water vapor, and CO_2 in a finite mass whose properties persist across time steps. This new parameterization produced more realistic diurnal and vertical variability at the ABRACOS towers (Fig 1), and also paved the way for the introduction of canopy recycling of respired CO_2 which is important for stable isotope calculations.

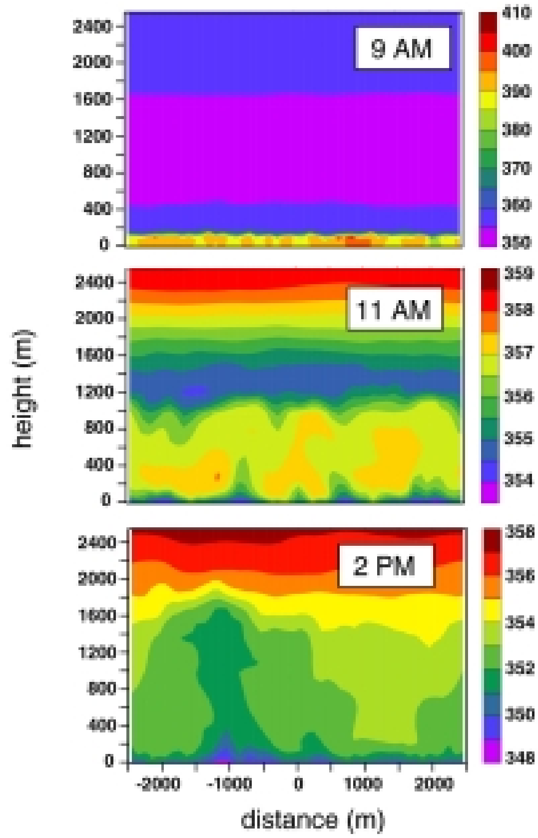

Figure 1: Evolution of CO_2 in the PBL over a forest site in Rondonia using the coupled SiB2-RAMS model. Very high values under the stable layer in the morning followed by decreases due to photosynthesis and turbulent entrainment and establishment of a mixed layer by mid-day

Studies of the Tapajos Region

Richey *et al* (2002) have recently suggested that evasion of CO_2 from supersaturated surface waters may play an important role in the regional carbon balance of the Amazôn Basin. To further investigate the effects of surface water CO_2 emission on the regional carbon balance, and to aid in planning for our field campaign, we performed full 3D simulations of regional meteorology and carbon exchange with and without specifying a CO_2 fluxes from the river and inundated land of 5 μMol m^{-2} s^{-1} (J. Richey, pers. comm.). We performed a 3-month "spin-up" simulation on a coarse grid, followed by a set of 10-day simulations on a 1-km grid. The model was driven by 6-hourly lateral boundary conditions derived from CPTEC (Center for Weather Forecasts and Climate Research) reanalysis products. At regional scales, the simulated impact of surface water evasion is felt most strongly over topographic lowlands at sunrise (Lu *et al*, 2001). Nocturnal accumulation is concentrated in lowlands by drainage flow along the surface. The additional CO_2 efflux from surface waters produces elevated CO_2 concentrations in the vicinity of the Tapajos River (Fig 2). The simulated CO_2 concentration anomaly arising from surface water evasion is quite shallow, and is strongly modified by the "riverbreeze" circulation, with the highest values along the east bank of the River along the convergence line where the riverbreeze decelerates the trade wind flow. The simulated signature of a river evasion flux of this magnitude is quite clear, and would be easy to detect in transects of continuous measurements using airborne platforms flying at low elevation.

We carried out an airborne field sampling program near Santarém in August 2001, using a local air taxi service. We performed five flights, making continuous measurements of CO_2 and water vapor with an infrared gas analyzer, and collected flasks for later analysis at NOAA/CMDL. This campaign was designed to (1) estimate fluxes with much larger footprints

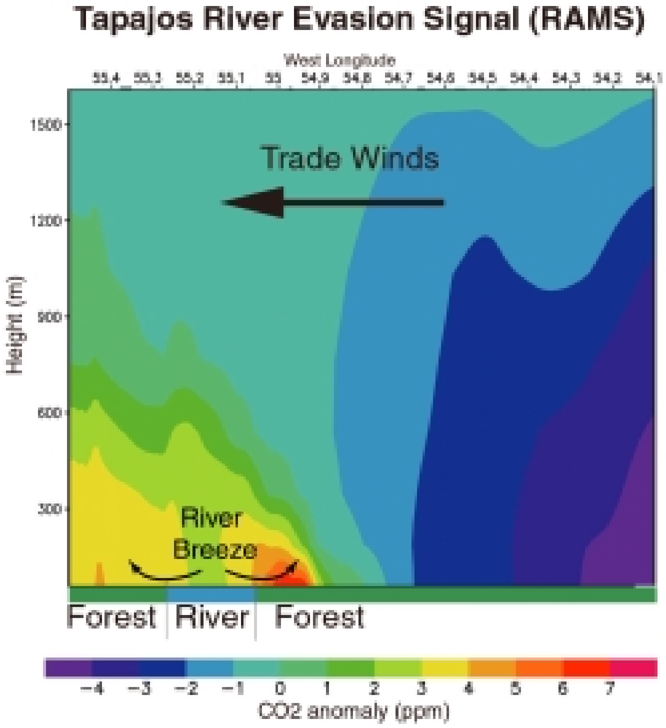

Figure 2: CO_2 concentration anomalies (ppm) simulated on a 1 km grid centered over Flona Tapajos for a river evasion flux of 5 μMol m^{-2} s^{-1}. Cross-section at 2.9° S, 3 PM on 8-AUG-2000.

than are measured from eddy flux towers; (2) to compare simulations of the variations of CO_2 and $\delta^{13}C$ in the mesoscale atmosphere with observations; (3) to evaluate the "river evasion" hypothesis of Richey *et al* (2002); and (4) to provide more detailed characterization of the atmospheric composition in the Santarém vicinity, in order to aid in the interpretation of the weekly profiles measured by Tans, Bakwin, and Artaxo. Unfortunately, we experienced several failures of critical equipment during the campaign, and collected much less useful data than we had hoped.

One very intriguing result was from a low-altitude morning flight along the mainstem of the Amazôn River, combined with a parallel track over the forest to the north of the River (Fig 3). This flight was one of three in which we attempted to address the river evasion hypothesis of Richey *et al* (2002). During this time, the stable boundary layer was beginning to break up over the forest, but conditions were still relatively stable over the River. The measurements showed strong CO_2 gradients between forest and river. These concentration differences (about 8 ppm!) are quite consistent with those predicted by RAMS for a river evasion flux of 5 μmol m^{-2} s^{-1}. Further evaluation of these data is necessary with the highest resolution model possible, to deconvolve contributions from river evasion from those of topographic drainage flow off the forest floor.

We have extended the theory of synthesis inversion calculations to the regional scale (Uliasz *et al*, 2000), and explored the limits of this technique with synthetic data generated by the model (Denning *et al*, 2001). Inverse modeling seeks to quantify sources and sinks of tracer (e.g., CO_2) at the surface from spatial and temporal variations of measured concentrations in the atmosphere. In practice, the method is applied at the global scale by discretizing global monthly CO_2 fluxes into regional "basis functions" of unit strength. The magnitude of each regional contribution to the observed variability is then estimated using least squares

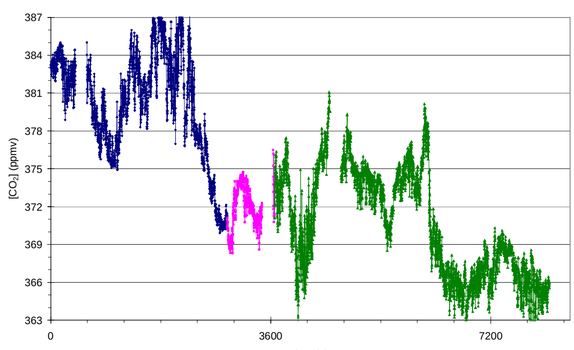

Figure 3: CO_2 concentration measured by a continuous analyzer flown at 300 m elevation over the Amazon River (blue) and adjacent forest (green) on the morning of August 13, 2001.

optimization subject to constraints (e.g., Enting *et al*, 1995; Bousquet *et al*, 2000, Gurney *et al* , 2002). At the regional scale, we discretize the space-time variations of CO_2 fluxes in terms of "influence functions" calculated for each measurement. These are determined by tracing the motion of a large ensemble of imaginary massless "particles" in a Lagrangian particle dispersion model (LPDM), and using the results to calculate the conditional probability that the last contact of a sampled airmass with the surface occurred at each grid cell and time step in the model. The measured concentration is then expressed as a linear combination of contributions from each grid cell and time, plus contributions from tracer fluxes into the modeling domain from the upwind boundary. Using the same mathematical method as the global synthesis inversions, we estimate each of these fluxes and their uncertainties subject to prior constraints. The new method is complementary to traditional convective boundary layer (CBL) budgets and other mass-balance techniques. Advantages include the estimation of spatial and temporal variations of fluxes, as opposed to just their mean values, and the formal estimation of uncertainty in the retrieved fluxes.

Another observational strategy we applied during the airborne field campaign involved repeated sampling of a single airmass as it advected into the Flona Tapajos with the Trade Wind flow. For this purpose, we developed an operational trajectory forecasting system using CSU RAMS and the Lagrangian Particle Dispersion Model (LPDM). The LPDM was driven by output from the 48-hour regional forecast performed by our collaborators at the Universidade de São Paulo, twice per day using RAMS with three nested grids. During the field experiment, the RAMS forecast was rerun at midnight at CSU each night and used to drive trajectory forecasting with the LPDM. The entire process from transferring RAMS input files from Brazil to running RAMS and LPDM to displaying the results on a web site available to field personnel was automated, so that flight planning and operations could be conducted in Santarém even though the meteorological analysis was performed in São Paulo and the trajectory forecasting was done in the US. This RAMS/LPDM forecast system can easily be adapted for other field experiments and sampling strategies (e.g., for COBRA-BRAZIL in 2002-03).

Basin-scale and Global Studies

We developed, implemented, and tested algorithms for stable carbon isotope fractionation in SiB2 (Denning *et al*, 2000; Suits *et al*, 2002). Simulated isotopic fractionation was evaluated against data collected at several sites in Amazônia. The model predicts the discrimination against ^{13}C by photosynthesis and its effect on the stable isotope ratio of both the organic matter formed and the canopy air space. Model calculations were compared against both of these quantities and their diurnal, seasonal, and interannual variations, generally quite favorably. The model was then used to simulate basin- and global-scale variations in isotopic fractionation of CO_2 over an 11-year period, from 1983-1993. These experiments indicated a small amount (less than 5%) of canopy-scale recycling of respired carbon into photosynthetic assimilation, primarily in the early morning under dense canopies. This recycling can nevertheless influence the stable isotope ratio of the organic matter formed (and therefore subsequent respiration) by as much as 0.6 permil. Interannual variability in carbon balance across the Amazôn Basin was primarily driven by climate variability associated with ENSO, and was also associated with substantial variation in isotopic discrimination. This covariation of carbon fluxes and fractionation violates the basic assumption of so-called "double deconvolution" analyses of the global carbon budget (Randerson *et al*, 2002), which interprets variations in $\delta^{13}C$ of the atmosphere as resulting from

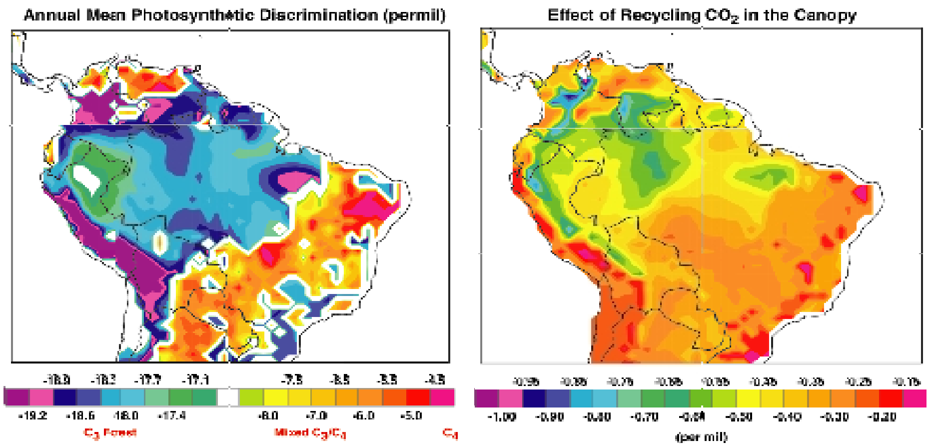

Figure 4: Isotopic fractionation simulated by SiB2 (annual mean for 1987) driven by analyzed climate, and the effect of canopy-scale recycling of respired carbon by photosynthesis

changes in fluxes from atmosphere and ocean with fixed isotope ratios. We found substantial seasonal and interannual variation across the Basin in isotope ratios to result from both changes in discrimination (resulting from physiological stress) and from shifts in the fractions of C_3 and C_4 photosynthesis.

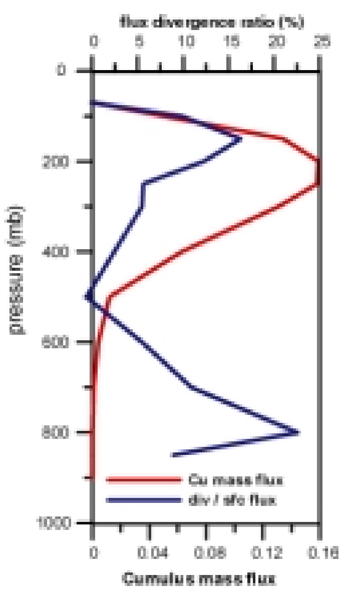

Figure 5: Simulated January vertical profiles of CO_2 flux divergence and cumulus mass flux

Another important issue in the interpretation of concentration measurements in the tropical atmosphere is the influence of deep cumulus convection on the distribution of trace gases. Global inverse models of the carbon budget are relatively insensitive to tropical fluxes because CO_2 anomalies produced by strong surface exchange (due to land use conversion, for example) are "vented" to the upper troposphere by deep convection and therefore "invisible" to the surface flask sampling network. We have investigated this phenomenon in our coupled models, and find that as much as 30% of photosynthetic uptake during the rainy season in the tropical forest is "felt" by the atmosphere above 300 mb (about 10 km), rather than at the surface (Fig 5). The blue line in the figure shows the fraction of the surface flux of CO_2 that leaves the atmospheric column at each model level. Most of the surface flux is felt as advective flux divergence below 600 mb, but the strong secondary maximum in the upper troposphere is associated with the detrainment mass flux from deep cumulus clouds (thunderstorms), which is shown by the red line in Fig 5. This represents a loss of information in inversion calculations, and must be carefully investigated. It is hoped that the deep tropospheric measurements planned under COBRA-BRAZIL may shed some light on the realism of these simulations.

Technical Plan

Background

Tropical forests and savannas make up a huge fraction of global net primary production of the biosphere, and experience dramatic interannual variability in response to climatic forcing by El Nino and other phenomena, yet their role in the global carbon cycle remains poorly understood (Malhi *et al*, 2000; Schimel *et al*, 2001). Widespread conversion of primary forests to pasture and agricultural land is believed to be a substantial source of atmospheric CO_2 (Houghton, 2000), but this source may be at least partly balanced by uptake of CO_2 by intact and regrowing forests. Studies of ecosystem carbon balance using micrometeorological methods have usually found strong sinks, but are complicated by questions about the proper treatment of nighttime fluxes when turbulence is insufficient for eddy covariance to provide reliable results (Grace *et al*, 1995, 1996; Malhi *et al*, 1998; M. Goulden, S. Saleska, D. Fitzjarrald, personal communications). Studies by ecosystem inventory methods have also found intact forests to be accumulating carbon, but it is difficult to balance these results with losses due to disturbance at regional scales (Malhi *et al*, 1998; Philipps *et al*, 1998).

Difficulties in assessing the regional carbon balance of Amazônia have implications for the understanding and prediction of the carbon cycle at global scales as well. Two recent simulations of the coupled climate and carbon cycle from 1850-2100 using interactive global models found dramatically different results due to different treatments of tropical biogeochemistry. One model predicted continuing uptake of carbon by forests in the region throughout the 21st century, leading to an atmospheric CO_2 concentration of about 700 ppm in 2100 (Friedlingstein *et al*, 2001). The forest was largely replaced by grassland in the other model (Cox *et al*, 2000), leading to over 900 ppm of CO_2 in 2100 and twice as much global warming, though both models used nearly identical fossil fuel combustion scenarios. Which of these simulations is closer to the truth? Is there any way to find out?

Field measurements are invaluable for establishing processes and magnitudes of fluxes, but the representativeness of local measurements is difficult to assess. Mass-balance and inverse modeling techniques can help to obtain area- and time-averaged fluxes from atmospheric observations, and have been used for over a decade to assess the carbon balance of large regions of the world (e.g., Enting *et al*, 1995; Bousquet *et al*, 2000; Gurney *et al*, 2002). The current observing system provides almost no data constraint in the deep tropics using this method. A recent intercomparison of inversions using many different transport models (Gurney *et al*, 2002) found that the uncertainty of the annual carbon balance of the Amazôn region was not significantly reduced by the inversion. Two studies using global tracer transport models sought to prioritize new measurements for reduction of uncertainty in global carbon budgets (Rayner *et al*, 1996; Gloor *et al*, 2000). Both found that new measurements over the tropical forests would yield the most uncertainty reduction in inversions, even if one was primarily interested in estimating extratropical fluxes.

Inverse modeling of sources and sinks from atmospheric CO_2 concentration has typically been applied at the global scale, but the same method can also be performed at regional scale if lateral boundary fluxes can be estimated (Uliasz *et al*, 2000; Denning *et al*, 2001, Chou *et al* , 2002). These estimates are most likely to be successful in campaign mode, as airborne observations of inflow fluxes or gridded measurements in the boundary layer are difficult and expensive to make. Mass-balance or inverse flux estimates are especially difficult in the tropics because of the frequency of deep cumulus convection, which effectively redistributes trace gases in the vertical. Organized lines of convective storms are spawned by sea-breeze circulations on the coast and propagate westward across Amazônia, systematically transporting boundary-layer air into the upper troposphere at different times of day in different parts of the Basin (Garstang *et al* , 1994; Cohen *et al* , 1995; Silva Dias, 1999). These squall lines, their timing, and their effects on tracer transport must be correctly simulated if large-scale tracer gradients are to yield reliable quantitative estimates of surface flux variations through inverse modeling.

Conversion of forest ecosystems to pasture across Amazônia is believed to constitute an important perturbation to the carbon balance of the region (Houghton, 2000). This land use change replaces ecosystems primarily built on the C_3 biochemical pathway of photosynthesis (forests) with C_4 grass. Stable isotope fractionation is very different between C_3 and C_4 ecosystems: C_3 forests discriminate much more strongly than C_4 grasses against ^{13}C during photosynthesis. This change is important for two reasons: (1) global deconvolution analyses (Francey *et al* , 1995; Ciais *et al* 1995; Battle *et al*, 2000) make use of changes in $\delta^{13}C$ to estimate the partition of marine and terrestrial fluxes in the global carbon budget. Changes in the C_4 fraction of tropical photosynthesis are typically not included in these calculations and may lead to bias, with exchange between C_4 ecosystems and the atmosphere interpreted as air-sea flux. (2) At regional scales, changes in CO_2 and $\delta^{13}C$ in the atmosphere may be analyzed to quantify the contribution of each land-cover type to regional carbon exchange.

Standard double deconvolution techniques use variations in both concentration and carbon isotopic ratio of atmospheric carbon dioxide to determine changes in global carbon sources and sinks. Because of a paucity of high-precision $\delta^{13}C$ analyses and uncertainties about the correct isotope ratios to use, these analyses have most often been performed only on the annual mean concentration and isotope ratio, at the global scale (Keeling *et al*, 1995; Francey *et al*, 1995; Battle *et al*, 2000). More information is available in the seasonal and spatial variations of $\delta^{13}C$ of the atmosphere (Keeling *et al*, 1989; Ciais *et al*, 1995), but is difficult to interpret reliably because of variations in isotopic fractionation during photosynthesis, carbon turnover in ecosystems, and the isotopic disequilibrium between the atmosphere and the oceans. In general, the models used in these inversions assume that carbon isotope discrimination of the terrestrial biosphere is constant in time and varies only by latitude, even though there is ample evidence for variation on diurnal, seasonal and interannual time scales (e.g., Lloyd and Farquhar, 1994; Lloyd et al., 1996; Flanagan et al, 1996, 1997; Buchmann *et al*, 1997a,b, 1998, Ehleringer and Cook, 1998; Miranda *et al* , 1997).

A recent analysis by Randerson *et al* (2002) pointed out that assuming invariant isotopic discrimination may produce systematic bias in deconvolution calculations. The advantage of making this simplifying assumption is that the influence of the terrestrial isotope disequilibrium, i.e. the isotopic difference between assimilated and respired fluxes, is multiplied by the *net* terrestrial CO_2 flux, which is only in the range of 2 to 4 Gt of carbon (Fung *et al* , 1997). If, on the other hand, carbon isotope discrimination changes over time, then subsequent respiration acts on organic matter with the new isotope ratio and therefore the disequilibrium must be applied to the *gross* respiration flux (typically 20 to 50 times greater!). As a result, a change of *0.2 per mil* in the global isotope discrimination factor can be interpreted as a *0.85 Gt-C* shift in the land versus ocean carbon sink. Of particular interest are the questions of whether interannual variations in discrimination and net assimilation are systematically related, and if they can be correlated with other environmental phenomena, such as El Niño Southern Oscillation (ENSO) or major volcanic activity. If discrimination and primary productivity do covary, then it may be possible to write a linear equation relating discrimination anomalies to productivity anomalies, which would simplify the solution to the inversion problem. Interannual variability provides "natural experiments," allowing us to examine the influence of climate variability on regional carbon balance. Changes in the stable isotopic composition of organic matter and atmospheric CO_2 provide a window into these processes.

Another important contribution to the regional carbon budget is fire. Biomass burning compensates for some of the sink measured in growing forests, and also complicates the interpretation of trace gas concentration data in terms of biological processes. One possible strategy for partitioning the contribution of fires and ecosystem metabolism to observed variations in atmospheric CO_2 is the use of a combustion product such as CO (e.g., Potosnak *et al*, 1999). Fire occurrence and intensity can be either modeled or inferred from satellite imagery, and with appropriate emission factors, CO can be prescribed as a tracer in regional or global tracer models. Observed variations of CO_2 and CO can then be used to estimate the contribution from combustion, and mass-balance or inverse methods can be employed to estimate biotic sources and sinks of CO_2.

The presence of large areas of wetlands and seasonally inundated lowlands in the Amazôn Basin has a huge effect on surface energy and water budgets, and may also impact the estimation of regional carbon balance. Surface waters in the Basin are usually supersaturated with dissolved inorganic carbon (DIC) relative to atmospheric CO_2 by factors of 10 to 100 (Richey *et al*, 1988; Richey *et al*, 1990; Devol *et al*, 1995). Evasion of CO_2 from surface waters (including the major rivers) may be an important contributor to atmospheric CO_2 concentrations in the overlying air (Wofsy *et al*, 1988; Quay *et al*, 1989). Typical land-surface classification schemes based on optical remote sensing include only major water features that are resolved at 1 km AVHRR resolution; the IGBP-DISCover product, for example, reveals an areal fraction of surface water of just 4%. A recent analysis of JERS-1 mosaics created from synthetic aperture radar (SAR) imagery by Richey *et al* (2002) estimates that 24% of the Basin is inundated at high water. Their analysis suggests that nearly 0.5 GtC yr^{-1} is lost from these waters by direct evasion, about 13 times the loss from river discharge to the ocean and of comparable magnitude to the accumulation measured in intact forest by inventory methods by Philipps *et al* (1998). Richey *et al* (2002) speculate that the source of the bulk of the evasion flux is lateral transport of carbon that was originally fixed on land, enters the water either as dissolved organic carbon or is swept there as debris during flood periods, and is then decomposed in the aquatic system. If their hypothesis is correct, the eddy flux measurements of huge sinks in *terra firme* forests may not be inconsistent with inversion estimates of a weak CO_2 source for the Basin as a whole. Once again, we are struck with the need for more spatially extensive estimates of carbon balance than are feasible at the scale of plots, towers, or floats in the rivers.

Objectives

1. **Evaluation of ecophysiological model simulations** of ecosystem fluxes of heat, water, momentum, CO_2, and $^{13}CO_2$ at flux towers in primary forest, logged forest, and pasture. Further evaluation of vertical structure in CO_2 and $\delta^{13}C$ from data collected by other teams. Focus on diurnal variability, rainy-season/dry-season controls, and interannual variability.

2. **Evaluation of coupled ecophysiology-mesoscale atmosphere model simulations** for case studies across Amazônia using COBRA data, radiosondes, and other atmospheric data;

3. **Quantify the impact of surface water, wetlands, and seasonally-flooded ecosystems** on local and regional energy budgets, climate, and carbon cycling.

4. **Quantify regional fluxes and their uncertainty** over well-defined spatial domains for intensive observing periods from data collected during COBRA experiments

5. Document **influences of advective transport, diurnal PBL dynamics and deep cumulus convection** on regional distribution of free-tropospheric CO_2, $\delta^{13}C$, and CO

6. **Estimate magnitude and uncertainty of basin-wide carbon flux** using inversion of atmospheric observations and transport at global scale.

Scientific Relevance

As specifically requested in the NRA, we plan to test models with observations and compare observations from a variety of scales and techniques. This includes local comparisons to observed fluxes of energy, water, and CO_2, broader comparisons to vertical and diurnal variations of CO_2 and $\delta^{13}C$ over the tower sites, and regional to Basin-wide evaluation against aircraft data collected during the COBRA campaigns and the weekly flask sampling of the Tans/Bakwin/Artaxo team. In addition, as requested, we will participate in the analysis of new observations of carbon tracers to evaluate the evasion of CO_2 from wetlands, temporarily inundated or saturated areas.

The work we propose to conduct is directly relevant to three of the Science Questions posed in the NRA:

> **CD–Q1** What is the (climatically driven) seasonal and interannual variability of the carbon dioxide flux between the atmosphere and different land cover/use types?
>
> Our model simulations provide quantitative answers to this question on local, regional, Basin-wide, and even global scales. We will use the multiscale model evaluation strategies outlined herein to test the realism of these answers.

CD–Q3 What are the relative contributions of fluxes from natural and disturbed ecosystems to the net Amazônia-wide flux?

We will answer this question using analysis of airborne trace gas data collected regionally during COBRA-Brazil, through mass-balance and mesoscale inversions. Over the longer term, we will provide answers at the regional to Basin-scale by inversion of CO_2 and $\delta^{13}C$ data collected by weekly flask profiling by Tans/Bakwin/Artaxo.

ND-Q5 What is the importance of periodically "wet" environments (from moist soils to standing and flowing waters) for the land and atmospheric balances of nutrients, carbon dioxide, trace gases, and water and energy on multiple scales?

This question will be answered by modeling the fluxes of water, energy, and CO_2 from these wet environments in SiB2-RAMS, with areal coverage specified from SAR imagery in collaboration with the Melack and Saatchi teams. The model calculations will be evaluated locally during field campaigns in collaboration with the Ehleringer/Berry and Tans/Bakwin/Artaxo teams, and at regional scale during the COBRA campaigns.

Technical Description of Proposed Work

Model Descriptions

The Simple Biosphere (SiB) Model, developed by Sellers et al (1986), has undergone substantial modification (Sellers et al, 1996a), and is now referred to as SiB2. The number of biome-specific parameters has been reduced, and most are now derived directly from processed satellite data (Sellers et al, 1996b) rather than prescribed from the literature. Another major change is in the parameterization of stomatal and canopy conductance used in the calculation of the surface energy budget over land. This parameterization involves the direct calculation of the rate of carbon assimilation by photosynthesis (Farquhar et al, 1980), making possible the calculation of CO2 exchange between the global atmosphere and the terrestrial biota on a timestep of several minutes (Denning et al, 1996a,b). Photosynthetic carbon assimilation is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate by the Ball-Berry equation (Collatz et al, 1991, 1992). Recent improvements include the introduction of a 6-layer soil temperature submodel based on the work of Bonan (1996, 1998), and a revised surface energy budget that includes prognostic temperature and moisture in the canopy air space reservoir. Particular strengths of SiB2 for this project include the treatment of biogeochemistry, the fact that the model has already been coupled to a suite of atmospheric models across a spectrum of spatial and temporal scales, and the ability to specify the vegetation parameters from globally-available satellite imagery. We have used SiB2 to predict the exchange of CO_2 between the atmosphere and the vegetated land surface, and coupled the model to the CSU GCM to predict atmospheric CO2 (Denning et al, 1996a,b). The coupled SiB2-GCM produced excellent agreement with the observed spatial and seasonal gradients, and is the only such global model that has yet been evaluated against diurnal data. The model can also be run at a single site from locally observed meteorology, or from gridded weather analyses, or coupled to the CSU Regional Atmospheric Modeling System (RAMS, Pielke *et al*, 1992).

SiB2 is parameterized partly from biome lookup tables, but also specifies LAI, FPAR, and other seasonally and interannually varying vegetation properties from NDVI (Sellers *et al* , 1996b, Prihodko *et al*, 2002). When we have a full year of MODIS products, these time varying parameters will be specified from MODIS VI, LAI, and FPAR. Other time-varying parameters that are calculated from LAI include roughness length, the zero-plane displacement height, and other properties used to calculate turbulent transfer within and above the canopy. A new roughness length product derived from Shuttle Radar Topography Mission data is expected to be provided on a 1 km grid by Sasan Saatchi under other support. We will use this product for our mesoscale simulations when it is available.

RAMS is a general purpose atmospheric simulation modeling system consisting of equations of motion, heat, moisture, and continuity in a terrain-following coordinate system (Pielke *et al* . 1992). The model has flexible vertical and horizontal resolution and a large range of options that permit the selection of processes to be included (such as cloud physics, radiative transfer, subgrid diffusion, and convective parameterization). Two-way interactive grid nesting (Nicholls *et al* . 1995; Walko *et al* . 1995*a*) allows for a wide range of motion scales to be modeled simultaneously and interactively. For example, with nesting, RAMS can feasibly model mesoscale circulations in a large domain where low resolution is adequate, and at the same time resolve the eddy fluxes caused by juxtaposition of different land cover types, such as occur when forest is adjacent to pasture land (Pielke *et al*. 1992).

Several major RAMS developments were completed in the last few years which greatly enhance its ability to simulate the components of the hydrological cycle. Among these is a new bulk microphysical code (Walko *et al* . 1995*b*, 1996*b*) which represents each water category (cloud, rain, large and small pristine ice, aggregates, graupel, and hail) as a generalized gamma distribution and prognoses both the mass mixing ratio and number concentration of all categories. The model includes homogeneous and heterogeneous nucleation of pristine ice, the representation of five different ice habits, conversion of ice between the large and small pristine categories resulting from vapor deposition or sublimation, and prognosis of aerosol (cloud condensation nuclei). Very efficient solvers for the stochastic collection equation based on new analytic solutions to the collection integral and for activation of cloud droplets are implemented. Accurate prediction of cloud droplet number based on aerosol concentrations and supersaturations allows the model to properly represent cloud albedo. The sedimentation routine allows differential fall speeds based on the gamma size distribution. Another development in RAMS is the ability to nest vertically to increase vertical resolution in selected areas (Walko *et al*. 1995*a*).

RAMS has a built-in interface to the ARC-Info Geographic Information System, which will facilitate the incorporation of other LBA data sets (MODIS imagery, topographic and hydrologic data for boundary conditions, etc) into the coupled simulations of carbon and isotope exchange with SiB2. The modeling system includes code for simulation of trace gas transport and concentration by two methods: a Lagrangian parcel dispersion scheme which can be run off-line from model output, and an Eulerian "in-line" scheme. We will use the Lagrangian module for most of the LES work described here, but will also use the Eulerian in-line module for

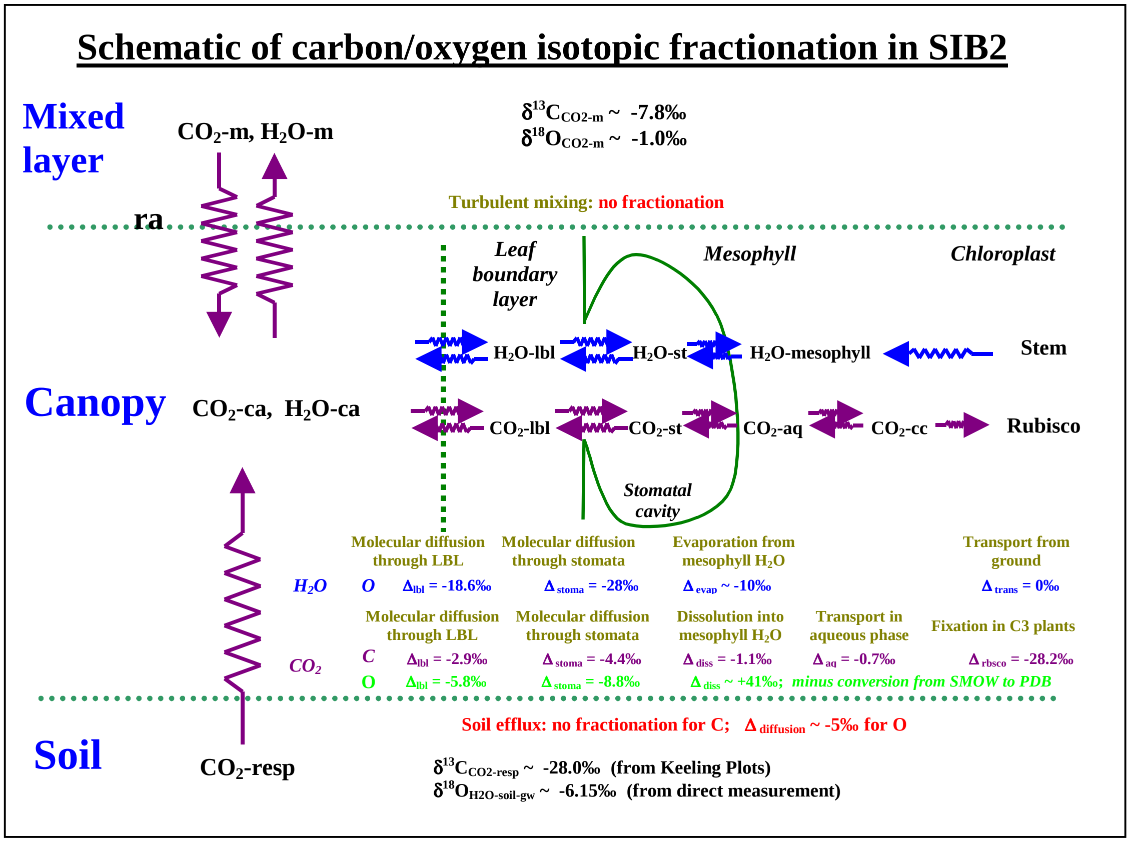

Figure 7: Stable isotope systematics in SiB2

investigating interactions between CO_2 concentration in the canopy air space and the physiological function of the forest. Lagrangian simulations will use the LES-scale output from simulations nested within regional assimilation system, and will be sufficient to resolve turbulent transport in the PBL and convective transport by individual clouds. We will perform prognostic simulation of within-canopy concentration and isotopic composition of CO_2. For the regional simulations proposed later in the study, we will also include parameterized transport by PBL turbulence and deep convection, which will be impossible to resolve at the basin scale.

A ^{13}C fractionation submodel of SiB2 will be used to predict δ^{13}C values of plant biomass, respired CO_2 and atmospheric CO_2 (Suits et al., 2002). The model calculates 1) kinetic isotope effects accompanying C_3 and C_4 photosynthesis, 2) carbon isotopic ratios of canopy CO_2 and assimilated plant biomass, and 3) the magnitude and carbon isotopic ratio of CO_2 fluxes between the canopy and overlying atmosphere (Fig. 7). The model calculates concentrations of CO_2 in the canopy (C_a), at the leaf surface (C_s), within the stomatal cavity (C_i) and chloroplast (C_c), and a coefficient of resistance to turbulent exchange between the canopy and the overlying atmosphere (r_a).

$$\frac{d}{dt}(C_{ca}\,\delta^{13}C_{ca}) = \frac{d}{dt}(Resp\quad \delta^{13}C_{resp}) - \frac{d}{dt}(A_n\quad \delta^{13}C_{PS}) + \frac{d}{dt}(1/r_a\ \ (C_m\,\delta^{13}C_m - C_{ca}\,\delta^{13}C_{ca}))$$

where $\delta^{13}C_{resp}$, $\delta^{13}C_{PS}$, $\delta^{13}C_{ca}$ and $\delta^{13}C_m$ are the carbon isotopic ratio of respiration, assimilation, the canopy and overlying atmosphere, respectively. C_{ca} and C_m are CO_2 concentrations in the canopy and overlying atmosphere. C_m and $\delta^{13}C_m$ can be measured or calculated interactively in a GCM,

In an approach similar to Lloyd and Farquhar (1994), transport of CO_2 and water vapor in C3 plants is divided into 4 separate steps: (1) diffusion of canopy CO_2 and H_2O across the laminar leaf boundary layer, (2) molecular diffusion through the stoma, (3) dissolution of CO_2 into mesophyll water, and finally (4) aqueous phase transport to the chloroplast:

$$\begin{aligned}\boldsymbol{\Delta_{C3} = \Delta_s\ C_{ca}/C_{ca} + (\Delta_i - \Delta_s)\ C_s/C_{ca}} &\boldsymbol{+} \\ &\boldsymbol{(\Delta_{diss} + \Delta_{aq} - \Delta_i)\ C_i/C_{ca} + (\Delta_{rbsco} - \Delta_{diss} - \Delta_{aq})\ C_{cc}/C_{ca}}\end{aligned}$$

Δ_s, Δ_i, Δ_{diss}, Δ_{aq} and Δ_{rbsco} are kinetic isotope effects associated with transport through the leaf boundary layer, into the stomatal cavity, into solution, aqueous phase transport and fixation by rubisco, respectively. C_{ca}, C_s, C_i and C_{cc} are the corresponding CO_2 concentrations in the canopy, at the leaf surface, within the stomatal cavity and chloroplast. Figure 2 shows this schematicallyC_4 photosynthesis also discriminates against ^{13}C, but to a much lesser extent. Currently, SiB2 assumes that carbon isotopic discrimination in C4 plants is constant at -4.4‰.

To treat exchanges of CO_2 and its stable isotopes in SiB2, we introduced a new prognostic calculation of scalar quantities in the canopy air space. Traditional land surface parameterizations (e.g., Bonan, 1996) typically diagnose the temperature and water vapor pressure of the canopy air space from mixed-layer temperature and heat flux through a resistance network. The current NCAR CLM2 follows an analogous strategy to diagnose CO_2 concentrations in the canopy:

$$\rho \Delta z \frac{C_a - C_m}{r_a} = R_H + R_A - A \qquad (2)$$

where C_a is the canopy air space CO_2 concentration, C_m is the mixed-layer (or measurement) CO_2, R_H is heterotrophic respiration, R_A is autotrophic respiration, A is the assimilation of CO_2 by photosynthesis (GPP), r_a is the aerodynamic resistance, ρ is the air density, and Δz is the height increment. This approach has the disadvantage that there is no "memory" or "storage" of previous conditions. At local scales, this approach was found to lead to unrealistic behavior in early morning and late afternoon as the sign of the net CO_2 flux reverses, producing instantaneous changes of CO_2 concentration of hundreds of ppm (Denning *et al*, 2002). We have therefore introduced prognostic equations for energy, water, and carbon species in the canopy air formulated as a flux divergence that is solved using implicit time differencing:

$$\rho \Delta z \frac{\partial C_a}{\partial t} = R_H + R_A - \frac{C_a - C_m}{r_a} \qquad (3)$$

Canopy storage of CO_2 allows the signals of photosynthetic assimilation (enriched in ^{13}C) and respiration (depletes ^{13}C) to mix in the canopy reservoir. Depending on the relative timing of light penetration into plant canopies and the onset of turbulence in the morning, some recycling

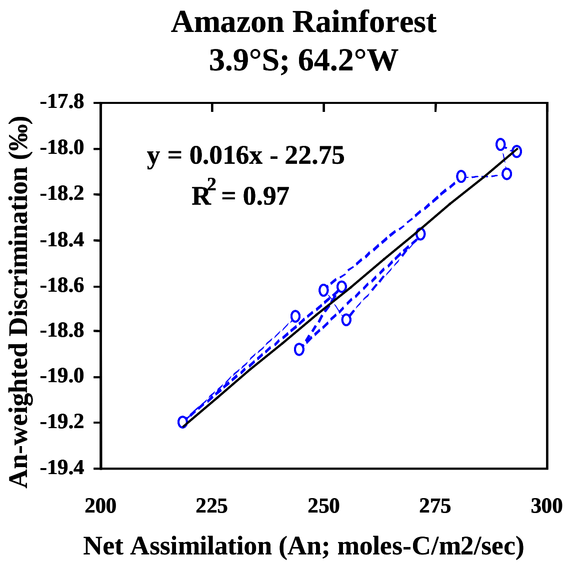

Figure 8. An example demonstrating the positive correlation between annual rates of net assimilation and assimilation-weighted discrimination for 1983 through 1993 from the SiB2 simulation.

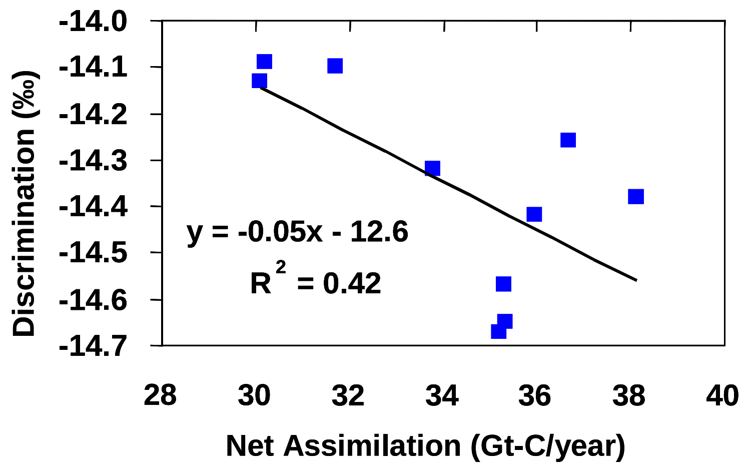

Figure 9. Correlation between annual Net Assimilation (GtC/year) and annual Net Assimilation-weighted Discrimination (‰) simulated by SiB2 over tropical South America for the years 1983 through 1993.

of respired carbon into new photosynthate may occur. In the model, this effect tends to deplete δ^{13}C of organic matter in very productive ecosystems (e.g., tropical forests) by as much as 0.75‰ (Suits *et al*, 2002).

The dependence of the kinetic isotope effect on C_i/C_a generally favors biochemical fractionation (more discrimination, lighter organic matter) when stomata are open, and diffusional effects when plants are stressed and stomates are closed. In simulations of interannual variability of isotope systematics in SiB2 driven by observed climate, we found substantial variation in isotopic discrimination of terrestrial ecosystems on a suite of temporal and spatial scales that was related to physiological stress. Locally, the relationships between light limitation, photosynthesis, and isotopic fractionation lead to a direct relationship between annual gross primary production and isotope discrimination (Fig 8). Coherent interannual variability in climate due to El Nino or other large-scale phenomena are expected to lead to substantial variation in isotopic discrimination and the isotope ratio of newly formed organic matter. This in turn must produce variations in the isotope ratio of respired carbon in subsequent years, which affects the isotopic disequilibrium and the gross flux of ^{13}C from the biosphere (Randerson *et al*, 2002). These correlated interannual variations between GPP and Δ violate the basic assumptions of the double deconvolution method, and are crucial to model correctly if the promise of isotopic constraints for inverse modeling is to be realized.

Given the local behavior of the model in response to interannual variations, it was surprising that the regional and even the global relationship between GPP and Δ had the opposite slope in our simulations (Fig 9). This reversal arises because of changes in the fraction of C_4 photosynthesis on interannual time scales (Fig 10). The C_4 fraction of grid-scale vegetation is parameterized in SiB2 from physiological considerations and continuous fractional vegetation coverage derived from satellite imagery (Defries *et al* , 1999). C_4 plants account for approximately 20% of total terrestrial net assimilation. The regions in which they are the dominant flora tend to be warm and dry, and subject to seasonal and interannual variations in water availability, which in turn can lead to fluctuations in rates of net assimilation on the same timescales In addition to local evaluation of against ecosystem biogeochemical measurements, the coupled model can be tested by comparison to data collected by the global flask sampling network. We have used the ecosystem fluxes of CO_2 and $^{13}CO_2$ simulated by SiB2 as boundary conditions for a set of global tracer transport experiments using TM2 (Heimann *et al*, 1996). At most stations, the model successfully predicts the seasonal variations in both CO_2 and δ^{13}C.

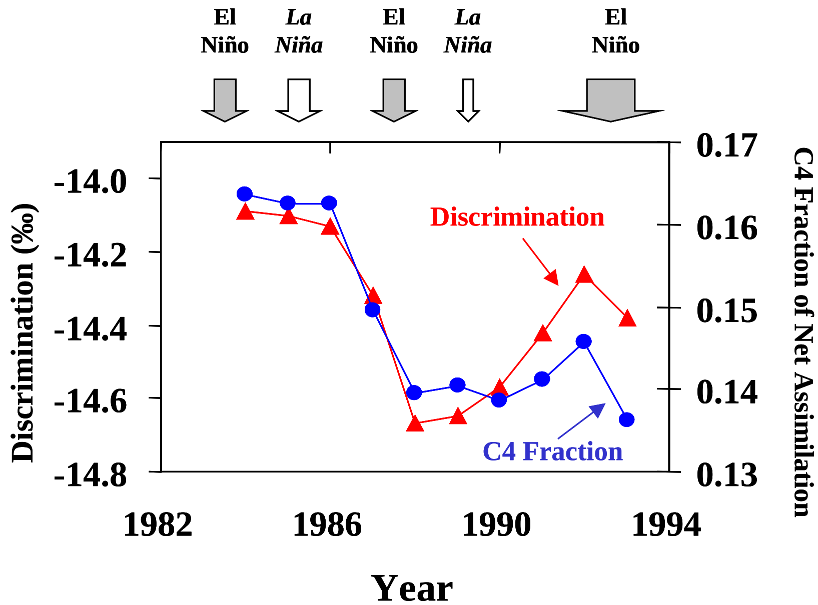

Figure 10. Annual Assimilation-weighted Discrimination (‰) and the fractional contribution of C_4 plants to annual Net Assimilation.

Model Evaluation

We will evaluate the performance of the models at local and regional scales at the three NASA flux tower sites and across the Tapajos region, against a suite of observations collected at several spatial scales. We have already performed detailed site evaluations using ABRACOS data at the Rebio Jaru forest and the Fazenda Nossa Senhora pasture site. Now that more than a year of nearly continuous micrometeorology and fluxes are available for the Forest (CD-14), Pasture (CD-03), and Logged Forest (CD-04) tower sites in the Tapajos region, we will compare timeseries of simulated fluxes of heat, water, momentum, and CO_2 with observations made from the towers.

We will particularly focus on the development of physiological stress (or lack thereof) during the dry season at the forest sites. Some of the flux tower data show that forests in the region show no water stress at all during the dry season (Mike Goulden, personal communication). Whether this is due to very deep roots and soil water holding capacity, or to a hydraulic lift mechanism is unknown. This issue is central to the seasonality of net carbon exchange: at the CD-04 tower site, the forest is a net sink during the dry season due to suppressed respiration and litter-layer drydown, but becomes a net source during the wet season as respiration recovers. Some of the isotope data do suggest reduced stomatal conductance during the dry season in the Flona Tapajos, so there is also some question about the representativeness of the unstressed flux measurements. We have already modified SiB2 to account for deep soils and roots in the region, and now match the seasonal and diurnal variations in the ABRACOS data quite closely. Like the tower data, our model predicts a regional sink during the dry season and a regional source during the wet season, but the model also tends to develop light limitation in the wet season so we may be getting the right answer for the wrong reasons. We will carefully evaluate the parameterization of physiological stresses due to root zone water content and vapor pressure deficits, with particular reference to the seasonal behavior. We will also examine the light limitation/light saturation dynamics of the model relative to the tower data.

One advantage of the approach taken in SiB2 is that it allows CO_2 and stable isotope simulations to be directly evaluated with data collected during field experiments. We have compared local-scale simulations of vertical structure and diurnal cycles of canopy air space CO_2 and $\delta^{13}C$ at a forested site in Wisconsin (e.g., Denning *et al*, 2002), an Oklahoma grassland/cropland (mixed C_3/C_4), and forests and pasture in Brazil. We will collborate closely with the CD-02 (Ehleringer) team to compare the results of our simulations to observed variations in stable isotope ratios of CO_2. Their data have shown a coherent response to physiological stress due to dry soils and to vapor pressure deficit (Fig 11). These data can help us evaluate the mechanisms by which the coupled model treats stable isotope exchange with the terrestrial biosphere, and also address the seasonal stress dynamics discussed above. Clearly, the isotope ratio of the respiring pool of organic matter is more dynamic in nature than it has previously been modeled to be, responding on time scales of weeks to months to changes in discrimination related to environmental factors. These data contain information about both the physiological stresses under which the organic matter was formed and the residence time and possible pathways of photosynthate through the ecosystems. We propose a detailed evaluation of the results of the diurnal, seasonal, spatial, and interannual variability of isotopic ratios of CO_2 fluxes against these data.

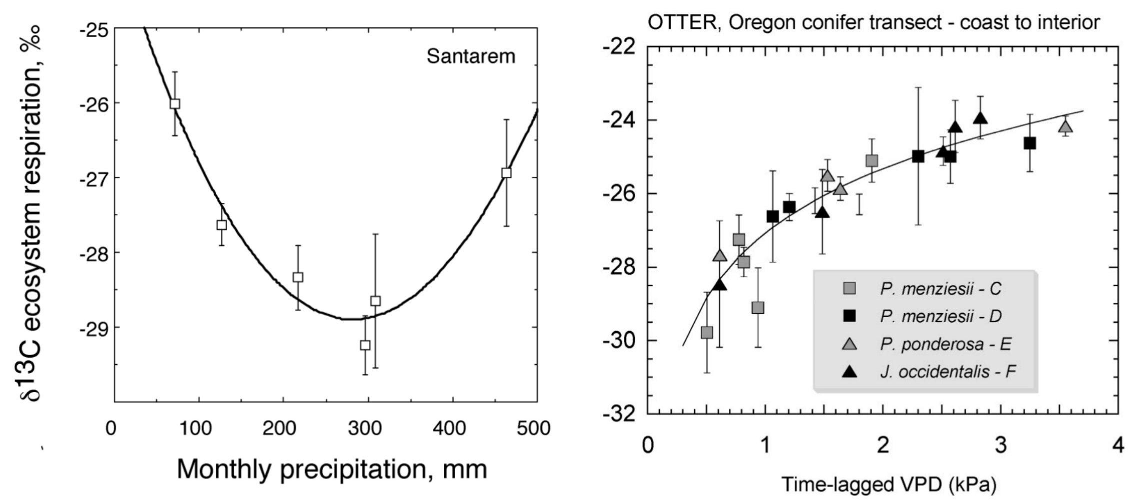

Fig 11: Variations of isotope ratio of respired CO_2 in response to soil moisture (left panel, for a tropical rainforest in Brazil; Ometto *et al* , 2002) and humidity stress (right panel, for a transect in Oregon; Bowling *et al* , 2002)

Using an offline version of SiB2 driven by ECMWF meteorology on a 10-minute time step for 11 years, we have evaluated these stress-related effects on the isotope fractionation (Fig 12). We also simulate a precipitation response in discrimination at Santarém, though it is less pronounced than in the observations, and shows no sign of heavier CO_2 at very high precipitation rates as is suggested by the single month in the data. The offline simulation does not include variations of $\delta^{13}C$ in the overlying atmosphere or recycling in the canopy, both of which will tend to amplify the stress effect. We will repeat this calculation in the fully coupled model, and analyze this effect in detail as part of our model evaluation activities.

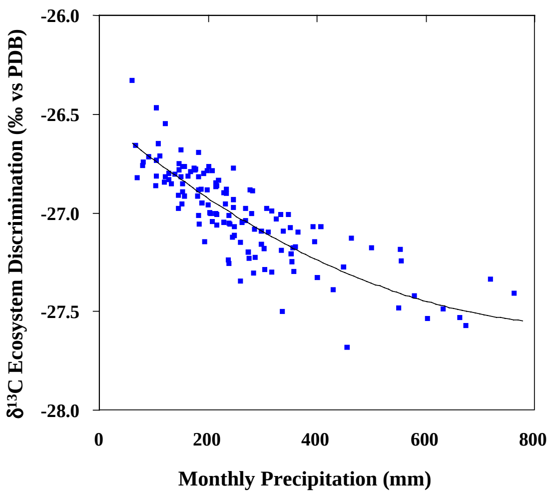

Figure 12: Simulated $\delta^{13}C$ of respiration *vs* precipitation from offline SiB2

Besides local site evaluation of model simulations against flux towers and stable isotope measurements, the coupled SiB2-RAMS system allows us to evaluate the realism of our simulations at much larger spatial scales. Working closely with our collaborators at USP, we will perform simulations of the coupled dynamics of Amazônia and its overlying atmosphere for period of one month on a nested set of four model grids. In previous simulations of the Santarém Mesoscale Campaign in 2001, we centered the grids on the Flona Tapajos. The outer grid covers most of the Amazôn Basin on a 100 km grid, with nested grids at 20 km, 5 km, and 1 km spacing. The inner grid is162 km on a side. Diurnal “riverbreeze” circulations are well resolved (see Fig 2), as are variations in CO_2 concentration arising from surface water evasion.

We will simulate the period of each of the COBRA-BRAZIL campaigns, adjusting the domain appropriately. Lateral boundary forcing will use the CPTEC global analysis, as is done for the operational forecasting using RAMS at USP, with boundary forcing of CO_2 from a global simulation produced by the PI under other support. Vegetation properties will be prescribed from MODIS products, or from 1-km AVHRR NDVI if the MODIS data are not available during the COBRA intensives. Tracer transport will include the effects of deep cumulus convection (resolved on the inner grid, parameterized on the coarser grids using the new scheme of Grell, 1993 and the convective tracer transport scheme of Freitas *et al*, 2000). In collaboration with TG-01/Chatfield, we will also simulate the regional distribution of atmospheric CO, emissions of which will be prescribed from combustion sources (see attached letter). These simulations will be evaluated in terms of their regional meteorology, as compared to measurements from radiosondes, radar, and satellite imagery. We will be particularly interested in comparing simulated and observed variations of CO_2 and $\delta^{13}C$ in the atmosphere. Important aspects of the simulation to test are the depth and diurnal cycle of PBL mixing, the jump in trace gas concentration at the top of the PBL, the coast-to-inland gradients in the PBL and free troposphere, and the effects of moist convection on the vertical structure of tracer concentrations.

Under separate support, we are already committed to providing modeling tools in support of flight operations for COBRA-BRAZIL. These will include daily trajectory forecasting to assist in flight planning and tracking of airmasses for Lagrangian experiments.

Influence of Surface Water and Seasonal Inundation

Another major thrust of the proposed research will be an evaluation of influence of surface waters and seasonally inundated land on regional budgets of water, energy, and CO_2. This will be a collaborative effort involving our modeling team and measurements made by other teams using remote sensing and analysis of surface and aircraft samples.

We have obtained gridded 1-km estimates of the fractional coverage of the land surface by water (open water plus inundated land), made from JERS-1 SAR mosaics at 100 m resolution (Sasan Saatchi, personal communication, Fig 13). These data are being used to drive regional simulations in RAMS. We are running a pair of three-month simulation on a large regional domain (June, July, and August of 2001, encompassing the period of the Santarém Mesoscale Campaign). The control case uses the standard vegetation classification and water coverage of the IGBP-DISCover product (version 2), whereas the second experiment adds the fractional water coverage derived from the SAR mosaic. The domain total coverage by water in the control experiment is 4%, vs 24% in the SAR-derived experiment. The extra surface water in the SAR experiment is expected to produce substantial changes in the Bowen ratio of he surface energy fluxes, the development of the PBL in the model, the formation and spatial variations of clouds, and the hydrologic cycle. These changes will be evaluated in terms of the observed meteorology during the period, including the daily soundings and PBL SODAR data collected at Santarém and Belterra during the SMC.

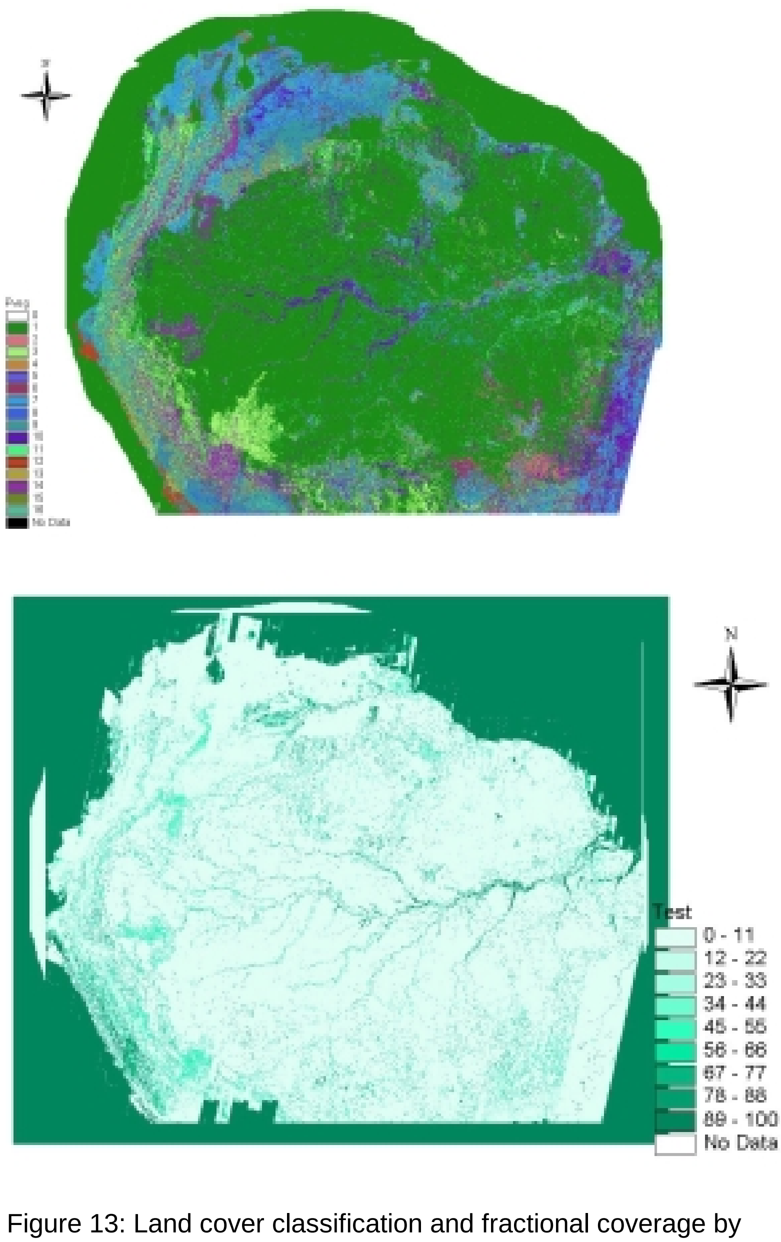

Figure 13: Land cover classification and fractional coverage by surface water, derived from JERS-1 imagery by S. Saatchi

In addition to the effects of surface water on the physical climate of the region, we are also evaluating the effects of CO_2 evasion from the surface waters in light of the recent work by Richey *et al* (2002). We have assumed that all water in the region emits an avsion flux of 5 μMol m^{-2} s^{-1} of CO_2 (J. Richey, personal communication), and prescribed this flxu as a boundary condition in the RAMS simulations. This “extra” CO_2 is transported in the atmospheric model as a separate tracer, so that we can isolate the change in spatial and temporal structure in CO_2 that would arise from a flux of this magnitude. Since the transport of a passive tracer like CO_2 is linear, we can scale the evasion flux to evaluate different scenarios of its magnitude. Preliminary results suggest that this flux may be too strong in the region of the Flona Tapajos (see Fig CC).

In collaboration with the CD-02 (Ehleringer/Martinelli), CD-06 (Richey/Ballester), TG-06 (Tans/Artaxo), and COBRA-BRAZIL teams, we are also planning a set of experiments using combined surface and airborne measurements to estimate river evasion fluxes (see attached letters of collaboration). Specifically, we will use the coupled SiB2-RAMS model to estimate CO_2 fluxes and stable isotope ratios of night-time respiration across the Tapajos region on a 1-km grid during measurement campaigns. Transport of CO_2 and $^{13}CO_2$ would also be simulated on the 1-km grid. These simulations would be evaluated at local scales by comparison to flux tower measurements. The stable isotope ratios of soil respiration and vegetation in forests and pastures, and in river water would be measured by Ehleringer *et al* (CD-02), and the surface water pCO_2 and evasion flux would be estimated for the Tapajos River by Richey *et al* (CD-06). These measurements would be used to parameterize the evasion flux and isotope ratios in RAMS. We would use the model to predict the deveopment of the night-time maximum of CO_2 over the Tapajos River, and the contributions of evasion and drainage flow from the land. Samples of air would be collected from boats in the River during the night for comparison to these simulations. In the early morning, samples would also be collected from low-flying aircraft (hired from a local air taxi service with local pilots) to document the spatial gradients of CO_2 and $\delta^{13}C$ under the stable boundary layer from west to east in a set of transects from forest across the River to the Flona Tapajos and on to the pasture site beyond. Both the Ehleringer (CD-02) and Tans (TG-06) teams have expressed interest in collecting these samples, which would be analyzed by a laboratory in São Paulo by LBA-ECO collaborators. We would use the LPDM trajectory model and RAMS, and the very distinct isotope ratios of each of the component fluxes to separate the contributions of pasture, forest, and River evasion to the development and maintenance of spatial gradients in CO_2 in the stable boundary layer. The mesoscale inversion method we have developed under LBA-E funding provides estimates of uncertainty as well as fluxes.

In addition to the targeted simulations and field experiments described above, we will address the influence of CO_2 evasion from water and seasonally flooded land by performing regional inversion calculations using data collected during the COBRA-BRAZIL campaigns and from the regular profiling done by the Tans/Bakwin/Artaxo team (TG-06). These regional flux estimates will include contributions by forests, cerrado, pasture, combustion, and water. The use of multiple tracers (CO_2, CO, $\delta^{13}C$) will allow some source attribution to be made within the regional mass-balance.

Regional and Global Inversions of Atmospheric Data

One of the major objectives of our work with regional and global tracer transport models has been the application of these models to inversion of trace gas concentrations to estimate surface fluxes. This method is applied as follows (e.g., Tarantola, 1987): CO_2 sources and sinks are decomposed into separate "basis functions" according to patterns in space, time, or processes. Responses to unit fluxes from each region or process or time slice are then computed using a forward tracer transport model. Linear combinations of these fluxes are then constructed, and the magnitudes of each basis flux is estimated by optimizing the fit of these combinations to observations, subject to constraints. Inverse modeling of area-averaged surface fluxes can leverage process studies in LBA-ECO by providing truly integrated estimates of the sum of all processes affecting CO_2 fluxes across huge areas and over long periods of time (e.g., months, years).

We propose to estimate integrated CO_2 fluxes from atmospheric measurements at three different time/space scales: (1) Surface water evasion fluxes will be estimated from data collected during one or more field campaigns, using high-resolution simulations with RAMS; (2) regional fluxes due to combustion, photosynthesis, respiration, and evasion will be estimated during the COBRA-BRAZIL campaigns using coarser resolution simulations of a much larger domain; and (3) monthly mean Basin-wide fluxes will be estimated over at least a year from time series of discrete samples using global tracer transport models. In each of these experiments, we will estimate the flux of CO_2 at the surface over well-defined spatial domains and time periods and also the uncertainty in these fluxes.

Estimation of the evasion flux of CO_2 from airborne observations across the forest-river-forest transect is essentially a scaling exercise of the "signal" revealed in Fig 2: given a model of the effect of each unit of evasion flux, one must measure the actual structure of the concentration field and then determine the magnitude of the flux by optimization. Uncertainties arise in such a calculation from errors in the atmospheric model and the observations, and will be propagated through the calculation to estimate the uncertainty of the fluxes *a posteriori*. Fortunately, this problem can be better constrained by observations of multiple tracers, because fluxes of CO_2

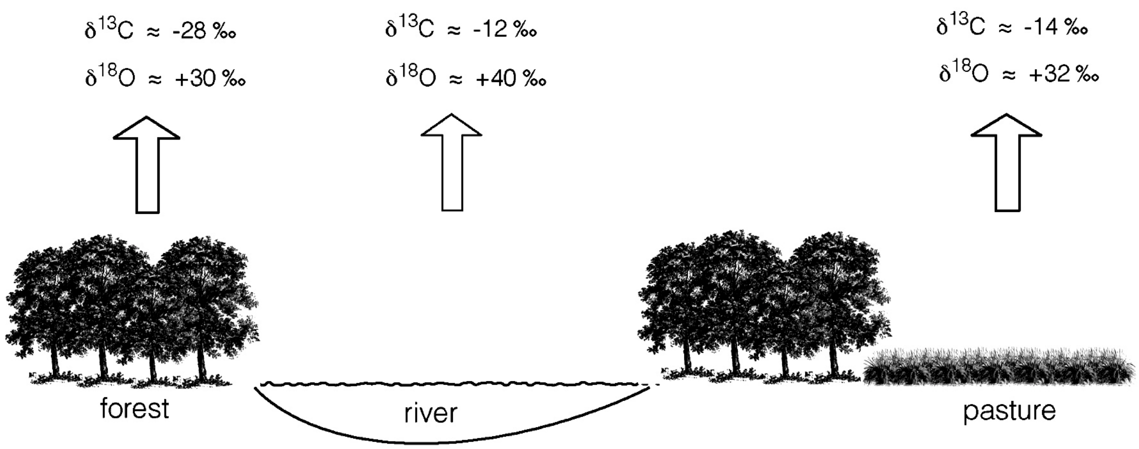

Figure 14: Expected stable isotope ratios of nocturnal CO_2 fluxes from three components of the Tapajos landscape (J. Ehleringer, per. comm.)

arising from exchange with C_3 forest, C_4 pasture, and the water each has a unique isotopic composition (Fig 14). In RAMS, we will simulate response functions (spatial and temporal variations in concentration) for three separate tracers: CO_2, $^{13}CO_2$, and $C^{16}O^{18}O$. The stable isotope ratios of each component flux will be estimated using *in-situ* measurements of organic matter, river water, soil pore water and gases, and Keeling plots made during the campaigns. These isotope ratios will be specified in the inversion basis functions as prior estimates with uncertainties, as will the space-time structure of the fluxes themselves, from highly-resolved SiB2 simulations. These priors will then be adjusted through the inversion procedure by comparing the mesoscale response functions to observations of all three tracers made during the night over the river and in the early morning atmosphere before the nocturnal stable layer begins to break up. Model transport features will be evaluated against observed meteorology and used to propagate transport error through the calculation to return *a posteriori* estimates of flux uncertainty.

At the regional scale, we will produce daily RAMS model simulations of the entire Amazôn Basin during the COBRA-BRAZIL intensives (operational support is provided by the MASTER lab at USP, see attached subcontract). These simulations will be used to compute upstream influence functions ("footprints") using the Lagrangian Particle Dispersion Model (LPDM). These simulations will be performed prior to each flight for operational planning under other support, and will later be repeated using reanalysis data for maximum realism of the simulated meteorology. Wofsy *et al* have designed their campaigns to allow direct estimation of area-averaged surface fluxes by mass-balance techniques (airmass-following flight plans and convective boundary-layer budgeting). Regional application of synthesis inversion methods is complementary to these methods, but is complicated by the need to know initial conditions and inflow fluxes through lateral boundaries. We have developed a method for regional synthesis inversion that treats these initial distributions and inflow fluxes as additional unknowns, and estimates them as well as surface fluxes, with *a posteriori* uncertainty (Uliasz *et al*, 2000; Denning *et al*, 2001). Given appropriate distributions of observations, the method has been shown to be successful in separately recovering component fluxes due to photosynthesis and respiration from synthetic data, because of their different concentration response functions. We will also apply the multiple tracer constraint to the inversion of COBRA-BRAZIL data, using CO_2, $\delta^{13}C$, and CO observations. Using the regional transport simulation, we will estimate surface fluxes and their uncertainty. The use of CO will add information on the effects of combustion, and $\delta^{13}C$ will add information on the regional contributions of C_3 and C_4 ecosystems to the net flux.

Inversion of concentration data from the flask observing network with global tracer transport models has the advantage that there are no lateral boundaries and the overall mass-balance (sum of all sources and sinks) is well known. Annual CO_2 exchanges with the tropical continents is notoriously poorly constrained by these models given the current observing network (e.g., Gurney *et al*, 2002), because there are so few stations in the region and deep convective mixing reduces the impact of these fluxes at the surface. As part of an intercomparison of every model in the world used for these calculations, response functions were produced for unit fluxes from each of 22 regions in each of 12 months (Gurney *et al*, 2001, 2002). We have used a number of these response functions to investigate the impact on the inversion for Amazonian fluxes of the collection of weekly vertical profiles collected over Santarém and off the coast east of Fortaleza, as is proposed by Tans, Bakwin, and Artaxo (TG-06). Without these stations, the mean a posteriori uncertainty in annual mean CO_2 flux from tropical South America is 0.9 GtC yr^{-1}, almost identical to the prior uncertainty of 1.0 GtC yr^{-1} (Table 1). Adding the weekly LBA-ECO airborne profiles reduced the model-mean a posteriori uncertainty by almost a factor of three, to just 0.35 GtC yr^{-1}.

	Current Network	Current network **+ weekly LBA-ECO profiles**
Model 1	0.89	0.08
Model 2	0.89	0.52
Model 3	0.92	0.73
Model 4	0.91	0.25
Model 5	0.85	0.16
Model 6	0.90	0.22
Model 7	0.89	0.47
Mean	**0.89**	**0.35**

Table 1: A priori uncertainty (GtC yr^{-1}) in annual mean CO_2 flux from Amazonia

Monthly response functions are available to us for 11 global models for estimation of fluxes from each region in each month of the year. When the LBA-ECO profile data become available, we will perform global inversions using the entire suite of models, to estimate the monthly Basin-wide CO_2 flux and its uncertainty, including an estimate of the uncertainty associated with transport error. We will also investigate the possible improvement of the inversion constraint on the Basin-wide flux by adding the $\delta^{13}C$ data to try to separately estimate the contribution of C_3 (forest) and C_4 (pasture and cerrado) ecosystems to the integrated flux. We will also investigate the possibility of subsampling the timeseries of high-precision CO_2 measurements at the flux towers for use in the inversions by evaluating several methods for estimating free tropospheric values by correcting for surface layer offsets and diurnal variations (e.g., Potosnak *et al*, 1999). This will be done by comparing such estimates to monthly means measured by the weekly vertical profiles, and in the context of information about tropospheric variations from the COBRA-BRAZIL campaigns. Finally, we will investigate the possible added constraint of global column CO_2 estimates retrieved from the AIRS instrument on EOS-Aqua and/or SCHIAMCHY on EnviSat (C. Barnet, personal communication).

Expected Significance

The research proposed here is expected to provide quantitative estimates (including uncertainty) of area-averaged CO_2 exchange by both forward, process-based modeling and inversion of atmospheric concentrations on local, regional, and Basin scales. Local and regional mass-balance will be used to evaluate process models and separate the contributions of disturbed C_4 and undisturbed C_3 ecosystems, and evasion from surface waters and seasonally inundated land. Regional and global inverse modeling constrained by additional tracers (CO and $\delta^{13}C$), better prior knowledge (from the process models), and most importantly by additional data (weekly LBA-ECO profiling) is expected to dramatically reduce the uncertainty in the annual mean carbon balance of the Amazôn region. Ironically, adding significant observational constraint to here may reduce the uncertainty in inversion estimates of CO_2 budgets in the midlatitudes more than adding new observations in the temperate zone, because the models will no longer be able to "hide the residual" in the unconstrained tropics!

By systematically ***evaluating the process models*** and their ability to integrate across scales, we expect to provide quantitative relationships between environmental ***forcing*** and carbon cycle ***responses*** in controlling the observed ***variability*** of atmospheric CO_2. In this way we hope to improve the ability to distinguish between conflicting ***predictions*** about the future evolution of the carbon cycle.

Synthesis and Integration

The proposed research is precisely a set of synthesis and integration activities. We intend to add value to the data collected by other research teams in both LBA-ECO and LBA-HYDROMET, using them for model evaluation across spatial scales and for making defensible regional and Basin-scale estimates of the effects of locally-studied processes. We have designed a set of activities that are directly collaborative and provide regional context for eddy flux studies (CD-03, CD-04, CD-10), ecophysiology/biogeochemical studies (CD-02), inundation/flooding studies (CD-06, LC-07, LC-15), and trace gas studies (TG-06, TG-01). The regional atmospheric modeling we propose here, especially coupled to process-based flux and stable isotope algorithms, is an excellent framework for interpreting and understanding the results of the COBRA-BRAZIL experiments (see attached letter of collaboration).

The investigation of the effects of surface water and inundated land on the water, energy, and carbon exchanges that we propose here will be conducted at local, regional, and Basin scales. Modeling at each scale will be paired with observational and experimental work planned by collaborators, so that we avoid over-reliance on the model at scales that have not been observed. Many climate models systematically underestimate the effects of extensive surface water and seasonally flooded land in the tropical lowlands, which undoubtedly affects their ability to simulate the regional Bowen ratio, convection, and the export of moist static energy from the tropics by the Hadley circulation. Regional energy and water budgets are the domain of LBA-HYDROMET, but the regional modeling and observations conducted by LBA-ECO in the next three years will certainly inform and assist that community as well. Much of the precipitation in Amazônia is recycled from evapotranspiration in the region, so neglect of subgrid-scale surface water may cause climate models to develop undue physiological stress over tropical forests. This could contribute to the simulated demise of the Amazôn forests in coupled climate/carbon cycle simulations (Cox *et al*, 2000), so the links to carbon and LBA-ECO go beyond the effect of direct CO_2 evasion fluxes from the water.

The use of stable isotopes in CO_2 in both the forward models and in the multitracer inversions we have proposed gives us unique opportunities for integration and synthesis. In the forward simulations, predicting stable isotope ratios of CO_2 in the canopy and overlying atmosphere allows us to test the representation of the mechanisms that produce CO_2 variations. We will work closely with the Ehleringer and Goulden teams to use this information to make sure we are not getting the right answers for the wrong reasons. In inverse calculations, the use of stable isotope ratios allows us to deconcolve the contributions of C_3 forests and C_4 cerrado and pasture to regional fluxes, providing a window into the effects of human disturbance and land use on the carbon balance of the region. These multitracer methods have the potential to facilitate continuing basin-scale monitoring of C_3 /C_4 conversion using atmospheric data and remotely sensed imagery after the LBA experiment is complete.

It is to be reasonably hoped that a better constraint on carbon balance of the Amazôn will allow more complete understanding of global changes in carbon cycling from top-down methods as well. Our results will be directly relevant to global inversion and flask sampling programs.

References

Battle, M., M.L. Bender, P.P. Tans, J.W.C. White, J.T. Ellis, T. Conway, and R.J. Francey, Global carbon sinks and their variability inferred from atmospheric O_2 and $\delta^{13}C$, *Science*, ***287*** (5462), 2467-2470, 2000.

Berry, J. A., 1989. Studies of mechanisms affecting the fractionation of carbon isotopes in photosynthesis. In: P. W. Rundel, J. R. Ehleringer, and K. A. Nagy (Eds.), Stable Isotopes in Ecological Research, Springer-Verlag, 82-94.

Bowling, D.R., N.G. McDowell, B.J. Bond, B.E. Law, and J.R. Ehleringer. 2002. ^{13}C content of ecosystem respiration is linked to precipitation and vapor pressure deficit. *Oecologia* (in press).

Chou, W. W., S. C. Wofsy, R. C. Harris, J. C. Lin, C. Gerbig, and G. W. Sachse, 2002. Net fluxes of CO_2 in Amazônia derived from aircraft observations. *Jour. Geophys. Res.*, in press.

Ciais, P., P.P. Tans, J.W. White, M. Trolier, R. Francey, J. A. Berry, D. Randall, P.J. Sellers, J.G. Collatz, and D.S. Schimel, Partitioning of ocean and land uptake of CO2 as inferred by $\delta^{13}C$ measurements from the NOAA Climate Monitoring and Diagnostic Laboratory global air sampling network, *Journal of Geophysical Research*, *100*, 5051-5070, 1995.

Ciais, P., P.P. Tans, M. Trolier, J.W.C. White, and R. J. Francey, A large northern hemisphere terrestrial sink induced by the ^{13}C /^{12}C ratio of atmospheric CO_2, *Science*, **269**, 1098-1102, 1995.

Cohen, J. C. P., M. A. Silva Dias and C. A. Nobre, 1995. Environmental conditions associated with Amazonian squall lines: Case study. *Mon. Wea. Rev.*, **123**, 3163-3174.

Collatz, G. J., J. T. Ball, C. Grivet, and J. A. Berry, Physiological and environmental regulation of stomatal conductance, photosynthesis, and transpiration: a model that includes a laminar boundary layer, *Agric. and Forest Meteorol*., **54**, 107-136, 1991.

Collatz, G. J., M. Ribas-Carbo, and J. A. Berry, Coupled photosynthesis-stomatal conductance model for leaves of C4 plants, *Aust. J. Plant Physiol*., **19**, 519-538, 1992.

Cox, P., R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell, 2000. Acceleration of global warming due to carbon cycle feedbacks in a coupled climate model. *Nature*, **408**, 184-187.

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

Denning, A. S., J. G. Collatz, C. Zhang, D. A. Randall, J. A. Berry, P. J. Sellers, G. D. Colello, and D. A. Dazlich, 1996. Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 1: Surface carbon fluxes. *Tellus*, **48B**, 521-542.

Denning, A. S., D. A. Randall, G. J. Collatz, and P. J. Sellers, 1996. Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 2: Spatial and temporal variations of atmospheric CO_2. *Tellus*, **48B**, 543-567.

Denning, A.S., M. Holzer, K.R. Gurney, M. Heimann, R.M. Law, P.J. Rayner, I.Y. Fung, S.-M. Fan, S. Taguchi, P. Friedlingstein, Y. Balkanski, J. Taylor, M. Maiss and I. Levin, 1999: Three-dimensional transport and concentration of SF_2: A model intercomparison study (TransCom 2). *Tellus*, **51B**, 266-297.

Denning, A.S., L. Prihodko, N. Suits, M. Uliasz, M. Nicholls, N. Hanan, E. Inazawa, and P.-L. Vidale, 2000: Estimating the exchange of CO_2 and its stable isotopes between Amazonian ecosystems and the atmosphere at multiple spatial scales. Presented at First LBA Scientific Conference, Belem, Brazil.

Denning, A. S., M. Uliasz, P. Silva Dias, M. A. Silva Dias, M. Nicholls, E. Inazawa, N. Suits, and R. Desjardins, 2000. Top-down constraints on regional CO2 flux in Amazonia: Inverse atmospheric modeling at multiple spatial scales. Presented at the Fall 2000 AGU Meeting, San Francisco. Abstracts, B52B-20.

Denning, A. S., M. Uliasz, R. Desjardins, E. Inazawa, M. Nicholls, L. Prihodko, L. Lu, P. Silva-Dias, and M. A. Silva-Dias, 2001. Atmospheric fingerprinting of CO_2 exchanges in Amazônia. Presented at the Second LBA Scientific conference, Atlanta, USA.

Devol, A. H., Forsberg, B.R., Richey, J.E. & Pimentel, T.P. Seasonal variation in chemical distributions in the Amazon (Solimões) River: a multiyear time series. *Global Biogeochemical Cycles* **9,** 307-328 (1995).

Engelen, R.J., A.S. Denning, K.R. Gurney and G.L. Stephens, 2001. Global observations of the carbon budget: I. Expected satellite capabilities in the EOS and NPOESS eras. *Journal of Geophysical Research*, **106,** (D17), 20055-20068.

Farquhar, G. D., S. von Caemmerer and J. A. Berry, A biochemical model of photosynthetic CO2 assimilation in C3 plants, *Planta*, **149**, 78-90, 1980.

Francey, R.J., P.P. Tans, C.E. Allison, I.G. Enting, J.W.C. White, and M. Trolier, Changes in oceanic and terrestrial carbon uptake since 1982, *Nature*, ***373***, 326-330, 1995.

Friedlingstein, P., L. Bopp, P. Ciais, J.-L. Dufresne, L. Fairhead, H. LeTreut, P. Monfray, and J. Orr, 2001. Positive feedback between future climate change and the carbon cycle. *Geophys. Res. Lett*. **29**:1543-1546.

Freitas, S.R., M.A.F. Silva Dias, and P.L. Siva Dias, K.M.Longo, P. Artaxo, M.O. Andreae and H. Fischer, 2000: A convective kinematic trajectory technique for low-resolution atmospheric models. *J.Geophys. Res*., **105**, D19, 24,375-24,386.

Garstang, M. et al., Amazon coastal squall lines. Part 1: Strucutre and Kinematics. Mon. Wea. Rev., 122, 608-622, 1994

Gloor, M., S.-M. Fan, S. Pacala, and J. Sarmiento, 2000. Optimal sampling of the atmosphere for purpose of inverse modelling: A model study. *Global Biogeochemical Cycles* **14**: 407-428.

Grace, J. *et al.* Carbon dioxide uptake by an undisturbed tropical rain forest in Southwest Amazônia, 1992 to 1993. *Science* **270**, 778-780 (1995).

Grace J, Malhi Y, Lloyd J, McIntyre J, Miranda AC, Meir P, Miranda HS (1996)The use of eddy covariance to infer the net carbon dioxide uptake of Brazilian rain forest. *Global Change Biology*, **2**, 209-218.

Grell, G., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev*., **121**, 764-787

Gurney, K.R., R. M. Law, A. S. Denning, P. J. Rayner, D. Baker, P. Bousquet, L. Bruhwiler, Y.-H. Chen, P. Ciais, S. Fan, I.Y. Fung, M. Gloor, M. Heimann, K. Higuchi, J. John, T. Maki, S. Maksyutov, K. Masarie, P. Peylin, M. Prather, B.C. Pak, J. Randerson, J. Sarmiento, S. Taguchi, T. Takahashi and C.-W. Yuen, 2001: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. *Nature*, **415**, 626-630, Feb. 2002.

Inazawa, E.E., A.S. Denning, M. Nicholls and N. Hanan, 2000: *Coupled Simulations of Physical Climate and CO_2 Exchange in Rondonia.* Presented at First LBA Scientific Conference, Belem, Brazil.

Inazawa, E.E., A.S. Denning, M. Nicholls and L. Prihodko, 2000: *Simulations of physical climate and CO_2 exchange in Rondonia and Para (Amazonia).* Presented at Fall Meeting of the American Geophysical Union, December 14-19, 2000, San Francisco, CA.

Keeling, C.D., T.P. Whorf, M. Wahlen, and J. van der Plicht, Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, *Nature*, ***375***, 666-669, 1995.

Krebs, T., J. Berry, A.S. Denning, N. Suits and J. Ehleringer 2001: Measuring and modeling the component influences of soil, vegetation and the atmospheric source on the isotope composition of canopy air. Presented at AGU Fall Meeting, 2001, San Francisco, CA.

Lloyd, J. and G.D. Farquhar, ^{13}C discrimination during CO_2 assimilation by the terrestrial biosphere, *Oecologia*, ***99***, 201-215, 1994.

Lloyd, J., B. Krujit, D.Y. Hollinger, J. Grace, R.J. Francey, S.-C. Wong, F.M. Kelliher, A.C. Miranda, G.D. Farquhar, J.H.C. Gash, N.N. Vygodskaya, I.R. Wright, H.S. Miranda, and E.D. Schulze, Vegetation effects on the isotopic composition of atmospheric CO_2 at local and regional scales: theoretical aspects and a comparison between rain forest in the Amazonia and a boreal forest in Siberia. *Australian Journal of Plant Physiology, **23**, 371-399*, 1996.

Law, R.M., P.J. Rayner, A.S. Denning, D. Erickson, M. Heimann, S.C. Piper, M. Ramonet, S. Taguchi, J.A. Taylor, C.M. Trudinger and I.G. Watterson, 1996: Variations in modeled atmospheric transport of carbon dioxide and the consequences for CO_2 inversions. *Global Biogeochemical Cycles*, **10**, 783-796.

Lu, L., A.S. Denning, P. Silva-Dias, M. Silva-Dias, J. Richey, M. Uliasz and E. Inazawa, 2001: *Simulated Mesoscale Circulations and CO_2 Concentration Variations in the Tapajos Region, Para, Brazil*. Presented at Spring AGU Meeting, May 29-June 2, 2001, Boston, MA.

Lu, L., A.S. Denning, J. Richey, P. Silva-Dias, M. Assuncao da Silva-Dias, K. Schaefer and E. Inazawa, 2001: *The potential influence of river and wetland CO_2 fluxes on regional carbon balance in the Tapajos Region, Para, Brazil.* Presented at 4th International GEWEX Meeting, Sept 11-14, 2001, Paris, France.

Malhi, Y. *et al.* 1998. Carbon dioxide transfer over a Central Amazonian rain forest. *Journal of Geophysical Research* **103**, 31,593-31,612.

Malhi, Y. and J. Grace, 2000. Tropical forests and atmospheric carbon dioxide. *Trends in Ecology and Evolution* **15**:332-337.

Nicholls, M.E., R.A. Pielke, J.L. Eastman, C.A. Finley, W. A. Lyons, C. J. Tremback, R.L. Walko, and W.R. Cotton, 1995: Applications of the RAMS numerical model to dispersion over urban areas. *Wind Climate in Cities*, J.E. Cermak *et al* . Eds., 703-732.

Ometto, J.P.H.B., L.B. Flanagan, L.A. Martinelli, M.Z. Moreira, N. Higuchi, and J.R. Ehleringer, 2002. Carbon isotope discrimination in forest and pasture ecosystems of the Amazon Basin, Brazil. *Global Biogechemical Cycles* (in press).

Phillips, O.L., Y. Malhi, N. Higuchi, W.F. Laurance, P. Nuñez V., R. Vásquez M., S.G. Laurance, L.V. Ferriera, M. Stern, S. Brown, and J. Grace, 1998. Changes in the carbon balance of tropical forest: evidence from long-term plots. *Science* **282**: 439-442.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, 1992. A comprehensive meteorological modeling system - RAMS. *Meteor. Atmos. Phys.*, **49**, 69-91.

Potosnak, M.J., S.C. Wofsy, A.S. Denning, T.J. Conway and D.H. Barnes, 1999. Influence of biotic exchange and combustion sources on atmospheric CO_2 concentrations in New England from observations at a forest flux tower. *Journal of Geophysical Research*, **104**, 9561-9569.

Prihodko, L., A. S. Denning, K. Schaefer, T. Krebs, 2001. Creating Mesoscale Land Surface Datasets for Regional Modeling of the WLEF-TV Tower Site, Wisconsin. Submitted to *Global Change Biology*.

Quay, P., King, S., Wilbur, D., Wofsy, S. & Richey, J. $^{13}C/^{12}C$ of atmospheric CO_2 in the Amazon Basin: forest and river sources. *Journal of Geophysical Research* **94**, 18327-18336 (1989).

Randerson, J. T., G. J. Collatz, J. E. Fessenden, A. D. Munoz, C. J. Still, J. A. Berry, I. Y. Fung, N. Suits, and A. S. Denning. A possible global covariance between terrestrial gross primary production and ^{13}C discrimination: Consequences for the atmospheric ^{13}C budget and its response to ENSO. Submitted to *Global Biogeochemical Cycles*.

Rayner, P. J., I. G. Enting, and C. M. Trudinger, 1996. Optimizing the CO_2 observing network for constraining sources and sinks, *Tellus*, **48B**, 433-444.

Richey, J.E., Devol, A.H., Wofsy, S.C., Victoria, R. & Ribeiro, M.N.G. Biogenic gases and the oxidation and reduction of carbon in the Amazon River and floodplain waters. *Limnology and Oceanography* **33**, 551-561 (1988).

Richey, J.E. *et al*. Biogeochemistry of carbon in the Amazon River. *Limnology and Oceanography* **35**, 352-371 (1990).

Richey, J. E., J. M. Melack, A. K. Aufdenkampe, V. M. Ballester, and L. L. Hess, 2002. Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2. *Nature*, in press.

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

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

Silva Dias, M.A.F., 1999. Storms in Brazil. In: *Hazards and Disasters Series, Storms Volume II*, R. Pielke Sr. , R. Pielke Jr., Eds., Routledge, 207-219.

Sippel, S.J., S.K. Hamilton, J.M. Melack, and E.M.M. Novo, 1998: Passive microwave observations of inundation area and the area/stage relation in the Amazon river floodplain. *Int. J. Remote Sensing*, **19**, 3055-3074.

Suits, N.S., A.S. Denning, J.A. Berry, C.J. Still, J.Kaduk and J.T. Randerson, 2001: Seasonal and spatial variations in carbon isotopic ratios of plant biomass, terrestrial CO_2 fluxes and atmospheric CO_2. Submitted to *Global Biogeochemical Cycles.*

Uliasz, M. and R.A. Pielke, 1991: Application of the receptor oriented approach in mesoscale dispersion modeling. *Air Pollution Modeling and Its Application VIII*, eds. H. van Dop and D. G. Steyn, Plenum Press, New York, 399-408.

Uliasz, M., A. S. Denning and N. Gimson, 2000: *A Modeling Approach to design a mesoscale sampling campaign in order to estimate surface emissions.* Presented at 11th Joint Conference on the Applications of Air Pollution Meteorology with the A&WMA. American Meteorological Society, 9-14 January, 2000, Long Beach, CA.

Walko, R.L., C.J. Tremback, R.A. Pielke, and W.R. Cotton,1995*a*: An interactive nesting algorithm for stretched grids and variable nesting ratios. *J. Appl. Meteor.*, **34**, 994-999.

Walko, R. L, W. R. Cotton, J. L. Harrington, M. P. Meyers, 1995*b*: New RAMS cloud microphysics parameterization. Part I: The single-moment scheme. *Atmos. Res.*, **38**, 29-621.

Wofsy, S. C., Harriss, R. C. & Kaplan, W. A. Carbon dioxide in the atmosphere over the Amazon basin. *Journal of Geophysical Research* **93**, 1377-1388 (1988).

Training and Education Plan

We understand that it is a goal of NASA to provide educational support to Brazil, resulting in strong collaborative relationships as well as supporting Brazil's environmental and global change research community. For our part, we are committed to this goal and plan to support it in several ways.

We have recruited a Ph.D. level student, Ms. Elicia Inazawa, from the Universidade de São Paulo, who continues to work with us using her extensive experience with Amazonian meteorology and numerical modeling. She is studying forward and inverse modeling of land-atmosphere exchanges of CO_2, and we anticipate that she will receive her Ph.D. and return to Brazil during the period of this study.

We will also continue our close collaboration with Professors Pedro and Maria Assuncao Silva Dias and their research group at the Universidade de Sao Paulo. In this renewal proposal, we have also sought support for collaborative work with Dr. Saulo Freitas at USP, who is a young scientist interested in convective transport and trace gas modeling..

We will make a major effort in this renewal in technology transfer. We have budgeted for a 10-week scientific visit by USP scientists to CSU, and several shorter visits by CSU scientists to USP to accomplish this. We will port our CO_2 and stable isotope codes to the USP version of RAMS, including the specification of surface properties from satellite imagery. They will port a new parameterization of deep cumulus convection and its effects on tracer gas transport into our version of the model.

We have also requested funding for the development of a short-course on numerical modeling, to be made available to Brazilian students and others through the World Wide Web. The course is targeted at advanced undergraduates or beginning graduate students. The content of this course has already been largely developed, but requires modification before it will be accessible enough for a web-based audience. The material has been developed for undergraduate level university students, and is intended to introduce them to the basic ideas and methods of numerical analysis and simulation. The course consists of seven chapters:

1) Introduction to numerical modeling
2) Finite difference equations and time differencing schemes, Part I
3) Dynamical systems and the development of a mathematical model
4) Time differencing schemes, Part II
5) Constrained optimization
6) Waves, Fourier transforms, and spectral space
7) Transport

The module also contains four sets of exercises, a math refresher to review concepts and techniques in undergraduate level mathematics, and exams. This course will help students to understand that, in modeling, equations are not problems to be solved but rather are parts of a language used to describe the world. After working through and understanding the course materials, the students will know what deterministic modeling is and will understand some common modeling pitfalls.

This web-based course will allow students and teachers in remote areas to gain an understanding of numerical modeling, preparing them for further work in the subject. It is basic enough to be of use to advanced undergraduates, while remaining scientifically accurate, so that nothing will have to be unlearned as the student advances and the problems become more complex.

We have not budgeted for the translation of this material into Portuguese, but would be excited to work with NASA on having this done at the discretion of the Program Manager.

Finally, we are interested in developing one or more short articles on numerical modeling and climate change, which we believe will be suitable for the Earth Science Enterprise *NASA Facts* series of pamphlets.

Data Plan

Unlike the first phase of our project, we do not plan to perform any measurements in the field under LBA-ECO. Instead, we will concentrate entirely on numerical modeling and data analysis, in collaboration with other teams making measurements. We anticipate producing a very large volume of model output, and will make these results available to the LBA data management system within 6 months of producing them, allowing time for quality assurance, data reduction, and documentation.

We will share any and all data and model results through the LBA data and information system. We will host our own data and model output on a server computer with large disk storage at CSU (included in our budget). Metadata will be stored on Beija-Flor, including detailed descriptions and documentation of the numerical experiments and the algorithms by which the model output was produced. Metadata will also include actual model code and documentation, as well as input data sets and sample experiments.

We will produce the following types of model output:

- Simulated hourly timeseries of fluxes of heat, water, momentum, CO_2, and $^{13}CO_2$ at each of the LBA-ECO flux towers for several years;
- Highly resolved (Δx=100 m, Δz = 30 m, Δt = 1 minute) simulations of CO_2 and $\delta^{13}C$ in the PBL and lower troposphere over the forest and pasture tower sites in the Tapajos region;
- Mesoscale simulations (Δx=1 km) of river-breeze dynamics and CO_2 and $\delta^{13}C$ anomalies associated with CO_2 evasion from the Tapajos River over a single diurnal cycle;
- Regional meteorology, CO_2 and $\delta^{13}C$ over the entire Basin for two one-month periods on a 10 km grid;
- Multiyear simulations of hourly surface fluxes of CO_2 and $^{13}CO_2$ on a 1-degree grid over the entire Basin;
- Particle trajectory analyses for each flight during the COBRA-BRAZIL campaigns.

Management Plan

The Principal Investigator (Denning) will be responsible for overall intellectual leadership in the development and implementation of the models, mentoring the graduate student assistant, and coordination and planning of the research activities. In addition, Denning will manage the extensive collaborative outreach proposed with other LBA-ECO projects.

We have budgeted $40,000 per year for a subcontract with our colleagues at the Universidade de São Paulo, who will be providing technical assistance with the numerical modeling and analysis of regional meteorology during the study. Please see the attached letter of commitment and Statement of Work for details.

The Research Scientist (Nicholls) will be responsible for consulting with the USP scientists in implementing the SiB2 carbon model into the parallel version of RAMS, and conducting experiments on the influence of organized cumulus convection of trace gas species, including analyzing and reporting results through publications and presentations.

The Research Associate (Lu) will be primarily responsible for simulations of regional scale case studies of the influence of surface water and seasonally inundated land on exchanges of water, energy, and CO_2 between the land and atmosphere, including analyzing and reporting results through publications and presentations.

Research Associate (M. Uliasz) will be responsible for our method for estimating spatially-resolved ecosystem carbon fluxes from airborne measurements of CO_2 concentrations. He will also continue to extend the regional flux estimation methodology by performing "pseudodata" inversions using the data from the analysis we prepare.

Our scientific and systems programmer (Kleist) will procure, set up and monitor the data archival system and software requested, assist with the analysis of the data for the study areas, and administer the computer systems required to conduct the research. Additionally, he will be responsible for making the processed data available through the Denning group website and submitting the megadata to LBA-DIS.

Our Research Coordinator (C. Uliasz) will produce scientific graphics and be responsible for Web development and for logistical duties communication and collaboration. Additionally, she will be responsible for the development and management of the web-based modeling course. She has several years of experience teaching, and has been a Graduate Teaching Assistant, working with university undergraduates for 4 years.

The Graduate Research Assistant (Inazawa) received her M.S. in Atmospheric Science from the Universidade de São Paulo under the supervision of Prof. Maria Assuncao Silva Dias. She has extensive experience with Amazonian meteorology and with RAMS simulations. She is studying forward and inverse modeling of CO_2 fluxes and concentrations through this collaborative research project, and is expected to earn her PhD during the period funded by this proposal.

We anticipate submitting articles to peer-reviewed journals as follows:

- December, 2002: results of numerical experiments on the influence of surface waters and seasonally inundated lands at the regional scale;

- December 2002: first model evaluation of SiB2 compared to eddy fluxes from sites in and near the Flona Tapajos;

- July 2003: evaluation of regional simulations of first COBRA-BRAZIL campaigns;

- January 2004: analysis of first set of field experiments to evaluate CO_2 evasion from the Tapajos River, including our model simulations and synthesis of data collected by other teams

- July 2004: regional inversions of surface flux from data collected during COBRA-BRAZIL campaigns and Tapajos experiments;

- January 2005: analysis of interannual variability in simulated and observed fluxes and isotopic discrimination at sites in the Tapajos region

- July 2005: Analysis of seasonal, annual, and interannual Basin-scale carbon budget variations using multitracer synthesis inversion of about 10 different global tracer transport models

Progress on each of these research areas will also be reported regularly to the community at Science Team meetings, national and international conferences, and annual progress reports to NASA.